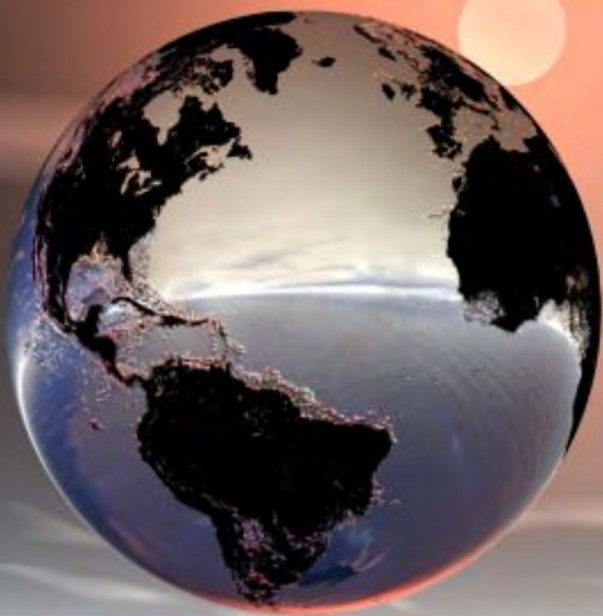
HYDROMIMICRY

Strategies for a Water Planet



West Marrin, PhD

HYDROMIMICRY
Strategies for a Water Planet

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Water Sciences & Insights

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Second Edition

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INTRODUCTION

In the beginning, this planet was almost entirely water and only when the planet's mantle cooled and its ocean basins deepened (about 2.5 billon years ago) did any sizable chunks of dry land appear. About the same time, oxygen made its debut as a major component of the atmosphere. As such, terrestrial oxygen-breathing organisms are the relative newcomers to a planet where water remains the dominant substance. As we approach the challenges of the 21st century, it is worth recalling that ours is truly a water planet and that recognizing and respecting water's critical roles in processes such as climate change, energy selection, food production, economic stability, technology development, human health, and global conflict is not only wise, but indeed mandatory. Many of our recent choices have ignored the wisdom of both water and nature in adopting technologies and management schemes that violate, ignore, or just override water's natural rhythms, patterns, and preferences.

This book presents diverse examples of technologies and management schemes that are actually or conceptually based on emulating, or mimicking, water and nature's use of water. The examples range in scale from molecular to planetary and encompass diverse levels of both applicability and technical complexity. Moreover, a number of the thirty examples raise questions about our common perceptions of water, the roles of water as a mediator or a model, the ethical and spiritual considerations of water, the practical or small-scale use of water resources, and the water-related processes designed to alter planetary conditions. In what ways do Earth's features and life forms mimic water and how might recognizing those features assist us at this point in history?

The second edition of *Hydromimicry* is divided into eight sections that begin with the topic of water's quintessence and continue with its application to several scientific disciplines and the development of engineering, modeling, and testing methods that could impact the global environment as well as individual lifestyles. However, each example is written as a stand-alone narrative that contains a brief synopsis of how water, or nature's use of water, was mimicked and how this mimicry may be practically applied to human endeavors in the near future.

D.L. 'West' Marrin
Yucatán, México
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ONE
Recognizing Water's Nature

This first example examines the nature of water's unusual behavior, rather than the behavior of water in nature—as do most of the subsequent examples. One of the most interesting students of water during the last hundred years was the German naturalist Theodor Schwenk, who considered water as the ideal medium for "form-creating" processes. Wherever there exist differences in water flows or surface boundaries (ocean currents, cell membranes, stream ripples), he believed that vortices form and then serve as delicate "sense organs" to allow a rhythmic merging of those differences. He posited that the creation of all recognizable forms (e.g., trees, stars, planets, animals, rocks) and their inevitable material changes were facilitated by water, acting as an energy and information mediator. He believed that this mediation role was not just limited to different forms of matter, but also included the link between matter and forces and between the physical and the spiritual realms. His view of the spiritual realm was one that emphasized formative and life-giving forces.

It should be noted that Schwenk arrived at these views by studying the behavior of water in diverse natural settings, rather than by mystical experiences or conventional scientific experiments. As such, he interpreted the physical properties of water in an expanded sense and, in doing so, surmised that our managing water primarily to satisfy human needs may actually be violating or restricting the nature of water itself. This is a view that is shared by many present-day indigenous people, who perceive our economic and engineering rationale for dealing with water as ultimately destroying both water and earthly life. So, how might we attempt to make different decisions regarding water—assuming that we are interested in doing so? And how could these rather esoteric descriptions of water assist us in the process?

Perhaps our emphasis could change from managing water (i.e., something that we do to it or force it to do) to working in concert with water, including its natural cycles and rhythms. Are we sufficiently humble to adapt to water's nature, or will we continue to demand that water adapt to ours? Can we use the gift of water and, at the same time, know that it is much more than its everyday or mundane uses? This change does not mean that water collection and conveyance systems will be abandoned, it means that the design for such systems will be influenced more by respecting water's nature than by appeasing short-term financial or political interests.

In other words, it means preserving natural watersheds and flow regimes, rather than forcing water to conform to man-made structures and boundaries. It means recognizing the underlying causes of local water problems (e.g., droughts and floods) are actually global in scope and are best viewed or addressed on that scale. It means halting the translocation of water from far-away sources in order to exploit otherwise uninhabitable and, from our limited viewpoint, unproductive environments. It means recognizing that global changes may not be the main cause of our many water crises, but instead an unforeseen consequence of our past management of water and watersheds. It means learning where the water from our taps originates and how dependent we are on the watersheds that provide our tap water. Finally, it means recognizing that other forms of planetary life depend upon and enhance both the quality and quantity of water that we divert from those watersheds to serve our needs.

The study of biomimicry has illustrated that nature seems to favor design and information over energy and materials in meeting the challenges of living organisms. Water is perhaps nature's favorite mediator for creating those designs and for transmitting much of the life-sustaining information between them. Most of the examples in this book address the ways in which we can utilize or mimic nature's ubiquitous mediator.

Two
Mimicking a Mediator

The concept of water's serving as a mediator is one that does not fit easily into the usual perception of this substance. What exactly is a mediator? Besides a person who intervenes between two disputing parties, a mediator is something that occupies an intermediate position and serves as a medium for causing a result or for transferring information. From global-scale phase changes and fluctuating sea surface temperatures to bioenergetics and cloud microphysics, water is a mediator of change for the planet. Life itself is sustained by water, not only as a molecular-scale mediator of biological processes, but also by making solar energy available to earthly systems. As yet, the extent of this mediation role in the natural world is unknown, as is its utility as a model for mediating other (e.g., technical, legal, political) differences.

One of the most interesting uses of water's mediation is for so-called "green chemistry," which utilizes nontoxic and recyclable materials or reagents in lieu of those that result in pollution or health problems. Green chemistry also promotes processes that require less energy and fewer materials than do conventional syntheses and that use wastes or renewable resources. The chemical syntheses of products ranging from fabrics to drugs are often performed in organic solvents, but *supercritical* water, which occurs at high temperatures and pressures, is an alternative solvent for organic molecules and a medium for oxidizing (destroying) some hazardous wastes. In fact, the reaction rates can often be accelerated by using a water emulsion to synthesize chemicals, thus mimicking the way that biological catalysts, or enzymes, function in living organisms. Water's heat capacity and redox stability are other physical properties that chemists exploit in the laboratory, similar to the ways that the biosphere has exploited them within the natural world.

The use of water as a mediator for performing analyses of air and soils is based on the tendency of chemicals (as liquids, gases, or solids) to partition or move into water, where they can be identified and measured quickly and less expensively. For instance, many pollutants are soluble enough in water to permit an estimate of their concentration in air or soil when exposed to liquid water. Water vapor is a mediator of rapid global climate change (especially in subtropical regions) and has been identified as a major factor in abrupt changes that have occurred in the past and may be occurring at present. Manipulating atmospheric water has become one focus of so-called *geoengineering* responses that are designed to halt or delay climate change.

The legal process of mediation has been referred to by author Barbara Phillips as the "strength of water," which is contrasted with the more obvious strength of rock that is often used as a metaphor for adversarial processes such as litigation. In noting that water always subdues rock, she recognizes that mediation is a route of minimal resistance and one that conserves energy and resources. Throughout history, people have sought to mimic water in their everyday lives and their spiritual practices. The external stillness and internal dynamism of water is a contrast that permits change to be met with a sense of calmness.

Water's power to sculpt landscapes is balanced by its flexibility to move around even the smallest obstacles when necessary. The complex molecular network of water permits this liquid to include or envelop a variety of substances without compromising its fundamental nature. Water is often used as a metaphor to describe the meaning of Taoism, as one of the major world philosophies. Similar to the Tao, water benefits all things without competing with them—as such, water is something to emulate in one's life. All things depend on water, but water does not claim dominance over them. Water is portrayed in numerous traditions as an observable mediator for an unobservable essence or life force that flows eternally through all things.

THREE
Using Water Spiritually

One of most frequently heard suggestions for dealing with the apparent shortage of usable fresh water on the planet is water reuse or recycling, whereby wastewater, graywater, and other forms of degraded freshwater are treated to a point that they are considered acceptable for irrigation or even for human consumption. The Maori are the native people of New Zealand and have some interesting and very useful ways of viewing water and its relationship to humans and the entire world. Rivers, lakes, wetlands, and all natural water sources are understood to possess their own *mauri* or connection to the spiritual realm. Hence, a consideration of the connection between the physical and spiritual is required for including indigenous perspectives in the design of infrastructure and policy pertaining to water. It is the integrity of *mauri* in the source water that determines which of its myriad uses are appropriate and which ones are not.

T.K.K.B. Morgan has described a rating system for *mauri* that indicates whether the use of recycled waters or the treatment of natural waters is unacceptable, acceptable, or neutral. It is a formal hierarchy for decision-making criteria that places the priorities of the environment above that of community and family, ensuring that water is in harmony with its watershed before being considered for human use. This tenet can be contrasted with modern practices whereby water is frequently exploited for human use to the point that watersheds and ecosystems are damaged. According to the Maori view, the appropriate scale for "managing" water is the watershed, rather than some legal or political designation.

When comparing the uses for recycled water, the rating is dependent on a weighted average among environmental and human factors. Using stormwater to irrigate public spaces, practicing rainwater harvesting with suitable tanks, installing composting toilets, and using graywater to irrigate home or community gardens are considered viable. By contrast, using treated wastewater to irrigate gardens is considered neutral, and using any type of water to flush toilets or carry human wastes is considered unacceptable. Transporting water from one watershed to another is also considered an unacceptable practice. These *mauri*-related ratings rarely corroborate the water recycling (reuse) priorities set by modern engineering or economic criteria, let alone by economic agendas.

Maori perceptions of water recycling emphasize that any infrastructure must be developed and operated in harmony with natural water cycles and watershed health. Otherwise, the water's life force energy is compromised and its value to all forms of life (including humans) is diminished, explaining why indigenous cultures often consider our modern water distribution and treatment systems to deliver a reasonably safe, but ultimately life-degrading, water. The perception that treated drinking water does not support the optimal health of people is one that has appeared frequently in the popular, as opposed to scientific, literature during recent years and has served as an impetus for the bottled water industry.

In conclusion, the *mauri* of water can only be preserved if it continues to support the ecosystems of a watershed, if it is utilized efficiently, and if it is not used to transport wastes. Including these principles in modern water management may permit us to live more sustainably with water, as did many ancient and indigenous cultures. A number of water resource experts (e.g., Peter Gleick) have concluded that local, small-scale, and energy-efficient methods of managing water will be more effective in addressing the current water crises than will additional large centralized projects. Could this mark our revival of previous water traditions? While difficult to find at present, water policies incorporating the understandings or customs of indigenous peoples may someday be ordinary.

