# Perspectives on Water

## Uses and Abuses

Edited by
David H. Speidel,
Lon C. Ruedisili,
& Allen F. Agnew

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# PERSPECTIVES ON WATER

This book is dedicated to the directors of the Water Research Institutes and Departments of Natural Resources of the various states, whose continuing efforts are essential for the development and protection of our water resource.

# PREFACE

The noblest of elements is water.—Pindar

The earth is a water world. From outer space the oceans are visible as great swirls of blue, green, and grey covering over 71 percent of the surface. The blue-white of ice and snow covers another 3.5 percent. Below the patches and linear streaks of clouds are lakes and rivers, ponds and streams; unseen beneath the surface are vast reservoirs of ground water.

Earth is the only water world we know, the only planet where the compound water exists as liquid, vapor, and solid. There appears to be only a very small set of conditions in any solar system where the three states of water can so exist. Earth's size and location relative to those of the sun fit within that small set. The change of water from one physical state to another in the hydrologic cycle is a major factor influencing the geological, chemical, physical, and biological processes operating on the surface of the earth, including the development and maintenance of all life.

Water is a resource. We drink it. We use it for bathing and cleaning, cooling and heating, growing food and fishing, recreation, transporting goods, disposal of waste, and decoration. Water is so useful that conflicts over its use have existed for thousands of years.

Until recently, concern about water usually occurred only when it was not available to us in the amounts we wanted (as in droughts), when it was present in overabundance (as in floods), or when its usefulness was limited by pollution. Today there is a growing awareness of the importance of water, of the key role it plays in supporting our society, and of the many problems other than drought and floods involved in its use. We have assembled this textbook to provide an overview of the full range of water as a resource.

Part I, "Water: The Compound, the Resource," first describes the unique physical and chemical properties of water and then reviews the many aspects involved in its use as a resource. Part II, "Water in the Environment," discusses the hydrologic cycle and illustrates the physical limitations of water as a resource.

The range of uses of water is illustrated in Part III, "Water Use," by chapters on irrigation, drinking water, energy and water, and industrial uses of water. Every use of a natural resource produces environmental problems; water is no exception. Part IV, "Problems and Hazards," examines issues of water quantity and quality, land-use and hydrologic hazards, and other natural and human-instigated problems.

Finally, Part V, "Law, Economics, and Management of Water," describes how society manages water use. Many of the problems associated with water are not about quality, quantity, or location of water but arise from legal, economic, and management procedures.

Our aim is to present a reasoned look at the problems of water, being neither apocalyptic (overly pessimistic) nor Pollyannish (blindly optimistic). Severe problems do exist, but if attention is paid to them, we feel that they can be handled.

Who should pay that attention? First, students of hydrology must be made aware that the hydrologic cycle is more than a geologic process; it is also a human process. This book provides a companion to the standard hydrology text by stressing the human interaction with the water cycle.

Second, students in arts, business, humanities, and social sciences from whose ranks will come the politicians, economists, and managers making future decisions about water should have a knowledgeable base for such decisions. The study of resources must include discussions of physical limits and systemic problems as well as economic arguments. We feel that this collection of articles provides the basis for a course on water resources for such nonscientists and nonengineers.

Third, individuals concerned with problems of resources and the environment should have an appreciation for this critical resource. History is spotted with the stories of cities, regions, and even civilizations that are believed to have failed because of the misuse of water. Everyone should be aware of how hearty, yet, at the same time, how fragile this resource is.

# CONTENTS

# PERSPECTIVES ON WATER

# PART I

# WATER: THE COMPOUND, THE RESOURCE

The earth is the only planet we know where water freely exists. Water is a critical factor in chemical, physical, and biological processes, and hence all aspects of this unusual compound deserve examination. In Chapter 1, "Water, Something Peculiar," J. Lyklema and T. E. A. Van Hylckama present a lighthearted discussion of some anomalous physical-chemical properties of water and their environmental and biological significance.

The structure of the water molecule, the "Mickey Mouse" of Figure 1-2b, is the key to many of the properties of water. What the diagram does not indicate is that while the water molecule as a whole is electrically neutral, the distribution of positive and negative charges is not uniform. The "ears" are slightly positive and the "chin" is slightly negative. Molecules of liquid water thus have a tendency to line up ears to chin, to ears to chin, and so on, held together by the attraction between a positive charge and a negative one. This "hydrogen bonding" is used to explain the anomalous stability of liquid water and its many properties.

