16. WATER

John Harte and Robert H. Socolow

Your share of the water on the earth is 100,000,000,000 gallons. Your share of the fresh water on earth, not counting the water in the two polar icecaps, is 600,000,000 gallons. Your share of daily rainfall is 80,000 gallons, but 75 percent of this rain falls on the sea, so 20,000 gallons is your share of the average daily rain on the land. Your share of the daily rain on the land which does not evaporate but instead flows into the sea (the so-called runoff water) is 7500 gallons.[1]

How much of this water can man actually use? Obviously, the question is not well defined until we specify what kind of use. Let us try to establish some of the general concepts that help make precise any discussion of water scarcity.

I. A General View of Water Use

The oceans can be used by man for transportation and exploited by man for natural resources. This will almost never interfere with evaporation from the ocean, which is the source of 37 percent of the rainfall onto the land.[2] (The other 63 percent evaporates from the land and rains back on the land.) This 37 percent, 9.8×10^{15} gallons for the whole world each year, moves in a cycle, evaporating from the sea, carried by winds to the land, raining onto the land, and running downhill in rivers and underground aquifers back to the sea. This entire cycle is powered by the sun and represents the world's most colossal desalination program.

Some uses of fresh water leave the water unsuitable for further use without costly treatment. These are the uses of fresh water that must be closely regulated lest contamination render unusable the permanent storage areas of fresh water such as lakes and underground rock formations. Examples of such uses are waste disposal, industrial chemical processing, and irrigation on farms that are subject to modern agricultural chemicals (insecticides, herbicides, and fertilizers).

[1] The volume of stored water in the world by location is given in Table 1. Water flow rates in the world and in the United States are given in Table 2.

[2] Extensive oil spills on the ocean surface *can* increase the fraction of the sunlight reflected by the ocean, reducing evaporation.

TABLE 1. Distribution of the Earth's Water Resources

Location	*Water Volume (gallons)*	*Percentage of Total Water*
Oceans	$348{,}700 \times 10^{15}$	97.2
Icecaps and glaciers	7700×10^{15}	2.15
Atmosphere	34.1×10^{15}	0.01
Fresh-water lakes	33×10^{15}	0.009
Saline lakes and inland seas	27.5×10^{15}	0.008
Average in stream channels	0.3×10^{15}	0.0001
Soil moisture	17.6×10^{15}	0.005
Groundwater within depth of half a mile	1100×10^{15}	0.31
Groundwater—deep lying	1100×10^{15}	0.31

SOURCE: Adapted from Brian J. Skinner, *Earth Resources*, Foundation of Earth Science Series. Englewood Cliffs, N.J.: Prentice-Hall, 1969.

Other uses of water, such as most forms of recreation, leave the water very nearly as it was. Intermediate between these two situations is the use of water for cooling a power plant: the heated water may be lethal to fish, or may speed the eutrophication of a lake, but after flowing a little while it will cool off and may be attractive to the managers of a second power plant (perhaps downstream on the same river) or may become municipal water.

The great natural fresh-water storage areas, above and under the ground, are part of the legacy we would like to pass on to our descendants altered as little as possible. These reservoirs lose water to the oceans and the atmosphere, and they are replenished by rainfall. We can interrupt this flow of water in order to use it, but if we go to the reservoir and remove year after year more water than falls as rain, the reservoirs will dry up. In this sense the rainfall, not the size of the reservoirs, determines the maximum amount of water that we can use. Only if we take care to return the used water to the reservoir as clean as when it was borrowed can we exceed the limit set by rainfall.

TABLE 2. Water Flow Rates for the World and the United States

Water Flow	*Gallons per Year*
World rainfall on the sea	85.5×10^{15}
World rainfall on the land	26.1×10^{15}
World evaporation from the sea	95.3×10^{15}
World evapotranspiration from the land	16.4×10^{15}
World runoff	9.8×10^{15}
United States rainfall	1.55×10^{15}
United States evapotranspiration	1.08×10^{15}
United States runoff	0.47×10^{15}

SOURCE: Adapted from Brian J. Skinner, *Earth Resources*, Foundation of Earth Science Series. Englewood Cliffs, N.J.: Prentice-Hall, 1969.

