Title
Taking the "waste" out of "wastewater" for human water security and ecosystem sustainability.

Permalink
https://escholarship.org/uc/item/1569x53m

Journal
Science (New York, N.Y.), 337(6095)

ISSN
0036-8075

Authors
Grant, Stanley B
Saphores, Jean-Daniel
Feldman, David L
et al.

Publication Date
2012-08-01

DOI
10.1126/science.1216852

Peer reviewed
Taking the "Waste" Out of "Wastewater" for Human Water Security and Ecosystem Sustainability
Stanley B. Grant et al.
Science 337, 681 (2012);
DOI: 10.1126/science.1216852

If you wish to distribute this article to others, you can order high-quality copies for your colleagues, clients, or customers by clicking here.

Permission to republish or repurpose articles or portions of articles can be obtained by following the guidelines here.

The following resources related to this article are available online at www.sciencemag.org (this information is current as of August 9, 2012):

Updated information and services, including high-resolution figures, can be found in the online version of this article at:
http://www.sciencemag.org/content/337/6095/681.full.html

A list of selected additional articles on the Science Web sites related to this article can be found at:
http://www.sciencemag.org/content/337/6095/681.full.html#related

This article cites 35 articles, 2 of which can be accessed free:
http://www.sciencemag.org/content/337/6095/681.full.html#ref-list-1

This article appears in the following subject collections:
Engineering
http://www.sciencemag.org/cgi/collection/engineering
Taking the “Waste” Out of “Wastewater” for Human Water Security and Ecosystem Sustainability


Humans create vast quantities of wastewater through inefficiencies and poor management of water systems. The wasting of water poses sustainability challenges, depletes energy reserves, and undermines human water security and ecosystem health. Here we review emerging approaches for reusing wastewater and minimizing its generation. These complementary options make it possible to use the most of scarce freshwater resources, serve the varying water needs of both developed and developing countries, and confer a variety of environmental benefits. Their widespread adoption will require changing how freshwater is sourced, used, managed, and priced.

More than 4 billion people live in parts of the world where freshwater scarcity directly threatens human water security or river biodiversity (1). Threats to human water security can be overcome by building centralized infrastructure that harvests, stores, treats, and transports water for agricultural, industrial, and municipal uses. For countries that can afford it, this approach has greatly benefited human health and economic development, but it is often energy-intensive and comes at a steep ecological price. In the developing world, on the other hand, an estimated 1 billion people lack access to safe affordable drinking water, 2.7 billion lack access to sanitation, and many millions die each year from preventable waterborne disease (2). Thus, developed and developing countries face separate but overlapping challenges. In developed countries, existing water infrastructure needs reengineering to sustain a high standard of living while reducing its environmental footprint and sustaining or restoring biodiversity. In developing countries, affordable infrastructure is needed to satisfy the water needs of humans and to preserve aquatic ecosystems (1). Meeting these twin challenges will require striking a balance between delivering new sources of water and using water more productively through pricing, conservation, and wastewater reuse.

How Is Water Used and Wasted?

Water use can be classified as consumptive or nonconsumptive, depending on how readily the used water can be reused. Consumptive use converts water into a form that cannot be reused. A portion of the water used for irrigation, for example, is evaporated, transpired, and incorporated into plant biomass. This consumed water is unavailable for reuse in the watershed over time scales of practical interest. In contrast, after nonconsumptive use, water can be captured, treated, and reused. If a nonconsumptive use degrades the quality of the water (for example, by adding contaminants), it is said to generate wastewater. An example of nonconsumptive use is the flushing of a toilet, which converts drinking water into domestic wastewater. In principle, domestic wastewater can be collected, treated to remove human pathogens and other contaminants, and then reused for potable or nonpotable purposes. Globally, the largest consumptive use of water is for agriculture, whereas the largest nonconsumptive use of water is for industrial and municipal supplies (3).

What Is Water Productivity and How Can It Be Improved?

