Supply Chain Resilience and the 2017 Hurricane Season

A collection of case studies about Hurricanes Harvey, Irma, and Maria and their impact on supply chain resilience

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October 2018

IRM-2018-U-018098

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This work was performed under Subcontract Agreement No. 2000009358 to the National Academies of Sciences, Engineering, and Medicine in completing Federal Government Contract No. HSHQDC-17-A-B0001/70FB7018F00000167.

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Approved by: Oct 2018

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Abstract

The 2017 Atlantic Hurricane Season (particularly Hurricanes Harvey, Irma, and Maria) was remarkable for its power and the extent of damage to communities in the path of its storms. The ability to deliver lifeline commodities (food, fuel, public water supply, medical goods) to affected communities is a core capability of the public sector "relief channel." The larger and more isolated the population, the more dependent affected communities are on private sector supply chains to deliver sufficient quantities of these commodities in a timely manner. This study consists of case studies which examine the resilience of, challenges to, and interactions among private sector supply chains and the relief channel in Texas, Florida, Puerto Rico and the US Virgin Islands. The evidence presented in these case studies reveals new insights and opportunities for intervention which may help speed the restoration of lifeline supply chains during and after disasters – to prevent catastrophe.

Acknowledgements

Benjamin Nieves, ISP, Inc. for contributions to the Hurricane Maria Case Studies

Image Credit: NASA

Preface: Engaging Reality. Avoiding Catastrophe.

The 2017 Atlantic Hurricane Season demonstrated that when extreme events impact large, densely concentrated populations, survival is dependent on the ability to quickly reestablish and, as necessary, redirect preexisting demand and supply networks. This is especially true for critical lifeline supply chains such as fuel, water, and food. The more extreme the event, the more dense the population, and the more distant the location from sources of supply – the greater the dependence on the preexisting network for human survival.

Although the scope and scale of the 2017 Hurricane Season was in many ways extraordinary, this reality had already been revealed by prior disasters, including Hurricane Katrina, the 2011 Triple Disaster in Japan, and Superstorm Sandy. As this report was finalized, Hurricanes Lane and Florence provided further evidence. And yet, Harvey, Irma, and Maria – in what they share and how they differ – offer especially helpful lessons-to-be-learned.

Federal, state, and local government supplies for water, food, pharmaceuticals, medical goods, fuel, transportation assets, back-up power generation, emergency telecommunications and more can be crucial gap-fillers. But public sector emergency relief channels are simply incapable of fully replacing the existing networks.

The only sources of supply sufficient to fulfill "dense" demand — especially over an extended period—are those sources, systems, and networks (i.e., supply chains) that were operational the day before the extreme event. Moreover, federal, state, and local actions can unintentionally suppress recovery of these crucial capacities. They can also intentionally accelerate their restoration. Intentional acceleration is highly preferred.

Harvey, Irma, and Maria can teach us how demand and supply networks behave under duress, and how public and private entities can enhance shared understanding, reduce complications and act in concert to target needs and help speed restoration, redirection, and surge. They also illuminate opportunities for strategic interventions that can alleviate bottlenecks in private demand and supply networks, providing better outcomes for disaster survivors, speeding supply chain restoration, and reducing the demand for public relief supplies.

This report consists primarily of case studies. These are evidence-based stories that can advance our understanding of how complex adaptive systems of humans, infrastructure, information, and the natural world interact. There are positive cases where informed understanding of these interactions led to creative and effective interventions. But there are also examples from 2017 where misunderstanding pushed the entire system closer to catastrophe.

In an increasingly urbanized and interconnected world, learning and applying the lessons from 2017 will be critical to enhancing the resilience of lifeline supply chains, and the dense populations they support.

