

One morning in June, Douglas Yoder climbed into a white government SUV on the edge of Miami and headed northwest, away from the glittering coastline and into the maze of water infrastructure that makes this city possible. He drove past drainage canals that sever backyards and industrial lots, ancient water-treatment plants peeking out from behind run-down bungalows, and immense rectangular pools tracing the outlines of limestone quarries. Finally, he reached a locked gate at the edge of the Everglades. Once through, he pointed out the row of 15 wells that make up the Northwest Wellfield, Miami-Dade County's clean water source of last resort.

Yoder, 71, is deputy director of the county's water and sewer department; his job is to think about how to defend the county's fresh drinking water against the effects of climate change. A large man with an ambling gait, Yoder exudes the calm of somebody who's lived with bad news for a long time.

"We have a very delicate balance in a highly managed system," he said in his rumbly voice. "That balance is very likely to get upset by sea-level rise." What nobody knows is when that will happen, or what happens next.

From ground level, greater Miami looks like any American megacity—a mostly dry expanse of buildings, roads, and lawns, sprinkled with the occasional canal or ornamental lake. But from above, the proportions of water and land are reversed. The glimmering metropolis between Biscayne Bay and the Everglades reveals itself to be a thin lattice of earth and concrete laid across a puddle that never stops forming.

Water seeps up through the gravel under construction sites, nibbles at the edges of fresh subdivisions, and shimmers through the cracks and in-between places of the city above it.

Miami-Dade is built on the Biscayne Aquifer, 4,000 square miles of unusually shallow and porous limestone whose tiny air pockets are filled with water from rain and the rivers that run from the swamp to the ocean. The aquifer and the infrastructure that draws from it, cleans its water, and keeps it from overrunning the city combine to form a giant but fragile machine. Without this abundant source of fresh water, made cheap by its proximity to the surface, this hot, remote city could become uninhabitable.

Climate change is slowly pulling that machine apart. Barring a stupendous reversal in greenhouse gas emissions, the rising Atlantic will cover much of Miami by the end of this century. The economic effects will be devastating: Zillow Inc. estimates that six feet of sea-level rise would put a quarter of Miami's homes underwater, rendering \$200 billion of real estate worthless. But global warming poses a more immediate danger: The permeability that makes the aquifer so easily accessible also makes it vulnerable. "It's very easy to contaminate our aquifer," says Rachel Silverstein, executive director of Miami Waterkeeper, a local environmental protection group. And the consequences could be sweeping. "Drinking-water supply is always an existential question."

County officials agree with her. "The minute the world thinks your water supply is in danger, you've got a problem," says James Murley, chief resilience officer for Miami-Dade, though he adds that the county's water system remains "one of the best" in the U.S. The questions hanging over Southeast Florida are how long it can keep its water safe, and at what

cost. As the region struggles with more visible climate problems, including increasingly frequent flooding and this summer's toxic algae blooms, the risks to the aquifer grow, and they're all the more insidious for being out of sight. If Miami-Dade can't protect its water supply, whether it can handle the other manifestations of climate change won't matter.

The threats to the Biscayne Aquifer are unfolding simultaneously, but from different directions and at different speeds. In that way, Miami's predicament is at once unique and typical: Climate change probes a city's weaknesses much as standing water finds cracks in the foundation of a house.

Twenty minutes east of the Northwest Wellfield sits the Hialeah Water Treatment Plant. With its walls built of coral rock in 1924, Hialeah was Miami's first major water-processing facility. The water drawn from the Northwest Wellfield is piped here to be cleaned along with water from another cluster of wells that pull from straight beneath the plant. As climate change worsens, this plant will matter more and more.

A few blocks from the Hialeah facility, buried beneath what's now a maintenance yard for the county's Metrorail trains, lies a 1.2-acre zone that the Environmental Protection Agency has ranked the second-most hazardous Superfund site in Miami-Dade. From 1966 until 1981, the land was used by Miami Drum Services Inc., a company that rinsed containers for an assortment of toxic chemicals, then disposed of the residue on-site.