Addressing threats to human water security and biodiversity will require getting the most out of locally available water resources. But what does that mean in practice? One way to evaluate water use is to consider its “productivity,” defined as the value of goods and services produced per unit of water used. By improving water productivity, communities can enjoy the same goods and services, generate less wastewater, and leave more freshwater in streams, rivers, lakes, and coastal estuaries to support biodiversity. Because less water is harvested, treated, and transported, fossil fuel consumption and greenhouse gas emissions are reduced. Although water productivity has steadily improved in the United States since the mid-1970s, additional gains are possible both here and around the world (4). In this Review, we focus on three general strategies for improving water productivity (Fig. 1): substituting higher-quality water with lower-quality water where appropriate, regenerating higher-quality water from lower-quality water by treatment, and reducing the volume of higher-quality water used to generate goods and services.

What Are the Opportunities for Substituting?

Many municipal, industrial, and agricultural uses can be satisfied by lower-quality water. For example, treated domestic wastewater that would not be suitable for municipal water supplies may be perfectly suitable for industrial cooling and landscape irrigation, to name a few (5). Although the use of treated wastewater in the United States is currently limited (~5% of municipal supply), it could be expanded to 17 teraliters per year (T l year-1) (~27% of municipal supply), providing a new drought-resistant source of water in coastal areas where treated wastewater is currently discharged to the sea (6). Large-scale (centralized) wastewater treatment and potable substitution schemes can reduce overall energy consumption and reduce greenhouse gas emissions. In southern California, substituting potable water with treated wastewater consumes less energy and generates fewer greenhouse gases as compared to interbasin transfers of water or desalination of seawater or brackish groundwater (7).

Treated domestic wastewater is not the only lower-quality water that can be exploited in potable substitution schemes. Hong Kong’s dual water system, which has been in operation for over 50 years, supplies seawater for toilet flushing to 80% of its 7 million residents, cutting municipal water use in the city by 20% (8). A triple-water distribution system at Hong Kong’s International Airport, consisting of freshwater, seawater, and treated graywater from sinks and aircraft washdown, cuts municipal water use by over 50% (8).

Potable substitution can also be implemented at neighborhood and single-family scales (Fig. 2). Rainwater (from roofs) and graywater (from
laundry, dishwashing, and bathing) can be used in place of drinking water for a variety of activities. The reuse of graywater for toilet flushing and yard irrigation can cut household municipal water use by 50% or more (9). The energy cost, water savings, and reliability associated with rainwater harvesting depend on engineering considerations (e.g., contributing roof area and storage tank volume), local climate, connected end uses (e.g., toilet, laundry, and hot water), and temporal patterns (10). In a case study of a model home in Melbourne, Australia, the use of rainwater tanks to supply water for laundry, dishwashing, toilets, and an outside garden reduced household municipal water use by 40% (9). However, even in Melbourne, where rainwater-harvesting schemes are commonplace, they contribute a modest 5 gigaliters (Gl) year\(^{-1}\) to the city’s overall water budget, which represents 1.2% of the city’s total water use and 1.4% of its municipal supply (11).

Stormwater runoff from roads and other impermeable surfaces is another locally available source of water, but here the challenge is harvesting and storing the runoff (which can be generated over very short periods of time) and adequately removing contaminants (pathogens, metals, and organic pollutants). These challenges can be overcome through the integration of natural treatment systems into the urban landscape, including green roofs, rain gardens, biofilters, and constructed wetlands (12). Processes responsible for pollutant removal in natural treatment systems include (12–15) gravitational sedimentation of large particles, pathogen removal by solar ultraviolet (UV) inactivation and predation, filtration of colloidal contaminants, oxidation of labile organics by hydrolysis and sunlight-generated reactive oxygen species, precipitation of metals, and nitrogen removal by bacterially mediated nitrification and denitrification in sediments. Plants play a key role, taking up excess nutrients and serving as both a source of organic carbon to fuel denitrification, and a source of oxygen through their root systems to fuel nitrification. As runoff moves through natural treatment systems, a portion of the water returns to the atmosphere (evapotranspiration); a portion infiltrates into the subsurface (groundwater recharge); and the rest can be harvested, stored, and ultimately used for nonpotable purposes. In Melbourne, stormwater harvesting is a relatively minor component (5 Gl year\(^{-1}\) or 1.4% of municipal water use) of the city’s water budget (11), but including stormwater reuse schemes in new greenfield and brownfield developments until 2050 could result in a sevenfold increase in nonpotable water availability for the city (35 Gl year\(^{-1}\) or 9.8% of municipal water use) (16).