Averaged over the whole world, rainfall on land is about equally likely to be transpired by plant life, to evaporate directly from the land, or to run into the sea. Man is very limited in his ability to alter this distribution; he cannot alter the transpiration rate without affecting the amount of plant life nor the evaporation rate without affecting rainfall. In this sense, the rate at which runoff water flows into the sea provides a kind of upper limit on the rate at which water can be used in ways which prevent its reuse.

In Comment 1: *Water for cooling and runoff water—an exercise,* the assumptions behind a frequently made comparison between runoff water and water used for cooling are made explicit.

Comment 1: Water for cooling and runoff water—an exercise

In considering water uses that do not prevent reuse, such as power plant cooling, the concept of runoff is not particularly relevant. Nevertheless, it is fashionable to compare annual runoff with the annual cooling requirements of power plants. The reader may find it interesting to investigate the statement quoted by Professor Eipper in his essay on page 115: "By the year 2000 . . . the total cooling water requirements of the United States' steam electric industry are expected to approximate one-third of the country's entire yearly supply of runoff water." This conclusion can be derived[3] from that fact that current (1969) United States electricity production is 1.3×10^{12} kilowatt-hours per year and from the following six assumptions:

---

[3] Appendix 3, on units, may be helpful.

1. The annual growth rate for electrical production, 7 percent, will continue.
2. Modern electrical power plants will continue to operate at 40 percent efficiency.
3. Water that cools power plants will be heated 20° F (11° C) on the average.
4. Half of the heat will be rejected to runoff water, the other half bring rejected to the atmosphere through cooling ponds and cooling towers and to the oceans.
5. Runoff water will never be used twice on its way to the sea.
6. The United States runoff, which is now 30 percent of rainfall (average annual rainfall is 30 inches), will not be modified.

The reader should also consider how such assumptions could be modified in practice and whether some other estimate might be more realistic.

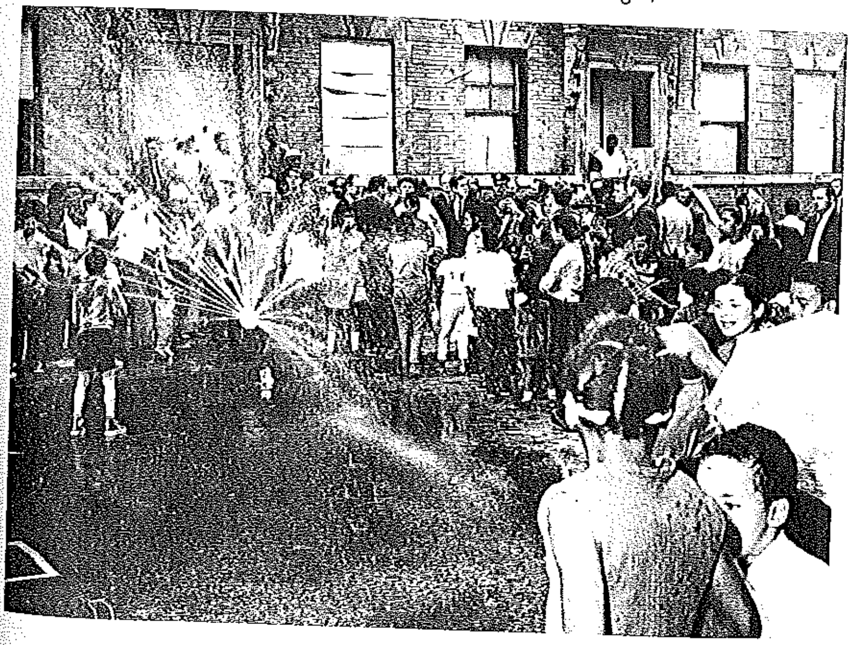
Water Management

Water scarcity is a problem in many parts of the world and has caused much attention to be paid to technologies that either permit the reuse of water or reduce evaporation. Waste water treatment is conventionally described in terms of three levels of technology. *Primary treatment* separates sewage by gravity, allowing the removal of the scum that floats and the sludge that settles. *Secondary treatment* uses biological organisms to break down organic matter in sewage before it is discharged; the intent is to lessen the burden on the biological organisms present in whatever body of water receives the sewage. *Tertiary treatment* refers to any chemical method designed to remove materials not separated out or broken down by primary or secondary treatment, including phosphates, nitrates, pesticides, and dissolved metals. Chemical methods exist to remove virtually any contaminant from water, but extensive tertiary treatment is rarely implemented because of its high cost.