County and state officials concluded in 1981 that the operations were contaminating the aquifer; the EPA later said the space was leaching arsenic, cyanide, mercury, nickel, lead, cadmium, chromium, chloroform, and oil into the groundwater. The county forced Miami Drum Services to abandon the property and spent two months removing all "visibly contaminated soils."

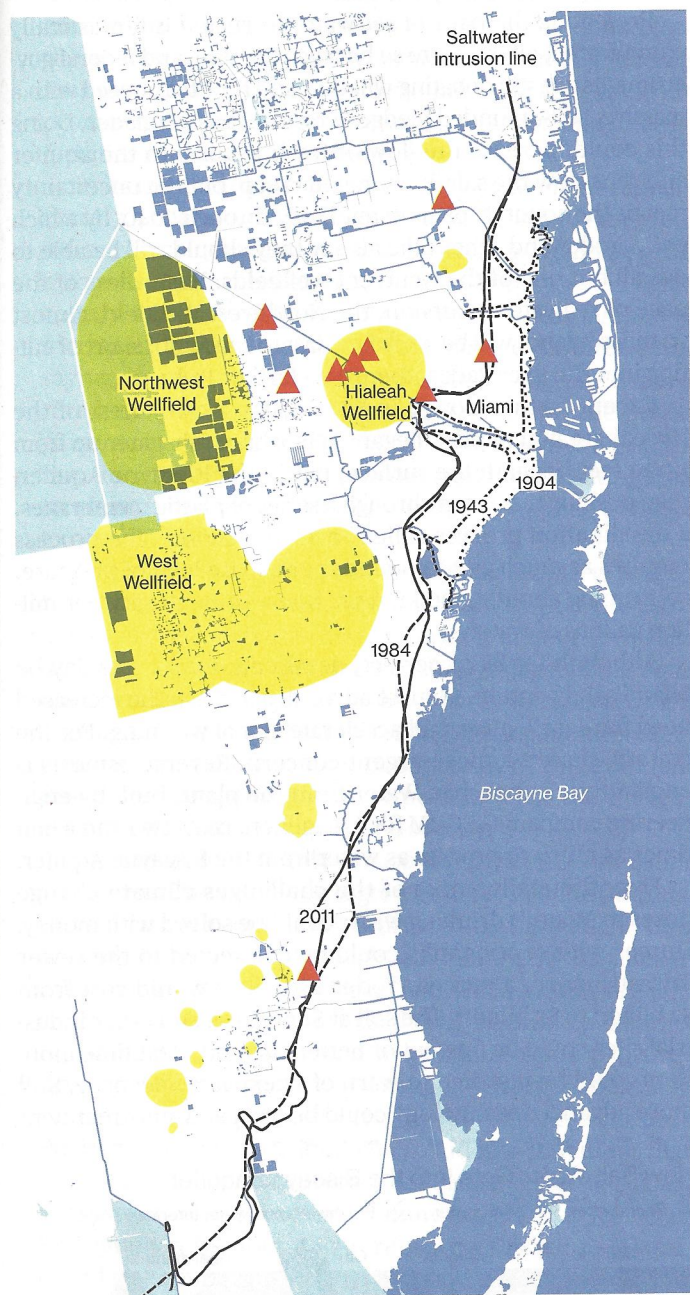
Until then, water from the Biscayne Aquifer required minimal treatment: The county would add lime to soften it and chlorine and ammonia to disinfect it, then filter out remaining particles. Once fluoride was added to help prevent tooth decay, the water would be piped to people's taps. In 1992, in response to the risks posed by toxins from the Miami Drum site and others near it, the county added a new stage at Hialeah, running the water through "air stripping" towers designed to remove toxic contaminants.

In 2014 an EPA report warned that "flooding from more intense and frequent storms" could push toxins from Superfund sites into underground water sources like the Biscayne Aquifer. Anna Michalak, a researcher at the Carnegie Institution for Science in Stanford, Calif., says climate change means U.S. cities are "entering a state that these systems were not built for." She adds: "As the incoming water quality becomes either worse or just less predictable, you have to have more and more systems in place to deal with all of that."