FOUR
Water Drops and Cell Networks

How are minute water droplets similar to biological cells? Chemists from Oxford University are addressing this question by using droplets as so-called *protocells*, which are connected together in networks that mimic the processes affecting living cells. Each water drop is encased in a lipid or fatty layer that keeps it intact and allows researchers to embed proteins and other types of biomolecules. Ions or salts can be added to the droplets in order to establish osmotic gradients that emulate ion channels (i.e., pores inside cell membranes that facilitate the spontaneous movement of dissolved salts). Furthermore, the water droplets can be added, removed, or rearranged without interfering with the integrity of the entire network. Perhaps the answer to the opening question is that water droplets and biological cells both constitute networks, albeit ones on very different scales.

The previous observation regarding network integrity is interesting for at least two reasons. First, many scientists now believe that living cells operate fundamentally as energy and information nodes of more complex networks, permitting the coordination and synchronization of complex biological processes. Second, connections between the water molecules comprising each droplet form one of the most fundamental, pervasive, and ultradynamic networks in nature. Much of the biological "information" that is shuttled between and within essential molecules (e.g., proteins, DNA) is water mediated. In other words, interconnected networks of water molecules (known as *hydrogen-bonded*) are instrumental in transferring information among and between different biomolecules that perform a variety of functions. For example, water assists enzymes in catalyzing biochemical reactions by binding them to target substrates, or chemicals, and by entering the active site at the moment the reaction occurs.

Water's molecular network is extremely variable in both its structure and dynamics. Structurally, water networks can be described hierarchically, whereby individual molecules represent the nodes of a primary network, simple clusters of molecules represent the nodes of a secondary network, and complex cluster aggregates represent the nodes of higher level networks. Depending on the location of the water and the size of the water assemblages, connections among water molecules can change as rapidly as a trillion times per second or as slowly as few times per hour. Hence, water's networks have been theorized to function simultaneously on different scales and at different rhythms in accordance with both the source and destination of information. While controversial from a scientific perspective, the adaptability and variability of water's molecular networks have been invoked to explain water's designation as a universal mediator. In addition, the geometry of these networks has served as a template for so-called water structuring or clustering techniques.

Returning to the use of water droplets to emulate living cells, one might ask whether the cellular networks emulate or actually reflect the more fundamental water networks. Nobel laureate and biochemist Albert Szent-Györgyi believed that water is not merely an inert substance within which life processes occur, but rather is an integral part of a "living state" that is closely tied to the building and destruction of its molecular structures. Perhaps water droplets are more than just inert surrogates for living cells—blurring the otherwise clear distinction between a model and its application. In any case, this example represents an interesting twist on the theme of scientists' using water and its rather odd physical properties (owing in large part to its mysterious and complex network behaviors) to mimic intricate biological or chemical processes.

FIVE
Neural Networks and Watersheds

The topic of complex networks is one that has garnered considerable attention in recent decades, primarily because many physical, chemical, biological, and social processes, as well as exchanges of information, can be described by such networks. Many of these real networks create self-repeating patterns on different scales, such that relationships among individual nodes (i.e., the connections between fundamental system components) are similar to the connections among clusters composed of many nodes. Whereas the nodes of water's network are individual molecules that hydrogen bond to one another, the nodes neural networks are neurons that are linked together via so-called *synapses*.

Water's molecular network is so enigmatic (i.e., structure and dynamics) that it is currently understood only in general terms; however, neural networks are sufficiently described (at least structurally) to use as models in designing artificial intelligence systems. Neural networks use parallel processing for their sensory information, distribute information over the entire network, and can learn. Applications of artificial neural networks to watersheds include predicting their hydrology and chemistry. For example, artificial neural networks (ANN) are used to predict how soils retain water and how sediment and pollutants present on the landscape are carried into small streams during rainfall events. In addition, water flow rates in rivers have been predicted in regions where it is not possible to make flow measurements. Even changes in the clarity and amount of salts in natural waters have been predicted over time without knowing the processes that led to the changes. In essence, ANNs can learn from information and patterns (in space and time) that have been previously processed.

The relationship of networks to watersheds runs deeper than the predictions made by artificial neural ones. Recall that real networks create self-repeating patterns on different scales. Perhaps not surprisingly, watersheds also exhibit this kind of patterning, which is sometimes referred to as fractal-like. A fractal is a repeating geometric pattern that has the exact same proportions on different spatial scales. Water and ice in the form of rivers and glaciers cut through the planet's surface in ways that leave behind landscapes that may appear random or haphazard if we are looking for straight edges, square corners, or perfect circles. However, organic patterns displayed by watersheds are so precise that those viewed from airplanes are indistinguishable from the much smaller ones observed in tiny sections of the watershed. Coastlines are another water-sculpted feature that both display fractal patterns and often represent the downgradient boundary of watersheds (i.e., the end point of surface and ground waters).

Although these patterns have been largely unrecognized or ignored in designing most man-made landscapes (and in altering natural ones), there is recent interest in emulating them to generate sustainable and eco-compatible creations. The intricate patterns created by water in sculpting every watershed are reflected in its hydrologic properties and its ability to withstand various natural phenomena. Recognizing neither the utility nor wisdom of these natural patterns, humans have embarked on altering the natural flow of water by installing and maintaining structures that are intended to prevent "disasters," but frequently encourage people to live in places where such events are inevitable. Unable to discern the natural patterning of watersheds beneath graded lots or city streets, people are perplexed by such disasters.

So, what is the underlying relationship between water's molecular network and the fractal patterns that it creates on vastly larger scales? Whatever the answer to this question, its networks, clusters, landscapes, waterscapes, and resulting flow forms appear to develop in a fractal-like manner.

SIX
Patterns in Time and Space

Perhaps the best example of designers emulating water's patterns in the natural world and then scaling them down to size are the so-called water *flowforms*, which are constructed with different shapes, lengths, heights, materials, and water flow rates. But all flowforms are designed to create specific flow patterns and rhythms in the water that cascades through them. By flowing down a series of ovoid vessels possessing a narrow entrance and exit, water spontaneously forms various whorls or vortices that can be easily seen, heard, and felt. Essentially, the cavities of the vessels are designed so that the incoming water flows from side to side in an oscillating-type fashion and interacts with itself in forming the recognizable patterns that continually renew themselves over a wide range of spatial scales.

For some time, water flowforms were considered unique architectural and/or landscape features and admired for their aesthetic qualities. However, a group of European naturalists began to look closer into the rhythms and vortical patterns of water cascading through these structures and discovered that they were very similar to those observed for blood moving in the heart. Additionally, they observed that water exiting the flowforms possessed physical properties that were slightly different than those of water entering the flowforms. They speculated that these observable macroscopic patterns and rhythms were somehow translated down to the microscopic scale, where restructuring of water's network (e.g., changing the connections among individual water molecules) occurred. While the mechanisms underlying this proposed translation have never been elucidated, the supposition is that water's vortices are somehow instrumental.

So, what was the inspiration for creating water flowforms in the first place? Naturalists such as Theodor Schwenk, John

Wilkes, and Jennifer Greene, who spent time closely studying the flow patterns, rhythms, and overall behavior of water in natural settings such as streams, rivers, and springs, noticed that these forms either disappeared or were compromised when water flowed through conventional water conveyance systems. Further, they surmised that a natural water's ability to stay within its boundaries, to rid itself of pollutants, and to maintain a healthy life-supporting state (perhaps related to its *mauri* or essence) were related to the formation of these patterns and rhythms. As noted earlier, attempts to control or alter water's natural cycles and flow paths as a means of avoiding water-related disasters may be encouraging them.

Based only on their repeated observations and meticulous descriptions, the naturalists' mandate was to design and build structures that would impart a similar, although certainly not identical, influence on water that is relocated from its natural setting (e.g., all municipal waters and wastewaters). Could water be *revitalized* simply by sending it through a flowform? While the question remains unanswered from a scientific perspective, these flowforms are now used in lieu of more conventional physical and chemical techniques to treat both drinking water and wastewater in several locations around the world. As the need for high quality water escalates, the use of relatively simple, inexpensive, and small-scale methods to treat water will become increasingly valuable.

Another area of research with respect to cascades and flowforms is their use in treating the irrigation water applied to plants or to soils where seeds are germinating. The intent is to determine whether there are differences in root length and density, germination success, and the inhibition of fungus and insects that decrease the productivity of crops. One of the challenges is to separate the effects that might be associated with the water's spin from those that result primarily from its oxygenation, from the leaching of construction materials, or from similar factors associated with water conveyance.

SEVEN
Mixing Water Naturally

While flowforms often look very much like water flowing in natural settings, inventor Jay Harman designed an impeller that is based on the geometry of flowing water itself. He was reportedly fascinated by the geometry of natural spirals and the efficiency with which whirlpools are able to mix large volumes of water using only a modest amount of energy. The elegant geometry of a whirlpool actually represents the most efficient way to mix water, air, or any other fluid; however, this mixing concept has not been universally applied because standard engineering designs rely on a different approach to fluid mechanics. His impeller is a small (15x10 centimeter) stainless steel device that looks remarkably similar to the inside of a conch shell.

So, what is the application for such a device? The answer is the gigantic tanks that hold drinking water supplies for a majority of people in the industrialized world. Regardless of the source of the drinking water, its treatment, disinfection, and storage normally takes place in massive (i.e., greater than one million gallon capacity) storage tanks where the water tends to stratify over time. This stratification, or the layering of water with slightly different temperatures, often causes problems with treating microbes and maintaining the water's chemical quality. The use of conventional pumps or aerators for addressing this problem is energy intensive and creates a number of secondary problems. By contrast, the tiny vortex mixer employs nature's efficiency in entraining all the water in a tank and mixing it with a fraction of the energy required by the pumps or stirrers that it replaces.

In addition to the water mixer, spirals and other forms commonly found in nature have been used to design so-called streamline products, which have been applied to engineering challenges as diverse as reducing the air drag on the blades of wind turbines to improving the performance of aircraft and cars. Even the hulls of high speed boats benefit from design changes that mimic the geometric patterns or forms that are either observed in or created by water. Finally, some of these same geometries have been employed to optimize the energy efficiency of compressors and the thermal transfer of heat exchangers. Why do whirlpools serve as a model for so many successful designs in nature and, more recently, in various human technologies?

One answer is that nature uses vortices to reduce the energy required to perform work by minimizing both friction and drag. Another may be that vortices, which remain one of nature's mechanistic mysteries, entrain their fluid particles on more levels or spatial scales than is currently recognized. This unconventional notion is rooted in a rotational force known as *vorticity*, which describes the spin of particles as they move along their path in a vortex. Vorticity is created by water flowing slightly faster on one side of an object than on the other, and it is influenced by the curvature of a flow path. Flowforms are often designed to influence both the rhythm of oscillations and the effects of vorticity on particles in water.

The unusual properties of whirlpools have been applied to spinning water droplets that scientists are now using to simulate the dynamics of physical objects as large as black holes and as small as subatomic particles. Water's surface tension holds the droplets together and can be used to model other forces such as those that prevail in outer space or the nucleus of an atom. When an electric field is applied to the water droplets, they begin their spin and assume various geometries, some of which have been observed in objects occupying the outskirts of our solar system. Actually, water itself has been observed in the farthest reaches of the galaxy, where it is a major component of the interstellar dust and gas clouds that, when compressed and heated by gravitational forces, give birth to stars, planets, and more water.

EIGHT
Replacing a Natural Wetland

The rapid and widespread destruction of natural wetlands worldwide has prompted the design and installation of so-called artificial wetlands. The actual process is referred to as *wetland mitigation*, which endeavors to recreate conditions that are similar (at least functionally) to those of the original wetland; however, the replacement can never really mimic the original because nature's intricacies are too numerous and complex to ever be completely understood or recreated. Nonetheless, the extent to which artificial wetlands emulate the structure and function of the lost wetlands (in terms of hydrologic regimes, vegetation types, and soil conditions) is the extent to which they serve as viable mitigation measures.

The interest in restoring wetlands is associated with functionality as much as it is with aesthetics. For example, wetlands provide habitat for flora and fauna, enhanced water quality, a buffer for floodwaters during storms, and a source of surface water during droughts. Replacing natural wetlands with flood control structures (e.g., levees) has proven to be an uncertain practice for protecting terrestrial ecosystems.

