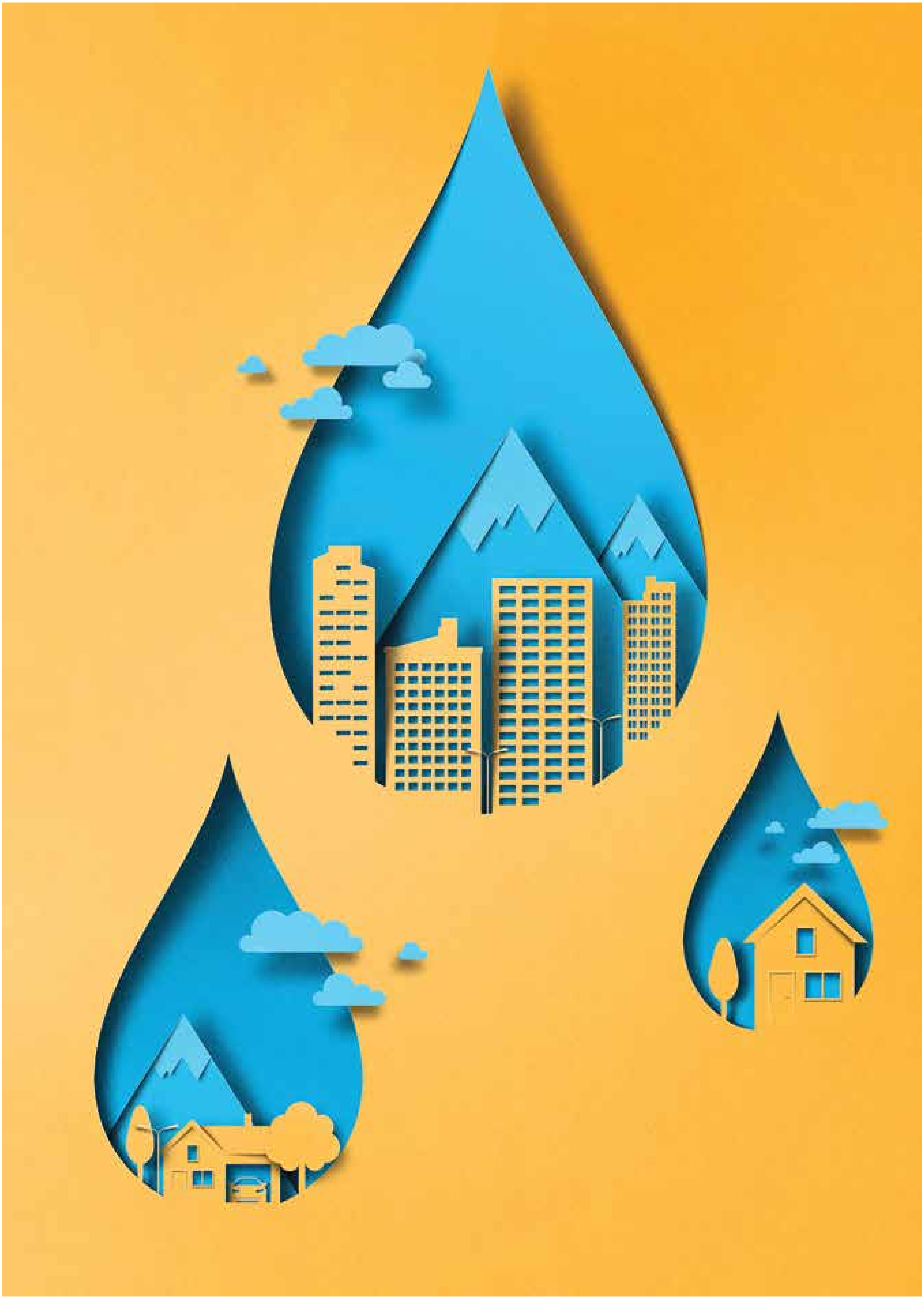

Environmental engineer Ed Bouwer and other researchers at the Johns Hopkins Water Institute are looking at new ways for developed countries to save and reuse water.