In South Florida that new state is already here. The amount of precipitation that falls during the heaviest storms has increased by about 7 percent in Miami-Dade since the 1960s, according to research by Constantine Samaras, an associate professor of civil and environmental engineering at Carnegie Mellon University. Although the disparity might not seem like

The Sea's Slow Creep Inland Threatens Freshwater Wells

● Wellfield protected zones ▲ Superfund site
 ■ Water ■ Wetlands



much, it could mean the difference between a lot of rain and an outright flood. The Union of Concerned Scientists estimates that by 2045, as much as 29 percent of Miami Beach and 26 percent of Key Biscayne could be “chronically inundated,” which UCS defines as flooding twice a month.

Earlier this year, Pamela Cabrera, a graduate student at Harvard, mapped the Superfund sites in Miami-Dade and their proximity to wellfields. Her hypothesis was simple: Increased flooding could dislodge the toxic chemicals that remain on Superfund and other industrial sites, pushing them into the aquifer. According to Cabrera’s map, the Miami

Drum site is 750 feet from the Hialeah Wellfield. A dozen other Superfund sites are scattered throughout the county. More severe flooding or rainstorms could overwhelm Hialeah’s controls or move toxins through the aquifer in new ways, sending them into one of the wellfields without that equipment.

In 2014 a storage tank in West Virginia leaked methylcyclohexane methanol, a chemical used to process coal, into the Elk River just upstream from Charleston’s water-intake center. The spill rendered the city’s water undrinkable, leaving 300,000 people with no water for days. “It’s extremely important for everybody to look upstream of their drinking-water systems and protect them,” says Gina McCarthy, who ran the EPA under President Obama. She cites Charleston, as well as Toledo, Ohio—which had to shut down its drinking-water supply later in 2014 because of an outbreak of cyanobacteria—as evidence of how a shock to the water supply can thrust a city into chaos.

Miami-Dade has regulations and testing procedures in place to prevent or detect contamination of the aquifer. Asked about the risk, Yoder chooses his words carefully. “I think it’s a fair question,” he says, but adds that the county at least has a history of dealing with those threats, noting its experience with the Miami Drum site.

Michalak warns that’s too easy. “Invariably,” she says, “we discover that we’re not quite as clever as we thought.”

In 1997 the state approved large-scale limestone mining at the edge of the Everglades. Pulling the rock out of the ground entails blasting holes in the aquifer, which almost immediately fill with groundwater to become dusty blue pools. Locals refer to them as “rock lakes,” though they’re not the kind that draw families for weekend picnics.

The mines happen to surround the Northwest Wellfields. The same conditions that made the area suitable for water wells—vast open space with no development in sight—also made it ideal for massive rock pits. Environmentalists have warned that the rock lakes act as a superhighway for pollutants from the mining, driving them straight to the heart of the aquifer. In 2005 one of the Northwest wells registered five times the federal limit for benzene, a chemical used to blast out rock, which the American Cancer Society says has been linked to leukemia. The county ordered the well, along with four adjoining ones, temporarily shut down. Yet regulators never successfully identified the source of the benzene, and the mining continued.

Yoder pulled over beside a rock lake lined by gravel roads and surrounded by swamp. The photographer with us made a half-hearted joke about alligators and then got out. Yoder and I stayed in the truck; the air outside was dusty and hot, and neither of us was particularly keen to take our chances with whatever might crawl out of the ditch.

The decision to surround the county’s most pristine wellfields with rock mines reflected a compromise, Yoder said. The Miami-Dade Limestone Products Association Inc., which represents some of the area’s biggest mining outfits, insists mining has no effect on the aquifer. Better that than to surround the wellfields with houses, Yoder said, adding: “More developed areas had higher contaminants.”