To evaluate the function of a natural wetland, landscape architects at Penn State University conducted a study to assess the effectiveness of mitigation wetlands by comparing their functions to selected parts of adjacent natural wetlands (e.g., depressions, slopes, floodplains). The most important parameters included the extent and duration of flooding, which had to be recreated in the artificial wetland by placing water inlets, outlets, weirs, and similar engineering control structures in a manner that best emulated the parameters. The selection of geotextiles (as soil or sediment cover), brush, and rocks for habitat improvement was intended to recreate the measured rates of water infiltration and evaporation, as well as to achieve a balance among the mineral, aqueous, and organic phases of the soil. Because the physics, chemistry, and biology of natural soils are so complex, this selection step represents a formidable task for constructing wetlands.

Artificial fill soils have to be compacted and amended with mulch so that the density and amount of organic material is appropriate for the microorganisms and vegetation. There are two predominant strategies for selecting the number, types, and spacing of plants in artificial wetlands. The first is to create a detailed map of plant locations and mixtures based on that observed in natural wetlands, while the second is to introduce a variety of appropriate plants and permit “natural forces” to determine their ultimate distribution, density, and mix. The latter strategy is one that illustrates nature’s way of achieving very similar results using dissimilar structures or processes. An interesting aspect of studying water-sculpted landscapes is the variety of ways in which similar patterns are created by seemingly different processes.

Even after a decade or more, the functioning of artificial wetlands has been observed to be considerably different than that of natural wetlands due principally to hydrologic regimes that remain quite distinct. In spite of the efforts to emulate small-scale hydrologic conditions in nature, controlling water in artificial wetlands remains perhaps the most difficult feat to master. A tradeoff is frequently made between precisely controlling hydrologic conditions via the use of water control structures and permitting artificial wetlands to respond to large-scale hydrologic processes via the construction of fewer control structures. The practice of wetland mitigation is a good example of the challenge that scientists, engineers, and designers encounter when emulating environmental water dynamics on the basis of only a few relevant parameters. As will be discussed in subsequent examples, the challenges with mimicking natural waters and wetlands are generally fewer at progressively smaller scales.

NINE
Practicing Rooftop Hydrology

The implementation of "green roof technology" is one that combines hydromimicry and biomimicry inasmuch as both watershed and hydrologic characteristics must be considered in its design and function. Green roofs are defined as those with a vegetated surface and substrate, thus permitting a variety of concurrent uses such as stormwater management, temperature regulation, and ecosystem or habitat creation. Concerns over the effects that buildings exert on the flow of energy and water through urban areas have prompted the innovation of green roofs, which are implemented to mitigate the runoff of rainwater from conventional roofs, to provide a habitat for local plant and animal species, and to insulate the building from heat and sound.

Whereas the earliest green roofs were merely "backyard gardens" transferred to roofs in large pots or planters, recent versions include an insulation layer, a waterproof membrane, and a soil layer that covers the roof and provides a growth substrate for plants. Green roof substrates typically have a high mineral content and a low organic matter content, which limits the kinds of plants that can be grown, but also provides for drainage and stormwater control. The ecosystem services provided by green roofs are shade, habitat, and vegetation appropriate for birds and insects, while the water services provided are flood control, water conservation (via plant transpiration releasing water back to the atmosphere), and pollutant reduction (avoiding chemicals that would otherwise be contributed by streets, lawns, and parking lots).

Conventional stormwater channels are either asphalt or concrete structures that may be supplemented with overflow reservoirs, retention basins, or other structures designed to deal with heavy runoff events. The advantage of green roofs is that they store water during precipitation events, thereby reducing the runoff volume, delaying the addition of runoff to most conventional systems, averting hydraulic overloads, and minimizing erosion and pollution. It has been estimated that green roofs can reduce building runoff by as much as 60%, depending on the thickness of the substrate and the types of plants. A potential complication with green roof techniques is the contribution of nutrients (nitrogen and phosphorus) from fertilizers; however, research has been conducted into the use of more inert substrates and the planting of vegetation that grows in low nutrient soils.

Not unlike artificial wetlands, the real trick to making green roofs perform optimally (at least from the standpoint of water management) is to mimic the complex interactions of natural small-scale ecosystems using only a minimal number of design parameters. Basically, urban green roofs represent an attempt to reduce both water runoff and pollution using principles similar to those that operate in natural watersheds. Green roofs could also be viewed as a special application of *rainwater harvesting*, which is applicable to the sustainable, small-scale use of water in arid regions.

Rainwater harvesting essentially uses water that runs off impervious surfaces such as roofs and pavement to irrigate landscapes or to store and treat for household purposes. An underlying principle of the technique is to use water as many ways as possible before it evaporates or infiltrates below the root zone of plants. Prerequisites for rainwater harvesting include observing and emulating water flows in the localized catchments and maximizing organic ground cover, both of which are applicable to green roof technologies. Harvesting rainwater is often used in combination with an agricultural technique called *permaculture*, which mimics natural patterns and processes in the local environment to create sustainable designs by using the outputs (wastes) from one compartment as inputs (resources) to another. Among the critical patterns and processes considered and emulated by permaculturists are those related to water and watersheds.

TEN
Building a Better Water Trap

If rooftop ecosystems are not feasible for your building or neighborhood, it may still be possible to mimic natural water flows by using more conventional stormwater management structures along with a little bit of ingenuity. The Australian program called Water Sensitive Urban Design (WSUD) was initiated to protect sensitive environments by reducing the volume and peak flows of urban runoff and, thus, preserving water quality. The success of the program is dependent, in large part, on how closely the natural hydrologic regimes can be emulated via the installation of retention and infiltration trenches, vegetated swales, and various sand filters along the path of the runoff. These structures are required not only to closely match natural flows in the basin, but also to reduce pollutants entering the runoff water from the impervious urban surfaces that were identified in the previous example.

Concrete pipes and detention basins used in traditional stormwater management can reduce the peak flows out of a particular catchment, but cannot either reduce the volume of runoff or permit the natural biodegradation, complexation, or sorption of pollutants—as do soils and stream sediments. In Australia and similarly industrialized nations, environmental impacts caused by the unmanaged discharge of stormwater from a variety of developments to adjacent ecosystems are readily apparent as erosion gullies and as persistent weeds. Mitigating this stormwater damage requires a knowledge of pre-development hydrologic regimes and an ability to model them (as a water balance among a series of interconnected or networked water storage volumes). Using this technique, the capacity and location of basins, trenches, and swales can be calculated and the resulting flows projected.

Experience indicates that pre-development water flows are rarely achieved because natural watersheds exert many unrecognized and unquantifiable influences. Researchers in the field have found that both the base flows and the major storm flows play a role in maintaining the aquatic habitat required for flora and fauna, in flushing the streams, and in maintaining stream banks and other features of the riparian environment. As a consequence, the installed water control structures are required to perform equally well under a range of rainfall events. This is an unrealistic expectation and, as such, tradeoffs among performance goals are nearly always made. Generally, base flow goals are least often achieved and water quality goals are most often achieved. The success in achieving the latter goal is related to the efficiency with which adequately designed basins permit the polluted sediments to settle and, subsequently, be removed.

The design of storage basins is critical to the success of a functional stormwater management system because it must accommodate the processes of evaporation, direct surface runoff, drainage through artificial or imported sediments, and water storage in the deeper sediments or soils. As indicated for artificial wetlands, selecting both the location and size of rocks and sediments laid down in the basins is as much an art as a science. Consequently, the design is often achieved via an iterative process whereby the final solution is more a product of performance (matching the natural flows) than of appearance (matching the geomorphology of ravines in pre-development ecosystems). In this example, the technology achieves its goal in a similar, but not identical, manner to that of the natural world.

The concept of urban runoff as a resource to be exploited, rather than a waste to be disposed, defies most conventional water management schemes. In a growing number of cities, curb cuts are being permitted to direct stormwater flow into landscaped areas along sidewalks or medians. In addition to irrigating common shade trees and ground cover plants, some permaculturists have suggested that specific varieties of food-producing trees could safely utilize this urban water.

ELEVEN
Backyard Pools and Ponds

Reducing the scale at which water is accessed, stored, and treated is a common theme when discussing hydromimicry. The backyard is among the smallest of scales at which one could practically borrow a design from nature, and swimming pools are a place to start. Conventional swimming pools have enormous water, energy, and chemical footprints as a result of their construction, operation, and maintenance; however, so-called *natural* swimming pools (more common in Europe) are an alternative that mimics nature. Instead of combining concrete, steel, fiberglass, acid, and chlorine for building and maintenance, natural pools blend into the landscape and use fewer manufactured materials and toxic chemicals.

In order to create a usable swimming area similar to that of a conventional pool, natural pools must be larger because their sides (consisting of gravel, stone, and clay) are sloped more gently and their filtering system (consisting of shallow aquatic plants) requires about half of the total surface area. Plants and associated microorganisms serve as a biological filter for nutrients and contaminants that are decomposed at the roots, thus preventing waste buildup on the bottom. A precise mix and depth of plants (supporting aquatic animals) is necessary to “stage” the water treatment, as is a pump and aerator to insure that the pool remains aerobic. The bottom is sealed with either a synthetic liner or compacted bentonite, after which clean gravel is applied. Finally, the perimeter soil is compacted and planted to stabilize the dirt and prevent its entering the natural pool.

Similar to creating artificial wetlands, the choice of plants, construction materials, and spatial layouts for pools usually complement the local climate and landscape. Perhaps the most common problem with these natural pools is freshwater algae, which can compete with aquatic and riparian plants for nutrients, space, and sunlight. Monitoring nutrients (nitrate, phosphate) and pH in the pool is as important as testing for pathogens, which are an unlikely—but possible—concern. A range of inexpensive test kits are available for checking the levels of potential pathogens. Many of the challenges inherent in keeping a natural pool healthy are identical to those in maintaining smaller ponds that attract local wildlife.

Traditional birdbaths composed of concrete basins are also susceptible to algae and pathogens; hence, the trend is toward more sustainable ponds created out of the natural landscape. While smaller than pools, the pond's edges also have a gentle slope and are lined with a synthetic material or compacted clay to minimize water leakage. Evaporation from the pond can be reduced by locating it beneath the shade of a tree or adding water lilies to decrease the exposed surface area—the latter is also recommended for pools. If pools and ponds are maintained in a way that emulates natural waters and their cycles, the required cost and work may be minimal. Almost invariably, nature chooses the most energy-efficient and material-conservative options for achieving its goals, and water is certainly no exception.

Whereas switching to a natural pool or birdbath cannot, in and of itself, solve the global water or energy crises, it does provide people with a useful opportunity to appreciate the interconnectedness of water, landscape, and biological life in working with the natural environment. As both energy and infrastructure constraints drive the collection, distribution, and treatment of water to ever smaller scales (e.g., household and community), a familiarity with processes that can sustain us on our local water resources will be important. In many ways, this shift will be less about austerity and more about using artistic and creative insights to maintain a lifestyle that is both sustainable and fulfilling. Water serves as an excellent teacher in that regard.

TWELVE
Plants Show Us the Way

Currently, the single largest use of water is for irrigating crops, and agriculture has not been the most efficient user of water for a variety of reasons. Nonetheless, recent attempts by scientists to emulate water-efficient natural vegetation and apply it to crop management may reverse this trend. By way of comparison, agricultural production lands are seldom ecologically sustainable because they leak both water and nutrients, thus producing soils that are often acidified, water-logged, and high in salts compared to the naturally vegetated lands. Moreover, these changes can result in the diminished quality of nearby stream flows. Native vegetation in arid climates can store water from seasonal rains in the root zone, where it can be captured and used during the dry season. By contrast, most non-native crops permit more water to drain from the root zone, requiring extensive irrigation during the dry season. As part of the reduced water requirement, natural vegetation maintains a relatively consistent leaf litter around plants that inhibits water evaporation from the soil.

As a means of emulating the cycling of water in soils that support native vegetation, planting natural perennials (e.g., grasses, trees) in agricultural lands or rotating deep-rooted crops (e.g., alfalfa) with shallow-rooted ones (e.g., wheat) may retain enough water in the root zone to reduce the irrigation requirements of the latter. There are limits on the volume of water that can be stored in the root zone, and any seasonal shifts in plant transpiration can influence the applicability of this technique. Even so, the seasonal carryover of water has succeeded in cutting irrigation requirements and limiting the downward transport, or infiltration, of fertilizers, pesticides, and herbicides to the ground water. Consequently, more plant nutrients are retained in the root zone and problems with soil pH and salinity are often averted.