In addition to the properties discussed in Chapter 1, several others are of environmental interest. One such set is the latent heats of melting (fusion) and vaporization (evaporation), illustrated in Figure I-1. The heat that is added to 1 g of material at its melting point sufficient to cause a change of state from solid to liquid, thus melting the material, is called the *latent heat of melting*. Similarly, the amount of heat necessary to change 1 g of liquid at its boiling point to vapor is called the *latent heat of vaporization*. For water the latent heat of melting is 80 cal, and the latent heat of vaporization is 540 cal. The term *latent* is used because the heat that is added to a given mass of ice to turn it into liquid or to a given mass of water to turn it into vapor is held by that mass of water or vapor and then released when the process is reversed. There are some practical effects to these latent heats. Cans of beer set in ice will cool. Heat energy drawn from the cans to the ice will provide sufficient energy to change water from the solid state to the liquid state as the ice melts. Water-cooled air-conditioning works the same way. Hot, dry air is passed through or over water and will lose heat to the water. The water will absorb a large amount of heat before it itself is vaporized.

The process works the other way also. Did you ever feel warmer when it started to snow than when you were in a cold rain? You were indeed warmed, because the latent heat of melting was released when the rain was turned into snow. Evaporation of water transfers solar energy from the liquid in the oceans to the vapor in the atmosphere. When the water falls as precipitation, the latent heat of vaporization is released. The rainfall releases heat into the atmosphere. Thus coastal regions generally have milder winters than inland, drier continental regions.

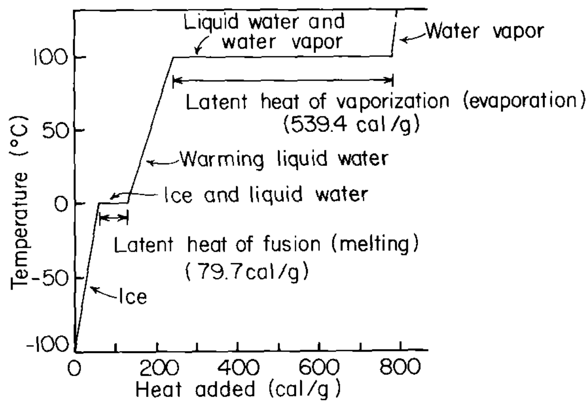


Figure I-1. Latent heats of melting and vaporization of water. (*Source:* L. Ruedisili.)

Density is another valuable property of water. Under normal pressure conditions liquid water at 4°C is the most dense form. Ice is less dense and will float. This means that water bodies will freeze from the surface downward and thus allow circulation to continue under the frozen surface, so that fish can survive.

Water as a resource has several characteristics that were described in the recent report *Global 2000:*

1. *Water is ubiquitous.* No place on earth is wholly without water. In general, most locales of human activity have vast quantities of water available nearby. While the means by which water is moved to the point of use may be of concern, and while the quality of available water may not be of the standard desired, the presence of water is constant.
2. *Water is a heterogeneous resource.* Water exists in three different physical states, each of which is commonly found. The liquid form, the state that is most often used as a resource, varies widely in chemical composition. The beneficial use of water requires that the characteristics of the water supplied must match the requirements of the use for which the water is demanded.
3. *Water is a renewable resource.* The water cycle was briefly discussed in the Preface and will be more fully discussed in Part II. The natural process is not completely independent of humans. Modern technology permits the exchange of water between surface sources and ground water sources, can restore quality to contaminated water, can remove salts from ocean water to provide new sources of fresh water, and can even alter the pattern of precipitation. These actions are capable of modifying the renewable characteristic of water.
4. *Water may be a common property.* Not only is water usually found everywhere, but it is nonstationary, with typically ill-defined property rights. If water is available to all without direct charge for use, any opportunity costs that might be associated with such use are not paid by the user. Without such charge no mechanism for allocation of water exists. Water can thus be treated as a free commodity, even during times of scarcity, when many potential users may be excluded. The costs of capturing, treating, and transporting water are clearly recognized, but the cost of water itself is not.

An important exception to common property occurs in the western United States where ownership of water does occur, usually on a first-come, first-served basis. The drought in the western United States during the 1985 summer was so severe in some places that only those individuals with water claims on the water made prior to 1886 still were able to obtain a supply.

