Fighting a Rising Tide

BY ALAN S. BROWN

Rising oceans threaten to overwhelm Miami. The city is fighting back with old and new engineering. Can it survive?

Google "Miami" and "sunny day flooding" and photo after photo of flooded neighborhoods pops up. As the sun shines brightly, cars slosh down streets and pedestrians parade through puddles, some up to their knees. In one photo, tall buildings rise from the water covering Miami Beach island. Another shows a neighborhood 60 miles south of Miami that has been flooded for 40 days.

Flooding is nothing new in Miami. The city was built on a swamp and more than half of it rides less than six feet above sea level. Storms and hurricanes have always brought rains and high winds that push water from Biscayne Bay through the city's streets.

Sunny day flooding is different. Caused by rising sea levels, it occurs during the highest tides, which push water into low-lying communities. They also force water through the porous limestone underneath Miami, where it percolates upwards, bubbling out of storm drains and covering streets.

According to the National Oceanic and Atmospheric Administration (NOAA), high tide flood days have increased 400 percent to 1000 percent along the Southeast Atlantic and Gulf Coast since 2000.

It has not taken much of a sea level rise to do this. According to an international satellite radar survey, the Atlantic Ocean rose only 3.6 inches between 1993 and 2023. A *Washington Post* study of more than a dozen tide gauges from Texas to North Carolina puts the figure at six inches between 2010 and 2023. As rising temperatures melt glaciers and polar and Greenland ice sheets, the American Meteorological Society predicts a sea level rise of 10 to 12 inches by 2050.

Today's infrastructure was not designed for this, said **Scott L. Douglass, Ph.D., P.E.,** *AL E '81*, a coastal engineer who founded South Coast Engineers. He points to Interstate 10's Escambia Bay Bridge in the Florida Panhandle. In 2004, Hurricane Ivan's storm surge knocked 58 spans off the bridge and misaligned another 66.

While modeling storm surges for a replacement bridge, Douglass realized the original span had just barely collapsed. "If sea levels hadn't risen, it probably would not have fallen down," he said. "That's how sensitive bridge elevation is to wave loads."

With rising seas come other threats as well. Higher ocean and air temperatures generate hurricanes with stronger winds and greater rainfall. Their high winds have ripped apart thousands of buildings and pushed salty seawater into Miami's freshwater aquifer. Their rainfall has wreaked havoc on the city's 120,000 septic tanks.

Miami is not alone. Neighboring communities flood as well. So do other low-lying communities along coastlines around the world.

Yet, Miami continues to grow. The Miami Standard Metropolitan Area stretches from the tip of Florida 100 miles north to West Palm Beach. It added 550,000 residents between 2014 and 2024, bringing its population to 6.3 million. The city's downtown is home to 18 of America's 100 tallest skyscrapers, trailing only Chicago and New York City. More are on the way.

Yet, Miami, a study in contradictions, faces an uncertain future. Everyone is planning for seas to rise, most likely by 1.5 to 4.5 feet within the next 50 years. How can Miami win this battle? And what lessons can we learn about resilience from its fight to survive?

STORMY WEATHER

Located in a hurricane-prone mangrove marsh, Miami faces three primary challenges: storm surge, rain, and wind.

Draining the marsh lowered the area's elevation five to six feet. Protected by Miami Beach three miles offshore, storm surges flooded the city only during the largest hurricanes.

Rain posed a greater challenge. In the late 1940s, a series of violent hurricanes ripped through southern Florida. One created a flood that stretched from Miami to the other side of the state.

To manage flooding, Florida built an 1,800-mile grid of canals buttressed with hundreds of flood gates and pump stations. During the wet season, canals move flood waters into the ocean or into the 734-square-mile Lake Okeechobee, 90 miles north of Miami. During the dry November-April tourist season, coastal cities draw water from the lake.

Since it was completed in the early 1960s, South Florida's population has tripled and warming temperatures have made hurricanes larger and more dangerous, according to Erik Salna, a meteorologist and associate director of Florida International University's (FIU) International Hurricane Research Center.