If the perennials do not constitute a food source, they can be used as cellulosic components (e.g., grass, wood, paper, crop wastes) of biofuels produced via a chemical process that uses ammonia to break-up the cellulose. Unlike conventional biofuels that require edible foods as inputs, cellulosic ethanol is produced from wastes that would otherwise decay or just be burned. Whether this "chemo-conversion" process actually yields a net energy gain is uncertain. What is certain is that a massive amount of edible food is wasted—as much as 30% in the U.S. Considering that 15% of our energy and 70% of our water is used to grow and transport food, this waste is so costly (in terms of money and resources) that even if it were all somehow converted into biofuels, the loss could not be compensated. Food waste is due to a number of factors, not the least of which is the inefficiency inherent in today's mega-scale production and distribution systems.

The relationship between plants and water is unique and may be the key to two "new" technologies. The first is a water purification technique that involves the thick sap or mucilage from a prickly pear cactus, which has been used in Mexico for centuries. The gooey sap acts a flocculent in adhering to and removing both sediment and bacteria from water. It is readily available and could potentially remove metals, pesticides, and other sediment-bound pollutants from drinking water. The second capitalizes on a plant's ability to split water molecules into oxygen and hydrogen for building the carbohydrates that ultimately feed us. An array of specialized proteins involved in photosynthesis captures solar radiation that powers the plant's water-splitting chore, which scientists are currently trying to emulate in designing artificial systems powered by sunlight. Their ultimate goal is a molecular-scale photovoltaic that generates an electric current and produces hydrogen gas, rather than carbohydrates, as a fuel source. If successful, this process would not only mimic the natural use of water by plants, it would substitute one kind of fuel for another.

THIRTEEN
Saltwater Agriculture

One way that agriculture's thirst for fresh water could be tempered is irrigating crops with either seawater or brackish waters. With land and water now at a premium for producing food, adding crops that are salt tolerant to those that are not (e.g., potatoes, corn, rice, wheat) may be prudent. Things like glasswort seeds, saltbush leaves, and even salt grasses could provide food for both humans and animals in deserts or arid regions that possess well-drained soils and a nearby source of salt water (e.g., oceans, aquifers). Besides water conservation, saltwater agriculture does not require the clearing of forests (increasing farming's already enormous carbon footprint) to create more arable land; however, it does require producing useful crops at acceptable yields and in a sustainable manner. Sustainability in this context refers to obtaining water in an energy-efficient manner and averting soil degradation.

Research on saltwater agriculture has focused on either increasing the salt tolerance of conventional food crops or boosting the nutritional value of already tolerant plants. The volume of saltwater needed for agriculture is greater than that of fresh water because of the requirement to prevent salt buildup near the roots. Crop yields are usually lower with saltwater than freshwater irrigation, but few modifications to farm equipment are necessary. Also, seawater irrigation near the coast can minimize pumping costs and permit the return of irrigation water to the ocean via the natural flow of shallow groundwater. It is likely that groundwater beneath such areas is already saline. While salt tolerant crops will never replace standard ones, they could supplement them as an edible food and as a proposed source of biodiesel or bioethanol.

The wisdom and efficiency of growing salt tolerant plants for biofuels is controversial, as is genetically modifying plants (i.e., mixing the genomes of standard crop species with those of salt tolerant species)—both of which have been suggested for "solving" the global food and water crises. Halophyte turf grasses have been used for coastal golf courses (especially in the tropics), permitting seawater to be used for irrigation; however, the required disposal of excess salts to prevent soil degradation is a drawback. Moreover, saltwater irrigation of either grasses or crops can result in water quality problems that are similar to those identified for fresh water irrigation, such as the leaching of fertilizers or pesticides.

In addition to watering plants, seawater or other brackish waters have been used to flush toilets in some arid regions, although conventional treatment of the resulting wastewater is difficult because of the salt content. As will be discussed in subsequent examples, there may be better ways to deal with human wastes than flushing them. Seawater is also used in coastal cities for fire suppression and for washing sidewalks and other surfaces. A more interesting and eco-friendly use of seawater is as a salt source for producing *bioinsecticides*, which are manufactured from the toxins produced by plants or microorganisms, rather than from chemicals crafted in the laboratory. In this process, seawater is combined with starch and soya to provide a medium in which a common species of bacteria produces toxins that can kill insect larvae.

At the other end of the spectrum is the use of seawater as a curative agent for a wide range of maladies and conditions. For instance, seawater has been used as a skin exfoliant and detoxifier, a nasal decongestant, and an antioxidant booster in the form of seawater irrigation. Higher levels of lipoic acid and vitamins C and E, which have been demonstrated to offer protection against cancer and heart disease, were found at higher levels in tomatoes irrigated with dilute seawater than those irrigated with fresh water. A salinity-induced stress may stimulate the plants to produce more of the antioxidants. Perhaps there are other advantages of saltwater irrigation that have yet to be discovered.

FOURTEEN
Moving Water Like a Tree

If water droplets can be used as surrogates for living cells, then it may not be too surprising that the behavior of water in larger organisms (those composed of biological cells) can also be emulated. A group of scientists at Cornell University have developed a *hydrogel*, which is the primary component of a "synthetic tree" that mimics the processes of water transport and transpiration. These processes simply involve the uptake of soil water from tree roots and the release of water vapor from leaves. Researchers believe that the operating principles (based on the cohesion-tension theory of transpiration) of the synthetic tree will lead to the design of new techniques for efficiently and effectively managing water in applications as diverse as chemical engineering, heat transfer dynamics, soil hydrology, and fuel cell technology.

To construct the synthetic tree, a special gel is etched with 80 tiny channels that run parallel to one another and simulate the tube-filled vascular system, or *xylem*, of a real tree trunk. Essentially, water wicks up the nanometer-scale pores of the hydrogel via the driving force of capillary action. A synthetic tree, which consists of a couple of circles (one representing a root network and the other a leaf network) in a thin gel could never be mistaken for a real tree; however, the mechanisms for their transporting water are quite similar. It is interesting to note that water responding to capillary action is under tension, a force that transforms liquid water into a *metastable* state whereby its molecular structure and physical properties differ from those in the more familiar liquid phase.

Scientists are very interested in water's metastable state, whether created by tension (capillary forces) or supercooled conditions, because of its role in biological and environmental phenomena. At a relatively high tension (negative pressure), the liquid water network is stretched so far that it tears apart and creates bubbles that appear suddenly. Researchers often use pulses of sound or ultrasound to stretch water's network and study its properties. The creation of bubbles in water has been investigated for decades in conjunction with a process called *sonoluminescence*, in which tiny gas bubbles trapped within water are collapsed by applying very specific sound waves. This bubble collapse generates both visible light and high temperatures that have yet to be fully explained.

The synthetic tree is essentially a continuous water pump that extracts water in the form of a vapor, converts the vapor to a metastable liquid that is drawn through the hydrogel, and finishes by expelling water as a vapor. Because transpiration is a passive mechanism, no energy (other than that required to produce the synthetic tree itself) is required to pump the water under negative pressure against the relentless force of gravity. Applications of the technology for increasing water availability include extracting pore water from soils where groundwater aquifers cannot be tapped because of the high energy costs or water quality issues. The operating principle of the synthetic tree is one that employs design, rather than additional energy, to achieve the desired goal. As such, the behavior of water (hydromimicry), the biomechanics of trees (biomimicry), and the properties of gels (materials science) are integrated into a single solution.

While on the subject of hydromimicry and biomimicry, it is worth noting that the fundamental substance of biological organisms is water and that much of the evolutionary design for the biosphere has hinged on exploiting water's physical and chemical properties in terms of function and structure. One could consider all biological organisms as simply water that appears as a vast array of forms due to the way in which it either structures or is structured by proteins and other biomolecules, which themselves incorporate water as both a component of their form and a medium for communicating with each other. Perhaps the evolution of the biosphere is itself an example of hydromimicry.

FIFTEEN
Emulating a Spring Water

The nuclear disaster at Chernobyl exposed a large number of people to high levels of radioactivity that resulted in both short- and long-term health effects. One of the people tasked with studying and ameliorating the effects of this widespread radiation exposure was a Russian scientist, Igor Smirnov, who noticed that a small group of people that were treated in the health care facilities experienced a much lower incidence of cancer than the majority. Smirnov noted that this small group lived near a natural spring in the Caucasus Mountains, and he surmised that their drinking the spring water was somehow protecting them from the radiation effects. Investigation of the water using a combination of nuclear magnetic resonance and ultraviolet luminescence spectroscopy suggested to him that natural geomagnetic fields in the region were somehow influencing the molecular structure of the spring water in a way that rendered it similar to intracellular water (i.e., that present inside every biological cell) in terms of its viscosity, surface tension, permittivity, density, and assessable physical and/or spectral properties.

Based on this hypothesis, Smirnov decided to see whether he could artificially create water that was structurally similar to this spring water. Eventually, he found that a specific polar polymer (i.e., a long chainlike sequence of tiny molecules with a repeating chemical pattern), when activated by an applied electromagnetic field, yielded a water that was similar in its molecular structure, physical properties, and clinical effects to the one he surmised was influenced by geomagnetic fields. He posited that his newly-developed polymer, when exposed to precise wavelengths and intensities of visible light, induced a shuffling of connections among individual water molecules that produced an arrangement, or geometry, similar to that observed in the mountain spring water.

The process was patented in a number of countries and, similar to other artificial structuring techniques, produces a water that is hypothesized to enter and hydrate biological cells more efficiently than does bulk or unstructured water—supposedly because the human body expends less energy to restructure water (i.e., via biomolecules and other bioactive surfaces) prior to its permeating the membrane and entering the cells. Regardless of the "outside" structuring of water, all water must ultimately be structured by organisms according to the very specific requirements of the cell, organelle, or biomolecule involved. Despite diverse claims to the contrary, there is probably no ideal drinking water that requires no further internal restructuring.

Whether or not Smirnov's water actually performs all of its purported feats (e.g., reducing free radicals, inhibiting the growth of cancerous cells, decreasing cortisol levels in the blood), its conception and formulation are another example of a scientist's mimicking the properties of a natural water for purposes of promoting human health. This technology raises two controversial points that have been identified for similar techniques employed to structure drinking water. The first is that water can be predictably structured by applying external fields (e.g., electromagnetic, vorticity, gravitational), and the second is that any of those changes in molecular structure (i.e., creation of clusters or changes in the connections among adjacent water molecules) are able to persist over extended time periods. This latter property is frequently associated with water's so-called memory and is frequently invoked as the mechanism to support claims about the health benefits of drinking structured or clustered waters. Whereas some of the structuring and clustering techniques actually mimic natural waters, others do not.

SIXTEEN
Recipe for Powdered Water

In the quest to produce an optimal aqueous elixir for the human body, there is no lack of examples. One of the most interesting is based on another alpine water—this time from Karakorum Mountains in Pakistan, where the Hunza people reportedly live unusually long lives. The Rumanian scientist Henri Coanda and his protégé Patrick Flanagan were led to believe that the people's longevity was a result of the water they drank. In researching the properties of the local stream water, Flanagan found that it had a relatively low surface tension, a rather milky or cloudy appearance, and a high ratio of colloidal to dissolved minerals. By contrast, water usually contains such minerals as dissolved ions or salts. Upon closer inspection, Flanagan reportedly found that these anomalies were due, at least in part, to the presence of *glacial silt* that was apparently picked-up by and then suspended within the flowing stream water.

Glacial silt is a geological term for a very fine powder that is created by glaciers moving over and pulverizing rocks. In addition, the silt particles were coated with organic matter and tended to remain suspended (as so-called *colloids*) if the stream exhibited particular kinds of flow characteristics—especially whirlpools or vortices. He hypothesized that the stream flows were somehow imparting an electrical charge to the colloids that kept them in suspension. After classifying this electrical charge as a so-called *zeta potential*, Flanagan set out to formulate an artificial water that was based on the properties of the glacial stream water. He believed that there would be multiple applications for this water in the human health and materials sciences.