The task of purifying water, to be sure, involves technical challenges that go beyond finding the optimum chemical treatment process: cities where both municipal sewage and storm water flow through the same system of pipes have to contend with enormous variations in the volumes of water requiring processing. And agricultural water cannot be purified unless it is first collected—a formidable task.

If we do not purify the water we use after we are done with it, it is possible that natural biological processes will purify it for us. Biological processes remove many contaminants from solution and break down others. When man seeks to "use" a body of water for sewage disposal, however, it is easy for him to overwhelm the natural purification system. Nor can nature deal effectively with *all* contaminants: an example of a contaminant that cannot be broken down is radioactive waste—short of using a cyclotron there is no way to deactivate a radioactive nucleus before it decays. On the contrary, biological systems are capable of concentrating many radioactive isotopes, thereby increasing their danger to man.

Water as menace and opportunity. *Above:* Children around a polluted water hole that may be a source for water for cooking and drinking. *Below:* The dedication in New York City in 1967 of a special cap on a fire hydrant that gives a spray suitable for playing on hot summer days. (UNATIONS; New York Police Athletic League)



Nature also purifies water by evaporation. Some contaminants, among them DDT, remain bonded to the water as it moves into the atmosphere, but many contaminants are left behind. Sewage disposal by spreading wastes on a field is an example of water purification by evaporation; if the sewage is properly selected, the field will be fertilized at the same time, and the disposal represents a kind of recycling.

It is often dangerous to allow contaminated water to evaporate, however. For example, consider what has happened to some of the land in West Pakistan that has been heavily irrigated. Irrigated water comes in laden with salts, and because the water evaporates from the land instead of flowing out again, the salts remain behind. As a result, the soil quality has deteriorated.

New technologies for retarding the evaporation of water have been proposed; they are designed, of course, to increase the amount of fresh water available to man at a single site. If such technologies are ever applied on a large scale, they will not only affect rainfall but also air and water temperature. A large amount of energy is required to evaporate the annual rainfall, and is ultimately dissipated in the form of heat. (See Comment 2: *Evaporation, rain, and energy.*) This heat is distributed over vast regions of the earth's surface and the lower atmosphere. If evaporation is retarded, some solar energy must find another outlet: local heating of lakes is likely to result. A lake, just like a person, keeps cool by evaporation, and the effects on life in the lake are likely to be harmful.[4]

In Egypt an *increased* amount of evaporation (and a reduced runoff) has been accepted in return for electric power and a greater capacity to control the Nile. Aswan Dam, now being completed, will cause a lake 300 miles long to form behind it. Evaporation from the lake will greatly exceed the earlier evaporation from the river. There is no chance that the increased evaporation will result in rainfall that gives back to Egypt all of the water that evaporates, for the low rainfall in Egypt (about 4 inches a year) is determined by broad geographical features. The evaporated water will fall somewhere else. Thus Aswan Dam will permanently reduce the amount of water available for use in Egypt.

Comment 2: Evaporation, rain, and energy

Considerable energy flows with the hydrocycle. Consider, for example, the energy needed to evaporate the 1.1×10^{17} gallons of water that fall as rain each year in the world. It takes 540 calories to evaporate a cubic centimeter of water, a quantity nearly independent of the temperature at which this is done. Using Appendix 1 to convert gallons to cubic centimeters, you can show that 2.2×10^{23} calories per year are required to evaporate the annual rainfall. This is far greater than the rate at which energy is utilized for photosynthesis and represents an energy flux equal to roughly one-third of the solar flux on earth. (See essay on Energy.)