Many elements of this report are based on interviews and research undertaken by CNA on behalf of the National Academies of Sciences, Engineering, and Medicine to support the Academies' own analysis of the 2017 hurricane season. This report and related recommendations are, however, distinct from the Academies' purposes. The Institute for Public Research at CNA is alone responsible for the quality, organization, and presentation of information herein. These findings represent the best opinion of CNA at the time of issue. CNA is a not-for-profit research organization that serves the public interest.

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Introduction

While the phenomena that cause natural disasters are largely outside of human control, the effects of disasters can be reduced through preparedness, mitigation, and response. The first concern is protecting human life. Even as natural disasters have increased over time in both frequency and cumulative magnitude, mortality has declined substantially. [1] The second concern is protecting property. Disasters have enormous power to cause damage to infrastructure (e.g., buildings, engineered systems). Fortunately, considerable advancements have been made in engineering and planning to build more resilient infrastructure and communities. Aside from threatening lives and causing damage, disasters also disrupt the normal order of society. Utility systems that are normally taken for granted can fail and the delivery of supplies needed for survival and the basic functioning of society (e.g., food, fuel, medicine) can be interrupted. The success or failure of lifelines to continue operations during disasters often depends on the ability of supply chains to deliver needed goods. More broadly, the effects of disasters can extend far beyond the declared disaster areas when the disaster causes damage or disruption to key nodes in national or global supply chains. Understanding these supply chains and their importance to disaster management is long overdue. The 2017 Atlantic Hurricane season provided myriad case studies in the importance of supply chains during disasters.

By many measures, the 2017 Atlantic Hurricane Season was historic, particularly for its effects on the US mainland and its territories. Three major hurricanes—Harvey, Irma, and Maria—made landfall on US coasts, and they exacted a large toll on affected communities, emergency responders, state and federal government agencies, and supply chains for key commodities. The overall toll from the 2017 hurricane season is still being tallied, but is likely record-setting. According to the National Oceanographic and Atmospheric Administration (NOAA), Harvey, Maria, and Irma will be the second-, third-, and fifth most costly US hurricanes on record. Costs from just these storms are expected to exceed to $265 billion, with $125 billion attributable to Harvey alone. The financial toll does not fully capture the difficulties in preparing for and responding to these disasters.

The storm season posed new challenges due to the scale, complexity, and timing of the storms. The trio of storms was particularly difficult to manage from a logistical standpoint. All three storms were extremely powerful, making landfall at Category 4 or above, and had other significant effects, such as Harvey's record flooding. The storms affected large areas including much of southeast Texas, the entire Florida peninsula, and the Caribbean. Forecasters had difficulty predicting the storms' strength (Harvey) and path (Irma), which complicated responses. The storms all made landfall in quick succession over the course of just three weeks and sometimes affected the same areas more than once (e.g., Irma and Maria in Puerto Rico and the US Virgin Islands).

The complexity of the storms themselves and the difficulties restoring basic utility service and the supply chains needed for day-to-day life were significant contributors to the heavy toll of these storms. The storms presented previously unseen meteorological challenges, but so will future storms. The supply chain effects caused by the storms were also unprecedented, but unlike natural meteorological phenomena (which cannot be changed), much can be done to better understand and build resiliency in supply chain.

SUPPLY CHAINS FOR LIFELINES – FUEL, FOOD, AND WATER

The Council of Supply Chain Management Professionals defines supply chains as "the material and informational interchanges in the logistical process stretching from acquisition of raw materials to delivery of finished products to the end user." [2] Federal Emergency Management Agency's (FEMA's) current strategic plan emphasizes the need to build resilience within supply chain systems so that they can be re-established as quickly as possible following a disaster. [3] Therefore, it is important to first understand the components of pre-disaster supply chains.

Under normal conditions, supply chains can become almost invisible to the end user. From the user's point of view, the finished product is ready for purchase or use at the store shelf, pharmacy counter, fuel pump, or faucet. Consumers rarely recognize the number of supply chain steps or the distances that the goods they purchase traveled.