The process of formulating an artificial, or *microclustered*, water was an arduous one, requiring the use of silica powder containing particles of a specific size and geometry, as well as a precise mix of minerals and organic matter. Moreover, the mountain stream vortices had to be mimicked by equipment that could be used in a laboratory to impart the kind of spin that theoretically resulted in the electrical charge on colloidal particles. A 33-step process was reportedly required to mimic the stream water, at least with respect to parameters that Flanagan considered to be the most critical. One of the many difficulties in mimicking natural waters is that only a few of its myriad properties can be measured or observed using the current investigative technologies. Despite such challenges, this microclustered water was patented and apparently has a number of applications, as do electrolyzed waters that green chemists use instead of organic solvents for semiconductor cleaning. Simple electrolysis units alter water's pH and redox conditions to produce this cleaning water, which is similar in some ways to waters found in extreme natural settings.

Not unlike other structured or clustered waters, artificial Hunza water is reportedly an optimum aqueous elixir for entering biological cells, carrying the life-sustaining nutrients, and removing toxic wastes. The explanation for its ability to perform these feats relates to its *low entropy* state, which just means that colloids structure water in a manner that renders it more ordered, or less random. Consequently, the water is often described in terms of its free energy because ordered or clustered arrangements have a greater free energy than do disordered, or random, networks. Free energy is a measure of the capacity of a physical system to perform work. The bulk or disordered water network may not actually be random, but only appear so because we cannot yet decipher its order. As a molecular information network, water is not currently described by science. Perhaps we will learn more about water networks as inventors and researchers continue to study and mimic the characteristics they believe are most relevant to their applications.

SEVENTEEN
Computer Mimicking of Water

Soil and Water Assessment Tool (SWAT) is a computer model that reportedly predicts the impact of weather, soils, and land uses on the quantity and quality of water in natural watersheds. Conceived over 30 years ago by environmental scientists at Texas A&M University, SWAT has developed over the decades into a virtual laboratory for testing the efficacy of proposed management schemes and pollution programs. It does so by accepting inputs for parameters such as soil types, rainfall patterns, nutrient and pesticide loadings, and various topographic features, which it runs through approximately 500 equations to predict the volume or concentration of its outputs (e.g., runoff waters, sediments, chemicals, microbes) entering nearby lakes and rivers.

SWAT is utilized by government agencies to evaluate the impacts of major legislation such as the Clean Water and Resource Conservation Acts. Not unlike the restricted set of inputs that are used to design artificial wetlands or rooftop watersheds, an important—although quite limited—number of input parameters are used by the mathematical model to predict the responses of water and natural watersheds on a very large scale. Scientists claim that they are trying to mimic nature; however, their mimicking is quite different than that described for the design of flowforms or drinking waters.

Instead of scientists intently studying a limited number of water's behavioral or structural properties and, on that basis, attempting to emulate them in a controlled environment, models like SWAT utilize statistical descriptions of water and its behavior in watersheds to produce a set of oversimplified projections that are influenced by a much larger number of parameters than is possible to either consider or recognize. In addition, the parameters vary and interact with each other in ways that are impossible to predict (scientists often refer to the mathematics of complex natural systems as *nonlinear*). The result is a virtual tool for predicting gross trends in the response of watersheds according to a few key variables that describe their properties or dynamics.

Virtual tools based on statistical inputs are increasingly applied to a wide range of water-related issues in an attempt to assist decision makers who address problems involving complex interactions or natural systems. For example, water scarcity and allocation is now a major concern for both developing and industrialized nations of the world. With the recognition that water is an integral component of all goods (agricultural or manufactured) exchanged among nations and regions, decision makers have sought to balance the scales between water-rich and water-deficient traders so that the latter do not deplete their limited water resources in the form of exports. In other words, arid regions should not export water-intensive commodities like cotton to humid regions. The underlying assumption of so-called *virtual water* is that the volume of water associated with or incorporated in any good can be estimated (as a water footprint) and, therefore, so can the inherent or implicit amount of water exchanged between exporters and importers.

There are a number of concerns regarding virtual water trading that merit consideration. First, it does not reduce the demand for water, but instead shifts demands geographically. Second, it can encourage development in regions where local resources are inadequate. Third, it assumes water scarcity becomes an impediment to the quality of life if a person's per capita usage is restricted to less than 135 liters per day. The latter point is of questionable validity and the former two illustrate the consequences of implementing short-term fixes or stopgap measures for water scarcity. While virtual water is a useful mathematical tool for assessing where importing or exporting is not appropriate, trading water credits may face problems similar to those of trading carbon credits.

EIGHTEEN
Tracking Water Footprints

The concept of a water footprint arose when researchers began to quantify a per capita usage for direct (e.g., drinking, cooking, bathing) and indirect (e.g., products, services) uses. Consumptive use is the most obvious component of the water footprint, but water is also lost to pollution, evaporation, and relocation. Perhaps not surprisingly, the water inherent in producing food and energy comprises the major portion of a person's water footprint. Water for transporting and treating wastes is a surprisingly large part of the footprint, while that for drinking and cooking is minor. Among the energy sources, fossil, nuclear, and biofuels need the most water, while wind, wave, and small-scale solar require the least. The largest per capita water use for power is hydroelectric; however, this is not a consumptive use, meaning that the water is available for other purposes. Because lakes and geologic dams are found in a wide variety of native landscapes, the creation of reservoirs was originally considered to mimic, or at least not to violate, water in a natural setting. History has proved otherwise.

From a geographic perspective, dams create perhaps the largest footprint of all water projects and are often cited as a solution to the water crises. But the highly subsidized costs of water from large reservoirs and their long-term damage to ecosystems are not really sustainable solutions. Nonetheless, China, India, and many developing nations around the globe are gearing up to dam their major rivers in order to generate both water and power—largely for big cities. Due to their population density, cities require a water catchment as much as 600 times larger than the area of their urban boundaries to produce sufficient water. Moreover, the considerable energy used to relocate, or pump, water from productive sources to urban centers comprises a major portion of the total energy footprint for city dwellers.

Whether in urban or rural settings, relationships between water and energy footprints are at the forefront of efforts to coordinate conservation and production. An example is citing power plants next to water treatment plants, where the waste heat produced by the former can be efficiently used by the latter. Similarly, biogas produced by wastewater plants can be used to generate electric power. Many uses of freshwater, such as cooling power plants, can be performed just as well by brackish or saline waters.

What does a water footprint tell us about water's natural behavior? Well, the Maori consider relocating water out of its watershed to violate its essence. But facing a situation where most people live far from viable watersheds, what options are available? A proposal to tow icebergs from polar to temperate regions was scrapped due to the already rapid conversion of ice sheets to liquid water resulting from climate changes. Replacing it is a proposal to ship liquid water across entire oceans, such as from Alaska to India for eventual use in the Middle East. Aside from the substantial energy requirement of shipping water in tankers, it is to be distributed in plastic bottles that are made from petroleum and represent a major source of oceanic pollution. Whereas nature transports water around the globe, it does so in the form of clouds that travel on the prevailing winds. No proposals for shipping airborne water are on the table, although the final section of this book examines how researchers are trying to create conditions in clouds that produce more precipitation.

The large energy-demanding infrastructure that satisfied water demands in prior decades appears to be headed for a downsizing. Previously described techniques of graywater and stormwater use, rainwater harvesting, permaculture, and other household or community technologies for dealing with water are similar to those of ancient and indigenous cultures. Downsizing the scale on which water is routinely managed should reduce the per capita water footprint and, along with it, the demand for energy that may not be readily available.

NINETEEN
Trying to Fool Mother Ocean

If natural watersheds are tremendously complex systems to model, then the oceans are impossibly complex. Not only do the oceans represent dynamic nonlinear systems, they are the master compartment for controlling planetary climate regimes. Other major compartments include the atmosphere, biosphere, and lithosphere (i.e., continents and ocean floors). The oceans are also a largely untapped source of clean energy in the form of wave or tidal power and, very recently, a prime candidate for sequestering the excess carbon that humans have added to the atmosphere—mostly as CO_2 from burning fossil fuels. In order to utilize the oceans as either an energy source or CO_2 repository, scientists have to understand more about how their complex systems function. And one of the most effective ways to learn about the oceans is to mimic the movement of water masses.

University-based scientists from Oregon and Hawaii have attempted to use wave energy to power a pump that lifts cold, nutrient-rich water from modest ocean depths to the warmer sunlit surface waters, where dissolved nutrients are utilized by phytoplankton (microscopic plants) in consuming CO_2 and producing oxygen and biomass. The biomass is then expected to sink to the ocean floor, where its eventual decomposition to CO_2 and methane (CH_4) gases are projected to stay trapped within the abyssal waters, as opposed to being released back into the atmosphere.

Unfortunately, the pump was destroyed by ocean waves before scientists could determine whether the pumped water contained the correct mixture of nutrients and CO_2—one that encourages the growth of phytoplankton and certain bacteria without adding too much dissolved carbon to the already acidic surface waters. The ocean can act as both a source and sink of CO_2; hence, inducing changes in its surface chemistry could locally affect the balance of this greenhouse gas. Can the cumulative effects of short-term localized remedies actually alter global climate trends? The answer depends, in part, on the ocean's long-term responses.

Difficulties associated with harnessing the sea's wave and tidal energy are quite well known. The platforms upon which pumps and converters are mounted, as well as the associated equipment and instrumentation, must be able to withstand the battering of waves and large storms. Although concerns about construction costs and power conversion efficiencies are legitimate, wave energy represents a currently untapped potential. Conversely, the notion that we can either pump liquid CO_2 into the ocean depths or alter nutrient levels at the surface to stimulate photosynthesis (thus transforming the atmospheric CO_2 into carbon-rich biomass that sinks to the ocean floor) is questionable. The original plan was to add a soluble form of iron (as a limiting nutrient for phytoplankton) to the shallow waters, but marine scientists warned that this scheme might disrupt the local ecology and chemistry, darken the sea surface, and stimulate bacteria that could immediately release CO_2 back into the atmosphere.

While the intent of the Oregon/Hawaii researchers was to investigate the effects of natural upwelling on the plankton communities of a subtropical ocean, a secondary goal was to observe the possible effects of large-scale perturbations, such as artificially induced upwelling, on the marine ecosystem as a prelude to our sequestering carbon in the oceans. The risk inherent in this carbon sequestration technique is that it involves changes to complex systems that are interconnected in ways that we do not understand—except at a rudimentary level. Typical marine systems are both nonlinear and chaotic, so that a seemingly minor alteration in one parameter could affect the others in a dramatic fashion. In attempting to foist our CO_2 waste on the oceans, we may be setting off a chain of events that exacerbates global climate change and/or nullifies subtle planetary responses already in effect.

TWENTY
Rescuing Dead Reefs and Seas

Whether or not we deliberately dump our CO_2 waste into the oceans, much of it ends up there. In fact, the oceans act as a CO_2 sink in keeping atmospheric CO_2 levels in check, or at least they did until precipitation patterns and evaporation rates changed due to global warming. The oceans are now able to uptake less atmospheric CO_2, and that which they do uptake is making seawater more acidic because the additional CO_2 has increased the concentration of carbonic acid through a natural equilibrium process. Not only do the oceans receive and store excess CO_2 associated with global climate change, they also receive and store excess heat. Scientists predict that one half of all coral reef species could face extinction if the acidity and temperature of the oceans continue to rise. One suggestion for rescuing these ailing coral reefs involves a modified version of the wave-powered pump discussed in the previous example.

This pump consists of a long plastic tube that is weighted at the bottom and buoyed at the top. As the buoy drops into the trough of a wave, water is pushed into the tube through a one-way valve at the bottom. Although the pump itself does not mimic any common form of water movement in nature, the process of raising colder and less acidic water from the ocean depths mimics the process of upwelling. Similar to the previous example, this technique faces both mechanical and ecological challenges, thus prompting researchers to propose alternative strategies such as seeding the reefs with heat-tolerant coral species—as might occur naturally if an unusual ocean current delivered them. Whereas these and other reef rescue techniques may indeed mimic ocean processes, their long-term ramifications are largely unknown. As discussed in several examples, attempting to mimic large-scale planetary processes or to affect them with repeated or numerous small-scale actions may or may not be effective. There are so many diverse inputs and feedback loops that collectively contribute to the observed trends and changes.

