Energy Bulletin (11 August 2011)

Hydromimicry:
Water as a Model for Technology and Management

Abstract

The concept of *hydromimicry* is related to the better known one of *biomimicry*, which is the process of applying biological designs or processes to human solutions. By analogy, hydromimicry is based on emulating water's natural patterns, rhythms, and behaviors in the design of human products, technologies, and management strategies. Although the primary focus is the hydrosphere (e.g., oceans, rivers), there is some overlap with biomimicry where organisms evolve strategies that specifically exploit water's physical or chemical properties. In addition to observing and applying water's more perceptible attributes, hydromimicry recognizes its integral roles in spiritual traditions and cosmic processes.

Natural systems, including those that use or are sculpted by water, typically are energy-efficient, produce minimal wastes, and achieve multiple goals simultaneously. As both a tool and creator of nature's designs, water's use as a model has applicability to topics as diverse as climate change, energy selection, food production, human health, ecosystem restoration, network design, chemical synthesis, resource management, infrastructure planning, and the fine arts. Specific examples reviewed in this article emphasize water's use as a model in addressing electricity generation, environmental degradation, and the production or treatment of freshwater. The applications range from those performed in people's backyards to those requiring sophisticated materials or instruments. In every case, the key is mimicking water or nature's use of water.

The concept of using water as a model for human designs is certainly not new, as many ancient cultures emulated familiar watershed features in designing their irrigation systems, waterways, and buildings. According to traditions of New Zealand's Maori culture, rivers, lakes, wetlands, and all natural water sources possess a connection to the spiritual realm, which determines the uses that are appropriate and those that are not. Kepa Morgan has described a rating system for the use of recycled water and the treatment of natural waters that is based on a weighted average among environmental and human factors.[1] His is a formal decision-making process that ensures water is in harmony with its watershed before being considered for human use. This approach may be contrasted with many of today's management practices, whereby water is often exploited for human use to the point that watersheds and ecosystems are functionally damaged.

Using stormwater to irrigate public spaces, practicing rainwater harvesting with suitable tanks, and using graywater to irrigate gardens are considered to be acceptable by Morgan's system. Using treated wastewater to irrigate gardens is considered neutral, while using any water to flush toilets or carry human wastes is considered unacceptable, as is transporting water from one watershed to another. 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 vital energy is compromised and its value to all forms of life (including humans) is diminished.

Wetlands and Watersheds

The rapid and widespread destruction of natural wetlands has prompted the design and installation of artificial wetlands, which endeavor to recreate conditions that are similar (at least functionally) to those of the natural wetlands; however, such replacements can never completely mimic the original because nature's intricacies are too numerous and complex. Hence, the extent to which artificial wetlands emulate the structure and function of lost wetlands is the extent to which they serve as mitigation measures. Researchers have found that the most important design parameters include the extent and duration of flooding, which must be recreated in the artificial wetland by placing water inlets, outlets, weirs, and other engineering control structures in a manner that best reproduces the parameters.[2] Adding geotextiles (as a soil or sediment cover), brush, and rocks for habitat improvement assists in recreating measured rates of water infiltration and evaporation and in balancing the mineral, aqueous, and organic components of the soil.

Despite efforts to emulate small-scale hydrologic conditions in nature, controlling water in artificial wetlands and reclaimed riparian habitats is extremely difficult, as is reproducing sediment dynamics, vegetation patterns, and fauna diversity.[3] 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 natural hydrologic processes via constructing fewer control structures. Taking this approach even further, proposals to allow highly regulated rivers such as the Mississippi to return to some semblance of their original flow regimes by slowly and carefully removing control structures have gained recognition by some conservationists.[4] Mitigating wetland and riparian loss exemplifies the challenges associated with emulating water dynamics on the basis of only a handful of relevant parameters. If mimicking water dynamics in a restored wetland is challenging, then mimicking water dynamics on the roof of a building must be daunting.

The implementation of "green roof technology" is one that combines hydromimicry and biomimicry inasmuch as both watershed and hydrologic parameters are considered in its design and function. Green roofs have a vegetated surface and an underlying substrate, thus permitting a variety of concurrent uses such as stormwater management, temperature regulation, and habitat creation.[5] Whereas the earliest green roofs were merely backyard gardens transferred to roofs in large planters, recent versions include an insulation layer, a waterproof membrane, and a soil layer that covers the entire roof and serves as 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. It has been estimated that green roofs can reduce building runoff by as much as 60%, depending on the substrate thickness and the plant types. Not unlike artificial wetlands, the key to green roofs that effectively mimic small-scale water dynamics is a design based on relatively few parameters.