Integrating natural treatment systems into urban landscapes confers many benefits beyond improving human water security. Improved water availability can be regulated for future needs, spurring economic growth (17). Water harvesting practices reduce reliance on imported water resources, providing a sustainable alternative to energy-intensive water conveyance and desalination processes. Water harvesting in cities can similarly help to reduce the amount of stormwater runoff entering streams and rivers, and provide a direct benefit to urban ecosystems (18). Urban water harvesting also offers opportunities to improve human health, as urban water harvesting systems can capture beneficial sediments. Plants play a key role, taking up excess nutrients and serving as both a source of organic carbon to fuel denitrification, and a source of oxygen through their root systems to fuel nitrification. (primary and secondary sewage treatment) and advanced (microfiltration, reverse osmosis, and UV disinfection) techniques (23). Water produced by the GWRS provides approximately 20% of the water needed to maintain the local groundwater aquifer in Orange County, a primary source of municipal supply for more than 2 million residents.
Internationally, the longest-running example of direct potable reuse is in Windhoek, Namibia, where recycled wastewater (mostly domestic sewage) has been added to the potable water distribution system more or less continuously since the late 1960s with no obvious adverse health effects among the population of several hundred thousand (24). The current facility produces enough water (7.7 Gl year\(^{-1}\)) to meet approximately 35% of the city’s municipal water needs.

Among the centralized options for augmenting potable water supplies, potable reuse is preferable to interbasin water transfers for several reasons (25): (i) Interbasin water transfers reduce the water available at the source for critical ecosystems and agricultural production; (ii) transporting water over long distances can be energy- and carbon-footprint-intensive; and (iii) the water transmission systems are vulnerable to disruption by natural and human-made disasters, such as earthquakes and acts of terrorism. All three problems are evident in California, where the southern part of the state has long relied on water imported from sources located hundreds of kilometers to the east and north. In 2001, an estimated 4% of the electric power consumption in California was used for water supply and treatment (largely transportation) for urban and agricultural users; this estimate increases to 7% if end uses in agriculture (which are mainly related to pumping) are included (26). The depletion of source waters in the state has led to habitat deterioration, the decline and extinction of native fish species, the near-collapse of the Sacramento–San Joaquin River Delta ecosystem (27), and the desiccation of Owens Lake, whose dry lake bed is arguably the single largest source of asthma- and cancer-inducing respirable suspended particles in the United States (28). Potable reuse also has advantages relative to the desalination of seawater. By one estimate, potable reuse consumes less than one-half the energy [~1000 to 1500 kilowatt-hours per megaliter (kWh ML\(^{-1}\))] required for the desalination of seawater (~3400 to 4000 kWh ML\(^{-1}\)) (25).

Relative to the classification scheme presented in Fig. 1, some nonpotable wastewater reuse is best described as regeneration, provided that the treated effluent replaces water of equal or lower quality, such as river diversions (Fig. 2). For example, 73% of Israel’s municipal sewage is treated and reused for agricultural irrigation, which is equal to roughly 5% of the country’s total water use (29) and 13% of its municipal supply. In Singapore, 27 Gl year\(^{-1}\) of highly treated domestic wastewater is used primarily for industrial applications, which is equal to 5% of its total water use and 9% of its municipal supply (30).