When the vaporized water condenses, as it does before a rainstorm, the 540 calories per cubic centimeter of water are released to the atmosphere. The result is that the moist air is warmed by this heat of vaporization and rises. This explains why you can tell that a rainstorm is coming when the leaves on the trees are drawn skyward in an updraft.

Of course, a rainstorm is a complicated process. Some of the energy released to the atmosphere upon condensation is radiated to outer space, and some may power the winds that drive the rain from sea to shore.

---

[4] Cayuga Lake is an example of a lake that would be adversely affected by warming. See Professor Eipper's essay in this book.

II. Water Limits in Southeast Florida

The amount of water available for use in southeast Florida must be estimated on the basis of the watershed for that region. This watershed extends from the northern reaches of the Kissimmee River near Orlando to the southern tip of the peninsula, and eastward from a line running almost down the middle of the peninsula all the way to the Atlantic Coast. (See Figure 1.) This watershed occupies about 15,000 square miles, is roughly coextensive with the Central and Southern Florida Flood Control District and Everglades National Park, and serves about 3 million residents, approximately half of whom live in metropolitan Miami. We consider this particular watershed in some detail in order to stress that water use is only sensibly discussed at the regional level and to give the reader a more quantitative appreciation for some of the issues raised in the essay about Everglades National Park earlier in this book.

The average annual rainfall in South Florida is 60 inches, which is double the national average. The annual runoff to the sea, however, is only 20 percent of the rainfall, compared to an average figure of 30 percent nationally. As a result, the number of inches of rain which become runoff water is 12 inches, not much above the national average of 9 inches. The amount of water which evaporates or is transpired by plants in South Florida, 48 inches, is so large for two reasons: (1) the climate is warm and (2) the land is flat, so that there is a large amount of surface water.[5]

Sixty inches of water falling on 15,000 square miles in a year corresponds to a volume of 1.6×10^{13} gallons of water. Divided among 3 million people, this comes to 14,000 gallons per person per day. The runoff water (20 percent of this amount) is 2800 gallons per person per day—less than half of the average per capita daily runoff for the United States as a whole, which is about 6500 gallons. The per capita daily runoff in South Florida scarcely exceeds the national average for per capita daily *use*, which is about 2000 gallons per person per day. (The 2000 gallons are accounted for approximately as follows: 150 gallons per person per day for domestic use, 1000 gallons for irrigation, and the rest for industrial purposes including cooling. All of these figures are rising, since more people are taking care of lawns and more people have swimming pools, to cite

---

[5] Transpiration would be even larger than it is were it not that many plants have adapted to the need to retain water by developing long narrow leaves which retard transpiration.