Green roofs could 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.[6] 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 roofs. Harvesting rainwater is often used in combination with an agricultural technique called *permaculture*, which mimics natural patterns and processes in the local watershed to create sustainable designs, principally by using the outputs (wastes) from one compartment as the inputs (resources) to others.

Fractals and Networks

Watersheds can be considered a type of real-world network that is characterized by self-repeating or fractal-like patterns. Fractals are geometric patterns that possess the same proportions on different scales. Rivers and glaciers cut through the planet's surface, leaving behind landscapes that may appear random or haphazard, but are actually quite precise.[7] Whereas such patterns have been frequently ignored in designing or altering man-made landscapes, there is now interest in emulating them to create more sustainable and eco-compatible designs. For example, a watershed's intricate patterns are responsible, at least in part, for its hydrologic properties and ability to buffer extreme weather events. Failing to grasp the importance of these natural patterns, humans have embarked on altering the natural flow of water by installing structures that are intended to prevent disasters, but may instead encourage them. Modeling watersheds as networks has permitted scientists to forecast their hydrology and chemistry using artificial networks.[8] For example, artificial networks have been used to predict how soils retain water, how sediment and pollutants enter streams, and even how the clarity and salinity of natural waters change over time.

Moving from landscapes to molecules, water's molecular-scale network is one of the most dynamic and complex ever discovered. Structurally, the network is sometimes described in terms of a hierarchy, whereby individual molecules represent the components of a primary network and clusters of molecules (often associated with dissolved substances) represent those of another network.[9] Depending on the location and properties of water assemblages, connections among water molecules can change as rapidly as a trillion times per second or as slowly as few times per hour. So, how might understanding the dynamics of this water network be exploited? Bioengineer Gerald Pollack found that water adjacent to common types of surfaces or water exposed to sunlight creates zones where dissolved substances, or solutes, are excluded in favor of a more ordered (or less random) network.[10] Further, he discovered an electrical charge separation between this ordered water and more common forms of disordered water, thus creating a battery—albeit a tiny one.

The applications of this unusual behavior within water's molecular network (consisting of regions with greater or lesser order and structure) appear to be numerous. First, the use of material surfaces that induce a solute-free zone can be used to remove salts, pollutants, and even microbes from water without expensive filters or the energy required to force water through such filters.[11] The use of sunlight to separate water in a similar manner may be used to either desalinate seawater or treat some types of wastewater more cost effectively than the alternatives. Finally, the electrical charge separation created by light may someday lead to the production of a usable electric current, which is based on a process that mimics photosynthesis in plants. Water treatment and energy production are among the highest priorities for researchers currently exploring hydromimicry.

Whirlpools and Waves

Perhaps the most obvious example of designers emulating water's patterns in the natural world and scaling them down to a manageable size are so-called water *flowforms*, which are constructed with different shapes, lengths, heights, materials, and water flow rates.[12] By cascading down a series of ovoid vessels possessing a narrow entrance and exit, water spontaneously forms vortices that possess distinct patterns and rhythms—often similar to those created within natural streams or waterfalls. Once considered strictly architectural features, flowforms were studied by a group of European naturalists who observed that water exiting the flowforms often possessed physical properties that were slightly different than those of water entering them. Although the mechanisms of such changes are not yet described, specific flowforms are reportedly used to treat wastewater and pre-irrigation waters as a means of restoring their quality and enhancing plant growth.

Naturalist and inventor Jay Harman designed an impeller that is based on the geometry of flowing water itself.[13] 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 widely applied because standard engineering designs rely on different approaches to fluid mechanics. The 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 this device? The answer is the gigantic tanks that hold drinking water supplies for a majority of people in the industrialized world. The stratification, or horizontal layering, of water with slightly different temperatures in these tanks frequently causes problems with its chemical and microbial quality. The vortex impeller employs nature's efficiency in mixing all the water in a tank with far less energy than that required by conventional pumps or stirrers.

Switching from tanks to oceans, one of the most effective ways to learn about the large-scale movement of water masses is to mimic them. James Lovelock (renowned for his Gaia hypothesis) and his associate designed a wave-powered pump that emulates the natural process of upwelling, which is normally powered by the ocean's wind-driven currents. The pump consists of a long plastic tube that is weighted at the bottom and buoyed at the top.[14] As the buoy drops into the trough of a wave, water is pushed into the tube through a one-way valve at the bottom, thus lifting deeper water to the surface using only wave power. Although the pump itself does not mimic any common form of natural water movement, the process of upwelling cold, nutrient-rich seawater from modest depths to the warmer sunlit surface is of considerable interest because of its potential to stimulate the growth of phytoplankton, which are tiny drifting plants that consume carbon dioxide.