Epic. Devastating. Apocalyptic. California's drought, now in its fourth year, has headline writers resorting to extreme terms. During a particularly dry period last year, fields lay fallow, wells ran dry, and the state imposed restrictions on outdoor water use. In at least one city, washing a car and watering the lawn became criminal offenses. The drought is the most severe the state has experienced in more than 1,000 years, according to one study. But the future looks even thirstier.

Climate change—with its accompanying reduction in mountain snowpack—will almost certainly reduce our water reserves. And those reserves are already diminished. In many places, we are currently "mining" groundwater, pumping it up faster than it can be replenished. As a result, vital resources like the Great Plains' Ogallala Aquifer are shrinking. The Colorado River is so heavily used that it only rarely reaches the sea.

"If you look at population growth in the United States, we've essentially tapped all of the so-called pristine water sources," says Ed Bouwer, a Johns Hopkins environmental engineer. Factor in the likely future impacts of climate change, and "we're at a tipping point" for water, he says.

A recent large-scale study found that by 2100, even using conservative estimates, up to one-fifth of the world's population could experience severe water shortages as a result of climate change. Regions that are already dry, like the Southwestern United States, will be most at risk. While our wealth as a country may shield us from the acute suffering scarcity is already bringing to developing countries, even here, our approach to water will have to change drastically.

Researchers under the umbrella of the Johns Hopkins Water Institute are devising ways to help us meet our water needs in a hotter, more crowded future. The institute brings together faculty from across the university with expertise in public health, medicine, engineering, economic development, and other fields. Projects range from encouraging collaboration on water management along the Israeli-Palestinian border to learning to build resilient water systems in Ethiopia given the uncertainties of climate change.

Under the aegis of the Water Institute, Bouwer and several of his colleagues from the Johns Hopkins Whiting School of Engineering are working closer to home. They are looking at new ways for developed countries like the United States to save and reuse water. Some of these projects are aimed at making the clunky elements of our infrastructure more efficient; others entail entirely new systems of water capture, treatment, and delivery.

The annual "water footprint" of the average American—the total amount of water needed for all the food, goods, and services we use—would fill an Olympic-sized swimming pool, the largest per capita consumption in the world. Technological innovations such as high-tech filtration systems will help us survive the dry times ahead, but citizens will also need to change their water use habits and their mindsets. As the research described below indicates, some of these changes may be difficult to swallow. But swallow them we must. After all, as civil and environmental engineer David Sedlak puts it in his book *Water 4.0: The Past, Present, and Future of the World's Most Vital Resource*, water is the "essential ingredient of civilization."

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Last summer, a water main ruptured and shot a powerful geyser aloft over Los Angeles' Sunset Boulevard. Over the next four hours, an estimated 20 million gallons of treated drinking water flooded the neighboring UCLA campus, stranding motorists and causing tens of millions of dollars in damage. The busted pipe represented just one of the roughly 240,000 water main breaks the United States experiences in a year. It's largely because of these breaks, along with slow leaks, that a sixth of our treated water—an estimated 2.1 trillion gallons—never reaches the tap.

The pipe that burst in Los Angeles was nearly a century old, like many still in the ground all over the country. The American Society of Civil Engineers recently concluded that "at the dawn of the 21st century, much of our drinking water infrastructure is nearing the end of its useful life." That is especially true of older urban areas, including many in the mid-Atlantic. Baltimore, for instance, has around 1,000 pipe breaks a year and routinely loses more than 20 percent of the water it treats.

In a perfect world, water utilities would conduct routine inspections of all their pipes to identify those in danger of rupture. But urban water delivery systems are composed of thousands of miles of pipe and city budgets tend to cover inspections for only a tiny percentage. As a result, most pipes are replaced only after an obvious break.

Johns Hopkins University systems engineer and risk analyst Seth Guikema hopes to help water utilities become more proactive. He is devising a computer program to predict which pipes in a given system are most at risk of a slow leak or break. With that information, utility companies should be able to conduct more targeted inspections and, it's hoped, reduce the amount of water lost to pipe breaks.

