Ode to H_2O[1]

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

ABSTRACT: Water is the wonder substance: no other has such a wide range of 'talents' (i.e. exceptional properties). As a liquid, it is 'Nature's fluid' - the solvent and support medium for life. In all three phases (ice, liquid and vapour) it is the main controller of Earth's climate, and (elusively !) is the greatest source of uncertainties in predicting future climate change. Yet sadly, freshwater degradation is among our top few environmental threats (Gleick, 1993). This article is one of a 'resource appreciation' series. It describes the 'wonder' properties of water, showing that Nature had only one choice for Nature's fluid, and encourages conservation. It is a natural sequel to a first paper, 'Ode to Planet Earth' (Buchan 1994), which describes the special, life-enabling features of spaceship Earth, the Sun's only watery planet.

INTRODUCTION

Water is the basis of life, being typically 65-70 % of human bodyweight, and 80-95 % of the fresh weight of non-woody plants. It is (apart from mercury) the only inorganic liquid found on Earth (See Fig.2). 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. As a CO_2 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 bodyweight, and has delivered the remainder, via breakdown of minerals, transport of the released nutrients, and carbon capture from the atmosphere ! It is further essential to everyday life. 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 (Lannoy and Nicholls, 1985).
- Water consumption in the USA is about 1,400 litres (=1.4 tonne!) per person per day, i.e. more than 500 times daily dietary need ! (Solley et al. 1993). Only 300 litres is indoor use, the remainder being used for irrigation, agriculture and industry. In NZ, consumption (which includes irrigation) is about 1,500 litres per person per day. However this consumption is dwarfed in NZ by throughput for hydro-electricity generation, which is over 50 times greater (Sherrin 1993).

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 excretion capacity of the kidneys, the dilution of the body's electrolytes (mainly sodium) can cause 'water

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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'.

SPECIAL FEATURES: Fundamentals

This section details water's unique properties, summarised in Appendix 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 (Fig.1a). This leads to the 'hydrogen bond' and hence to: strong self-*cohesion* of the liquid (hence its 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 powerful electrophilic ('electron-loving') nature of the oxygen atom. This very property makes O_2 the key to respiration (which fuels animal and human life), and also gives us the term 'oxidation'. Hence an 'Ode to H_2O' might almost be an 'Ode to Oxygen' ! Some recent research suggests there may be two types of hydrogen bonds, one stronger than the other (Matthews 1997).

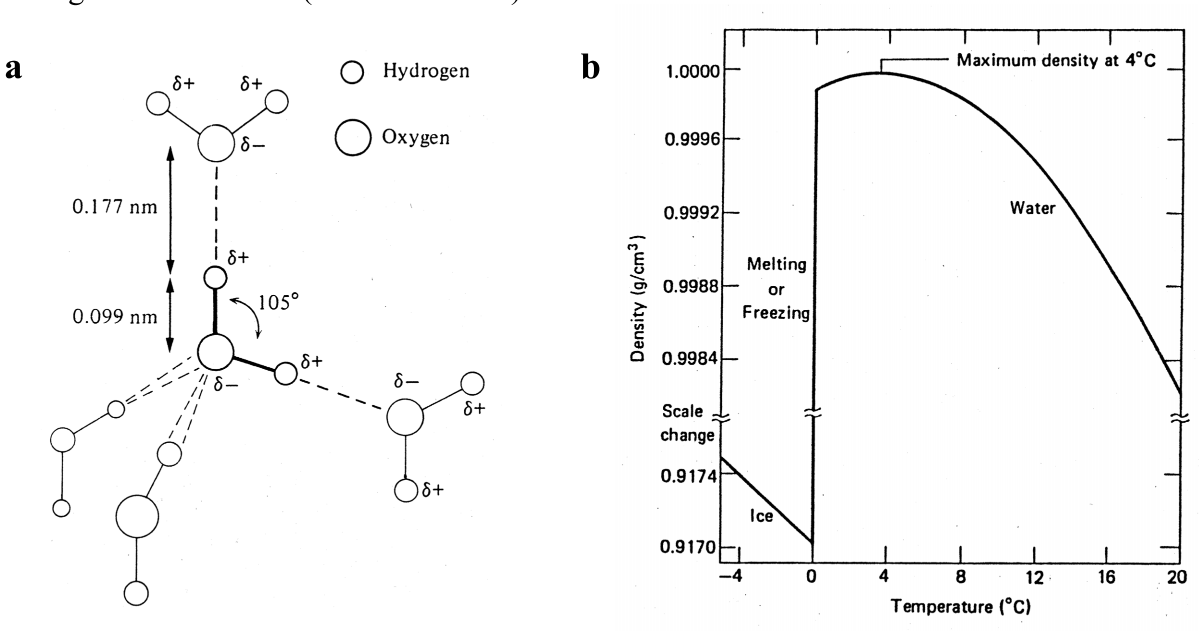

Figure 1.
a) Structure of the water molecule, and of ice crystals. Attraction between the net +ve and -ve charges on H and O atoms creates hydrogen bonds. In ice, the tetrahedral structure is fairly rigid, but deforms slightly under pressure, contributing to ice's low friction. Residual ordering in liquid water causes anomalous expansion, i.e. maximum density at 4°C (Fig. 1b). (After Jones, 1983. Reproduced by permission of Cambridge University Press).
b) Density changes of water. 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 grows by 9%. 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) - curiously close to the typical freezing point of plant cell sap.