Warmer temperatures energize storms, creating larger surges and increasing the amount of water (and rain) they hold, he explained. Warmth also slows air currents, prolonging storms' duration and the damage they inflict. These hurricanes have begun to overwhelm southern Florida's drainage system.

Rising sea levels also threaten Miami's drinking water, the Biscayne Aquifer. Its sponge-like limestone holds one of the world's largest bodies of fresh underground water, explained Jayantha Obeysekera, director of FIU's Sea Level Solutions Center and chief modeler for the South Florida Water Management District.

Florida recharges the aquifer by releasing water from its canals. In years of low rainfall, however, rising seas push saltwater into the aquifer. "Saltwater penetrates the limestone fast," he said. "Several wells on the coast have been abandoned, and once abandoned, we cannot get them back. This all happens underground, so we cannot build a levee to stop it."

High tides and rain also threaten Miami's 120,000 septic tanks, more than any other U.S. metropolitan area. "When water makes contact with septic tanks, it releases contaminants and then all that contaminated water moves through the groundwater into Biscayne Bay," Obeysekera said.

Hurricane winds also inflict damage. Since wind pressure is the square of velocity, even slight differences in speed ramp up forces quickly. In 1994, Hurricane Andrew demonstrated what could happen when its 157-miles-per-hour winds slammed into Florida south of Miami and then moved north and east. It displaced 250,000 people and destroyed or damaged tens of thousands of homes. Based on such recent hurricanes as Dorian and Patricia, researchers are now planning for 200-miles-per-hour winds and 20-foot surges.

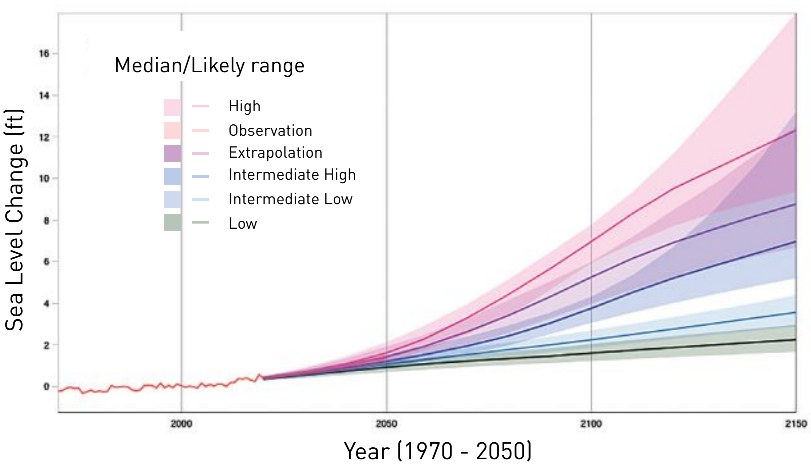
BARRIER ISLANDS

Most plans to preserve the Miami area start with taming ocean surges. Three miles offshore, Miami Beach takes the brunt of those forces from the Atlantic Ocean. The nine-mile-long and one-mile-wide barrier island started life as a ribbon of sand, dunes, and vegetation running parallel to the coast.

In nature, barrier islands move, Douglass said. Storm surges wash over them and slice channels through them, rolling sand over itself like a tractor tread. The city of 90,000 residents must fight nature if it does not want to disappear.

The island built 53 miles of seawalls to protect it from surges, recently mandating a minimum height of 5.7 feet. To cope with flooding through porous limestone, the city has created low-lying parks and landscaped areas to capture water and installed pumps to remove it. It is also raising street levels.

U.S. Interagency Sea Level Rise Projections for South Florida



Hurricane Andrew's 157 mph winds ripped apart this home when it drove through Florida and Louisiana.

Miami Beach has also embraced greener solutions. Offshore, it is evaluating a hybrid reef made of interlocked hollow hexagonal and trapezoidal members buttressed by rocks to drain energy from surges while fostering marine life. The city seeds its beaches with vegetation, which could mature into a scrub maritime forest if it survives long enough, Douglass said. Plants lock dunes in place during high winds but they are still vulnerable to surging waves.