"I had been reading a lot about what terrible shape water distribution systems were in," he says of his initial interest in the project. "And I thought this was a pretty interesting and challenging statistical problem."

Ideally, Guikema's algorithms include information from a utility's pipe system map as well as detailed historical, geological, geographical, and environmental data. The locations of previous pipe breaks are key. It's important to know a pipe's age, the material it's made of, and the type of soil that surrounds it. Repeated exposure to vibration can also weaken a pipe. "In some cases," Guikema says, "we've looked at proximity to major transportation corridors like highways, airports, and rail lines."

Weather is another important variable. Pipe breaks tend to spike in the winter in cold areas, while precipitation can increase or decrease the likelihood of a break depending on the surrounding soil. These are just a few of the dozens of factors that can lead to a break. And as one might expect, all of these variables interact in complex ways. Some soils, for example, are more corrosive to steel pipe than to other types. And even under harsh temperatures, snow cover can have an insulating effect, lowering the risk of a break. In the face of such complexity, it's clear why the traditional pipe inspection strategy—simply checking where pipes have broken before—is less than effective.

Once a user has Guikema's computer program in hand, he or she will plug in the weather forecast, among other variables. Out will come a color-coded map showing pipe segments at high, moderate, or low risk of breaks. "It tells you that those [high-risk pipes] should be the priority for inspection," Guikema says.

The algorithms Guikema's team is developing are, of course, only as effective as the data a given utility provides. The quality of that data varies a great deal from utility to utility, Guikema says. A bigger problem is that some cities don't have the budget for even a targeted pipe maintenance program. "Our system can provide information, but we can't provide them the money to act on it," Guikema says.

The American Water Works Association recently calculated that it would cost more than a trillion dollars to replace the country's buried water infrastructure. Unless public attitudes about water change, that's not likely to materialize anytime soon; Americans pay relatively little for water compared to citizens in other developed countries.

"We take water for granted," Bouwer says. "It's very hard to pass a 10 percent rate increase. People just scream about that. Yet we'll pay for cable TV, cellphones. If you think about banking for our future water supply, we aren't paying the true costs now."

Ending pipe breaks in this country would save enough water for every American to take more than 100 extra baths a year. (Not, it should be noted, the wisest use for such water.) But even a brand new underground pipe system would not eliminate future water scarcity. Before long, many cities—particularly those in arid regions—will have to turn to lower quality options. One of those is stormwater.

Once upon a time, when it rained, water percolated into the soil or meandered downhill to join the nearest stream. In the process, it recharged groundwater and replenished waterways. Then, we paved our cities. Water no longer soaked into the earth, and in places where the ground was flat, huge puddles formed. As a result, cities built storm drains. Storm drains swiftly transport water to sewage treatment plants or waterways, keeping our streets dry. But this system prevents natural filtering processes from removing pollutants—everything from oil to pesticides. As a result, polluted water ends up in rivers, streams, and oceans.

Water treatment engineers have begun to advocate recapturing that stormwater and storing it for later use. Once that might have meant channeling it to a reservoir. But surface reservoirs have fallen from favor in the developed world in recent decades. They are prone to high rates of evaporation and can quickly fill up with silt. (Dams also have a notorious impact on aquatic ecosystems.)

Instead, water treatment experts like Bouwer say stormwater could be rescued via a method that mimics natural processes. So rather than funnel water away through storm drains, “we could inject water underground when it’s available in excess and then pump it out later when it’s a drought,” Bouwer says. “It’s a way of stretching the available water.” Known as aquifer storage and recovery, this system is already in use in a few American coastal resort areas.

The benefits go beyond saving wasted stormwater. En route to storage, untreated water can be injected through the banks of a river or lake to help make it potable. Europeans have used this technique, known as riverbank filtration, for more than a century. Research indicates it can remove many of the same contaminants as conventional water treatment. The soil binds to contaminants and mechanically removes solids from the water, while a naturally occurring biofilm—the slimy film of microorganisms that forms on wet surfaces—does the rest. Bacteria and other organisms in the biofilm consume the organic matter, pathogens, and other contaminants in the water, allowing purified liquid to pass through.