5. *Water is used in vast quantities.* The quantity of water used far exceeds the total quantity used of any other single resource. For example, the world's production of minerals, including coal, petroleum, metal ores, and nonmetals, has been estimated to be about 8 billion metric tons per year. Total water use has been estimated to be about 3000 billion metric tons worldwide, or approximately 800 metric tons per person per year.
6. *Water is very inexpensive.* Water's common-property aspect, the nature of water supply technology, and economies of scale combine to make water very inexpensive. For example, municipal water supplied to its point of use usually costs less than 30 cents a metric ton, and irrigation water can cost as little as 3 cents per metric ton. Sand and gravel, probably the cheapest mineral commodity, costs approximately $3 per ton, and iron ore is approximately $30 per ton.

Of the six characteristics of water, the first three—ubiquity, heterogeneity, and renewability—make it difficult to characterize the available water supply, either now or in the future. The quantity and quality of water available at a particular time and place constitute the relevant supply; aggregate or summary statistics, therefore, are nearly meaningless.

The common-property characteristic of water, the large quantities used, and the low user costs all act as deterrents to accurate forcasting of future water use.

Chapter 2 in this part, "Water Resource Adequacy: Illusion and Reality" by Gilbert W. White, examines recent shifts in technical thinking on how to assess the adequacy of fresh water supplies for the future. White's paper was one of the inspirations for this book.

# 1

# WATER, SOMETHING PECULIAR

J. LYKLEMA and T. E. A. VAN HYLCKAMA

Water would be an excellent topic for an after-dinner talk. Not only do we have it in our drinks, (which are mostly water anyway—whether you like it or not), but even our solid food is nearly 50 percent water. It should not amaze us that water is the most abundant chemical substance in the earth's crust. More than half of the 5-km (3 mi) deep outer shell of the earth is water. And that is just one peculiarity of water.

Nearly all living things also consist mostly of water. You and I are about 65 percent water. You may consider this undignified, but that's the way we're built. A 1-month-old fetus is 90 percent water, and babies are more watery than grown-ups. Most mothers are aware of this. It is also the reason that babies can suck more out of their thumbs than we can.

The word for "water" occurs in any language. Table 1-1 gives just a small example. Contrast this with the word for "ice," which does not occur in all languages. In Indonesian, for instance, ice is described as *air batu*, or "stone water," although in modern Indonesian one finds *es*, a transliteration of the Dutch *ijs*.

Table 1-1. Water in 30 Languages

| | | | |
|---|---|---|---|
| Algonquin/Cree | nibi | Hungarian | viz |
| Arabic | mayah | Indonesian | air |
| Chinese | shuĭ | Italian | acqua |
| Danish | vand | Japanese | mizu'k |
| Dutch | water | Latin | aqua |
| English | water | Norwegian | vann |
| Esperanto | akvo | Polish | woda |
| Finnish | vettä | Portuguese | agua |
| French | eau | Russian | woda |
| Frisian | wetter | Sanskrit | udan |
| German | wasser | Spanish | agua |
| Greek | hydōr | Swahili | maji |
| Hawaiian | wai | Swedish | vatten |
| Hebrew | măyĭm | Tchech | woda |
| Hindi | păni | Turkish | su |

We are so completely familiar with water that even if the word is not mentioned it is taken for granted. If somebody says: "My cup runneth over", nobody thinks the overflow to consist of syrup or gravel (although alcohol may be considered). If we talk about irrigation, nobody thinks we mean whisky, and when I mention drainage, nobody refers to tequila. When we say that a fish or a swimmer is in his element, again we mean water, even though water is not an element but a chemical combination, notwithstanding the fact that the Greek and Chinese had different opinions about this.

Water and watery solutions play an all-important role in the physical and biological processes on the earth. Of the physical ones I'll mention only the effects of rainfall on riverflow and of erosion on the landscape.

In living organisms water is active (1) in the transportation of nutrients and other chemicals; (2) in determining the structure and properties of large molecules such as proteins and nucleic acids; (3) in the biochemical reactions taking place in cells and in tissues; and (4) in heat-regulating processes such as moisture absorption and transpiration.

All these factors are essential for the processes in living organisms, and it is therefore most likely that life on this earth originated in the oceans. So we may pose this question: What are the unique properties of water, and is it possible to comprehend them on the basis of molecular interpretation? To answer this question, we must first assemble

Dr. Lyklema was professor of physics, Agricultural University, Wageningen, The Netherlands. Mr. van Hylckama, now retired, was a hydrologist with the U.S. Geological Survey, Tucson, Arizona 85701. This material was originally presented by Dr. Lyklema on the occasion of the 56th Dies Natalis of the University. This article was freely translated, with Dr. Lyklema's approval, by Mr. van Hylckama and published in *WRD Bulletin* (April–June 1975): 64–68. It was also published in *Hydrological Science Bulletin*, 24 (4) (1979): 499. Reprinted by permission of Mr. van Hylckama.

