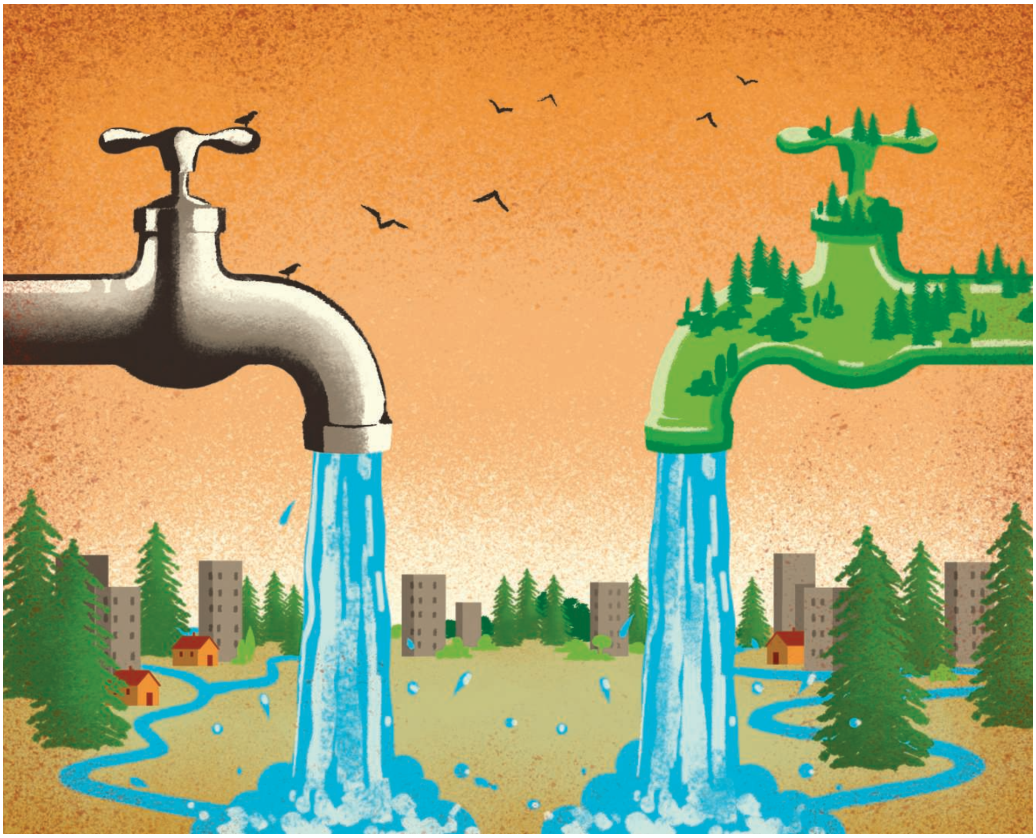

WATER

Water security: Gray or green?

Building engineered structures, such as dams and dikes, has been the conventional approach to water management. Some suggest that such "gray" infrastructure make way for "green" ecosystem-based approaches. In this second of three debates, *Science* invited arguments for how these approaches can address the challenge of building the water security of rapidly growing societies worldwide.

Manage water in a green way

By **Margaret A. Palmer**,[1*] **Junguo Liu**,[2,3*] **John H. Matthews**,[4] **Musonda Mumba**,[5] **Paolo D'Odorico**[1,6]

Reliance on "hard," human-engineered structures—"gray" infrastructure—has been the conventional way to manage water needs for economic development. But building dams, piping water, and constructing protective barriers is capital intensive and may address only a few water problems (*1*). Gray infrastructure often damages or eliminates biophysical processes necessary to sustain people, ecosystems and habitats, and livelihoods. Consequently, there is renewed focus on "green" infrastructure, which can be more flexible and cost effective for providing benefits besides water provision. Supplementing or integrating gray infrastructure with biophysical systems is critical to meeting current and future water needs. Gray and green infrastructures combined are synergistic and can have superior results to one or the other.

POLICY

Green infrastructure is a network of natural or seminatural features that has the same objectives as gray infrastructure. Gray infrastructure may always be needed to pipe and store water, but careful planning can limit its magnitude and extent. Green infrastructure—wetlands, healthy soils and forest ecosystems, as well as snowpack and its contributions to runoff—supplies clean drinking water, regulates flooding, controls erosion, and "stores" water for hydropower and irrigation.

For thousands of years, civilizations have been capturing and distributing water by combining natural processes, adaptive approaches, technologies with low external input, and sophisticated hydraulic and hydrological knowledge (*2*). Today, some developing countries create small-scale, environmentally sustainable water projects without large dams, massive infrastructure investments, or systems that depend on groundwater (*3*).

Green approaches to crop and soil management can reduce evaporative losses of water from fields (*4*). Rainwater harvesting and small, farm-scale reservoirs allow more efficient use of water in agriculture (*4*). Smallholders can access these methods, whereas large-scale irrigation projects benefit fewer local people. Such approaches can enhance farmers' resilience and long-term adaptation to climate change.

Coastlines can be protected by conserving coastal sand dunes, mangrove swamps, salt marshes, and coral and/or oyster reefs. Although loss of these buffers can be irreversible and has led to wide use of built structures, soft engineering, ecological restoration, and combined approaches are increasingly being used (*5*). In the Netherlands, recent approaches rely on coastal geomorphological processes that reinforce ecological and human benefits while buffering impacts from sea-level rise and increasingly powerful storms (*6*).