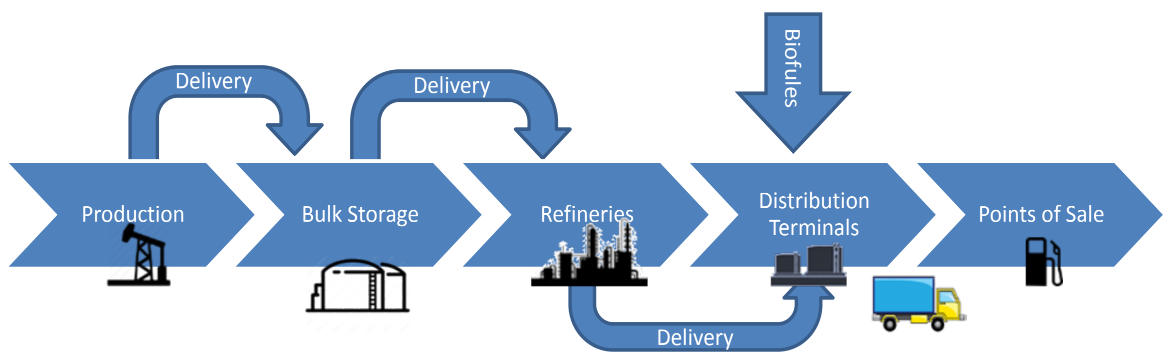
When there are disruptions to the supply chain, one way or another, the end user simply notices that they are unable to purchase or acquire the good they desire. From their perspective, it is difficult to ascertain where or why the supply chain experienced a failure. But the nature of the supply chain failure is critically important for the provider of goods or services and emergency managers trying to manage a disaster. The speed at which a supply chain disruption can be remedied is a critical piece of information for allocation of resources. And understanding how to remedy a supply chain failure requires comprehension of the structure of supply chain network, and how to repair it, or bypass the damaged component.

This section includes an overview of three critical supply chains during natural disasters: **fuel, food,** and **public water supply systems**. Each has a very particular structure and key vulnerabilities and dependencies. A basic understanding of these supply chains is crucial to understanding what happened in case studies of the supply chain failures during the 2017 Hurricane season.

Motor Fuel

Fuel is a critical commodity during disasters. Transportation of goods or people requires fuel, and often there is an increased need for fuel to operate emergency vehicles and run equipment such as generators. The supply chain for fuels can be quite diverse because there are many types of fuel and a wide variety of fuel sources (petroleum, coal, natural gas, and biofuels). This work focuses on the supply chain for motor fuels derived from petroleum, including **gasoline** and **diesel**. Motor fuels are critical to the operation of many supply chains for transportation and allow consumers to use vehicles to acquire goods. The US demand for motor fuels is large, amounting to over 375 million gallons per day for gasoline, and 144 million gallons per day for Number 2 diesel fuel. [4-5] Figure1 shows a generalized example of the fuel supply chain.

Figure 1. Supply chain for motor fuels including gasoline and diesel fuel



Source: CNA

Production is the first step in the fuel supply chain; it includes the drilling, extraction, and recovery of crude oil from wells drilled either on land or from off-shore drilling platforms. Following production, the crude oil is moved by ship, rail, or pipeline into short-term bulk storage, which is located at US ports of entry (typically for imported oil) or near refineries. [6] Due in part to recent advances in drilling technology (e.g., hydraulic fracturing), the portion of crude oil imported has fallen to 19 percent of net US consumption. [7]

At refineries, the crude oil is transformed into its various products, including gasoline and diesel fuels, using several physical and chemical separation processes that isolate different hydrocarbons based on chemical composition and density. There are 137 refineries operating in the US, totaling 18.3 million barrels a day of capacity; about half of these refineries in are located on the US Gulf Coast. [8]