Even so, Miami Beach must constantly replenish sand washed away by storms. “If you get the sand quality right, if it’s pure, plants thrive and fish and marine animals colonize the area,” Douglass said.

Finding the right sand is not easy. “Geophysical firms will survey the upper 20 to 40 feet of the seabed, looking for pure deposits from 6,000-to-10,000-year-old beaches and from inlets,” he explained. “Several harbor dredging companies have developed specialized equipment to harvest sand, but many of the best deposits have been used up.”

This is expensive. Douglass recalls a beach in Ponte Vedra in northern Florida. “They just built it but it looked like it had been there for 20 years,” Douglass said. “It was a $40 million project, but it was not expensive compared with the $10 million houses that lined the beach.”

SAVING MIAMI

Miami Beach blocks ocean surges in northern Miami, but water still rushes in from south Biscayne Bay. To keep the water at bay, the city reached out to the U.S. Army Corps of Engineers.

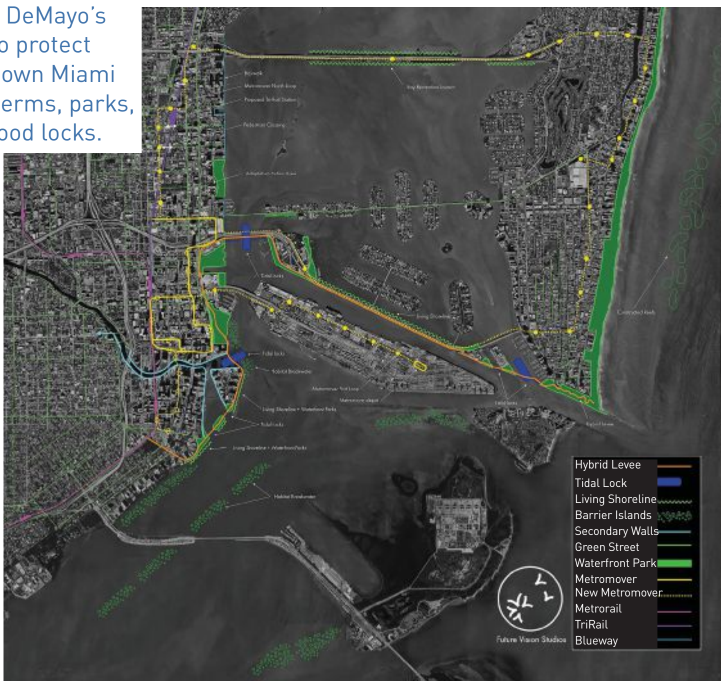
The Corps’ 2020 plan included features often found in other coastal projects, such as levees, flood locks, pumps, raised roads, and hardened buildings. It also called for a six-mile-long seawall up to 20 feet tall.

Citizens (and real estate developers) went crazy. Miami’s shoreline defines the city and its lifestyle. No one wanted to lose it. The plan also infuriated low-lying communities who were left on the wrong side of the seawall. This led both sides to rethink their approach.

Miami now realizes that sea level rise is inevitable. “Instead, Miami is rethinking how we can live with the water,” said Patricia Gomez, Miami-Dade County’s acting chief resilience officer.

The Corps, meanwhile, broke from tradition. Its Congressional mandate calls for it to build cost-efficient infrastructure. That usually results in giant civil projects. In 2021, however, the Corps began embracing natural and nature-based solutions, such as living shorelines, artificial reefs and islands, and restored wetlands. They all appear in its most recent plan, which was developed after extensive community feedback.

One participant was Aaron DeMayo, founder of eco design firm Future Vision Studio and now chair of Miami’s Climate Resilience Committee.



Aaron DeMayo’s plan to protect downtown Miami with berms, parks, and flood locks.