More worrisome than the mining itself is the whole ►

◀ vast world of toxicity to which the mining has opened up the aquifer. “The rock belt is going to become a place where contaminants can enter and move deeper,” says Philip Stoddard, the mayor of South Miami, one of the cities in Miami-Dade that’s most exposed to sea-level rise. As flooding and rainstorms get worse, Stoddard warns, they’ll move surface water around the county in increasingly unpredictable ways. “You’ve always been able to count on the water going west to east,” drawing runoff away from the water supply, he says. “What happens when it starts going back toward the wellfield? You don’t have to be a genius to figure out it could be a bad thing.”

Then there’s the feces. As developers built out Southeast Florida, they found that instead of connecting each new home to the local sewer system, it was often easier to install a septic tank. Miami-Dade has about 90,000. “It was the magic carpet for quick, cheap development in Florida,” says Brian Lapointe, a research professor at Florida Atlantic University who focuses on the role of septic tanks in water contamination. These tanks are typically used in rural areas where homes are too far apart to justify connecting them to a central sewage system—but also in places where residential construction happens faster than municipal infrastructure development. Septic tanks trap solid waste, which is supposed to be pumped out, while the liquid stuff drains into the soil, where gravity and time filter out bacteria and whatever else is in it before it reaches groundwater. In Southeast Florida, that groundwater is especially close to the surface—and rising.

The state requires at least two feet of dry soil between the bottom of the drainage field and the top of the water table, but Lapointe says that during the wet season, the groundwater in parts of southern Florida already comes above that two-foot threshold. More intense flooding and rainstorms will swell the water table further, on top of the gains caused by sea level rise, sending partially treated human waste into the aquifer. That waste can contain *E. coli* bacteria, which cause diarrhea, vomiting, and even kidney failure. High levels of nitrates, another component of untreated waste, cause what’s called blue baby syndrome, in which infants’ blood can no longer carry sufficient oxygen.

Lapointe adds that one of the ways researchers assess septic-tank contamination is by tracking the levels of acetaminophen in the groundwater. “People’s medications are coming with that septic-tank effluent.” The wonders of the human digestive system are many and varied, containing any number of other bacteria and viruses—“all these other organic compounds that may or may not be affected by the treatment at the utility plant,” he says.

How long does Miami have before the water table overwhelms the septic system? Officials, including the South Miami mayor, worry that the point of failure is closer than people realize. Says Stoddard, “I’m convinced that some of those septic systems are working by force of habit rather than by the laws of physics.”

The slowest-moving threat to Miami’s drinking water is also the most sweeping: As the ocean rises, salt water is being pushed into the limestone, forming a wall of brine that’s creeping inland along the aquifer’s floor. The county’s

wells are essentially giant straws drawing water from 60 feet to 80 feet beneath the ground. As the saltwater front advances westward across the aquifer, reaching each of those intake valves and enveloping them in saline water, it risks rendering them useless in succession—a sort of Sherman’s March in reverse, prosecuted by the sea.

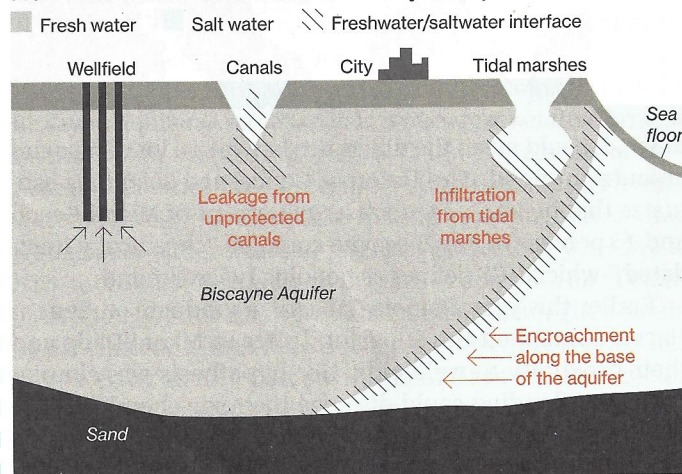
Projecting the pace of saltwater intrusion is fantastically complicated, all the more so because the state and federal governments are still debating whether and how to proceed with a massive, still-unfunded pledge to restore the Everglades. Doing this could increase the flow of fresh water into the aquifer and thus slow the salt line’s inland creep, but the uncertainty means the county’s plans extend only through 2040, by which point Yoder and other officials say they should still be able to use all but one of their current wellfields. Regardless of the pace of seawater incursion, the Northwest Wellfield, almost 20 miles inland, will be one of the last to succumb; short of cutting into the Everglades, there’s no farther to go.