Refined crude oil products like gas and diesel fuel are then transported, typically by pipeline, to petroleum product terminals (or “distribution terminals”), which are located across the US, often near transportation hubs. In some locations, particularly in Florida and on islands, the refined products are transported primarily by ship. Ethanol and other biofuels produced in the United States are shipped via rail directly to selected distribution terminals, where they are blended with the refined gasoline or diesel fuels. Branded fuel suppliers will also add proprietary fuel additives, detergents, or other chemicals before selling to their retail distributors. Distribution terminals also include the facilities to transfer fuel to tanker trucks (often called “fuel racks”), which deliver the finished product to the final points of sale. [6]

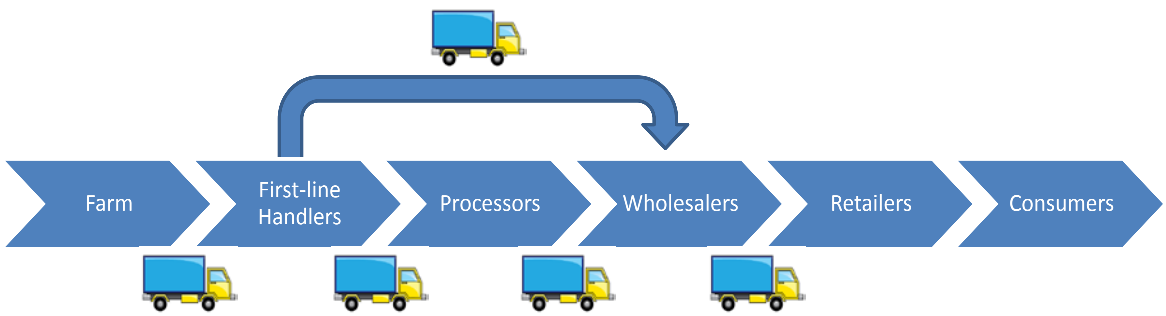
The final critical component of the fuel supply chain is the retail point of sale. Retail gas stations, public sector refueling depots, and fuel delivery companies are where end users acquire fuel for their vehicles and equipment. Retail gas stations store fuel in underground tanks that are refilled by supply trucks and use fuel pumps to allow consumers to fill their vehicles at one of several fueling positions on their property. These stations rely on regular fuel deliveries, electric power to run their pumps, and network connectivity to run their payment systems. Very few retail gas stations have backup generators, so power outages can have a significant effect on motor fuel access. There are also practical limits on tank sizes, so extreme demand surges can make retail stations highly dependent on regular truck deliveries to avoid going empty.

Overall, the motor fuel supply chain moves a large volume of product and must deal with the geographic realities of its production sites and refineries being far from certain areas with large populations. For a given area, the mode of transport of fuel (e.g., pipeline, ship) and the location and density of distribution terminals can have a large effect on whether products can get to retail gas stations. Furthermore, gas stations themselves can be vulnerable to power outages, payment system crashes, and demand surges. Understanding these facets of the supply chain in a particular area can offer a view of vulnerability when a disaster comes.

Retail Food

People need food to live, so food is a critical commodity during disasters. Figure 2 shows a generalized supply chain for food products ultimately sold to consumers. The food supply in the United States generally begins on a farm, ranch, or fishery where agricultural products are grown or raised (e.g., crops and livestock). Most agricultural products are then sold to first-line handlers, who store and prepare agricultural products (e.g., grain mills, fruit and vegetable packers, slaughterhouses).

Figure 2. Generalized supply chain for food products



Source: CNA

First-line handlers sell and transport the prepared agriculture products to both processors and wholesalers. Processors include the meat packers, bakeries, and other companies that turn raw agriculture products into packaged food products. Processors then sell the finished food products to wholesalers. Wholesalers store the food products purchased from the first-line handlers and processors, and then sell and distribute these products to retailers. The number of steps any individual food product goes through can vary widely. Fresh produce can be sold directly from first-line handlers to wholesalers, or even retailers. Packaged baked goods may incorporate ingredients from multiple first-line handlers, processors, and even wholesalers, before they are processed and packaged and sold. Imported food products can enter the supply chain at almost any stage.