After his Edgewater neighborhood flooded, DeMayo began driving around Miami to see which neighborhoods flooded and how the water got there.

He found that surges entered Biscayne Bay and Miami from the south, streaming around several smaller islands. To prevent this, he proposed a tall berm that would stretch to Miami Beach with a tidal lock to stop surges into the bay. Waterfront parks and berms, some up to 18 feet high, and tidal locks would also keep seawater from entering the Miami River, which flows through downtown. Decorating the berm were parks, pedestrian walkways, bicycle lanes, and living shorelines. In the bay, living reefs doubled as breakwaters.

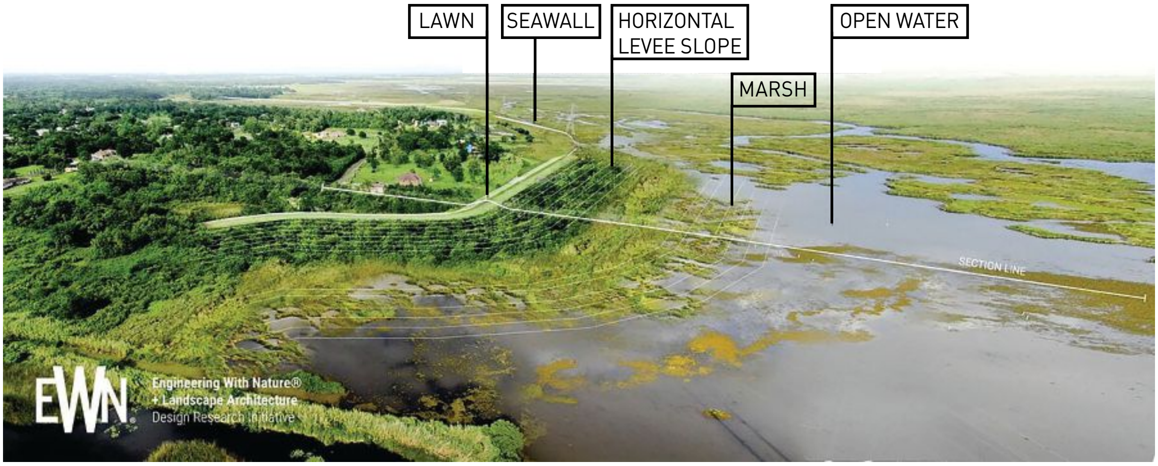
The Corps’ new plan incorporates many of the same elements to create multiple lines of defense. These include human-made islands, reinforced dune systems, and artificial reefs to absorb surge energy. The Corps recommends restoring mangrove forests and coastal marshes to help filter water after a storm as well as elevating roads. It also wants to see more parkland and more living shorelines as well as the usual levees, pumps, and locks.

UNDERGROUND ISSUES

Even without surges, tidal flooding and rain pose challenges to Miami’s septic tanks. The county estimates that 9,000 septic tanks are vulnerable today and 13,500 will be vulnerable by 2040.

The problem is not engineering, it is money. The county expects individual homeowners to pay for connecting their homes to the wastewater system. Not everyone can afford it. Miami-Dade hopes to subsidize sewer links for low-income families with vulnerable septic tanks. “The county is starting the process to pursue grants to fund it,” Gomez said.

What happens to wastewater after treatment? Miami could pump it into the bay if it meets EPA standards. Or, like other cities, it could dilute partially purified wastewater by putting it in aquifers, lakes, or reservoirs, and purify it before use. Others recycle it to water commercial lawns and golf courses or to cool buildings, industrial processes, and power plants.



The U.S. Army Corps of Engineers has embraced the use of natural features to reduce the force of water surging onto its seawalls.

Miami could also store it under the Biscayne Aquifer, creating large water bubbles that could be pumped to the surface during droughts, Obeysekera said. A 5-million-gallon-per-day pilot test is underway, but it is too early to say if it is scalable or not.