Relatively low-energy centralized approaches for nonpotable wastewater reuse are also available, such as waste stabilization ponds (WSPs), in which sewage is directed through a series of open-air shallow ponds where physical processes (floculation and gravitational sedimentation), microbial processes (algal growth, aerobic and anaerobic heterotrophic metabolism, nitrification, and denitrification), and exposure to sunlight jointly remove pathogens, organic contaminants, and nitrogen (31). Effluent from WSPs can irrigate crops (Fig. 2) or recharge groundwater aquifers, and the ponds themselves may provide a much needed quasinetland habitat for waterbird conservation (18). The world’s largest WSP system, the Western Treatment Plant in Melbourne, produces 40 Gl year\(^{-1}\) of treated wastewater, equivalent to 11%

![Fig. 2. Practical examples of substitution (A), regeneration (B), and reduction (C) at the household scale. Substitution includes watering a garden with rainwater from a rainwater tank and flushing toilets and washing laundry with treated stormwater effluent from a biofilter. For regeneration, a waste stabilization pond (WSP) transforms sewage from the house into high-quality water used for irrigating an orchard. Reduction includes repairing leaks in the water distribution system, drip irrigation, a dual-flush toilet, a low-flow shower rose, and a front-loading clothes washer. Other water infrastructure elements shown include a conventional drinking water plant (DWTP); a conventional wastewater treatment plant (WWTP); and a river diversion (supplying the orchard).](image-url)
Fig. 3. Wastewater reuse and water-saving schemes discussed in the text, arrayed relative to a few key attributes (A) and performance indicators (B). The color scheme matches that in Fig. 1; substituting, red; regenerating, blue; and reducing, green. Certain schemes can be classified in more than one way; for example, wastewater recycling with wastewater stabilization ponds might be considered blue or red, depending on the end use and what water is being substituted or regenerated. The adoption of water-saving schemes is influenced by policy, law, regulations, markets, and incentives.

of Melbourne’s municipal supply, and uses approximately 500 kWh M⁻¹ less energy than conventional wastewater treatment (32). Recycled water from the Western Treatment Plant is used for a variety of nonpotable applications, including in-plant uses and dual pipe schemes for the irrigation of agricultural crops, gardens, golf courses, and conservation areas.

Primary concerns associated with wastewater reuse include the buildup of contaminants and salts in soils (in the case of wastewater irrigation) and the possibility that incomplete removal of chemical or microbiological hazards during treatment may cause disease in an exposed population (6). Disease risk can be evaluated on a case-by-case basis using a statistical framework, such as quantitative microbial risk assessment, that predicts a population’s disease burden, given the types and concentrations of pathogens that are likely to be present in the water, as well as particular exposure scenarios (33).

What Are the Opportunities for Reduction?
Water productivity can also be improved by reducing the volume of water used to produce a fixed value of goods and services. A modeling study of the water supply system in Florianopolis, Brazil, concluded that replacing single-flush toilets with dual-flush toilets would reduce municipal water use in the city by 14 to 28% and reducing, green. Certain schemes can be classified in more than one way; for example, wastewater recycling with wastewater stabilization ponds might be considered blue or red, depending on the end use and what water is being substituted or regenerated. The adoption of water-saving schemes is influenced by policy, law, regulations, markets, and incentives.

Beyond the equilibrium point, further reductions in water use require increasing either energy use (if high-tech options are used) or land use (if low-tech options are used) (41). Human behavior should also be considered in the assessments of optimal water management strategies, as was...
done in an elegant systems modeling study of water supply options in Chennai, India (42).

Because end-user behavior affects all aspects of water and wastewater management (Fig. 3B), changing attitudes and expectations may be more effective than finding infrastructure solutions to water scarcity. Turf grass consumes upward of 75% of residential drinking water in arid and semi-arid areas of the United States (43). If water resources in this region continue to dwindle, reducing the volume of water used for yard irrigation (for example, by implementing advanced irrigation technologies) may not be sufficient. Homeowners may have no choice but to replace turf grass with xeric landscaping (44). Such wholesale rethinking of our relationship with water is an example of a “soft-path” approach to water management. As a general principle, the soft-path approach is characterized by (4, 45) (i) viewing water as a service rather than an end in itself, (ii) adopting ecological sustainability as a fundamental criterion, (iii) matching the quality of water delivered to that needed by its use, (iv) planning from the future back to the present, and (v) ensuring community and citizen involvement in water management planning.

