

Ode to H₂O

Graeme D. Buchan

"And a river went out of Eden to water the garden." Genesis 2, v. 10

Water is the basis of life, being typically 65-70 percent of human body weight and 80-95 percent of the fresh weight of non-woody plants. It is (apart from mercury) the only inorganic liquid found on earth (Figure 3). Thanks to earth's special mix of temperature and air pressure, it is also the only substance found in all three phases in the biosphere. Its importance extends beyond the bio-world into the physical world: it weathers rocks into soils (the substrate of land life), and then transports nutrients into plants and hence animals.

carbon capture from the atmosphere! And a typical adult daily diet requires about 1 kg of food dry matter, but 2.5 kg of water.

Did you know?

- Even under ideal conditions, one could live for over a month without food, but only 10 days without water.

- Water consumption in the United States is about 1,400 liters (1.4 ton) per person per day, i.e. more than 500 times dietary need! (U.S. Geological Survey 1993). Only 300 liters is indoor use, the remainder being used for irrigation, agri-

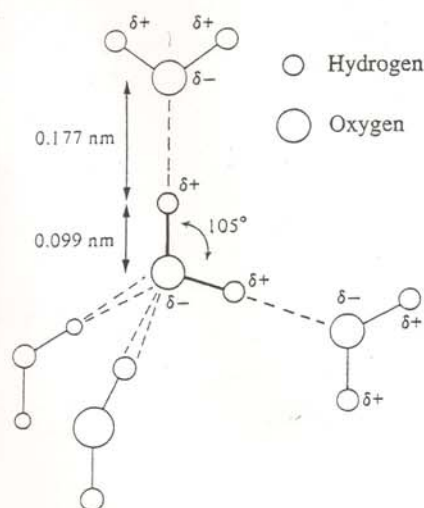


Figure 1. Structure of the water molecule, and of ice crystals

NOTE: Hydrogen bonding results from attraction between the net positive and negative charges on H and O atoms. In ice, the tetrahedral structure is fairly rigid, but deforms slightly under pressure, contributing to ice's low friction. Residual ordering in liquid water causes anomalous expansion, i.e. maximum density at 4°C. (After Jones, 1983).

Table 1. Exceptional properties of water (at 20°C).

Note: Properties marked* have extreme (or close to extreme) values for water, compared to other substances. Ethyl alcohol (C₂H₅OH) has been chosen (arbitrarily?) as a reference substance.

Property	Value for water	Value for alcohol	Comments for water
Density (kg m ⁻³)	998	789	Liquid has anomalous expansion: max. density at 4°C (11.2°C for heavy water D ₂ O). Anomalous expansion destroyed in seawater.
Volume expansion on freezing	9%*	—	Large. Ice floats on water. Initiates rock and soil weathering.
Heat capacity (J kg ⁻¹ K ⁻¹)	4182*	2440	Higher than any other liquid except ammonia or NH ₄ OH. Thermoregulation effect in water bodies and biological tissues.
Thermal conductivity (W m ⁻¹ K ⁻¹)	0.598*	0.168	Highest of common liquids (but fortunately lower than many solids, reinforcing water's thermoregulation effect).
Latent heat (MJ kg ⁻¹) of vaporization	2.45*	0.92	Highest of common liquids. Vapour a very effective 'energy carrier' e.g. in evaporative cooling, global energy redistribution.
Latent heat of fusion	0.334*	0.109	Highest of common liquids. Freezing is slow and stabilizes at 0°C.
Dielectric constant	80.2*	24.3	Very high. 'Buffers' forces between ions, and charged colloids: water an excellent solvent, and 'softens' materials, e.g. soils.
Surface tension (mN m ⁻¹)	72.8*	22.4	Highest of common liquids. Strong capillary retention of water in soils. Lowered by surfactants, including soaps, detergents and 'adjuvants' used in agricultural sprays.

As a CO₂ solvent, it captures carbon into nature's basic foodstocks, i.e., land plants and ocean or lake algae.

So water makes up two-thirds of your body weight and has delivered the remainder, via breakdown of minerals, transport of the released nutrients, and

culture, and industry.