Except farther down. In 2013 a new facility west of the Hialeah treatment plant began pulling brackish water up from 1,000 feet beneath the surface, below the Biscayne Aquifer, then pushing that water through a series of plastic membranes, a desalination process called reverse osmosis. The process requires as much as 200 pounds per square inch of pressure, consuming about 5,000 kilowatt-hours of electricity per million gallons of water.

Although far from perfect, desalination may one day be Miami’s only option. Climate advocates fret that the increased need for desalination will accelerate global warming. For the county, there’s a more urgent concern: Reverse osmosis is enormously expensive. Water from the plant, built by engineering company AECOM for \$55 million, costs two and a half times as much to process as water from the Biscayne Aquifer.

Hypothetically, most of the challenges climate change poses to Miami’s drinking water could be solved with money. Homes with septic tanks could be connected to the sewer infrastructure, a process Yoder estimates would cost from \$2 billion to \$3 billion. The soil at Superfund and other industrial sites could be dug out or better encased. Real-time monitors could be installed to warn of unexpected seepage. Still more advanced technology could be used at water-treatment

How Salt Water Gets Into the Biscayne Aquifer



plants. But those projects would need funding. And there's already a long line.

In 2008 the Florida legislature passed a law dictating that the state's water utilities stop discharging sewage into the ocean by 2025; complying with that timeline could cost as much as \$5 billion, Yoder says. Then, in 2013, Miami-Dade entered into an agreement with the EPA, which had found the county unlawfully discharged more than 28 million gallons of untreated wastewater into Biscayne Bay. The county promised to upgrade its wastewater collection and treatment facilities at a cost of \$1.6 billion.

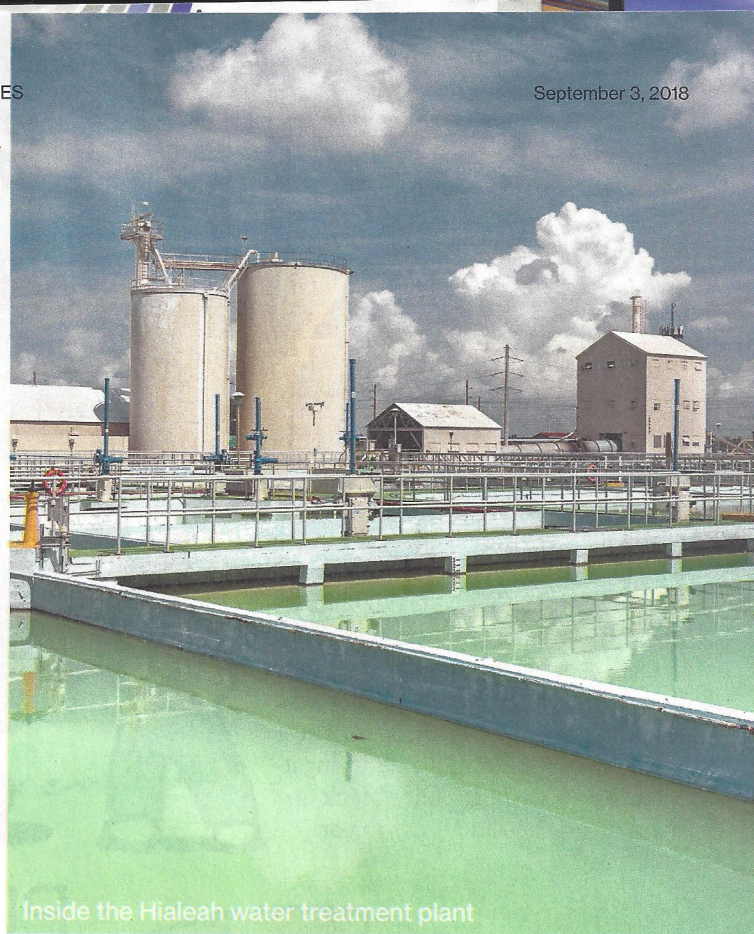
In its latest capital budget, Yoder's department estimated that \$13.5 billion would be required for these and other future infrastructure projects, of which \$9.5 billion would be funded by bonds. But last November, Moody's Corp. warned that the county's creditworthiness depends on "future annual rate increases to meet escalating debt service requirements"—saying, in effect, that the elected officials who must approve rate increases had better be willing to accept the political pain associated with ratcheting up their voters' water bills. If not, the county's credit rating could fall, necessitating higher interest payments on its bonds—and even higher water bills to cover them.

