FRESH SURFACE WATER

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Summary

The occurrence of surface water in abundance is unique to planet Earth among the inner or terrestrial planets. This is only one of the environmental consequences of the anomalous properties of water. Water has been central to human life and human thought throughout history. The availability of fresh surface water varies between continents, between regions within any given continent, between countries in a given region, and between catchments in a given country. The use of available water increased by about 700 percent in the course of the twentieth century due to the combined effects of population increase and economic development. The increase in the withdrawal and use of freshwater resources has led to serious environmental impacts and raised the question of the sustainability of water resources in a number of regions. Five key topics have been identified under the theme of Fresh Surface Water. These are:

- the regional distribution of freshwater
- the characteristics of river systems
- transport processes in rivers
- river ecosystems
- impacts involving river systems.

1. Introduction

The distinction between fresh and salt water is essentially based on the total amount of dissolved solids (TDS) in the water concerned. A commonly used classification is to designate all waters as fresh water where the TDS is less than 1,000 milligrams per liter. The water is said to be brackish if the TDS lies in the general region of 10,000 to 20,000 milligrams per liter. The salt water of the ocean has an average total dissolved solids content of about 35,000 milligrams per liter. Waters in closed inland lakes are said to be brines when the total dissolved solids is more than ten times the latter amount. Surface water refers to water that is either stored in ponds or lakes on the land surface or is flowing across the surface of the ground, or is already in the network of streams and rivers conveying the water to the oceans or to closed inland seas.

Liquid water accounts for just over 97 percent of the Earth's hydrosphere but of this 96 percent is salt water and only 1.1 percent of it is fresh liquid water. Of this 1.1 percent fresh water, 99 percent is groundwater and only 1 percent is fresh surface water. Thus the fresh surface water represents only 1 part in 10,000 of the liquid hydrosphere. Nevertheless it plays a vital role in the shaping of the environment and in the maintenance of the various forms of life on this planet. Fresh water is essential to all forms of life, to human health, to food production and to most industrial processes. One quarter of the earth's population have no access to a safe water supply and water scarcity is increasing with time. One half of the world's population is without adequate sanitary facilities and over 5 million deaths per year are due to water-based and water-related diseases.

The purpose of this article is to serve as an introduction to the more detailed articles concerned with important topics on the theme of fresh surface water appearing as part of this encyclopedia. A brief historical background of various aspects of the subject will be provided and, where appropriate, related to present problems and future aspects of the topic. There will be an emphasis on the interaction between various features of the freshwater part of the liquid hydrosphere and consequently an emphasis on the inter-disciplinarity required to understand and to manage this part of the environment. Because of the increasing pressure on water resources, due both to population increase and to progress in development, attention will be given to the changing requirements for the sustainable use of fresh water resources.

2. Liquid Water on Planet Earth

2.1. Occurrence of Liquid Water

Water in some quantity and in some form exists on every planet except Mercury. Water also exists on many of the planetary satellites though not on our moon. The phase in which water occurs (solid, liquid, gaseous) depends on the temperature and the pressure at the surface of the planet in question. The Earth is unique among the planets of the solar system in the abundance of liquid water on its surface. This happens because the average surface temperature of our planet is about 15 °C and this falls within the liquid range of water which runs from 0 °C to 100 °C. This raises two questions and the answers to both are complex. The first question is: why does the surface temperature of our planet have this particular value of 15 °C? The second question is: why is the liquid range of water between 0 °C and 100 °C? The answer to each of these two questions involves a number of the strange physical and chemical properties of water, which appears to our senses as the simplest of substances.

The surface temperature of any planet depends on its distance from the sun and the nature of the planetary atmosphere. Table 1 shows the relevant data for each of the four terrestrial planets. These inner planets receive virtually all of their energy from the sun and the incoming long-wave solar flux to each planet is inversely proportional to the square of the distance from the sun. If we consider the four terrestrial planets as black bodies (i.e. no reflection of radiation), then the planetary temperatures would take the values shown in the second column of Table 1.

Planet	**Temperature (^{o} Celsius)**		
	blackbody	**effective**	**surface**
Mercury	194	189	194
Venus	79	–9	547
Earth	27	0	15
Mars	–27	–37	–35

Table 1. Planetary temperatures

Actually the planetary albedo (i.e. its reflective capacity) is not zero and varies widely because of differences in the individual planetary atmospheres. The effective surface planetary temperature of the earth including its atmosphere is about 0 °C, which is substantially lower than the present observed average global temperature at the earth's surface. The difference is accounted for by the greenhouse effect i.e. the reflection back to the surface by the atmosphere of the outgoing short wave radiation from the earth's surface.