Table 1-2. A Rundown on Water

| | |
|---|---|
| Chemical formula: $H_2O$ | |
| Molecular weight: 18 | |
| Physical characteristics (at room temperature and standard atmosphere) | |
| Freezes at 0°C | |
| Boils at 100°C | |
| Colorless, odorless | |
| Expands on freezing | |
| Maximum density at 4°C | |
| Specific heat: 1 cal/(g/°C) = 75.25J/mole·°C | |
| Heat of vaporization at 100°C: 538 cal/g = 40.6 kJ/mole | |
| Solubility for selected substances | |
| Kitchen salt (NaCl) | 360 g/L |
| 1-Butanol ($C_4H_9OH$) | 80 g/L |
| Ethanol (alcohol)($C_2H_5OH$) | All proportions |
| Fatty substances | Very small |
| Viscosity at 20°C: 1 centipoise (cP = mPa·s); diminishes slightly with temperature | |
| Conductivity at 20°C: $4 \times 10^{-8}$ mho/cm = $4 \times 10^{-6}$ siemen (S)/m | |
| Dielectric constant at 25°C: 78.5 times that in vacuum | |
| Relaxation time: $10^{-10}$ to $10^{-11}$ s | |

the facts, facts that are usually expressed in form of numbers.

Table 1-2 is a small collection of facts. When you look at this list, I would not be surprised if some of the items sound familiar to you, while others are incomprehensible. *Familiar* means that it fits into one's frame of reference. If I say that Florida bananas are 12 to 15 cm (or 5 to 6 in.) long, then such a statement has meaning to you because it fits in your frame of reference. But if I asked you if Mr. X in Kandahar, who earns 100,000 puls per month, has a decent income, then most of you won't be able to answer that question unless you happen to be a specialist in Afghanistan economy. Even if I tell you that 100,000 puls is about equivalent to $25, that won't be of much help because you have to know what the average income of an Afghan is and what he can do with $25. Well, the average income is about $5 per month, so you see Mr. X has a princely income and should be taxed much heavier.

Well, back to water. It boils at 100°C and it freezes at 0°C. We are used to that; we consider it self-evident. But in our daily lives we usually do not talk about viscosities of 1 centipoise (cP) or relaxation times of a millionth of a millionth of a second. Therefore we consider such numbers uncommon or unusual. Here truly lurks a danger of jumping to conclusions, for we might consider that something we are familiar with is also scientifically self-evident. And in the case of water this just is

Table 1-3. Boiling Points of Fluids (°C at Sea Level)

| Fluid | Formula | Molecular Weight | °C |
|---|---|---|---|
| Water | $H_2O$ | 18 | 100.0 |
| Alcohol | $C_2H_5OH$ | 46 | 78.5 |
| Ether | $C_2H_5OC_2H_5$ | 74 | 34.6 |
| Propane | $C_3H_8$ | 44 | −44.5 |
| Carbon dioxide | $CO_2$ | 44 | −78.5 |
| Methane | $CH_4$ | 16 | −161.0 |

not so. There is hardly another fluid with such a small molecule that has such a very high boiling point. On the other hand, viscosities of 1 cP are not at all uncommon among fluids.

To compare water with other fluids in an objective manner, we'll have to look for other frames of reference. We'll have to compare the boiling point of water with the boiling point of other fluids and forget about making tea.

A few examples are given in Table 1-3. First of all, keep in mind that the boiling point of fluids generally increases with the weight of the molecule. The best frame of reference is therefore a series of fluids with a molecular weight comparable to that of water. As you can see, the boiling point goes up as the molecular weight goes up, but alcohol is out of line and water completely so.

Figure 1-1 presents another way of illustrating how peculiar water is. Here are three substances

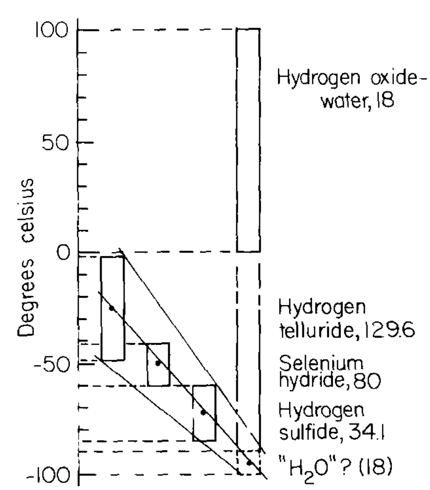


Figure 1-1. Boiling and freezing temperatures of water and waterlike substances. The numbers following the chemical names are molecular weights. (*Source:* After K. S. Davis and J. A. Day, 1961, *Water, the mirror of science*. New York: Doubleday.)