If pumping enough cold water from the ocean depths to reduce the temperature of surface waters surrounding coral reefs seems far-fetched, the concept of pumping water from one sea to another borders on the surreal. Nonetheless, the World Bank may fund the *Red-Dead Conduit* that purports to pump water from the Red Sea to the Dead Sea in an effort to halt the rapidly declining water levels of the latter. Although waters from major oceans have filled inland seas at various times throughout the planet's long history, this scheme is the antithesis of mimicking nature. Water from the Red Sea must be lifted 120 meters over the ridge that separates it from the Dead Sea. Once over the ridge, seawater flows down a pipe and generates the hydroelectricity required for desalinating it—thus providing the local communities with both power and fresh water. Finally, the resulting brine water flows into the already salty Dead Sea and raises its water level.

The main criticism of this grandiose scheme is that it will be performed in lieu of restoring the Jordan River, which has historically fed the Dead Sea. The river has been degraded via unsustainable water withdrawals for the purpose of growing water-intensive crops and via a continual introduction of raw wastewater. A review of the Maori guidelines for ethically and spiritually dealing with water reveals that the degradation of the Jordan River and the construction of a Red-Dead Conduit include actions that are considered unacceptable because they violate water's vital energy. In addition, exporting water-intensive crops from water-deficient regions also violates the tenets of virtual water and its footprints. We often fail to emulate water or to even recognize its natural patterns and rhythms in arid regions, where water is often visibly scarce and where economic incentives encourage people to ignore the carrying capacity of local water resources.

TWENTY-ONE
Sea Shells and Sidewalks

Ocean acidification has elicited an unexpected response from marine organisms that may serve as model for dealing with global climate change—in more ways than one. Acidified oceans often show a reduced concentration of carbonate ions, which are used along with calcium and magnesium to build shells and skeletons. This was a cause of concern to biologists who predicted a thinning and weakening of the shells among all marine organisms that build calcium carbonate shells. Surprisingly, a recent study indicated that some species (e.g., crabs and lobsters) actually built thicker shells, while others (e.g., clams and urchins) do indeed lose their shells. Whereas nutrient levels in seawater may influence the organisms' ability to obtain carbonate, at least some species seem to be removing this excess inorganic carbon, which the oceans have absorbed through slowly dissolving atmospheric CO_2. Hence, a natural planetary response (e.g., biospheric) to the elevated levels of inorganic carbon may be occurring already.

Planetary responses aside, the ability of some marine organisms to sequester inorganic carbon in their shells has prompted various suggestions for reducing atmospheric CO_2 levels. The first is to react CO_2 with magnesium- or calcium-containing minerals that form very stable carbonate rocks, similar to those comprising natural sedimentary formations. The otherwise slow process could be accelerated by pumping liquid CO_2 into subsurface formations, but this could be risky. Schemes to pump CO_2 into saline aquifers and/or depleted petroleum reservoirs as a means of sequestering carbon have been criticized on the basis of their potential to contaminate adjacent (i.e., potable) aquifers, blowout injections wells, and initiate shallow seismic activity. Instead of pumping CO_2 into geologic formations, magnesium and calcium silicates could be mined, grinded, and then mixed with CO_2 under controlled conditions in an above-ground reactor. This would accelerate the process but increase the energy demand.

To offset the increased energy demand of such reactors, a number of entrepreneurial groups around the world suggest that a viable product (i.e., cement) should be produced and sold as a byproduct. Carbonate cement is an eco-alternative to conventional cements that actually require more energy and water to produce. There are still the energy costs of capturing CO_2, as well as those of mining the minerals from geologic formations or separating them from desalination brines or seawater. Initially, the cement is likely to encounter resistance from the construction industry; however, if carbon credits are figured into the price of carbonate cements, they may be cheaper than the conventional alternative. Whatever obstacles may confront the new cement, it represents another example of biomimicking a water-related process to fashion a useful product—in this case, one that is able to store a human waste in a city sidewalk instead of burying it beneath the land or in the ocean.

One of the hallmarks of the natural world is the absence of wastes, at least in the anthropocentric sense of the word. An output (waste) from one species or ecosystem invariably acts as an input (resource) to another. It is water that predictably returns our wastes to us and assists in transforming wastes to resources. Water and soil microorganisms convert much of the refuse in landfills to methane, which is captured as a fuel. Recently, the combination of water and ambient noise, which are described as random vibrations in the environment, was used to induce a piezoelectric effect in nanocrystals that are capable of splitting water and producing hydrogen gas—a fuel that does not generate CO_2 when burned. The process requires vibrating crystal fibers that are used to convert the mechanical energy to the more useful chemical energy. Even more interesting, the microcrystal vibrations can actually be powered by the sounds of flowing or cascading water.

Twenty-two
Desalination and Water Tubes

Seawater desalination is frequently offered as one of the best candidates for our producing more freshwater because the oceans represent an almost unlimited supply and because much of the world's population lives near the coast. A major drawback to desalination (besides producing a concentrated brine solution) has been the tremendous energy required to force water through the reverse osmosis (RO) membranes, which permit passage of water, but not of salts or pollutants. While today's synthetic membranes are far more efficient and solar energy could someday power desalination, the process remains limited by conventional design. Researchers are now taking a lesson from water movement and filtration in the biological world and applying it to the technological world. This new nanotechnology is based on a specialized protein, known as an *aquaporin*, which is found in cellular walls and acts to rapidly transport water in and out of cells.

Aquaporins are narrow tubes lined with protein groups and electrical charges that repel water (sometimes referred to as hydrophobic). These nanometer diameter tubes only permit the single-file passage of water molecules, which link to one another like a chain gang. Salts and larger molecules cannot enter the tube because the hydration shells (i.e., large enveloping clusters) required to dissolve them cannot pass through the narrow opening. This is why "structured waters," as discussed in previous examples, probably cannot enter the cells—at least not in their original form.

Scientists have designed carbon nanotubules that mimic the aquaporins and that are able to either fill or empty based on changes in the electrical charge or geometry of the tubule. Applied to seawater, these carbon tubes rapidly move pure water through them, while stranding the salts or dissolved ions on the opposite side of the carbon sheets in which they are embedded. There have been a number of suggestions for "gating" the entrance to the tubules so that desalination may be performed more efficiently. Whereas a multi-tube pump does not require huge amounts of energy to force the water through membranes, it does require some energy to maintain the electric charges.

Another piece of the desalination puzzle that has emerged is a process known as forward osmosis (FO), which produces fresh water from seawater using an even more concentrated draw solution on the other side of the membrane. A solution of ammonium bicarbonate is used to draw water through the membrane, after which the solution is heated to 40°C to drive off ammonia and CO_2 gases, thus leaving behind fresh water. The two keys to FO include a sufficiently thin membrane and a source of waste heat. The microtubule technology may also be applied to FO. All desalination methods share a problem of biofouling, which can be addressed by biomimicry in the form of enzymes (i.e., biochemical catalysts that accelerate reaction rates) released into the water.

Biofouling is a term that denotes the buildup of bacterial films or mats on the surface of RO or FO membranes, quickly reducing their overall efficiency by blocking the pores. The addition of an enzyme, which bacteria routinely use to break-up mats created by their competitors, to water could prevent this biofouling problem without the use of chemical agents such as bleach, detergent, or a host of toxic metals that create disposal liabilities. Anti-fouling and the related anti-scaling agents, along with a highly concentrated brine, are identified as common drawbacks to desalination. Nature removes salts from seawater (producing precipitation) through the process of solar-powered evaporation at the sea surface, spreading slightly saltier water over the world's oceans. If desalination-produced brines could be economically disposed over a much larger area of the ocean surface, their negative impacts would be diminished.

TWENTY-THREE
Power from Seawater

As the most abundant fluid on Earth, seawater is now being seriously considered as source of clean and renewable energy in conjunction with several different technologies. The first is actually a revival of an old technology known as Ocean Thermal Energy Conversion (OTEC), whereby the heat associated with shallow tropical and subtropical oceans is used to vaporize a liquid such as ammonia, creating enough vapor pressure within a closed system to drive a turbine and generate electricity. The ammonia vapor is then cooled and condensed by passing it through a chamber that is in contact with cold water pumped from greater depths, thus permitting the vaporization process to be repeated over and over. This technology mimics the process of ocean upwelling and is generally considered to yield clean energy because its major pollutants are limited to slightly heated seawater and the chemicals used for treating algae or barnacle fouling in the intake and discharge pipes.

An even more innovative conversion of seawater to power is illustrated by so-called *salinity power*. This power is driven by the osmotic gradient created between seawater and fresh water stored on either side of a synthetic membrane. As fresh water moves spontaneously through the membrane to dilute the dissolved salts on the other side, seawater is pressurized and then piped through a turbine to generate the electricity. Technical challenges to salinity power include developing a membrane that is efficient, strong, and resistant to biofouling, as well as building facilities that can operate safely in deltas, estuaries, or other locations where rivers and oceans meet. Anticipated environmental impacts include the disposal of a brackish water (although less salty than the brine produced by desalination plants), the presence of platforms or pylons in potentially sensitive aquatic habitats, and the disposal of chemicals that are used to prevent biofouling of the pipes. Nevertheless, salinity power is based on emulating a chemical process that occurs naturally where inland or fresh waters flow into the sea.

The notion that water can be split into its two component gases (similar to photosynthesis) and then used as a fuel is one that has a long history, but more recent applications. Several working prototypes of a "water car" have indicated that converting autos to an onboard hydrogen-generating system is feasible and averts the problems associated with remotely producing and transporting hydrogen gas. Water cars are equipped with *electrolysis* cells that use DC current to split water molecules into oxygen and hydrogen atoms, which combine to form their respective molecular gases. Because pure water is a poor conductor of electricity, the cars usually run on seawater or on water with specific ions (salts) added to maximize the gas production and to minimize any trace byproducts that may be formed during the reaction.

All water cars are equipped with one or more batteries (for powering the electrolysis cell) that are charged by an alternator when the car is running and by some external electrical source if the batteries discharge. Gases produced by electrolysis are fed into the fuel injector and then ignited in the cylinders to power the car's engine. A newly patented electrolyzer reportedly produces a gas consisting of uniquely clustered molecules and atoms that are known as *HHO*, which reportedly burns differently than do the gases produced by conventional electrolysis. Water cars are distinct from the more commonly described electric cars, which are powered by fuel cells that utilize hydrogen gas to produce a type of electrochemical energy. While hydrogen gas is being touted at the clean, non-carbon fuel of the future, the most common sources of hydrogen include the electrolysis of water and the reformation of natural gas—the latter of which produces CO_2 as a byproduct of its formation. Several species of algae may also be used to produce hydrogen gas sometime in the future.

TWENTY-FOUR
Hydrothermal Energies

There is more than one way to extract energy from the oceans, as has been proposed by a number of companies that have filed patents for recovering the massive amounts of heat associated with hydrothermal vents on the seafloor. These vents are most prevalent along zones where the planet's tectonic plates are spreading as a result of molten rock upwelling from below. The systems typically consist of a recovery station at the surface that is connected to the vent via insulated piping and a capping device to extract the heated seawater for its eventual use in electricity generation or seawater desalination. In addition to the heat energy, all magmatic water (accompanying the molten rock and mixing with seawater) contains a variety of dissolved minerals and gases, as well as precious metals, which are commercially valuable and will precipitate out of solution as the water cools. The weight of the overlying water in the connecting pipes is projected to be the only driving force necessary to retrieve the vent water from the seafloor.