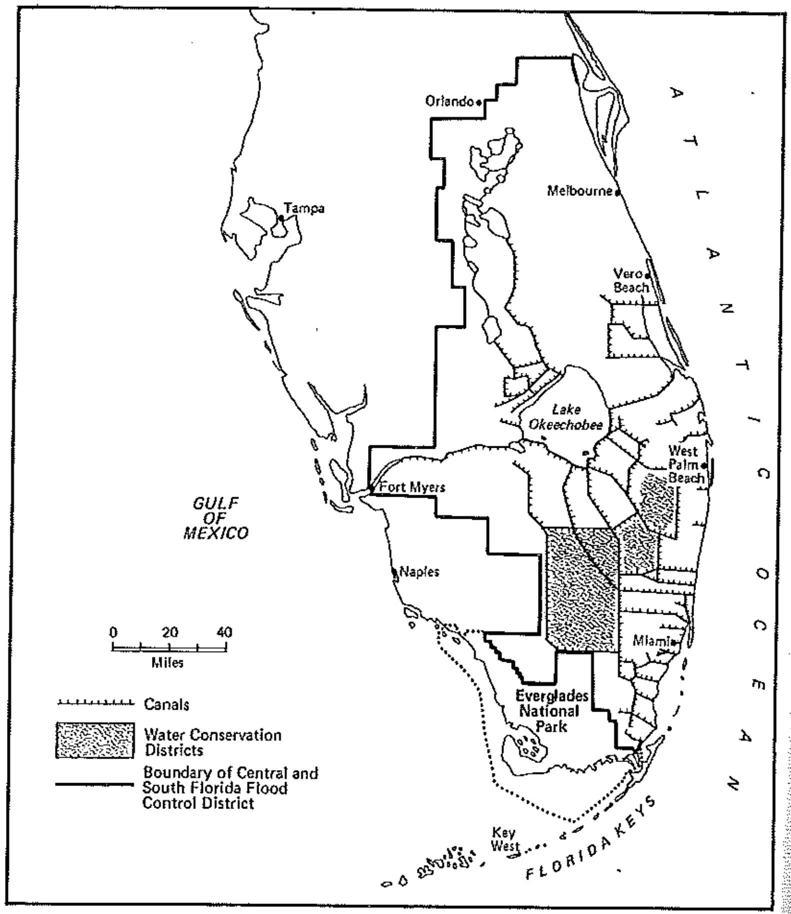


FIGURE 1 Map of South Florida showing the Central and South Florida Flood Control District. (Adapted from "Environmental Problems in South Florida." Report of the National Academy of Sciences and National Academy of Engineering, Washington, D.C., 1970)

two obvious examples.) The comparison of runoff water with water use is certainly crude, as we have remarked earlier, but it gives the correct impression that water is in short supply in South Florida.

Actual per capita water use in South Florida is difficult to estimate. Much of the water used for irrigation is not metered; a lot of it does not become runoff water either. Industrial water use is less than the national average; the factory that made the automobile of the Miami resident was cooled by water in Michigan, not Florida. Domestic water use is probably about 150 gallons, not much different from the national average.

The needs of Everglades National Park for water compete with those of agriculture, industry, and municipalities. The northern boundary of the park cuts right across the watershed region that we are discussing, and the park has customarily depended on water flowing south across that boundary from what are now the water conservation areas. New legislation, quoted in Essay 12, page 197, requires the Flood Control District to supply at least 315,000 acre-feet (100 billion gallons) of water per year to the park when water is plentiful. This corresponds to the household needs (at 150 gallons per person per day) of 1.9 million people, or the total water needs (at 2000 gallons per person per day) of 140,000 people. In 1968, a year of abundant rainfall, the park received 290 billion gallons from the Flood Control District which is about three times the new legal minimum and approximately the amount the park would have received from that area under natural conditions. The new legislation is intended to prevent a repetition of what happened during the years of low rainfall in the early 1960s, when the Flood Control District shut the sluice gates at the northern border of the park and cut the flow to the park nearly to zero.

The Central and Southern Florida Flood Control District has built so many dikes, canals, and pumping stations that the natural water flow patterns have been completely altered. This construction work has given the Flood Control District the capacity to bring water from the less populated regions north of Lake Okeechobee to the more populated regions south of the lake. However, population is growing rapidly all along the east coast, and inland near Orlando, and it is clear that there will be competing urban demands for the District's water, superimposed upon the already existing competition with the needs of agriculture for irrigation and the needs of the park. We can imagine waterworks extended northward up the peninsula almost indefinitely, the cost of water and the loss due to evaporation rising with each extra mile the water is pumped. But eventually the process must cease.

III. The Intrusion of Salt Water into Coastal Aquifers

Another water management problem in Florida is the problem of salt water intrusion into coastal aquifers. This problem is faced by any coastal settlement that derives its water from wells, and is especially serious when the land near the coast is flat. The problem is easily explained.

To begin with, ask yourself whether a well dug near the ocean shore will encounter salt water or fresh water. The answer turns out to depend on how deep the well is and how high the water table is where the well is being dug. A simple model will tell us where the salt water leaves off and the fresh water begins.

Water permeates any porous subsurface rock and moves within it. This is just as true for the sand and limestone beneath the ocean as for the soil and limestone beneath the land. Water in either case keeps on seeping downward until some kind of impermeable rock is encountered; on the two coasts of Florida, this is roughly 100 feet below sea level. In the permeable rock under the ocean, far from the coast, we find salt water, and in the permeable rock under the land far from the coast we find fresh water that has earlier fallen as rain. But near the coast there must be a combat zone.