What Are the Main Roadblocks?

Efforts to improve water productivity will require overcoming economic, planning, regulatory, institutional, and public acceptance challenges. Key obstacles include uncertainty regarding the longevity and maintenance costs of infrastructure; upfront costs for piping, storage, and land; quantifying unpriced benefits; and overcoming water underpricing.

The first obstacle will probably resolve as experience is gained by vendors who develop wastewater-reuse and water-saving infrastructure, by community planning agencies that introduce them, and by municipal agencies or households that maintain them.

Underpricing of water is more serious because it leads to excess water demand and revenue shortfalls for water utilities. Underfunded utilities tend not to maintain infrastructure or repair leaks, adequately treat wastewater (spoilng scarce water resources), or extend service to the urban poor, who are then forced to buy expensive water from street vendors (46). Policies that inhibit full-cost pricing for water to ensure social equity or for other reasons may exacerbate this situation (47). When implemented in ways that ensure utility accountability to users and fair rate structures, full-cost pricing may help manage water resources sustainably and equitably (48), sending appropriate and realistic price signals that reflect the true cost (including externalities) of water use. Many of the approaches discussed in this review require fundamental changes to the built environment, which can be promoted through a multi-objective approach that fosters collaboration with developers, a culture of innovation, and community implementation capacity (49). Distributed water infrastructure can be introduced as part of comprehensive planning strategies that promote compact urban forms with mixed land uses and a focus on urban amenities, encourage alternative forms of transportation to permit narrower streets and reduce demand for parking, foster energy saving and waste recycling, promote water savings, and reduce liability for innovative developers.

Regulatory changes are needed to promote water conservation by mandating water-efficient plumbing, fixtures, and appliances. Regulatory changes are also needed to provide a consistent risk-management framework for water recycling schemes. Australian water reuse regulations, for example, emphasize protecting human health, which may foster a more favorable regulatory environment than in the United States, where water laws emphasize environmental health (6).

Finally, lessons from wastewater recycling systems indicate that the adoption of new water infrastructure depends on public acceptance. Public support for wastewater reuse, for example, is higher for uses such as landscape irrigation or car washing that minimize human contact (6). Public acceptance is also a necessary condition for utilities to embrace wastewater reuse and for firms to incorporate it in their production processes, provided that recycling wastewater neither substantially increases their costs nor triggers additional regulatory scrutiny.

To increase the likelihood of public acceptance, decision-makers should first demonstrate why changes are required to avert water shortages and that these water-saving schemes are safe. In addition, concerted and sustained efforts must focus on properly maintaining water infrastructure, especially when it pertains to wastewater reuse; on allowing stakeholders to monitor the uses and operations of wastewater recycling; and on vigilantly ensuring the protection of public and environmental health (50). Overcoming obstacles to the widespread adoption of wastewater recycling and water-saving measures is a sine quo non for meeting the water challenges of the future.

References and Notes

43. C. Miles et al., Environ. Manage. 42, 626 (2005).
Conversion of Wastes into Bioelectricity and Chemicals by Using Microbial Electrochemical Technologies

Bruce E. Logan1* and Korneel Rabaey2

Waste biomass is a cheap and relatively abundant source of electrons for microbes capable of producing electrical current outside the cell. Rapidly developing microbial electrochemical technologies, such as microbial fuel cells, are part of a diverse platform of future sustainable energy and chemical production technologies. We review the key advances that will enable the use of exoelectrogenic microorganisms to generate biofuels, hydrogen gas, methane, and other valuable inorganic and organic chemicals. Moreover, we examine the key challenges for implementing these systems and compare them to similar renewable energy technologies. Although commercial development is already underway in several different applications, ranging from wastewater treatment to industrial chemical production, further research is needed regarding efficiency, scalability, system lifetimes, and reliability.