Saltwater is also degrading the Biscayne Aquifer. Conservation is helping. "We use 150 gallons of water per person per day with irrigation, landscaping, and lakes," Obeysekera said. "We should be closer to 50 gallons per day." The more freshwater in the aquifer, the less space for saltwater.

Another solution involves directing water to the Everglades, where it seeps into the aquifer. In addition to restoring the Everglades, Florida is also building levee-enclosed artificial wetlands where native plants filter nutrients from agricultural runoff before directing the water to the Everglades.

Then there are the canals. They were built to discharge rainwater into the ocean via gravity flow. With rising ocean levels, however, they no longer release water passively. Instead, flood gates must remain closed to keep saltwater from entering the canals and flooding neighborhoods. One way to surmount this problem is to pump canal water directly into the ocean, Obeysekera noted. Another is to direct water to large reservoirs and pump it out when the storm has passed.

In the long run, he says, Miamians may have to do what the Dutch have done for generations: build levees around neighborhoods and put in pump stations.

That leaves seawater surging through the porous limestone during high tides. "Some have suggested a seepage barrier underground to some depth," Obeysekera said. "That, in my mind, is not a practical solution." Instead, pump systems must continue to empty flooded areas. Eventually, he said, communities will have to "vertically retreat" to avoid groundwater flooding.

TAKING A BLOW

Hurricane winds can do enormous damage. Andrew, one of the few Category 5 hurricanes to ever make landfall, destroyed 63,000 homes and damaged 124,000 others when it struck Florida, Louisiana, and the Bahamas. If it had hit Miami instead of moving south, it would have been worse, Salna said.

"People love the old cottages and restaurants that have been there forever," he explained. "When a storm hits, all that old charm is gone. Think of it as a form of urban renewal. The buildings that replace them will look different but will do better surviving the next storm."

Building codes are the best way to fight wind. "The good news is that codes proved they work," said Marc Levitan, lead research engineer at the National Institute of Science & Technology's National Windstorm Impact Reduction Program. "When Hurricane Irma hit the Florida Keys [in 2017], the old buildings washed away but the new stuff survived."

Codes focus on three key weak spots: building envelope (roofs and walls), openings (windows and doors), and load path (structural anchors).

Take roofs, for example. Once a few shingles give way, wind will get under the rest and tear them away. Wind then drives rain under the roof, soaking insulation until it collapses the ceiling. Hurricane-rated shingles, nails, roof sealers, and vinyl siding improve performance significantly.

Homes damaged by hurricanes usually have missing windows and doors. Once a storm pulls off a door or window, it can pressurize a house, pulverize its rooms and walls, and tear off its roof. Wind-rated metal doors, braced garage doors, and easy-to-close shutters help.

A positive load path anchors a building's components to the ground. It might include roof straps to transfer loads from roofs to walls whose studs are screwed into a concrete foundation.

Building standards are likely to grow stricter as wind speeds increase, Levitan added. Most homes, shops, apartments, and factories are governed by Category 2 windspeed maps. Under new codes, they will need to withstand a one-in-700-year event. "That sounds highly unlikely, but there is a seven percent probability that it could happen over a 50-year period," Levitan said.

BUILDING BOOM

Despite wind and flooding, Miami is undergoing a building boom, especially in the low-lying Brickell business district. This makes the city a laboratory for advanced coastal construction techniques.

New skyscrapers are prepared to live with water. Many have stairs leading up to their lobbies, making them easy to modify if the city raises sidewalk elevation (as it has done up to 2.5 feet in some places). Mechanicals are also on higher floors to keep them away from water. Their hurricane-rated laminated glass resists high winds. They sit on elevated platforms with solid gates to keep storm surges from rushing up their driveways.

To build high, Miami digs low. Porous limestone makes a poor foundation: it is weak and prone to water seepage. In the past, contractors excavated around tides to keep sites from flooding.

For the foundation of the Waldorf Astoria, which will become Miami's first 1,000-foot-tall building when completed in 2027, contractor Keller used a technique called deep soil mixing, said vice president Andres Baquerizo in a video. It involves mixing concrete directly with wet soil to form a stiff, almost impermeable material called soilcrete.