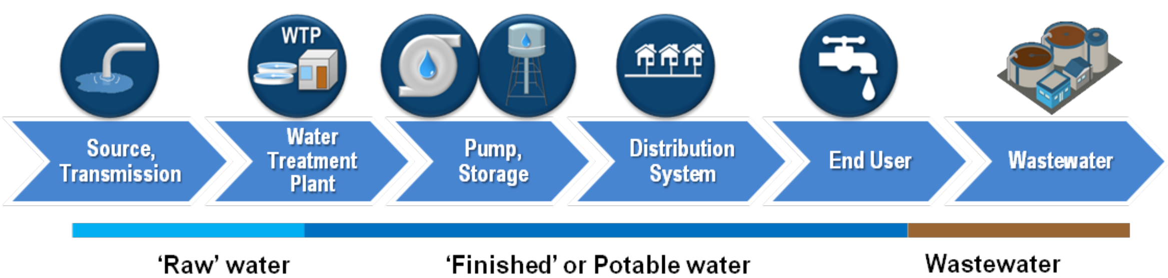
The final step in the supply chain is getting finished, packaged food products to customers. Retailers include grocery stores and other retail outlets (big-box stores), where consumers buy food products to prepare and eat at home, as well as the food service industry. [9] The retailers price, display, store, and sell the food to consumers. In many cases, the retailers also perform some additional processing (e.g., in-store meat departments, bakeries). The supermarkets and even smaller stores (convenience stores, tiendas) are the neighborhood-level link for populations to obtain food. They need power, clean water, and functioning communications to operate their stores and refrigerate, wash, and sell food.

The other major component of the food supply chain is the transportation network. Unlike water and petroleum products, most agricultural goods cannot be moved by pipeline. Instead, the food supply chain relies on transport by train and ship for long distance movement of raw and bulk agricultural commodities. After food is packaged at processors, however, the majority of transport occurs by truck. Americans purchase over 430 billion of pounds of food a year, and much of that food has to be moved over hundreds of miles, multiple times.

Public Water Supply

Water and wastewater service is critically important during disasters for basic life sustainment, sanitation, and fire suppression. By volume, public water supply is the commodity with by far the largest consumer demand. Public water systems produce an average of 39 billion gallons of water per day.[1] The magnitude of the demand and the weight and low unit value of water as a commodity has dramatic effects on the water supply chain. Unlike food, or even oil, it is impractical and not cost-effective to transport water over long distances, so most areas rely on highly localized supply sources, and move water almost exclusively by pumping it through pipelines. Wherever possible, water systems and wastewater systems take advantage of gravity to lower the cost of moving the product. Figure 3 shows the supply chain for water systems.

Figure 3. Supply chain for public water systems



Source: CNA

The supply chain for public water supply is made up of a considerable amount of infrastructure that must function together and in sequence to properly provide adequate, safe, reliable water service to customers. The water supply chain starts with a water source, which is generally surface water (reservoir, lake, or river) or groundwater. From the water source, the "raw" water is conveyed by a transmission system (generally a pipe) to a water treatment plant (WTP). The WTP removes physical, chemical, and biological contaminants to make the water safe to drink (as mandated by federal and state drinking water regulations). After treatment, the water is considered to be finished or potable water that is fit for human consumption. From the treatment plant, the finished water is pumped into storage (generally

[1] By weight, this is more than 270 times the total food supply and 140 times average gasoline demand. [4, 10-11]

elevated), which in turn releases water into the network of pipes known as the distribution system. The storage provides a reserve of water to ensure service will not be interrupted if the WTP has a breakdown or there is major leak of water from the distribution system. Elevated storage also keeps the distribution system under pressure using gravity instead of needing constant pumping. The distribution system must remain pressurized at all times to get the water to customers, prevent contaminants from entering the system during breaks, and ensure water is available for fire suppression. Finally, from the distribution system, the water enters smaller pipes called service laterals that bring the water into homes and other buildings. Then, once in the plumbing system of the building, the water can go to any desired fixture or appliance.