Water is also the best medicine, both inside and outside the body. The finest prevention for malaise (after an evening of excess consumption!) is a pint of water before bed. Paradoxically, if you drink very large quantities of water, in excess of the excretory capacity of the kidneys, the dilution of the body's electrolytes (mainly sodium) can cause water intoxication. Symptoms include nausea, malaise,

headache, and, in severe cases, seizures and coma (Rubenstein and Federman 1996). Outside the body, a good hot shower or bath is an excellent restorer for the maldisposed. Daily, we submit ourselves to water's healing and cleansing powers, both internally consumed and externally applied. Water is the basis of both our creation and recreation (e.g., swimming, skiing, beverage-drinking), and in every sense is aqua vitae, the water of life.

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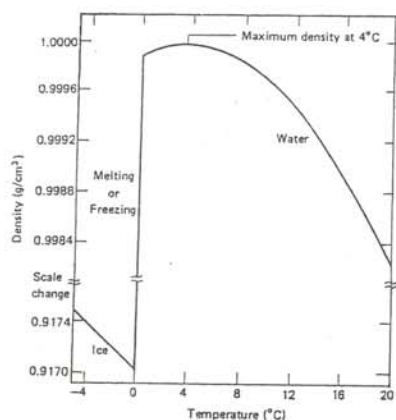


Figure 2. Density changes of water

NOTE: As water cools from 4°C (maximum density) to 0°C, it begins to gain some of the open ice crystal structure, and density decreases slightly. This anomalous expansion forces colder water to float over water at 4°C. On freezing at 0°C, density decreases abruptly from 999 to 917 kg m⁻³, and volume increases by 9 percent. The huge forces cause frost shattering and frost heave. Salts in sea water destroy this anomalous expansion, and lower the freezing point to -1.9°C (Denny 1993), which is curiously close to the typical freezing point of plant cell sap.

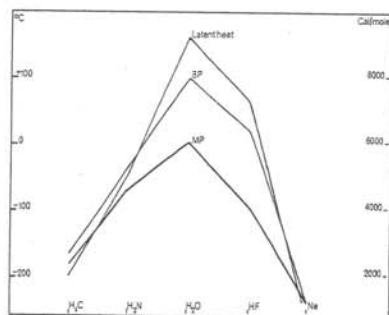


Figure 3. Unique status of water in its isoelectronic series

NOTE: The plot shows the melting (MP) and boiling (BP) points and latent heat of vaporization of the hydride series which is 'isoelectronic', i.e., all compounds in the series have total nuclear (and hence electronic) charge of 10 units. Water's strong hydrogen bonding raises its MP and BP, making it liquid over most of earth's ambient temperature range (Taylor 1966).

Fundamentals

We look at water's unique properties, summarized in Table 1. For reference, values are also shown for ethyl alcohol. (Why alcohol? Well, water has no real competitors among liquids, but humans have a long-standing fascination with this organic liquid).

What gives water its exceptional properties? Mainly it is the strong polarity of its molecule (Figure 1). This leads to the

hydrogen bond and hence to strong self-cohesion of the liquid (hence exceptionally large latent heat, specific heat, and surface tension); strong adhesion to other substances (e.g., soil particles); and water's role as the universal solvent. Underlying this polarity is the potent electrophilic (electron-loving) nature of the oxygen atom—precisely the property that makes O₂ the key to the respiratory cycle fueling animal and human life (and gives us the term oxidation). Hence, an Ode to H₂O might almost be an Ode to Oxygen.

A further feature is the H₂O bond angles (Figure 1), leading to the open, tetrahedral crystal structure within ice, which persists (loosely) even after melting (Figure 2).

Water's truly special status is highlighted in Figure 3, which compares properties of the so-called isoelectronic series H₄C, H₃N, H₂O, HF, and Ne (Taylor 1966). Note how water's range of liquidity is neatly lifted into earth's ambient temperature range.

The liquid form

Volume changes. Not only does ice float on water; freshwater also displays anomalous expansion, with maximum density at 4°C (Figure 2). So in a freezing pond or lake, warmer water settles to the bottom to provide a sanctuary for life.

Hydraulic pressure effects. Water also has low compressibility. Water pressure in cells produces their turgor, which has the following effects: it forces cell enlargement and growth; it maintains shape in herbaceous plants (as well as our body tissues); and pressure adjustments can move plant parts, including opening of stomata, and movement of leaves and petals. (Kramer and Boyer 1995). Cell expansion can also produce powerful forces, sufficient to displace soil during emergence or root penetration (Figure 5).

Specific heat capacity, *c*. A leading talent of water is its large heat capacity, almost the largest among all substances. Thus water is an excellent thermostat, slowing temperature changes in oceans, water bodies, biological cells, and tissues. Ocean currents become vast and powerful heat carriers, redistributing heat and moderating climate over earth's surface.