One of Bouwer’s studies found that riverbank filtration also appears to lower concentrations of chlorinated byproducts formed during water disinfection. Americans unwittingly gulp down hundreds of these byproducts every day, and some are potentially carcinogenic. (Many other developed countries have stricter standards on their presence in drinking water.) More recently, Bouwer and his colleagues have found that biofilms are a promising way to filter out pharmaceuticals and personal care products, a class of contaminants that includes everything from prescription and illicit drugs to antiseptics to soap. These have been detected throughout the country in waterways exposed to treated sewage. (Most water treatment systems are not designed to remove them.)

The effects on human health are unknown, but studies indicate that even at low concentrations, some pharmaceuticals and personal care products delay development and alter behavior in aquatic organisms. Estrogens in treated wastewater, for example, can lead to hermaphroditic fish. "If every one of these substances is at a low concentration, but you have a hundred of them, the sum of the hundred could cause harm," Bouwer says. "We'll need to be able to take out these chemicals as we go to more water reuse."

Reuse? Here we come to another potential future source of drinking water. It's abundant, accessible, and reliable. It's just something we'd rather not think about.

The process goes by many names: potable reuse, water reclamation, water recycling. Among critics, it's known as "toilet to tap."

Wastewater was converted into drinking water for the first time more than 50 years ago, but the idea has failed to gain traction nationally. Public opinion has been the major obstacle. In 2011, psychologist Carol Nemeroff of the University of Southern Maine reported the results of a five-city survey that asked people whether they were willing to drink recycled water. Only 38 percent said they were.

Those surveyed might be surprised to learn that they are already drinking wastewater. As David Sedlak blithely puts it in his book, "Since piped water first enabled us to easily dispose of our wastes in rivers, drinking water supplies have frequently contained sewage." Most surface waters are composed of 5 to 15 percent wastewater, according to Bouwer. The Mississippi River, for example, passes through any number of major cities. In each place, drinking water is drawn from the river and treated wastewater is dumped back in. By the time it gets to New Orleans, the river's waters have been treated and consumed many times over. In the business, this is called "de facto reuse."

Given water scarcity projections, we will have no choice in the future but to deliberately use treated wastewater. "We have to think more creatively now and tap into all the resources we can," Bouwer says. An efficient water treatment and reuse plan could extend available water by 75 percent, he says. (We currently recover only 5 percent of it.) One option is to reserve reclaimed water for uses like watering lawns and supplying fire hydrants. The problem is that most of the country currently operates on a one-pipe system, and using two sets of pipes—one for potable water and one for nonpotable—means an expensive overhaul to existing infrastructure. Purifying wastewater to the degree that it is drinkable would stretch our resources and require fewer changes in infrastructure.

One technology currently used to make waterwater reusable is a thin sheet of polymer called a membrane, riddled with pores of varying sizes. Contaminated water, when forced through the membrane, leaves behind anything that doesn't fit through those pores. The membranes with the smallest pores are capable of removing the majority of contaminants from water, including organic matter, viruses, and bacteria.

Semipermeable membranes are used in both water recycling and desalination plants. In desalination, seawater is converted to drinking water through a process called reverse osmosis. Powerful pumps push seawater through tight membranes, removing the salt. Because seawater contains so much salt and dissolved salts pass through all but the tightest membranes, a vast amount of pumping energy is required. In most places, desalination is thus unlikely to represent the sole long-term solution to water scarcity problems. (In areas with cash and few alternatives, like Saudi Arabia and Singapore, desalination is proving helpful.)

It requires much less energy to treat wastewater using reverse osmosis; salts are less abundant in wastewater and contaminants generally larger. Yet one serious problem plagues both desalination and water recycling plants. All those contaminants that are successfully filtered out have a tendency to cling to the membrane, clogging or "fouling" it. The culprits range from particles of clay to microorganisms. Before long, the membrane must be either cleaned or replaced; either way, a plant's operating costs shoot up.