Water systems are generally extremely reliable, but they can be vulnerable in times of disaster. Infrastructure breakdowns at any point in the supply chain can cause failures. Sources can fail during drought, transmission pipelines can break, water treatment plants can lose power or run out of chemicals, pumps can fail or lose power, water towers can fall, distribution systems can have major water main breaks, and internal plumbing can break. Indeed, the water supply chain has several key dependencies. Notably, water systems require power to run treatment plants and pumps and ensure the system holds pressure. Losing pressure in the distribution system is the most common cause of boil water advisories. Water treatment plants also require chemicals to treat the water, laboratory supplies to test the water, and telecommunications access to run Supervisory Control and Data Acquisition (SCADA) systems and meters. Finally, water systems need replacement parts (e.g., pipes, valves), construction vehicles, and communications equipment to repair and replace distribution systems.

THE STORMS: HARVEY, IRMA AND MARIA

The 2017 Atlantic Hurricane Season was one of the most active and impactful seasons in history, headlined by three storms: Harvey, Irma, and Maria. In terms of cumulative total energy contained in the season's named storms, the 2017 season ranked seventh of all time, based on Accumulated Cyclone Energy Index. The 2017 season also stood out based on the number of named storms (17), hurricanes (10), and major hurricanes (6) at Category 3 or higher on the Saffir-Simpson scale. But the real story of the season was the *impact* that the storms caused in the United States and the Caribbean. In terms of impact, Harvey, Irma, and Maria stood above the rest.

The destructive power of the storms was not just tied to the winds that buffeted structures at initial landfall. Hurricane Harvey remained a tropical storm for days after landfall and stalled out over Houston, dropping record-setting rainfall—exceeding 51 inches in places—across southeast Texas and Louisiana. Hurricane Irma has been called the largest storm in the history of the Atlantic Basin, and had a rapidly changing forecast track. It ultimately affected nearly the entire Florida peninsula as it moved north, making multiple landfalls along the way. Puerto Rico and the US Virgin Islands were hit sequentially by both Irma and Maria, with less than two weeks to recover in between. These circumstances led to disasters than unfolded over weeks instead of days. The effects of these long-lived and complex disasters presented multiple challenges to communities trying to get back to a normal state of functionality so they could begin to recover. They also posed considerable challenges to state and federal emergency managers trying to manage the response and movement of relief supplies.