Did you know?

- Ocean currents carry much if not most of the burden of transporting heat from the planet's warm equatorial regions toward the poles (Covey 1991), and are a major unknown in predicting climate change.

- The Atlantic Gulf Stream transfers energy at a vast rate, from the Gulf of

Mexico to the Arctic Ocean: All the coal mined in the world in one year could supply energy at this rate for only 12 hours (Franks 1984).

Thermal conductivity, *k*. Compared to other liquids, water has high *k*. This speeds up heat redistribution in living tissues, which regularly experience uneven metabolic and external heating or cooling. Thankfully, compared to solids, water has low conductivity. This slows heat exchanges, reinforcing the thermoregulation effect of water's exceptional heat capacity. (By contrast, a metal robot would experience much greater temperature shocks.)

Surface tension, *γ*. This arises from the attractive tugging forces between molecules at the liquid surface, and so is exceptionally high for water. Hence water is absorbed strongly by capillary attraction into porous materials, making soils excellent water reservoirs. If water's *γ* were as low as alcohol's, soils would drain to much lower moisture contents, and quickly become droughty. Water's polarity also ensures strong adsorption onto surfaces of clay particles and organic matter. By contrast, absorption can be blocked by water-repellent surface coatings: leaves and insects have repellent coatings to prevent flooding of their 'breathing pores', i.e., stomata and trachea respectively (Denny, 1993); and artificial materials (like fabrics or concrete) can be waterproofed with silicone-based coatings.

Did you know?

- Surfactants are added to pesticide spray solutions to lower the surface tension. This encourages leaf wetting and stomatal entry (Buick et al. 1993), and also generates finer sprays for more efficient dispersal. Similarly, commercial surfactants can be added to irrigation water to promote wetting of water-repellent soils.

- In humans, natural surfactants play a wonderfully subtle role within the lungs. They continuously adjust the surface tension of the water films lining the myriad tiny alveoli (air-filled cavities), preventing their partial collapse (Cameron and Skofronick 1978).

Viscosity, *η*. Water's viscosity is moderately high compared to most organic liquids, since the hydrogen bonds resist rearrangement. However it is low compared to extremes such as paraffin oil, an important factor for blood and sap-flow. Doubling the viscosity of blood would double the pumping work of the heart. Viscosity also controls land hydrology. If water were more viscous, infiltration would be reduced, causing increased runoff and erosion. *η* approximately halves between 0 and 30°C. Hence soil water flow and

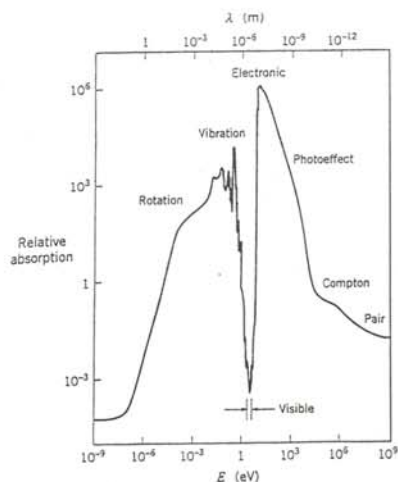


Figure 4. Absorption spectrum of water

NOTE: Water absorbs all wavelengths except in the visible, i.e., the photochemical waveband which 'drives' the biochemistry of both the human retina and photosynthesizing plants and algae. This tiny window is crucial for the success of life on the watery planet. (After Rohlf, 1994. Reprinted by permission of John Wiley & Sons, Inc.).

drainage may be up to twice as fast in summer as in winter!

The dielectric constant (ϵ) of water is remarkable. ϵ measures the tendency of molecules or charges to interact (line up) with an applied electric field ($\epsilon=1$ for vacuum). Strong polarity (Figure 1) gives water the highest value among the common liquids, $\epsilon = 80$. ϵ is also a measure of the "ability to neutralize the attraction between electric charges" (Kramer and Boyer 1995). Thus water 'buffers' or weakens the forces between dissolved ions and molecules, making it a powerful solvent and medium for biochemical reactions. This buffering also operates between charged colloid particles, including clay and organic matter. So water has remarkable 'softening' powers, visible in the drastic reduction by wetting of the hardness and strength of soils and other materials. It controls soil cohesion, dispersion, and strength. Without this softening action, roots would fail to penetrate soil. Soaking of dirty surfaces (dishes, clothes) also exploits the softening powers of water.