Tapping hydrothermal vents for energy has some hurdles ahead with respect to international ocean law and its effects on a unique and newly discovered ecosystem. Hydrothermal vent technology does not represent hydromimicry, but its use of a heated water resource is similar to a much older practice that may indeed be hydromimetic. Hydrothermal vents on land are better known as geothermal and typically contain a mixture of magmatic water, ground water, and formational brines. Some of the more famous ones include the geysers of western North America and New Zealand. However, humans have been using geothermal water for millennia to heat their homes, baths, and food by emulating geological and biological structures that are encountered in the vicinity of hot springs or heated ground waters.

Geothermal energy is generally considered both clean and renewable because it does not require the burning of fuel and it is replenished by water that contacts hot rocks deep within the Earth. A typical geothermal power plant pumps steam or hot water to the ground surface, where it turns turbines (for electricity) and is subsequently returned to the underground reservoir from which it was extracted. Issues associated with this energy source relate to the quality of re-injected water, as well as to aesthetics and indigenous land rights. In lieu of building power plants, low-temperature hydrothermal fluids can be used directly to heat homes, fish farms, greenhouses, and food drying facilities. Direct applications do not require either the high temperatures or infrastructure necessary for producing electricity. In fact, the direct use of hydrothermal water is consistent with more traditional and even spiritual uses of this resource.

Returning to hydrothermal vents in the seafloor, there are a number of valuable attributes that may exceed those of heat or minerals. For example, temperatures and pressures within the vents create the previously described *supercritical* water, which displays physical properties of both a gas and a liquid, while supporting a number of chemical reactions that cannot be easily performed using normal water. The vents' unusual ecological community is also of considerable interest because it is based on chemosynthetic bacteria that utilize hydrogen sulfide and heat to produce organic matter. Most ecological communities on the planet are based on the photosynthetic production of organic matter, whereby plants use the visible portion of sunlight to split water. Chemosynthesis has been suggested as a possible option for producing food or biomass underground in regions where the availability of agricultural land is limited. Perhaps chemosynthetic food production can slow the current trend of industrialized nations purchasing both land and water rights in poorer nations as a means of securing future food supplies.

TWENTY-FIVE
Decentralized Water Designs

Recognizing that the existing infrastructure for drinking water, stormwater, and wastewater systems is in disrepair and that current methods of treatment are wasteful and often exacerbate climate and environmental problems, engineer Valerie Nelson has proposed that implementing *decentralized* water technologies and designs could be a possible answer. Implementing these new designs will require people and institutions to change their perceptions of and approaches to water systems, which may turn out to be the major obstacle. Many of these designs are based on biomimicry and, arguably, hydromimicry principles that include the interdependence of coexisting species, the natural movement of water through various cycles, and the storage, reuse, and cleaning of water at the local level to support those species.

The allure of decentralized technologies is enhanced by truly sustainable policies such as increased water efficiency, full cost pricing, and a comprehensive watershed approach to both quality and quantity issues. One of the ways that surface water could be stored within its own watershed for later retrieval is to infiltrate it into the underlying groundwater. Whereas storing water in aquifers requires energy to pump it back to the surface, evaporative losses are minimal compared to surface reservoirs. Assuming permeable and pollutant-free soils are available, the practice of artificial recharge mimics a natural infiltration process.

Current practices of transporting water out of its native watershed, treating wastewater and disposing its effluent in a remote location, and hiding stormwater in underground pipes has contributed to most people's inability to answer questions about the origin of their tap water, the amount of water they dispose of, or the patterns of surface water flow in their own neighborhood. This water "alienation" is countered by practices such as rainwater harvesting, gray water usage, rooftop ecosystems, and natural stormwater channels, as was previously discussed. But decentralized water infrastructure goes even further in its restoring local streams with urban runoff, requiring onsite treatment of wastewater in lagoons or artificial wetlands that would also provide wildlife habitat, and re-hydrating soils to increase local infiltration, to absorb heat, and to retain atmospheric moisture.

The initial shift will probably be to a *hybrid* infrastructure, which utilizes the functional and complementary components of the older centralized systems, as well as the most easily installed or adapted components of the new decentralized systems. A gradual shift would permit the costs of changing systems to be spread out over a longer time period and could lessen the resistance from municipalities or water treatment works (both private and public) that have a vested interest in maintaining the status quo. If people shift their perception of water and its importance in their immediate environment, in their health, and perhaps even in their property values, then the grassroots pressure for a more decentralized system of managing water may succeed in leading both the private- and public-sector institutions along.

The recognition that we have to work with the natural rhythms and patterns of water is one that is long overdue. Additionally, the era of brute-force engineering projects and seemingly unlimited natural resources is near its endpoint. Replacing it is one of living sustainably and of recognizing and emulating the intelligence of water, nature, and the biosphere. Ironically, the factor that is likely to push us into this new era is the lack (or at least the high cost) of power to operate the energy-inefficient centralized systems. The huge amount of power currently used to pump and treat water could be reduced, thus permitting us more time to research and develop new sources of energy. As has been noted by a number of water resource experts, there exists an intimate connection among *water*, *energy*, and *money*.

TWENTY-SIX
Is Urine Wastewater?

If the decentralized treatment of water in neighborhood lagoons or artificial wetlands represents a slight change in our behavior, then using wastewater without any treatment surely represents radical change. Specifically, the use of both human and animal urine has some emerging applications that could save both water and energy. The direct use of human urine, which is sterile and serves as a source of nutrients for plants, requires the use of a separating or "no-mix" toilet for routing the urine and feces to different storage or transport systems. The use of urine on a household or community basis saves energy by reducing the requirement for wastewater treatment and chemical fertilizers. Calculations suggest that the associated energy and greenhouse gas (CO_2) savings could be substantial; moreover, the volume of solid and liquid wastes could be reduced.

What about the safety of using humans' primary aqueous waste, which contains nitrogen, phosphorus, and potassium, as a fertilizer on edible plants? European research indicated that crops fertilized with urine tasted no different than those fertilized as usual and that the risks of urine-borne pathogens are minimal due to the presence of competing soil bacteria. Fresh urine is often diluted with water (to reduce its strength as a fertilizer) before being added to soils; however, it has been added in an undiluted form to hydroponic systems and to *biochar*, which is a type of carbon-rich charcoal created by burning plant wastes under low oxygen conditions. Biochar has been added to soils to increase fertility, to enhance water retention, and to sequester carbon.

Among the carbon sequestration techniques, biochar is unique inasmuch as it has been practiced for centuries, it has small-scale applicability, it requires minimal energy, and it is unlikely to cause contamination or catastrophic events. The major objection to biochar seems to be its potential takeover by industry for purposes of producing commercially valuable gases (fuels) and oils, thus converting food crops to industrial crops that are geared to maximize profits—not unlike a major argument used against conventional biofuels. Regarding soil applications, biochar's drawbacks include its powdery nature and its ability to absorb soluble nutrients (initially reducing fertility). Interestingly, both of the drawbacks are minimized by the treatment of biochar with urine.

Whereas the preceding examples highlight urine's ability to save water and energy, this multi-faceted liquid can also be used to produce energy. A major component of urine is urea, which can be used directly as fuel in electrochemical cells and used indirectly to produce hydrogen gas that can be used for various purposes. Moreover, the toxic byproducts of diesel fuel engines can be reacted with urea to form nontoxic gases. In order to garner energy from urine, urea must be separated from the bulk liquid; hence, separating toilets are important in providing an undiluted and uncontaminated source. In theory, an adult annually produces enough urine to drive a car about 2700 kilometers (1700 miles). The use of urine-produced energy could be most applicable to farms, where animals generate enough urine to power entire buildings.

Even if urine is not used to produce power or to fertilize soil, its separation from the toxic or pathogenic elements of wastewater would reduce the treatment requirements for either disposal or reuse. As water recycling (i.e., treatment of municipal wastewater or raw sewage to a usable quality) continues to expand—especially in urban settings—the direct application of stormwater, graywater, harvested rainwater, and other types of untreated wastewaters to soils and plants will reduce demands on water, energy, and the global climate. As noted in the previous example, the rapidly deteriorating infrastructure for conventional wastewater treatment will be costly to renovate in terms of capital outlays and user fees.

TWENTY-SEVEN
Making Glaciers and Clouds

Previous examples have involved emulating the physical, chemical, or dynamic properties of water in its liquid phase; however, scientists have also begun to mimic processes that involve water's solid (ice) and gaseous (vapor) phases. The practice of growing glaciers, which is also known as glacier *grafting*, has been utilized for centuries by villagers in the mountains of Asia to augment their water supply. There are two types of glaciers—a slow growing type with lots of rocks and soil and a fast growing type with more ice. Indigenous peoples recognize that both are required to successfully grow a glacier and, as such, ice or snow that is relocated to the foot of a glacier must also be seeded with rocks, sawdust, and charcoal that can trap and shield the frozen water, as well as ensure that the glacier incorporates these materials during its growth down the mountain.

Once the mixture of rock and ice is sufficiently heavy, it begins to move downhill (usually after about three years) as a self-sustaining glacier. Whereas these grafts could never be mistaken for a naturally-formed glacier, they can grow to lengths exceeding 100 meters and provide a reliable source of water for local communities. Researchers are investigating the physical processes that contribute to growing grafts and the potential for expanding the practice on a considerably larger scale; however, local people claim that a precise mix of materials is the key. In this example, humans observing the dynamics of glaciers have attempted to mimic the structures and patterns supporting these dynamics through the addition of readily available materials.

Water vapor is one of the most abundant and ubiquitous gases in the Earth's atmosphere (ranking third behind oxygen and nitrogen), although only a fraction of that water vapor ever condenses to form the tiny droplets or ice crystals that comprise clouds. While some of the factors resulting in the formation of clouds are well known, others remain a mystery. Why some clouds produce rain and others do not is a topic of current research because of its application to manipulating the amount and distribution of rain during this time of rapid climate change. The tiny particles around which water vapor condenses (including things as diverse as airborne bacteria and sea salt), the amount of air turbulence, and the size of water droplets all contribute to the cloud's probability of producing rainfall. Can scientists mimic the conditions that yield rain from clouds?

The answer to this question is uncertain; however, the practice of "seeding" clouds with dry ice or silver iodide to produce precipitation from rainless clouds has been studied for decades. Cloud seeding seeks to maximize the conversion of supercooled water to ice, which has been demonstrated to increase rainfall—particularly in mountainous regions where clouds containing supercooled water are lifted over the peaks by the prevailing winds. Studies have indicated that cloud seeding may increase rainfall amounts from about 5% to 20% (depending on the exact types of clouds) and could lessen the severity of hail storms, hurricanes, and extreme precipitation events. Nonetheless, the study results compiled over several decades display substantial variations; hence, regional-scale cloud seeding has yet to be adopted anywhere.

While the outcome of cloud seeding is based on mimicking the natural process of converting supercooled water to ice, the practice itself has likely encouraged a scheme to seed the upper atmosphere with sulfur dioxide or silicon chips in an attempt to reflect sunlight and, therefore, mitigate the global warming trend. Potential effects of this atmospheric shading scheme on water dynamics at high altitudes, let alone on the planetary water cycle, are currently unknown. A look at some popular geoengineering schemes and their probable impacts on water is reserved for the final example.

TWENTY-EIGHT
Trading Water for Diamonds

In a remote sector of the Canadian tundra, two lakes and their connecting stream were drained of all water to provide mining access to a geologic formation containing diamonds. As compensation for the ecological and hydrological impact of converting the lakes to open pit mines, the government required a 3400 meter-long stream channel to be blasted out of granitic bedrock. Whereas arctic streams may not appear to be as complex as their temperate or tropical counterparts, difficulties associated with emulating natural aquatic systems (including the chemical/physical conditions and the habitat for native flora/fauna) anywhere are many and varied, as was illustrated in the earlier hydrology examples.

Because the stream environment was dominated by thin soils, sparse shrubs, and lots of rocks and boulders, attempts to recreate the aquatic habitat (as was previously described for wetland mitigation) were largely unsuccessful. Pools and riffles were engineered into the design of the stream through the use of varying slopes, and large rocks were moved into the channel to produce natural flow forms such as whirlpools and eddies in the cascading water. The planting of riparian and aquatic vegetation was even less successful than stream alterations and produced few lasting results.