Although green infrastructure is not a panacea, it has fewer negative impacts than large water-infrastructure projects that displace local people, destroy habitat, or extirpate or shift fisheries (*7*, *8*). Green infrastructures allow for more flexibility and fewer environmental impacts.

COSTS AND BENEFITS. Most national water-management strategies now include ecosystems as natural capital, emphasizing the specific functions they can play economically. Green infrastructure, efficiency improvements, use of reclaimed wastewater, and policy instruments are proposed as more sustainable and affordable alternatives to tradi-

ILLUSTRATION: DAVIDE BONAZZI

tional water development schemes. Yet more is known about the costs and effectiveness of gray infrastructure in a development context.

Economic efficiency, typically used to estimate the cost of gray projects, can lead to underestimates if changing environmental, economic, or social conditions are not taken into account (*9*). For example, although large dams may produce energy and protect the nearby populace and fields from floods, an estimated three out of four dam projects have cost overruns, on average, 96% greater than estimated (*10*). Underestimates are compounded if the burden of potential remediation costs is not considered, such as removal of contaminated sediments.

Gray water infrastructure is not always reliable; for example, levees lead to increased flood levels downstream (*11*). Levees can give a false sense of security that favors human encroachment in floodplains and, consequently, more flood damage than when levees are absent.

Evaluations of the economic benefits of green options that consider a range of social and environmental uncertainty, have, for example, ranked wetlands, tidal marshes, and coral reefs as particularly valuable (*12*). However, few studies have compared costs of green versus gray approaches, e.g., questioning the wisdom of replacing mangroves and corals with seawalls and breakwaters in peninsular Malaysia (*13*).

RESEARCH FOREFRONTS. The developed world has studied urban green infrastructure, but more research is needed to predict the performance of a network of structures within different environmental contexts (*14*). Even when existing finance, risk, and investment theories can be combined to compare gray and green (*15*), critical biophysical performance data are needed.

A new generation of "sociohydrologic" models is exploring social acceptability and biophysical trade-offs for different configurations of infrastructure. Testing and validation using case studies and data on social and biophysical drivers and ecological constraints will be required for broad application (*16*).

Most forest restoration programs are based on the assumption that forest area is a proxy for ecosystem services based on rainfall and water use. Reforestation can provide water regulation benefits by reducing streamflow variability and peak flows (*17*) and, in some cases, can enhance soil water storage (*4*); yet water flows that result from reforestation in larger tropical basins are rarely quantified. Modeling studies suggest that large-scale [i.e., >10^4 to 10^5 km^2 (*18*)] deforestation can reduce rainfall through changes in the surface energy balance and evapotranspiration; this effect, however, depends on the geography and other factors (*19*). Work is still needed to determine whether large-scale forest restoration could become a valuable approach to increase rainfall and water yield.

ADOPTION. When reliability needs are high and/or tolerance for failure is low, gray water infrastructure probably represents the most effective approach to meeting the needs of developing countries. However, gray infrastructure can result in substantial damage to ecosystems and livelihoods; thus green infrastructure may represent a safer, more conservative pathway. The multiple benefits of green infrastructure are not broadly recognized, and the lack of cost-benefit data increases perceived risks. However, ongoing geographic shifts in agricultural production, needed growth in developing countries, and uncertainty about future climates provide an opportunity to renegotiate how we quantify sustainable infrastructure over long periods and express trade-offs between environmental and economic parameters (*12*). ■

[1]National Socio-Environmental Synthesis Center, University of Maryland, Annapolis, MD 21401, USA. [2]School of Nature Conservation, Beijing Forestry University, Beijing 10083, China. [3]School of Environmental Science and Engineering, South University of Science and Technology of China, Shenzhen 518055, China. [4]Alliance for Global Water Adaptation, Corvallis, OR 97330, USA. [5]United Nations Environment Programme, Nairobi, Kenya. [6]University of Virginia, Charlottesville, VA 22904, USA.
*Corresponding author. E-mail: mpalmer@umd.edu (M.A.P.); junguo.liu@gmail.com (J.L.)

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Built infrastructure is essential

By **Mike Muller,**[1*] **Asit Biswas,**[2,3] **Roberto Martin-Hurtado,**[4] **Cecilia Tortajada**[2,3]

WATER DEBATE SERIES

Built water infrastructure supported the evolution of all human societies and will remain an integral part of socioeconomic development and modernization. Some postindustrial societies not only seek to "preserve" existing aquatic ecosystems in their otherwise transformed landscapes but also insist that others do the same. They suggest that "green infrastructure" can provide "equivalent or similar benefits to conventional (built) 'gray' water infrastructure" (*1*).

Fast developing countries have a different perspective. For them, built infrastructure underpins "water security": enough water of adequate quality, reliably available to meet health, livelihoods, ecosystems, and production needs, as well as protection from water's destructive extremes (*2*). Their challenge is to enable an expanding global population, seeking a better quality of life, to determine the nature of their new environment, not simply to preserve the old.

21ST-CENTURY CHALLENGES. By 2050, water systems will have to support a global population of 9.6 billion, up from 7.2 billion in 2013 (*3*), most in expanding cities far larger than those of Europe and North America. More people and property will need infrastructure for services far beyond the capacity of "green infrastructure," based on natural ecosystems, to provide.