The processes resulting in the formation of a planetary atmosphere are equally complicated (Budyko et al., 1985). It is generally believed that the present atmosphere and hydrosphere of the earth developed at a late stage of planetary evolution through the degassing of the surface mantle. The processes in the formation of the atmosphere must have been extremely complex and varied but the end result can be represented by a highly simplified view of the process.

In the case of Mars the surface temperature in the absence of any atmosphere would have been well below zero as indicated in the second column of Table1. Accordingly, as an atmosphere began to form and the atmospheric surface pressure to develop, the surface temperature would only have risen by a few degrees before the pressure reached the saturation vapor pressure of ice appropriate to the low values of temperature and pressure. Accordingly, any additional water released to the atmosphere of Mars would condense on the surface in the form of frost and the increase in surface temperature would come to an end. In the case of Venus, condensation never occurred because of the high initial temperature of around 80 °C. Accordingly, the surface temperature continued to increase producing a massive atmosphere covering the entire planet. This resulted in a runaway greenhouse effect which caused an ultimate rise in temperature of over 500 °C so that water only exists on Venus in the form of water vapor. The case of the earth is intermediate between these two extremes, with only a moderate greenhouse effect resulting in the present average global temperature of 15 °C.

The second question remains as to whether one would expect water to be liquid at 15 °C. The formula for H_2O is probably the best-known chemical formula. Since elements, which are neighbors in the periodic table, are expected to show similar chemical characteristics, we would expect that the melting point and the boiling point of water would be consistent with the values for similar compounds with hydrogen of the elements in the same column of the periodic table (sulphur, selenium, tellurium). However, water (H_2O) in its pure form is a colorless, odorless liquid between 0 °C and 100 °C, whereas the dihydride of its nearest neighbor sulphur (H_2S) is a pungent gas.

The melting points and boiling points of these group VI dihydrides increase with the molecular weight as shown by the values shown in Table 2. On the basis of the general tendency shown for the other three compounds we would expect the melting point of water to be about –100 °C and the boiling point to be about –80 °C. If this were so, then all of the water in the hydrosphere of the earth would be in gaseous form. It is clear that there is some peculiarity of water not shared by the other three compounds, which is responsible for the fact that water is liquid at a far higher temperature and over a much wider range.

Compound	Molecular weight	Melting point °C	Boiling point °C	Range °C
H_2O	18.0	0	100	100
H_2S	34.1	–82	–62	20
H_2Se	81.0	–64	–42	22
H_2Te	129.6	–51	–4	47

Table 2. Group VI dihydrides

The physical chemist explains this anomalous behavior as being the result of hydrogen bonding. This weak form of bonding arises from the fact that the water molecule is a polar molecule, i.e. is electrically balanced but has a dipole moment. One of the effects of hydrogen bonding is to increase the melting point and boiling point of a compound. As will be seen in Section 2.3, this is only one of the anomalous properties of water.

2.2. Concepts of the Water Cycle

Since water is both an essential for human life and health and a key factor in the abundance of plants and animals, human communities from the earliest time were concerned with the location of adequate supplies of fresh water. The emergence of agriculture some 10,000 years ago accentuated the need to take into account the location and the behavior of water in order to breed herds of domestic animals efficiently and to raise crops efficiently. In consequence, water was central to ancient cosmologies, to early systems of philosophy and to the early development of water technology and water science. The cosmologies of ancient peoples had many features in common and water played a prominent part in all of them. Central to nearly all of these cosmologies was the notion that the earth floated on a primeval ocean.

The transition from such ancient cosmologies to a primitive philosophical and scientific approach can be dated from the work of Thales about 580 B.C. Thales, who is generally reckoned as the first of the Greek philosophers, held not only that the earth rested on water but that water was the origin of all things. Anaximander (610–545 B.C.), who was a pupil of Thales, described the process of evaporation and thus was the first to draw attention to this main component of the water cycle. In the next generation, Xenophanes (570–475 B.C.), who was reputed to have been in turn a pupil of Anaximander, assumed that clouds were formed by evaporation from the ocean and that these clouds when transported over the land produced rain which gave rise to rivers and streams. He also explained the salt content of the sea as being due to the uptake of substances from the earth during the flow of rivers and the fact that these accumulated salts were not cleared from seawater by the evaporation. Anaxagaros (500–428 B.C.) asserted clearly that the natural processes concerning water (precipitation, runoff, evaporation) constituted a closed cycle.

For over 1,000 years afterwards, the predominant viewpoint was that the precipitation on the land surface was insufficient to account for the flow of springs and rivers. Most writers postulated a combination of first, some route from the oceans to a large body of water beneath the land surface and second, some mechanism for the raising of this water to a higher level where springs and streams originated. Thales, about 580 B.C. speculated that this rise could be due to the existence in mid-ocean of a higher surface elevation than at the margins. 200 years later, Plato postulated a great underground lake at sea level from which water rose through narrow veins in the rocks and overlying earth. Aristotle shortly afterwards suggested an alternative mechanism whereby water vapor would be formed under the ground at sea level and then rise and condense at levels close to the surface.