This is done using 10-foot-diameter drills whose business end looks like blender blades. The blades mix the soil while injecting concrete into it. Drilling an overlapping grid creates a solid soilcrete foundation that goes down well over 100 feet.

Soilcrete anchors tall buildings when wind tilts them, putting one side in compression and the other in tension, Baquerizo explained. The stiffer foundation also keeps the building from tilting or sinking over time.

The Waldorf, like most very tall skyscrapers, may sway in moderate winds. Another innovation, a tuned mass damper, suppresses that motion. Suspended on pistons, springs, or moveable arms near the top of a building, tuned dampers adjust their mass to resonate out of phase with a moving structure. This reduces swaying. The technology became a YouTube sensation in April 2024, when a damper on Taipei 101 kept the tower from rocking during a 7.4 earthquake in Taiwan.

One Thousand Museum, a 709-foot-tall, 62-story tower also features another safeguard against wind: a glass fiber-reinforced concrete (GFRC) exoskeleton. Designed to carry structural loads from the building's base to its podium, it replaces most of the interior pillars that would ordinarily support the building.

CHALLENGING UNCERTAINTY

Miami's response to climate-driven sea level rise and more intense hurricanes is engineering on a heroic scale. It may provide an inspiration, if not a blueprint, for other coastal communities.

Still, uncertainty remains. That starts with climate. The Southeast Florida Regional Climate Compact, a regional alliance to coordinate responses to climate change, has analyzed multiple forecasts. It projects sea levels will rise 7 to 14 inches in less than 20 years. It calls for architects to plan for a 1.5-to-4.5-foot sea level rise for buildings with 50-year lifespans and a 3-to-13-foot increase for those with 100-year service lives.

Those ranges are so wide because our understanding of climate continues to evolve. Scientists are still deciphering how warming temperatures drive ice sheet melting in Greenland and Antarctica and alter the ocean's moderating currents. New satellite Lidar measurements suggest low-lying areas will flood faster than radar data indicate. Warming rates also depend on emissions, which are determined by public policy.

Still, it could not be clearer that water levels are rising and engineers need to plan for this. That means reworking codes and standards.

The American Society of Civil Engineers, for example, plans to add "Future Conditions" to its structural engineering bible, Standard 7, in 2028. NIST's Levitan, who chairs the chapter's wind task committee, says his group plans to take input from a variety of climate models to develop new hurricane maps.

Douglass hopes to pin down sea levels for the Federal Highway Administration. While scientists project a wide range of outcomes, Douglass believes the most likely scenarios call for a two-foot rise by 2100. The more critical the project, the greater the safety margin he builds in. "Adding an extra 20 or 25 feet to the height of a bridge is not that expensive, given the total cost of construction," he said.

Planning for uncertainty may require new ways of thinking. Obeysekera, for example, embraces the dynamic adaptive policy pathway (DAPP). It involves planning projects for modification as needs change.

"In Miami Beach, for instance, we might build a four-pump system but only install one pump now," Obeysekera explains. "Then we could add pumps as needed. This way, we make sure the land and infrastructure are available for an upgrade."

What might Miami look like in 20 or 40 years?

DeMayo expects a denser city as residents abandon low-lying neighborhoods and move into larger apartments on higher ground. Miami will have more flood-resistant infrastructure along the water's edge, and more parks and trees to provide cooling shade as summer grows hotter.

Salna says the real estate market is already changing. The most expensive new homes are now 20 miles off the beach. Within 40 years, Miami is likely to experience two or three direct hurricane hits. "Then all the old buildings will be gone, replaced by better, more water- and wind-resistant buildings," he said.

It many ways, it is a losing battle. Yet, as Obeysekera noted, the Dutch have lived below sea level for centuries.

Douglass remains an optimist. "I think we're figuring it out," he said. "We're getting better science, and also a better understanding of climate change within the political system. The incremental adaptions we're doing today are just going to continue to get bigger and better."

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