A further feature is the H_2O bond angles (Fig. 1a). This leads to the open, tetrahedral crystal structure within ice, which persists (loosely) even after melting (Fig. 1b).
Water's truly special status is highlighted in Fig.2, which compares properties of the so-called 'isoelectronic series' H_4C, H_3N, H_2O, HF and Ne (Taylor, 1966). Note how water's range of liquidity is neatly 'lifted' into Earth's ambient temperature range.

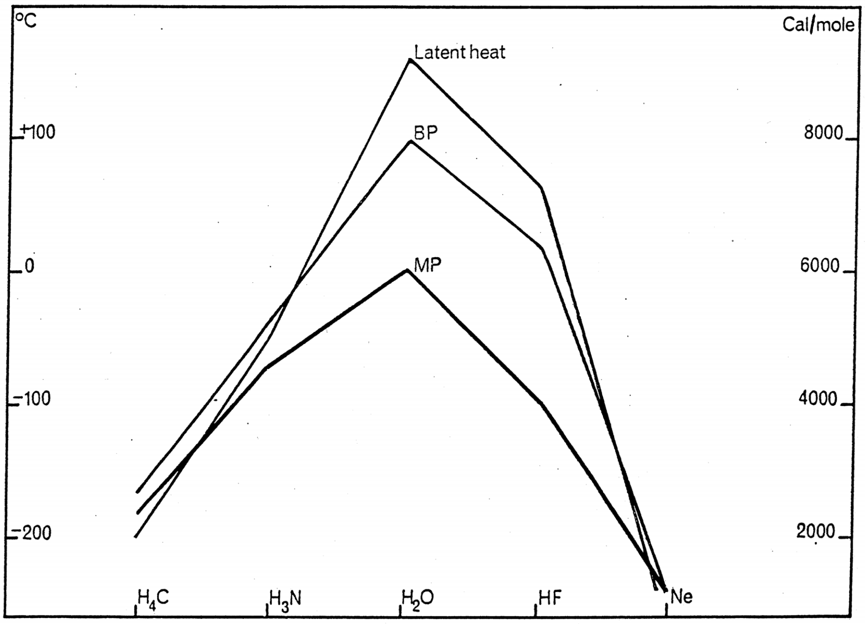

Figure 2. Unique status of water in its isoelectronic series.
The plot shows the melting (MP) and boiling (BP) points and latent heat of vaporization of the hydride series which is 'isoelectronic', i.e. all compounds in the series have total nuclear (and hence electronic) charge of 10 units. Water's strong hydrogen bonding raises its MP and BP, making it liquid over most of Earth's ambient temperature range. (From Taylor 1966, reproduced with permission of Unilever PLC).

SPECIAL FEATURES: the LIQUID form.

Volume changes. Not only does ice float on water; freshwater also displays anomalous expansion, with maximum density at 4^{o}C (Fig.1b). 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 (Fig. 3).
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.

Figure 3. Hydraulic pressure effects
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).

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 (e.g. fabrics, concrete) can be waterproofed with e.g. 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 & 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^{o}C. Hence soil water flow and 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 (ε=1 for vacuum). Strong polarity (Fig.1a) gives water the highest value among the common liquids, ε=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 (e.g. 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. (Cellphone 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 microwaving 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.

Absorption spectrum. As shown in Fig.4, liquid water absorbs radiation of all wavelengths, except in a very narrow window in the visible (i.e. photochemical) waveband ! This window is crucial for the development of life in lakes and oceans. Interestingly, pure water is not perfectly transparent, but has a blue colour (Fig. 5).