Table 1-4. Specific Heat of Fluids at 25°C

| Fluid | Formula | J/g·°C |
|---|---|---|
| Water | $H_2O$ | 4.18 |
| Alcohol | $C_2H_5OH$ | 2.49 |
| Carbon tetrachloride | $CCl_4$ | 0.98 |
| Chloroform | $CHCl_3$ | 0.90 |
| Ether | $C_2H_5OC_2H_5$ | 2.31 |
| Mercury | Hg | 0.14 |

with a molecule similar to that of water. As the molecular weight goes down, so do boiling and freezing points. Water should be boiling at −91 and freezing at −100—but it is peculiar and behaves differently.

Why is water so exceptional, and once we know that, is it possible to make other fluids that also take such an exceptional position? We can at least say this: During the process of evaporation, molecules of a fluid have to dissociate themselves from each other. A high boiling point means that the molecules can, so to speak, resist such a dissociation. In this case we get the impression that there are very strong attractive forces between molecules of water, much stronger than in any other fluid.

Another interesting comparison is given in Table 1-4. (Don't bother about the units; we're just comparing numbers.) It deals with the specific heat, that is, the amount of heat a fluid needs to raise the temperature of one unit volume by one degree. As you can see, mercury needs a very small quantity, and that is fortunate, because it accounts for the fact that mercury is such a fast indicator of the rise and fall of temperatures. By contrast, water needs about thirty times as much heat. That is why we speak also of heat capacity.

Now this large heat capacity of water has an equalizing effect on our climate. Long after the summer is gone, the oceans are still warmer than the continent, and areas close to the ocean enjoy a much milder climate than those remote from the seas. As you can see, alcohol also has a pretty high heat capacity. That is not completely accidental, but it has nothing to do with diluting wine with water and other diverting chemical pastimes, such as making cocktails. (Incidentally, the units used here are those of the international system. Remember that we used to talk about calories or British thermal units.)

The relatively constant temperature of the ocean has possibly played a role in the formation of life on earth, although it may not have been the most important one. Whatever the history, specific heat does play a role in the heat-regulating mechanism of higher developed organisms and especially of warm-blooded animals. One can imagine that somebody with chloroform instead of water in his or her blood, and suffering from influenza, would have a much higher fever than ordinary, we might say, watery patients have. From a physical-chemical point of view the high specific heat means that water, notwithstanding the fact it is a fluid, must be highly structured or, you might say, organized. It needs a lot of heat to break that structure down and make the molecules move around individually, which happens when temperature rises.

Table 1-5 illustrates another property of water. It deals with viscosity. (Don't worry about the unit centipoise; as before, we're only comparing numbers.) Viscosity indicates how easily a fluid runs. The higher the number of centipoise, the more the stuff runs like molasses in January. For a solid we could say that the viscosity is infinitely high. Gases, of course, have very low viscosities, and fluids are in between. As you can see in this case, water is not particularly exceptional compared with, say, alcohol or carbon tetrachloride. But the interesting part is that this is completely unexpected. We just mentioned that water is structured, and when the molecules are so strongly attached to each other, one would expect that it also would be difficult for them to move around the way molecules do when a fluid is running. What we have here is a strong coherence without loss of mobility. This is most important for living organisms, because they do not need extra sources of energy to keep their blood moving around.

Viscosity depends on temperature and pressure. During influenza epidemics people ask themselves why they get fever. I do that, too. But an advantage is, anyway, that for any degree of fever the viscosity goes down by about 2½ percent and so your heart has to do comparatively less work to pump the blood around. Now this should make you happier when you come down with influenza.

In nearly all fluids viscosity increases with increasing pressure. That is not the case with water. The viscosity diminishes with increasing pressure,

Table 1-5. Viscosity of Fluids at 20°C

| Fluid | cP = Pa·s |
|---|---|
| Water | 1.00 |
| Alcohol | 1.20 |
| Chloroform | 0.58 |
| Carbon tetrachloride | 0.97 |
| Ether | 0.23 |
| Glycerine | 1.50 |
| Sulfuric acid | 25.4 |
| Olive oil | 84.0 |