Did you know?

- Water's polarity is exploited in microwave ovens, where the rotations induced in the H_2O dipole absorb energy from the electric field, oscillating at around 2.45 GHz. (Cell phone antenna radiation is about 1 GHz, and also has a warming effect, though very weak.) By contrast, water molecules in ice are frozen into a relatively unresponsive structure, so that ϵ for ice is only 3.5. (Try microwave-



Figure 5. Hydraulic pressure effects

NOTE: Water pressure in biological cells plays several key roles, e.g. maintaining shape in plant and animal tissues, regulation of stomata, and in soil penetration by roots. Here, expanding fungal cells exert pressures strong enough to rupture a hard, dry soil. (Photo: David Hollander, Lincoln University).

ing very cold, dry ice cubes.)

Water's large ϵ is also exploited in electromagnetic measurement of the water content of materials such as soils and foods. Time Domain Reflectometry (TDR) and capacitance methods are growing technologies, with applications in soil science and in industry including the globally expanding composting industry.

Absorption spectrum. As shown in Figure 4, liquid water absorbs radiation of all wavelengths, except in a very narrow window in the visible (photochemical) waveband. This window is crucial for the development of life in lakes and oceans.

Dissolving power. Water is an excellent solvent in rock and soil weathering, in transporting nutrients and gases, and as the support medium for life. Its ability to dissolve gases (O_2 , CO_2) is also crucial for life: e.g., at blood temperature ($37^\circ C$) the saturation concentration (moles m^{-3}) of O_2 in water is high, about 2.5 percent that in air (Denny 1993).

Chemical properties. A curious feature is water's dissociative behavior. It sits benignly at neutral pH, midway between the hazardous acid and alkali extremes, produced by the dissolution of ions. In an acid, some water molecules are 'protonated', i.e., gain a proton (H^+) to form the hydronium ion H_3O^+ (usually simplified to H^+). Conversely in an alkali some molecules are 'deprotonated' to yield the hydroxyl ion OH^- . Thus pure water is the neutral combination of two components, whose chemical potencies cancel. (Another of nature's paradoxes).

Biochemical importance. Water plays two key roles in biochemical reactions: passively, as a solvent for minerals, organic solutes, and gases; and actively as a reactant in vital processes such as photosyn-



Figure 6. Thermoregulation effects

NOTE: Water helps to slow or regulate temperature changes, thanks to its large specific and latent heats. Here (almost paradoxically) frost protection is achieved by the water-sprinkler method. The freezing water stabilizes plant temperature at $0^\circ C$, typically a few degrees above the freezing temperature of cell sap. (Photo: Peter John, Lincoln Ventures Ltd.).

thesis and respiration.

Did you know?

- Biochemical reactions are very sensitively attuned to water's precise properties, i.e., its molecular energy levels, and H-bonding conformation. Even the minor isotopic substitution of D_2O for H_2O causes "chaos to the coupling in biochemical reactions... Thus heavy water is toxic to all higher forms of life" (Franks 1984).

Clouds. Clouds consist of myriads of water droplets or ice crystals. Collectively, they are highly reflective, and act as a major feedback mechanism in controlling earth's climate.

Did you know?

- Clouds are one of the most unpredictable factors in models of global climate. They have been called "the wildcard in the game of climate change" (Monastersky 1989).

Special features: The solid form

Expansion on freezing. Water expands by about 9 percent on freezing (Figure 2). The powerful forces can shatter rocks to initiate soil formation. Continued fragmentation by physical weathering, allied with water-borne chemical weathering, further develops soils. Thus water is the prime converter of rocks into soil.

Frost protection. Freezing within cells can rupture and kill them, forcing frost protection in horticulture (Figure 6). Cell solutes act like a moderate antifreeze, lowering the freezing point in typical plant cells to about -1.5 to $-2^\circ C$ (Jones 1983). (Curiously, seawater has a similar freezing point of $-1.9^\circ C$!). The natural frost hardening of plants is partly due to an increase in this antifreeze action, via accumulation of extra cell solutes, including carbohydrates. This helps explain the sweetening of

overwintered vegetables. Strangely, water-sprinkling onto plants protects them on frosty nights: the applied water freezes and stabilizes tissue temperature at 0°C, above the critical freezing point of cell contents! (See Figure 6).