If salt and fresh water had the same density, the combat zone would lie directly beneath the shoreline. But, in fact, salt water is 2½ percent heavier than fresh water (that is, its density is 1.025 grams per cubic centimeter). Accordingly, beneath a column of salt water, the pressure is 2.5 percent greater than beneath a column of fresh water of the same height. Thus, right at the coast, where the water table must be at sea level, if one started with a column of fresh water beneath the shoreline, it would literally be pushed inland by the sea. Hence the combat zone is under the land.

The only thing that finally stops the salt water is the fact that away from the coast, the water table has a chance to rise above sea level, and thereby the fresh water has a chance to build up extra pressure. Below any point on land, the boundary between the fresh water and the salt water occurs where the fresh water depth (measured from the water table) is just 2½ percent greater than the depth below sea level. At that depth, the pressures of the salt-water column and the fresh-water column are equal. The fresh-water column is 1.025 (or 41/40) times as high as the salt-water column.

Thus, near the coast one will find 40 times as much fresh water below sea level as above sea level in the aquifer. For example, if the water table is 2 feet above sea level, the boundary between salt and fresh water will be 80 feet below sea level.

Accordingly, the boundary surface that marks the farthest advance inland of the ocean waters reflects the shape of the water table like an elongating image. Figure 2 should make this clear. Of course, in practice, the boundary between salt and fresh water is not sharp, but the transition zone of intermediate salinity is actually quite well defined, and this crude model is reasonably accurate.

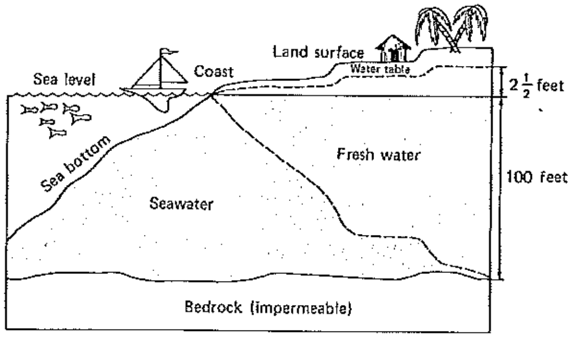


FIGURE 2 Schematic representation of the extent of salt water intrusion in a coastal aquifer. The boundary region between fresh and saltwater mimics the shape of the water table above it. If the water table is lowered a given distance, the boundary region rises 40 times that distance.

If the water table is lowered anywhere between the coast and that inland region where fresh water is found all the way down to the impermeable rock, there will evidently be increased salt intrusion. Inland drainage where the land is as flat as in South Florida will lower the water table over large distances, not just near the drainage area.

There are ways to prevent salt intrusion, but they are costly, complicated, and unpredictable. It is possible, for example, to force fresh water *down* wells into the aquifers to drive the salt water out. One can admire the prowess of hydrologists, which has permitted Holland and Israel, for example, to live at the outermost limits of what the local water situation will permit. Still, these same examples serve to reinforce an obvious lesson: that water quantity eventually poses limits on regional development.

IV. Desalination

New technologies for extracting fresh water from seawater have been suggested as a possible means of breaking once and for all the bonds of water scarcity. Obviously, much of our previous discussion of water limits, which carried connotations of imminent restrictions on some of man's activities, would be quite misleading if desalination were a possible large-scale solution.

There are three main ways to remove the salt from seawater: (1) One can boil the seawater and condense the vapor in a different place. The vapor will have no salt in it and the salt will be left behind. (2) One can freeze the water. The water that freezes first will be lower in salt concentration than the remainder; this relatively salt-free ice can be separated out and then allowed to melt. (3) We can use certain membranes that water molecules pass through more easily than the sodium, chloride, and other ions that are "salt" in solution. The second and third methods lead to a step-by-step reduction in salinity; they have proved difficult to operate on a large scale. The first method, which is called *distillation*, is the one that has been most often exploited commercially (for example, on board ships and more recently in large plants in locations like Key West, Florida, which are remote from fresh water supplies), and it will be discussed here.