There is substantial energy in organic matter that is currently wasted or lost in treatment processes. Treatment of organic-rich wastewater currently consumes about 15 GW, or about 3% of all electrical power produced in the United States (1), but domestic, industrial, and animal wastewater together contain \( \sim 1.5 \times 10^{11} \) kilowatt-hour (kWh) of potential energy (17 GW of power) (2). Capturing part of this energy would provide a new source of electrical power that would also avoid the consumption of energy for wastewater treatment. Furthermore, agricultural practices could be modified to annually produce an additional 1.34 billion tons of biomass for energy production, without affecting food production (3), which is equivalent to more than 600 GW of continuous power. These different sources of waste organic matter can be a rich resource for energy production if we can develop cost-effective methods for harnessing this energy. Alternatively, we could capture this waste biomass energy in industrial processes to make other useful chemicals, such as biofuels or industrial chemicals, that currently require electricity or organic substrates for this purpose.

Recently developed microbial electrochemical technologies (METs) that use microorganisms to catalyze different electrochemical reactions, such as microbial fuel cells (MFCs) that generated electrical power, are promising approaches for capturing the energy in waste biomass for diverse purposes. Energy production by electrochemical processes or conventional combustion requires a fuel to provide electrons and an electron acceptor (oxidizer). In METs, organic matter is the fuel, and oxygen is the primary oxidizer for aerobic respiration by bacteria. However, many other soluble chemical species can serve as oxidizers for anaerobic bacteria, including nitrate, sulfate, and carbon dioxide. Bacteria known as exoelectrogens have the ability to transfer electrons outside the cell to insoluble electron acceptors, such as iron and other metal oxides, or to electrodes in bioelectrochemical systems. The most commonly studied microorganisms are various Geobacter and Shewanella spp., but many other bacteria have been found to possess exoelectrogenic abilities (4). Electrons are transferred by these bacteria outside the cell indirectly, by using electron shuttles such as flavins and phenazines (5–7), or directly by using outer membrane proteins (8). These mechanisms can occur in combination with self-produced conductive pili called nanowires (9, 10). In contrast, electrotyrophic microorganisms can directly or indirectly accept electrons into the cell (11).

How Do Microorganisms Generate Electricity from Organic Matter?

The use of exoelectrogenic microorganisms in MFCs allows electrical power generation from nearly any source of biodegradable organic or inorganic matter in water that does not directly require oxygen as a part of the degradation process. These organic sources include simple molecules such as acetate, ethanol, glucose, and hydrogen gas; polymers such as polysaccharides, proteins, and cellulose; and many types of wastewaters from domestic, food processing, and animal sources (12, 13) (Fig. 1). In an MFC, bacteria release electrons to the anode and protons into solution, resulting in a negative anode potential of about −0.2 V (versus a standard hydrogen electrode) that is generally only slightly more positive than that of the half-cell reaction for the substrate (e.g., a midpoint potential at pH = 7 of −0.28 V for acetate) (14). In most cases, oxygen in air is used as a sustainable oxidizer at the cathode, with a typical maximum potential of +0.3 V, producing an overall maximum cell potential of +0.5 V. Cathode potentials obtained in MFCs are considerably lower than theoretical values (−0.8 V, with oxygen) even with Pt-catalyzed cathodes (15, 16) (Fig. 1). One of the most promising nonprecious metal materials used for oxygen reduction in MFCs is activated carbon, because it is both inexpensive and renewable produced from waste biomass (17). Nitrate is an alternate electron acceptor that produces comparable cell voltages because of its high solubility relative to oxygen (18). Voltages cannot be increased by linking MFCs in series as is done with batteries (19, 20). However, higher voltages can be captured from arrays of MFCs by wiring them to charge capacitors in parallel and then discharging the capacitors in series, resulting in nearly additive voltages from the individual MFCs (21).

The power densities produced by MFCs are lower than those possible by using hydrogen fuel cells because of high internal resistances, the limited temperature and solution conditions tolerated by microorganisms, substrate degradability, and biofilm kinetics. Hydrogen fuel cells use an ion-exchange membrane as a solid electrolyte for charge transfer. Membranes are not required in MFCs, and using a membrane between the anode and cathode can add internal resistance, which will