The latent heat of freezing is large, slowing freezing of puddles and lakes, and living tissues. It also slows melting. (Cooler ice packs contain a fluid with larger latent heat, to slow melting even further).

Friction

Did you ever wonder?

- What makes skiing, skating and sledging possible? Well, yet another unique property of water is the very low coefficient of friction of ice near 0°C. Contributing factors are pressure melting and the deformability of the ice crystal structure.

Special features: The gas form

Water vapour is typically only 1 percent of the air around us, yet water dominates climate processes: another paradox!

Infrared absorption. The strong polarity of the H₂O molecule makes water vapour a very strong absorber and emitter of infrared radiation, and hence earth's leading greenhouse gas.

Did you know?

- Without atmospheric vapour, earth's surface would be more than 20°C colder: a frozen planet!

- N₂ and O₂, together about 98 percent of the air around us, are totally transparent to infrared radiation, and contribute nothing to the natural greenhouse effect!

Latent heat. Water's remarkably large latent heat makes vapour a very efficient energy carrier. Earth's hydrological cycle pumps vapour from lower to higher latitudes. The heat released on condensation helps redistribute the sun's energy, moderating climate extremes.

Did you know?

- As vapour condenses to form clouds, it releases large quantities of latent heat. This is the main cause of the heating of Föhn-type winds, such as the Chinook.

Plant evaporation occurs on a massive scale, and is also a major leaf cooling mechanism. Without it leaves would overheat in summer.

Did you know?

- Plants are very leaky. In their attempt to dissolve and capture meagre atmospheric CO₂, their moist tissues unavoidably transpire vast amounts of water into the air. Over its growing season, a typical temperate crop (e.g., wheat) evaporates about 500 kg of water to produce just 1

kg of useful dry matter. Thus the water in a typical 25m swimming pool would suffice to produce only 15 sacks of grain.

- Irrigation consumes over two thirds of global freshwater used.

Conclusions

Nature is full of paradoxes. Water is one: it is at the same time a stunningly simple yet wonderfully complex substance. It has more exceptional properties than any other substance, properties crucial for life and climate processes. It has extreme (or close to extreme) values among liquids of heat capacity; latent heat of vaporization; dielectric constant; surface tension; tensile strength; thermal conductivity; chemical dissociation (into hydrogen and hydroxyl ions); compressibility; thermal expansion properties; volume change on freezing; and friction of its solid phase (ice). While a few freak substances have more extreme single properties (e.g., hydrocyanic acid has a dielectric constant of 158), they are life-unfriendly. Further, Figures 3 and 4 reveal beautifully how the properties of water are tuned to life on earth, i.e., to earth's ambient temperature range, and the biochemically effective (visible or PAR) waveband.

Thus there simply was no competition when it came to choosing "Nature's fluid."

In the unfolding drama of climate change, earth's water may well play unexpected tricks. The big unknowns in climate models include the following feedback effects: how changing cloud patterns will alter Earth's energy balance in a warmer, more humid world (Monastersky 1989); how ocean currents might change, and produce unpleasant surprises in the form of relatively sudden reorganizations of ocean circulation (Covey 1991); the albedo effects of changing snow and ice cover; and ocean absorption of rising atmospheric carbon dioxide.

Earth is special—the sun's only watery planet. Water in turn is special: it is the basis of life, and the main controller of climate. Nature, via distillation in the hydrological cycle, has supplied the land with large volumes of freshwater, both surface waters and huge buried lenses of groundwater; and flushed 90 percent of earth's soils free of excess or imbalanced salts. Humans are rapidly despoiling much of this. It is time to value and conserve our water resources—without them life is impossible.

Earth's land-ocean balance

Does it benefit the Earth to have as much as 70 percent ocean? Subtly, it enables the richness and diversity of life on land. Currently, only 10 percent of all land suffers from salt-affected soils (Szabolcs 1989). Nature, via hydrological distillation, has flushed the remaining 90 percent of our soils free of excess or imbalanced salt concentrations. Absence of this flushing can lead to salt-affected soils in arid regions. Imagine Earth with much less ocean and much more land. Average land rainfall would be less, arid regions would spread, and much more land would be salt-affected.

Did you know?

- Australia, the driest continent, has about one-third of its land covered with salt-affected soils. (Szabolcs 1989).

- The spread of salt-affected soils is the second largest cause (after erosion) of soil degradation. Globally, it is estimated to remove from production about 3 hectares of land every minute.

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