It takes 540 calories to vaporize 1 gram of water—an amount of energy that is quite insensitive to the temperature at which vaporization occurs and to the concentration of dissolved salts (provided the solution is dilute enough that the great majority of the molecules are water molecules). In a completely inefficient distillation process, these 540 calories per gram would not be recovered. The most obvious way to improve the efficiency of the process is to have the steam condense back to water on the pipes that are bringing the salt water into the area where the boiling is taking place. In condensation 540 calories are given off, and this energy can serve to heat the incoming salt water. It is by use of such a multistage process that one of today's most efficient distillation plants, on the island of Aruba in the West Indies, has brought down the energy cost per gram from 540 calories to 40 calories.[6]

It is illuminating to consider how much energy would be required to supply the water needs of a typical American. Taking 40 calories per gram as the energy required for desalination and 2000 gallons per day as an estimate of per capita water use for all purposes (including irrigation and industrial cooling), we find that 3×10^8 calories per day would be required. Just to supply this individual with his domestic water (150 gallons per day) would require 2×10^7 calories per day.

Let us compare this energy expenditure with the energy required to supply our typical American with all his electricity. Assuming that he consumes electric power at a rate of 0.75 kilowatt, and assuming 40 percent efficiency in energy production at the power plant, we find that 4×10^7 calories per day are required, only one-seventh of what would be needed for his total water needs, and twice what would be needed for his domestic water.

In other words, if any coastal city that had a water shortage were to get its water, just for domestic use, from the sea, this would raise its energy consumption for electricity by 50 percent.[7] With all of the problems that the present scale of energy consumption present, this is hardly a welcome prospect. Like most energy-intensive "panaceas," desalination looks much less attractive as a large-scale enterprise when it is viewed in a larger environmental context, which evaluates the injurious side effects of energy production (resource depletion, air pollution, thermal pollution, and others).

No matter what improvements in technology occur, there is an absolute minimum amount of energy required to reduce the concentration of salt in water by any given amount, working with water of any given temperature. The existence of such a minimum energy is a consequence of the laws of thermodynamics. Salt dissolved in water is a highly dispersed arrangement of salt and water; salt separated from water is a more ordered —or lower entropy—arrangement. It takes energy, which must be supplied from an external source, to go from a less ordered to a more ordered arrangement, that is, to decrease entropy.

At 20° C the minimum energy to separate the first gram of pure water from a very much larger but fixed volume of seawater is 0.66 calories. (This result is derived in Comment 3: *The minimum energy required to desalinate seawater.*) As one removes fresh water from a fixed volume of seawater, the seawater becomes steadily saltier, and the energy required to remove each successive gram of fresh water steadily increases. In practice, one does not continue desalination past the point where half of the initial seawater has been extracted as fresh water; at that point, the minimum energy cost is about 0.9 calories per gram of fresh water. These limits are completely general; that is, they apply whatever desalination method is used.

At the absolute theoretical limit (that is, 0.66 calories per gram), we still find an energy cost for the 2000 gallons of water per person per day of 5×10^6 calories per day.

It is amusing to discuss absolute limits like these, but in commerical installations limits from physics are almost always dwarfed by limitations imposed by engineering and economics. There is always a trade-off in any industrial process between fixed costs of construction and operating costs. Energy consumption is an operating cost, of course, and to approach thermodynamic minima for energy consumption requres using enormous installations and greatly increasing fixed costs. The reason for this is that the minimum energy requirements dictated by thermodynamics are calculated on the basis of reversible changes, which means, in practice, small temperature differences between parts of the apparatus and slow movement of parts; to accomplish the same rate of output under such constraints requires much larger installation than if temperature gradients and velocities of moving parts are increased.

Comment 3: The minimum energy required to desalinate seawater

Suppose the desalination of seawater takes place by the method idealized in Figure 3. A membrane divides a vessel into two compartments, and the membrane, by being mounted on a piston, can move in such a way as to change the relative sizes of the two compartments. The membrane permits water molecules to pass from one compartment to the other but blocks the movement of the ions into which salt breaks up in solution. (A membrane with this property is called semipermeable.) If seawater is placed in one compartment and fresh water in the other and the piston is locked in place, then water molecules will pass freely back and forth through the membrane until the pressures attributable to the water molecules on each side of the membrane are equal. There is an additional pressure on one side of the membrane due to the salt ions striking the membrane from only one side, and this pressure would force the membrane and the piston toward the fresh water if the piston were not locked in place. This pressure on a semipermeable membrane due to ions in solutions is called *osmotic pressure.*

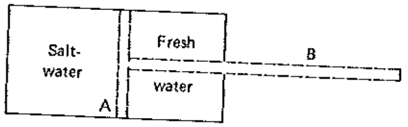


FIGURE 3 Piston B with semipermeable membrane mounted at A. Moving the piston to the left makes the saltwater more concentrated and increases the volume of fresh water.