The crush of climate-related spending requirements goes beyond protecting drinking water. Add to that the cost of pumps and sea walls as rising seas turn the area's gravity-reliant drainage canals back on themselves. "Anything that this county relies on that is gravity-based is in jeopardy with sea-level rise," says Wilbur Mayorga, head of environmental monitoring and restoration at the county's Department of Environmental Resources Management. "We've been lucky all this time. The time will come that it may not be so easy."

Spending on that scale is hard for any county to manage on its own. The challenge is greater here: Despite pockets of extreme wealth—one study estimated that the Miami metro area has the nation's eighth-highest number of millionaires—the county overall is poor. Its median household income of \$44,224 is almost one-quarter lower than that of the country as a whole.

Asked if the state would help Miami-Dade protect its drinking water from climate change, Governor Rick Scott's office directed questions to the Florida Department of Environmental Protection, which said in a statement that it "continues to work to protect the resiliency of our coastal ecosystems and shoreline communities." But José Javier Rodríguez, a Democrat who represents much of Miami in Florida's Republican-held senate, says his city is unlikely to get bailed out by the state. It's not a question of believing in science. "The massive political and institutional resistance to taking action, in my view, is not largely ideological," he says. "It's not largely even political. It's a question of being intimidated by the price tag." As the low-tax state struggles against a revolt among school districts protesting meager budget increases and a \$28 million prison funding deficit, there's no appetite to pay for solutions to future crises, even when the future is almost here.

The obvious solutions would cause problems of their own. Why not stop mining near the wellfields, for instance? Because the limestone from those mines goes into the concrete used



Inside the Hialeah water treatment plant

to construct sea walls and build higher off the ground along Florida's coast. There's little disagreement about the need to get rid of the septic tanks, but which homes get help first? If a coastal neighborhood will have to be abandoned anyway, is it worth spending money on new sewers?

Now pull the lens back further. Miami's drinking-water problems are merely one facet of the still-accumulating effects of climate change that officials must identify, decipher, and combat. These include new diseases such as Zika, more frequent toxic algae blooms, disappearing beaches, heat waves, the growing threat of a real estate crash, and the eventual need to relocate people away from the coast. Protecting the aquifer isn't the end of adapting to climate change; it may not even be the hardest part. It's simply the price the city will have to pay to keep trying.

That leaves the cruelest lesson of climate adaptation: The costs of saving Miami will mostly fall on the people who live here—testing how much they're willing to pay for the privilege, a sort of free-market Darwinism for the life of whole cities. "There will always be drinking water here," says Virginia Walsh, a hydrogeologist with Yoder's department. "It's just a question of how much you want to pay for it."

Stoddard, the South Miami mayor, says people who already have homes here will accept almost any price to stay. But those who would otherwise come to South Florida will start looking at the growing cost of protecting it—measured in water rates, in property taxes, in insurance premiums, in uncertain future home sales—and go elsewhere.

"People will hang on with their fingernails to keep what they've got," Stoddard says. "But who's going to move here? And that's what's going to kill us." **B**