Johns Hopkins University environmental engineer Kai Loon Chen is working on creating membranes that clog less frequently. He is targeting living foes, the bacteria that tend to form biofilms on membrane surfaces. Biofilms are helpful in some water treatment scenarios, including those used in many sewage treatment plants. But for membrane processes like reverse osmosis, they are a hindrance. They slow the flow of water, degrade membranes, and are extremely difficult to clean off.

Chen is looking for ways to stop biofilms from forming. One method he's devised, through funding from the National Science Foundation, involves "polyelectrolyte multilayers," a technique borrowed from the biomedical field. Thin sheets of polymer carrying opposing electrical charges are layered one on top of the other, resulting in what Chen describes as "a lasagna-like structure." When a membrane is coated with this structure, it retains water. The membrane is now "hydrophilic," or water-loving. Bacteria typically have trouble adhering to extremely hydrophilic surfaces. "It actually pushes the bacteria away and doesn't allow them to stick to the membrane surface," Chen says.

Even under this scenario, a few bacteria inevitably pass through to the membrane itself; it only takes a few to form a biofilm. So Chen's lab is working on a backup strategy. In the days before refrigeration, silver coins were often used to preserve milk. That's because silver kills bacteria and other microbes. Now engineers are increasingly turning to silver nanoparticles as potential antimicrobial agents in the water treatment process. Chen hopes that by embedding these nanoparticles within his "lasagna-like structure" of polymers, he can zap those few rogue bacteria that elude the polymers.

Chen hopes his research will help extend the life of membranes and make processes like water recycling, and perhaps even desalination, more sustainable in the future.

If we hope to preserve our way of life in this country, technological fixes to our urban water systems—such as those Chen, Bouwer and Guikema are undertaking—will one day be necessary. But they alone will not suffice. A real water scarcity crisis could require a fundamental rethinking of how we manage water.

The typical American urban water enterprise consists of a complex, often energy-intensive network of pipes, storm sewers, and treatment plants. Our drinking water, wastewater, and stormwater are transported to and from centralized locations and then to desired endpoints. It's taken thousands of years to develop this system. But engineers are beginning to question its efficacy. "Perhaps the best long-term solution to our water problems will be to abandon centralized water systems altogether," notes Sedlak in *Water 4.0*.

Guikema agrees. "The historical approach," he says, "is very much about separation of drinking water and waste from the environment. It's not leveraging natural treatment processes." Guikema, along with an interdisciplinary team, hopes to come up with a new design. He has submitted an ambitious proposal to the National Science Foundation for a grant to develop a new water system from scratch. Guikema wants to unite human, natural, and engineered systems, to the benefit of both human beings and the environment.

The project, if funded, would use Baltimore as a case study. Experts in ecology, water treatment, human behavior, policy analysis, and statistical modeling would come together to redesign the water system, as a modeling exercise. The team would study how an array of engineering enhancements involving natural features, like capturing stormwater, could improve water quality and local ecology. In this virtual Baltimore, buried streams would be unearthed and local wetlands put to use as natural water treatment systems. The new model would rely on the public much more heavily than the system currently does. The team plans to study how consumers might react to new water scenarios—like drinking reclaimed wastewater and reusing water from the sink or shower—and shape their system accordingly.

Designing a statistical model is a far cry from actually calling in the construction crew, of course. "If we take the 'clean slate' approach, we'll come up with an ideal system that we'll never actually get to," Guikema says. "We know that. But it will give us a goal that we can start to decide policies against."

Bouwer is part of the team submitting the proposal. He dreams of someday treating water on a local scale, perhaps employing some of the natural methods he studies, like riverbank filtration. "Right now, the idea's in its infancy," he says. "But I could see 'local' meaning perhaps 50 homes, at the smallest scale." Much less energy would go toward distribution, Bouwer says, and the public would have more of a vested interest in conserving water and keeping pollutants out of storm drains and local waterways.

Such dramatic changes are unlikely in the short term. "Right now, our infrastructure, we're really stuck with what we have," Bouwer says. "We really can't change overnight."

But, he adds, we'll live to regret it if we don't plan for future water scarcity now. "A hundred years from now, we're going to have a lot of problems," he says. "We can't just keep doing it the way we're doing it." /