---

[6] Barnett F. Dodge, "Fresh Water from Saline Waters. An Engineering Research Problem," *American Scientist,* Vol. 48, p. 476 (1960).

[7] To supply the water to an inland city from the sea would cost even more energy because of transportation requirements.

Now suppose that the piston is unlocked and slowly pushed by an external force *toward* the seawater. In the process water molecules will pass through the membrane, permitting the piston to move, and the salt ions will be concentrated in a smaller volume of water. A volume v of seawater will be desalinated when the piston is moved so that the fresh-water compartment is larger and the seawater compartment is smaller by that amount. To move the piston against the osmotic pressure, the external force must do work on (that is, add energy to) the system.

The work done (W) by the force moving the piston is just the product of the osmotic pressure (P) and the change in volume of the seawater compartment v.

$$W = P \cdot v \tag{1}$$

We assume the fractional change in the volume of the seawater compartment is small enough that we can neglect the slight increase in P that occurs during the displacement of the piston. This is assured if v is much less than the initial volume of the seawater compartment, which we call V.

The value of the osmotic pressure is found in a quite accurate way by treating the ions in the seawater compartment exactly as if they were gas molecules moving in a vacuum. The equation that relates pressure (P), volume (V), and absolute temperature (T) for an *ideal* gas also relates osmotic pressure, volume, and absolute temperature for a *dilute* solution. This equation, which underlies the "gas laws" of chemistry, is

$$PV = nRT \tag{2}$$

where n is the number of moles present (either moles of gas or moles of ions) and R is a fundamental constant of nature:

$$R = 1.99 \text{ calories per mole per Kelvin degree}$$

There are typically 1.11×10^{-3} moles of ions in a gram of seawater,[8] and its density is 1.025 grams per cubic centimeter. Assuming that we can treat seawater as a dilute solution, we can calculate the osmotic pressure at room temperature ($T = 20°\text{C} = 293°\text{K}$) from equation (2):

$$\begin{aligned} P &= (1.11 \times 10^{-3}) \times (1.99) \times (293) \times (1.025) \\ &= 0.66 \text{ calories per cubic centimeter} \end{aligned}$$

or about 27 times atmospheric pressure.

To desalinate 1 gram of seawater requires moving the membrane so that the fresh-water compartment is enlarged by $v = 1.00$ cubic centimeter (since the density of fresh water is 1.00 gram per cubic centimeter). Thus, using equation (1), 0.66 calories must be expended to desalinate 1 gram of fresh water by this method.

We stipulated earlier that the piston be moved *slowly* because then the system always stays close to equilibrium and it is possible to retrace the states of the system by reversing the direction of motion of the piston (moving it slowly toward the fresh water). A process carried out in such a way that the states of the system can be retraced is said to be carried out *reversibly*. A starting point of thermodynamics is the statement that the amount of energy used to bring about a change from one state to another is smallest when that change is carried out reversibly and that this minimum amount of energy is independent of which reversible procedure is chosen to bring about that change. Thus thermodynamic arguments permit us to generalize the result we have just obtained: *no matter what desalination process is tried* 0.66 calories is the minimum amount of energy required to desalinate 1 gram of seawater, given that the initial and final temperatures are both 20° C.

---

[8] The reader can get this answer approximately by knowing that the salinity of seawater is generally within a few percent of 35 parts per thousand by weight and by assuming that all of the salt is sodium chloride. He can then look up the actual composition of seawater in Appendix 4 to work out the 5 to 10 percent corrections due to magnesium, sulfate, and other ions.