In the higher Middle Ages, writers such as Bartholomeus (c. A.D. 1240) accounted for the rise by suggesting that water moves through the veins of the earth and reaches the surface as springs in the same manner that blood runs through the veins of the human body and can emerge at a particular place where the surface is broken. 250 years later, Leonardo da Vinci drew a similar analogy. Kircher, who has been described as the last of the renaissance men, suggested in his book *Mundus Subterraneus* (A.D. 1664), that the lifting process could be due to the energy provided by hot springs in the interior of the earth.

The first clear assertion that rainfall over the land surface would be sufficient to provide the water in springs, streams and rivers, is attributed to Bernard Palissy (1510–1590) who is better known to history as an innovator in the glazing of pottery. In his *Discours Admirables* (1580) Palissy wrote:

> When I had long and closely examined the sources of the springs of natural fountains and the places from whence they could come, I finally understood that they could not come from or be produced by anything but rain.
>
> (Palissy, 1580)

This conclusion, for which Palissy advanced several arguments, was not verified experimentally until 100 years later, was not widely accepted until more than 200 years later, and not universally accepted until 100 years after that.

The generally accepted view that precipitation was insufficient to produce the observed runoff was not tested by measurement until towards the end of the seventeenth century. In 1674, *The Origin of Fountains* was published anonymously in Paris, and this is now generally accepted to be the work of Pierre Perrault (1608–1640). In part one of the book Perrault reviewed the opinions of previous authors and then described the problem posed by this question as requiring the measurement or estimation of the water in a river as it flows from its source, to a point of confluence. He made such observations on a catchment area of about 100 square km from the source of the Seine near Dijon to Aignay le Duc. He estimated the precipitation on the catchment on the basis of three years of rainfall measurements at Dijon and estimated the runoff by upscaling the measured flow of the Gobelins River near Versailles on the basis of the ratio of the areas of the two catchments. These calculations indicated that the runoff was only about one sixth of the rainfall, and therefore that rain was fully adequate to account for the flow of the river.

A few years later Mariotte (1630–1684) made an improved estimate of the runoff for the much larger catchment area (53,500 square km) of the river Seine at Paris. Mariotte, who was a renowned experimenter in hydraulics and physics, estimated the flow of the Seine at Paris on the basis of measurement by floats and the reduction of the surface velocity to a mean velocity by multiplying by a coefficient of 0.6. In his comparison, he calculated the ratio of runoff to rainfall as about one seventh. In 1715 Vallisnieri (1661–1730) of Padua University published the results of his comparison of rainfall and snowmelt with observed flows of rivers in the Italian Alps and came to similar conclusions.

The pioneering quantitative comparisons of precipitation in runoff, discussed above, apparently did not command the assent of the scientific community for some considerable time. In 1799 John Dalton, often referred to as the father of modern chemistry, introduced his paper on the water cycle by stating:

> Naturalists, however, are not unanimous in their opinions whether the rainfall

> is sufficient to supply the demands of springs and rivers and to afford the earth beside such a large portion for evaporation as is well known is raised daily.
>
> (Dalton, 1799)

Dalton proceeded to tackle this problem by calculating a regional water balance for England and Wales. In this study he estimated the regional precipitation on the basis of thirty gauges in England and Wales. He still took a value of runoff by upscaling from a crude estimate of the flow of the Thames by a factor of nine. However, he made a new departure by seeking to determine actual evaporation *in situ* by means of an early form of lysimeter. On the basis of monthly values of actual evaporation determined on his lysimeter over the years 1796–8, he estimated the mean annual evaporation as twenty-five inches.

In the twentieth century, understanding of the details of the hydrological cycle was greatly enhanced, particularly in relation to the non-linear effects due to such features as first, the switching of the control of land surfaces fluxes (i.e. infiltration and evaportranspiration) between the atmosphere and the soil and second, the feedback effect of localized re-precipation of local evaporation. Another important development was the improvement in the understanding, recording and analysis of the various elements of the hydrologic cycle. This has been important both for the understanding of the hydrological cycle and for the optimal management of water resources.

An important development in the second half of the twentieth century was the rise of palaeohydrology, which studies the relationship of runoff, sediment yield and concentration of suspended sediment to precipitation and temperature in the remote past. This discipline is linked with palaeogeography, palaeoclimatology and palaeoecology and like them has benefited from the significant development in techniques for the accumulation and interpretation of relevant proxy data from the pre-historic past. Thus we are now able to assemble proxy data for the past 40,000 years, sporadic measurements for the past 4,000 years and a wide range of sustained systematic records for the past 40 years.

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