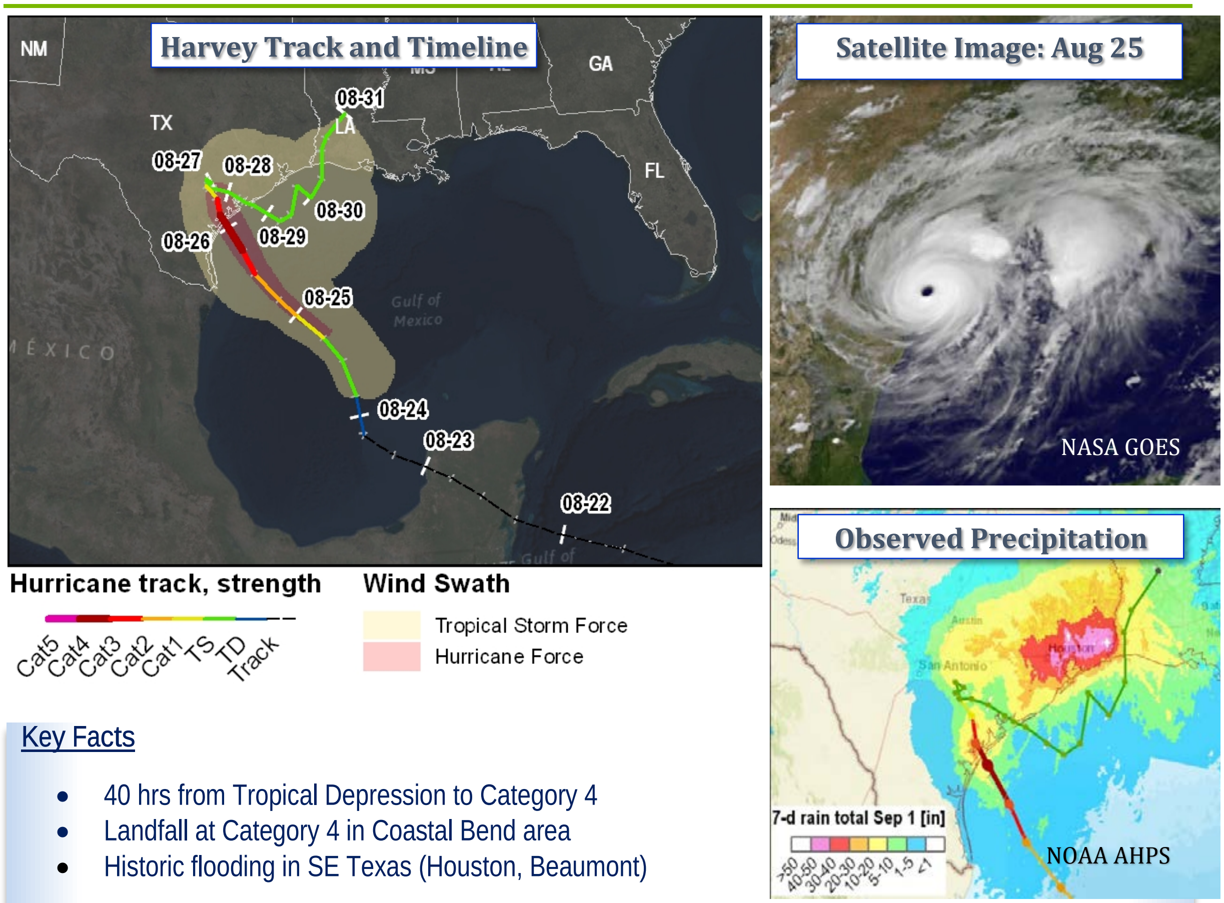
Harvey and Irma affected hundreds of thousands of structures in Texas and Florida. In Texas, over 1 million people had their water service temporarily affected, and some remained on boil water advisories for more than three weeks. Over half of Florida's population lost power after Irma. The entire island of Puerto Rico lost power after Maria, about half of the population had no water, and the process of restoring basic utility service to residents took months in some places. There is a fierce ongoing debate about the morbidity and mortality associated with the storms (particularly Maria), with deaths estimates ranging from a few hundred confirmed fatalities as a direct result of the storm to over 4,000 additional deaths in the months that followed. While statistical sampling methods account for much of the range in estimates, the success or failure of supply chains to supply basic commodities necessary for survival played a large role in determining the human and societal toll of these storms.

Hurricane Harvey

The weather system that developed into Hurricane Harvey started off the coast of Africa on August 13, 2017, and reached tropical storm status on August 17, 2017 as the ninth tropical cyclone in the 2017 Atlantic hurricane season. On August 20, the storm dropped below tropical storm strength until August 23, 2017, when it crossed the Yucatán peninsula and entered the Gulf of Campeche in the southern part of the Gulf of Mexico.