Real and Unreal Plants

Currently, the single largest use of water is the irrigation of crops, and agriculture has not traditionally been the most efficient user of water for a variety of reasons. However, recent attempts by scientists to emulate the cycling of water by native plants and apply it to high-production crops could alter that trend.[15] Native vegetation in arid climates can store water from seasonal rainfall in the root zone, where it can be captured and used in the dry season when drought conditions prevail. By contrast, most non-native crops permit more water to drain from the root zone, requiring extensive irrigation during the dry season that often results in acidified, water-logged, and increasingly saline soils.

In an effort to emulate the soil water cycle observed for native vegetation, perennials (e.g., grasses, trees) are planted in agricultural lands and deep-rooted crops (e.g., alfalfa) are rotated with shallow-rooted crops (e.g., wheat) to reduce irrigation requirements of the latter. There are limits to the volume of water that can be stored in the root zone; however, the seasonal carryover of water has succeeded in cutting irrigation requirements and limiting the infiltration of fertilizers, pesticides, and herbicides to ground water. As a result of mimicking the soil water cycle for native vegetation, more nutrients are retained in the root zone and problems with soil acidity and salinity are often averted.

Mimicking the interaction between plant substances and water may be the key to two other technologies. The first is a simple water purification technique that involves the thick sap or mucilage from a prickly pear cactus, which has been used in Mexico for centuries.[16] The gooey sap acts a flocculent in adhering to and removing both sediment and bacteria from water. It could potentially remove metals, pesticides, and other sediment-bound pollutants from drinking water. The second capitalizes on plants' ability to split water molecules into oxygen and hydrogen for building the carbohydrates that ultimately feed us. Thanks to the specialized proteins involved in photosynthesis, plants capture solar radiation to power this water-splitting chore, which scientists are now trying to emulate in designing artificial systems powered by sunlight.[17] Their ultimate goal is a molecular-scale photovoltaic that generates an electric current and produces hydrogen gas, rather than carbohydrates, as a fuel. If successful, this process would mimic the natural use of water by plants.

Scientists at Cornell University developed a *hydrogel*, which is the primary component of a "synthetic tree" that mimics the processes of water transport and transpiration in plants.[18] To construct a 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. Consisting of two circles that represent the root and leaf networks, the synthetic tree could never be mistaken for a real one; however, the mechanisms for their transporting water are quite similar. Potential applications of this technology include heat transfer dynamics, soil hydrology, and fuel cell technology. The operating principle of the synthetic tree is one that employs design, rather than additional energy, to achieve its goal. As such, the behavior of water (hydromimicry), biomechanics of trees (biomimicry), and properties of gels (materials science) are integrated into a single solution.

Energy and Salt

As the most abundant fluid on Earth, seawater is now being considered as source of clean and renewable energy in conjunction with several different technologies. The first is so-called *salinity power*, which is driven by the osmotic gradient created between seawater and fresh water stored on either side of a synthetic membrane.[19] As fresh water moves spontaneously through the membrane to dilute dissolved salts on the other side, the seawater is pressurized and subsequently piped through a turbine to generate electricity. Technical challenges to salinity power include developing a membrane that is efficient and resistant to biofouling, as well as building a facility that can operate in deltas, estuaries, or other locations where rivers meet oceans. Anticipated environmental impacts include the disposal of a brackish water (although less salty than the brines produced by conventional desalination), the presence of platforms in sensitive aquatic habitats, and the disposal of chemicals used to prevent biofouling in the pipes. Nevertheless, salinity power does mimic a chemical process that occurs naturally where inland waters flow into the sea.

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 energy required to force water through the reverse osmosis (RO) membranes, which permit passage of water while excluding salts and pollutants. While today's synthetic membranes are more efficient and solar energy can assist in powering some types of desalination, the process remains limited by conventional designs. Researchers are now taking a lesson from water movement and filtration in the biological world and applying it to the technological world. This so-called nanotechnology is based on a specialized protein, known as an *aquaporin*, which is found in cellular walls and acts to rapidly move water in and out of cells without also transporting water's dissolved substances. Aquaporins are narrow tubes lined with protein groups and electrical charges that only permit a single-file passage of water molecules.[20]