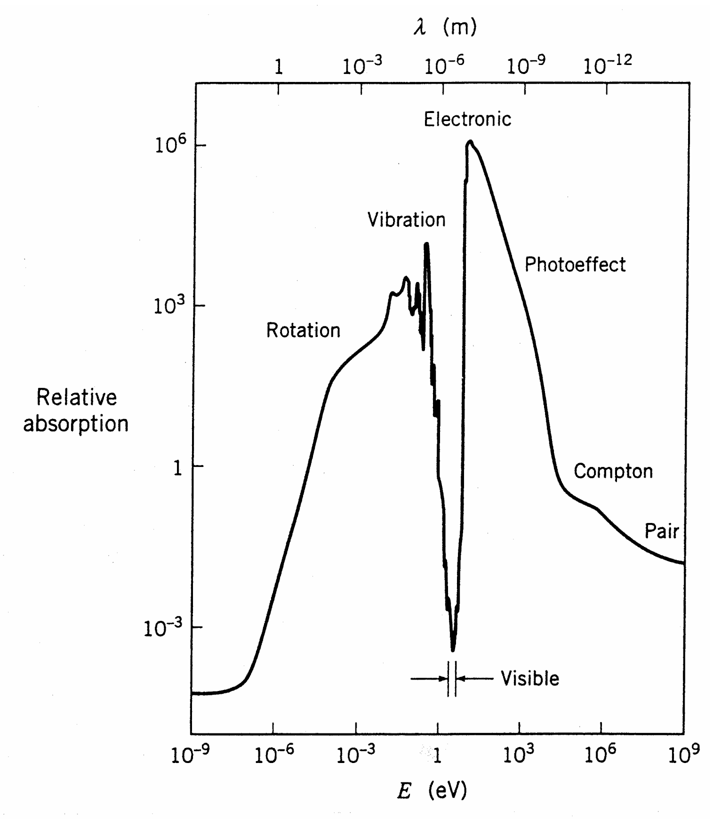

Figure 4. Absorption spectrum of water. Water absorbs all wavelengths except in the visible, i.e. the photochemical waveband which 'drives' the biochemistry of both the human retina, and photosynthesis in plants and algae. This tiny window is crucial for the success of life on the watery planet. (After Rohlf, 1994. Reprinted by permission of John Wiley & Sons, Inc.).

Figure 5. 'True Blue' : the colour of pure water
Waihou River, North Island, New Zealand. This river is 'spring-fed' by water which 'springs' from under the riverbed, and has been filtered by subsurface sediments to a very high quality. (Photo by the author, G. Buchan).

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^oC) the saturation concentration (moles m^{-3}) of O_2 in water is high, about 2.5% of that in air (Denny 1993).
Chemical properties. A curious feature is water's dissociation behaviour. It sits benignly at neutral pH, mid-way 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 photosynthesis and respiration.
Currently researchers are exploring the role of so-called 'flickering clusters', i.e. *very* transient linkages between groups of up to six or more molecules. Evidence suggests there may be two types of hydrogen bond, one stronger than the other. The change of bonds from strong to weak may require water to reach critical temperatures. Curiously, one of these temperatures may be 37^OC (Matthews 1997). So the set-point for human body temperature (also 37^OC) may be determined by the behaviour of water !

Did you know ?
Biochemical reactions are very sensitively tuned 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% on freezing (Fig.1b). The powerful forces can shatter rocks to initiate soil formation. Continued fragmentation by physical weathering, along 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 (Fig. 6). Cell solutes act like a moderate antifreeze, lowering the freezing point in typical plant cells to about -1.5 to -2^oC (Jones 1983). (Curiously, seawater has a similar freezing point of -1.9^oC !). 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 stabilises tissue temperature at 0^oC, above the critical freezing point of cell contents ! (Fig.6).

Figure 6. Thermoregulation effects
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 stabilises plant temperature at 0^{o}C, typically a few degrees above the freezing temperature of cell sap. (Photo: Peter John, Lincoln Ventures Ltd.).

The **latent heat of freezing** is large, slowing freezing of puddles and lakes, and living tissues. It also slows melting. (Chilly-bin 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^{o}C. Contributing factors are pressure melting, and the deformability of the ice crystal structure. (See Fig. 1a).

SPECIAL FEATURES: the GAS form

Water vapour is typically only 1% of the air around us, yet water dominates climate processes - another paradox !
Infrared absorption. The strong polarity of the H_2O 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 over 20 C^{o} colder - a frozen planet !
* N_2 and O_2, together about 98% 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 Fohn-type winds, such as the Canterbury "Nor'wester" in NZ, and the Chinook in the USA.

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 CO_2, 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, Figs. 2 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 reorganisations 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: a) supplied the land with large volumes of freshwater, both surface waters, and huge buried 'lenses' of groundwater; and b) flushed 90% of Earth's soils free of excess or imbalanced salts (see Appendix 2). Humans are rapidly despoiling much of this. It is time to value and conserve our water resources: without them life is impossible.

APPENDIX 1

Table 1. Exceptional properties of water (at 20°C). (See e.g. Lide, 1995).
Properties marked * have extreme (or close to extreme) values for water, compared to other substances. Ethyl alcohol (C_2H_5OH) 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_2O). Anomalous expansion destroyed in seawater. (See Fig. 1a).
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_4OH. 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.
- of fusion	0.334*	0.109	Highest of common liquids. Freezing is slow and stabilises 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, or food remains on your dishes !
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.

APPENDIX 2
Earth's land-ocean balance

Does Earth benefit from its 70% ocean cover? Subtly, it enables the richness and diversity of life on land. Currently, only 10% of all land suffers from salt-affected soils (Szabolcs, 1989). Nature, via hydrological distillation, has flushed 90% 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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