The artificial stream was permitted to stabilize for period of three years before its properties were compared to those of nearby natural streams. As might be expected, densities of invertebrates (e.g., worms, snails, insects) were substantially lower in the artificial stream, as were levels of natural organic matter—including material that is either produced within or falls into the stream. Moreover, the banks and bottom of the stream displayed greater instability and more fine-grained sediment (i.e., less gravel) than did the natural streams. None of the data suggested that the artificial stream would provide adequate habitat or food resources for native fishes, which are due to be reintroduced at some point in the future.

In addition to literally trading water resources (or at least water quality) for diamonds, there is a metaphorical tradeoff between the two known as the *diamond-water paradox*. This paradox is rooted in the field of economics and describes the apparent contradiction that diamonds command a higher price than water in the marketplace, despite water's greater usefulness. Also recognized by economist Adam Smith as a *paradox of value*, things with the greatest exchange value often have little or no use value. The value disparity persists until truly useful things become scarce, as seems to be the case with water in the twenty-first century. The actual or perceived water scarcity feeds into the demand side of the market and, consequently, water's price goes up. Regardless of temporal changes in market demand, the true value and utility of water remain unchanged.

Paradoxes and markets aside, water and diamonds have similarities that are related to their molecular geometry and origin. The carbon atoms comprising diamonds are arranged and bonded to one another in a rigid tetrahedral network. Likewise, water molecules are bonded to each other in a less rigid tetrahedral network that actually permits the switching of bonds among neighboring molecules. Water's very rapid network dynamics are responsible for its unusual properties and its ability to flow, despite its similarity to solid crystals. Conversely, the more steadfast arrangement of a diamond's network is responsible for its extreme hardness. Finally, both water and diamonds may be created and/or stored deep within the Earth or transported to our planet on meteorites, comets, and other carriers of star dust that ultimately crash into and spread their debris over the planet's landscapes or waterscapes.

TWENTY-NINE
Water's Phase Dance

The penultimate example in this book includes one of the most frequently cited and, perhaps, underrated attributes of water—namely its ability to switch between solid, liquid, and vapor states at temperatures encountered on Earth's surface. As previously noted, water's ceaseless "dance" between the three phases is responsible for distributing solar energy on a global scale, and its presence as a vapor in the atmosphere constitutes the only greenhouse gas that can change the trend of climate change on a short-term basis. Recent research has sparked debate on methods that humans could use to shift this phase dance and ameliorate global climate change. While our tampering with the global water cycle may be no more fruitful than sequestering carbon for this purpose, the former is an activity in which humans are already heavily engaged—both deliberately and inadvertently.

Perhaps the most easily observed way that humans alter the water cycle is evident from its distribution on the surface of the continents, particularly as large dams. An interesting question regarding climate change is whether large dams are having an effect on extreme weather events. While a number of factors influence the intensity and frequency of major precipitation events, the data suggest that large dams locally affect water's liquid-vapor phase change. Might large dams increase the amount of water vapor in the local atmosphere?

This liquid to vapor phase change has also been recreated in evaporative or "swamp" coolers that are often used in arid regions instead of more energy-consumptive air conditioners. The coolers emulate a natural evaporative process that takes place near water bodies, beneath vegetation canopies, and on the surfaces of plants and animals. Ancient swamp coolers consisted of woven grass mats that were wetted and placed over doors or windows on the dwelling's windward side.

As a major greenhouse gas, water vapor's conversion to a liquid or solid (as enhanced by artificial processes) has been proposed as a possible means to slow down global climate change. A difficulty is that cooling the air in locations where water vapor concentrations are highest requires energy. In addition, the condensed water has to be sequestered from the air so that it does not evaporate back into the atmosphere.

One of the major processes responsible for keeping the planet's surface cool is the reflection of sunlight (up to 85% of it) by snow. Converting liquid water to snow using the kind of blowers that are routinely employed on ski slopes could locally increase snow cover, but the energy requirements are large. As was discussed previously, the use of cloud seeding to increase snow cover is also energy intensive. Interestingly, the tiny airborne particles created by burning diesel fuel, coal, and wood reduce the amount of sunlight reflected by snow. Hence, keeping these particles out of the air may be a more efficient means of increasing the amount of reflected sunlight than is trying to influence the total area of snow cover.

It seems that our further influencing the global water cycle as a primary means of reversing climate change may not be prudent. The costs are high and the uncertainties even higher. Unable to predict the consequences of altering the water cycle with our twentieth century technologies, we have little reason to expect that we are better able to predict the consequences of altering the carbon cycle with our twenty-first century technologies. In the end, the realization that our behaviors, lifestyles, and possessions are more easily changed than our watery environment is one that is difficult to escape. The degree to which humans are responsible for the rate or extent of climate change will likely be debated for decades. A more pertinent question may be which of the planet's species (including humans) will adapt to these upcoming changes and which will face extinction.

THIRTY
Geoengineering and Water

Geoengineering is loosely defined as an attempt to modify or manipulate aspects of the Earth's climate in order to lessen the effects of rapid global climate change. Geoengineering is often subdivided into *remediation* technologies that address the causes of climate change (e.g., carbon sequestration) and *intervention* technologies that address the results of climate change (e.g., solar radiation management). The intervention techniques are often considered to be the more desperate of the two because they are designed to alleviate the symptoms of climate change very rapidly by blocking sunlight or altering temperatures. By definition, they represent techniques that must be implemented indefinitely or as long as "unfavorable" climate changes persist. Remediation technologies purport to reduce the amount of carbon in the planet's short-term cycle, thereby reducing or stabilizing atmospheric CO_2 levels. In reality, remediation only treats a symptom if the production of anthropogenic greenhouse gases is not curtailed as well.

There are three assumptions regarding climate change that are inherent in considering geoengineering: [1] changes in global climate will be catastrophic, [2] the course of climate change can be altered, and [3] given sufficient time and proof of climate change, human activities responsible for producing greenhouse gases will be curtailed. In addition, there is an underlying assumption that through discussion and debate, the world community can agree on ways to implement and monitor geoengineering. The validity of these assumptions is not known at this time. What is known is that fast feedback processes (on the order of decades) will be associated with water in the form of atmospheric vapor, clouds, and sea ice. So, how will shooting seawater aerosols into the air to whiten clouds or releasing tons of aluminum or sulfate particles into the air to reflect sunlight indirectly affect the planetary water cycle? Scientists simply do not know, but the prevailing belief seems to be that any unknown effects of geoengineering on water or the environment are likely to be less catastrophic (at least to humans) than are those of climate change.

It is interesting to note that some researchers believe that irreversible temperature "signals" in the form of melting sea ice (inducing temperature and salinity changes) have already been injected into the thermohaline circulation—also known as the oceanic conveyor belt—and will slowly make their way around the globe as they modify ocean currents, winds, heat budgets, and ultimately global climate regimes. If true, many geoengineering schemes may turn out to be as ineffective as they are uncertain in maintaining the status quo for world climates. In addition to the thermohaline circulation, oceans eventually absorb and store most of the heat and CO_2 that are measured in the atmosphere. As a true water planet, the fate of Earth's climate will be determined by its oceans.

So, is geoengineering an example of hydromimicry? The answer seems to be mixed. Pumping liquid CO_2 into saline aquifers, depleted petroleum reservoirs, and ocean basins is clearly not hydromimicry, nor is creating biochar, biofuels, or tree plantations. Capturing CO_2 from the atmosphere perhaps resembles ocean uptake, and producing carbonate cements emulates the shell-making of aquatic organisms. Launching sulfur into the upper atmosphere or iron onto the sea surface might emulate natural processes (e.g., volcanoes, upwelling) that affect global water, but they fall short of hydromimcry. Spraying a fine mist of seawater into the sky mimics a natural process as do certain types of ocean mixing technologies. As such, a few geoengineering techniques seem to mimic water's natural processes or those occurring within water. Perhaps the more relevant question is which geoengineering schemes (or any techniques reviewed in this book) acknowledge the wisdom, as well as the mechanisms, of water. Adapting to a changing planet may require the recognition of its wisdom as much as the emulation of its mechanisms.

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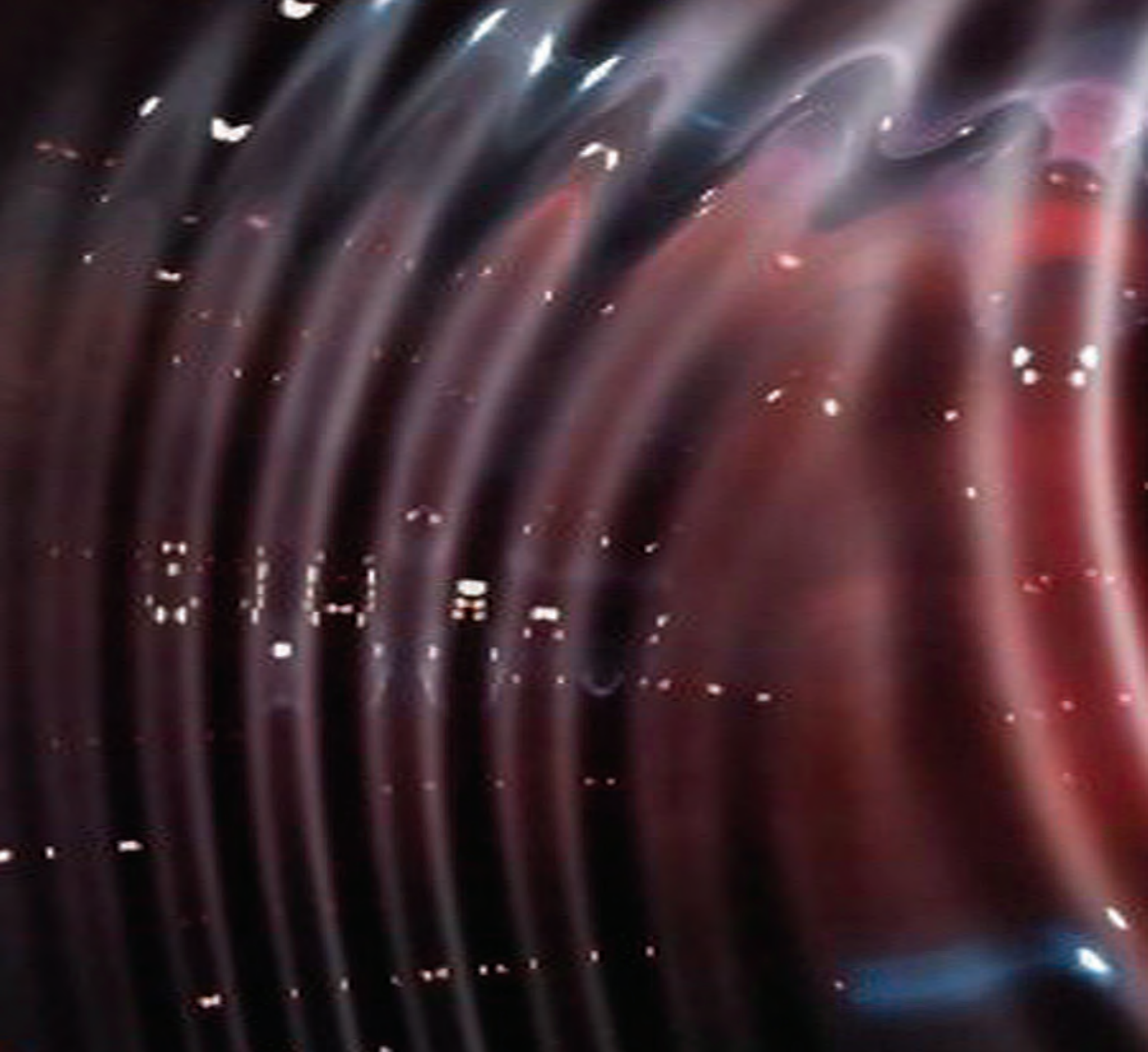

West Marrin, Ph.D. is a scientist, naturalist and educator as well as the author of *Universal Water* and *Altered Perceptions*. He founded Water Sciences & Insights and advises corporations, institutes, and nonprofits on educational and research projects. He is a former Adjunct Professor at San Diego State University and has degrees in the biological, environmental and water resource sciences.