Scientists have designed carbon nanotubules that mimic the aquaporins and are able to fill or empty by changing the tubule's electrical charge or geometry.[21] Applied to seawater, the carbon tubes rapidly move pure water through them, while stranding the dissolved salts on the opposite side of the carbon sheets in which they are embedded. Whereas a multi-tube pump does not require huge amounts of energy to force water through the membranes, it does require some energy to sustain the electrical charges. Another emerging approach to desalination is a process known as forward osmosis (FO), which produces freshwater from seawater by using an even more concentrated salt solution (sodium bicarbonate) on the other side of the membrane.[22] This solution draws pure water through the membrane from the seawater side, after which it is heated to 40°C to drive off ammonia and carbon dioxide gases—thus leaving behind fresh water. FO mimics an osmotic process that occurs when natural waters of differing salinities intermingle.

Glaciers and Pools

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.[23] There are two recognized 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. Once the mixture of rock and ice is sufficiently heavy (usually about three years), it begins to move downhill as a self-sustaining glacier that can grow to lengths exceeding 100 meters. Researchers are investigating the expansion this water resource technology, which is an example of people observing local watershed dynamics and then mimicking relevant structures and patterns via the addition of available materials.

One's backyard is among the smallest of scales on which one could practically borrow a water design from nature, and swimming pools may be just the place to start. Conventional swimming pools have enormous water, energy, and chemical footprints as a result of their construction, operation, and maintenance. By contrast, so-called "natural" swimming pools (more common in Europe) are an alternative that mimics natural waters and blends into the landscape.[24] In order to create a usable swimming area similar to that of a conventional pool, natural pools have be larger because their sides (consisting of gravel, stone, and clay) are sloped more gently and their filtering systems (consisting of shallow aquatic plants) require about half of the water's total surface area.

Aquatic 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 pool's bottom. A precise mix and depth of plants (supporting aquatic infauna) 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 clay, after which the perimeter soil is compacted and planted to prevent its entering the natural pool. The choice of plants, construction materials, and pool layouts are matched to the local climate and landscape. Perhaps the most common problem with natural pools is freshwater algae that compete with the designed plants for nutrients and sunlight; however, algae can be controlled by limiting the concentrations of soluble nitrogen and phosphorus.

Chemicals and Climate

An interesting application of water's mediating abilities 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. For example, green chemists now use electrolyzed waters instead of organic solvents to clean semiconductors and electronic components.[25] Simple electrolysis units alter water's pH and redox conditions to produce this cleaning water, which is similar in some respects to waters found in extreme natural settings. Green chemistry also promotes processes that require less energy and fewer materials than do conventional syntheses and that utilize wastes or renewable resources. The chemical syntheses of products ranging from fabrics to drugs are usually performed in organic solvents; however, *supercritical* water—produced both naturally and artificially at high temperatures and pressures—is an alternative to organic solvents. In fact, reaction rates can often be accelerated by using a water emulsion to synthesize chemicals, thus mimicking the medium within which biological catalysts (enzymes) function in living organisms.[26]

In addition to facilitating chemical reactions, water itself has been used throughout history as a curative agent for a wide range of maladies and conditions. For instance, seawater is used as a skin exfoliant and detoxifier, a nasal decongestant, and an antioxidant booster in the form of irrigation for certain crops. Higher levels of lipoic acid, as well as vitamins C and E, which have been shown to offer protection against cancer and heart disease, were found at higher concentrations in tomatoes irrigated with dilute seawater than those irrigated with freshwater.[27] A salinity-induced stress may stimulate the plants to produce more of the antioxidants. On a larger scale, seawater plays a very different type of curative, or at least supportive, role for the planet by absorbing much of the heat and carbon dioxide that is linked to global climate change. As a water planet, Earth's future climate is dependent, in large part, on changes in the oceans and their effects on the global water cycle.

Considering the inseparable link between the water cycle and nearly every aspect of global climate change, the question of whether geoengineering schemes qualify as hydromimicry is a fitting one to conclude this article. Pumping liquid carbon dioxide into saline aquifers, depleted oil reservoirs, or ocean basins is not hydromimicry; nor is producing biofuels, burying biochar, or planting trees. Launching sulfur into the upper atmosphere or iron onto the sea surface may emulate natural processes (e.g., volcanoes, upwelling) that affect the water cycle, but they fall short of hydromimicry. Capturing carbon dioxide from the air resembles ocean uptake and spraying a fine mist of seawater into the air resembles ocean spray. So, perhaps a few geoengineering schemes emulate water's natural processes, but most do not. A more pertinent question may be which of these techniques (geoengineering or otherwise) mimic the wisdom, as well as the processes, of water and nature.

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