Hurricane Harvey was remarkable for its rapid intensification, durability after landfall, and capacity to deliver huge amounts of rain. In a span of just over 40 hours (from 6:00 a.m. on August 24 to 10:00 p.m. on August 25), the storm strengthened from a tropical depression to a Category 4 hurricane. Harvey made landfall just north of Rockport, Texas, late in the evening of Friday, August 25, with maximum winds reaching 152 miles per hour and storm surges in the range of five to ten feet. But the storm was not finished. For the next four days (through August 30), Harvey remained a tropical storm as it slowly[2] moved eastward back into the Gulf, making a second landfall near the Texas-Louisiana border. In that time, prodigious bands of rain set up in the greater Houston area and ultimately dropped between 27 and 33 trillion gallons of precipitation on a largely flat landscape. Maximum five-day rain totals reached over 64 inches in Nederland, Texas, exceeding the previous US record by about 12 inches. [12]

Figure 4. Hurricane Harvey track and key effects



Source: CNA, NOAA, National Hurricane Center (NHC), National Aeronautics and Space Administration (NASA)

Harvey was a slow-moving and complex disaster that acted as two separate events. The Coastal Bend area received the brunt of a powerful hurricane making landfall and dealt with violent wind and wave damage to structures and utility systems. The storm's slow movement

[2] The storm's estimated track speed was only two miles per hour.

at tropical storm strength prevented federal aid from reaching the Coastal Bend area for days. [13] Then, the large volumes of rainfall produced a second disaster: flooding. Houston, Beaumont, and many other communities in southeast Texas experienced flooding on a scale and of a type never witnessed before in the US. In many ways, it was more like a monsoon than any other type of flooding. Waters rose slowly and relentlessly, and collected in areas that were not typical for the "expected" types of riverine floods, coastal storm surges, or even flash floods previously experienced. The low-lying terrain and general pattern of development may have made this area particularly vulnerable, and also lengthened the event, as it took days for waters to drain. The lack of an evacuation, the stagnant flood waters blocking roadways, and the sheer number of structures affected—at least 350,000 [14]—complicated the disaster response.

Table 1. Hurricane Harvey timeline

Aug 17	▪ Formation in Atlantic Ocean.
Aug 22	▪ Storm crosses into Gulf of Campeche, strengthens to tropical storm.
Aug 23	▪ Maritime effects: Oil platforms begin shutdowns. Port of Corpus Christi prepares.
Aug 24	▪ Rapid strengthening from Tropical Depression to Cat. 4 hurricane over ~ 40 hours.
Aug 25	▪ Storm makes landfall in Rockport/Fulton Texas at Cat. 4 strength. ▪ Federal disaster declaration in Texas. ▪ Heavy rainfall bands set up over Houston and much of southeast Texas.
Aug 26	▪ Power outages: 258,000 people without power in Texas ▪ Coastal Bend communities of Port Aransas, Aransas Pass, Rockport completely without utilities or communications. Over 40,000 structures damaged by wind and flooding. ▪ Relief supplies from the private sector and NGOs begin arriving in Coastal Bend.
Aug 27	▪ Harvey weakens to Tropical Storm, reverses course and moves back over Gulf of Mexico. ▪ Intense rainfall moves over Houston area, starting significant flooding in rivers and bayous.
Aug 28	▪ Flooding: Releases from Addicks, Barker reservoirs; levee systems fail in Fort Bend.
Aug 29	▪ Mandatory evacuations for Fort Bend, Brazoria County due to flooding.
Aug 30	▪ Harvey moves into Louisiana. A portion of I-10 is shut down due to flooding. ▪ Flooding increases # of oil refineries shut-down to 15, 25% of US refining capacity.
Aug 31	▪ The main water pumps at Beaumont are flooded, causing water service to be shut-off. ▪ Floodwaters isolate and damage the Arkema chemical plant in Houston, resulting in fires. ▪ Power outages: 200,000 people still without power.
Sep 1	▪ Beaumont's Baptist Hospital is evacuated due to lack of water service. ▪ Beaumont's water system makes temporary repairs, institutes boil water advisory. ▪ 10 Gulf Coast oil refineries remain shut down.
Sep 9	▪ Beaumont water pump station fully back online, boil water advisory lifted.
Oct 2	▪ All boil water advisories in Harris County are lifted.

Sources: [12, 14-41]

A significant amount of fear and unusual circumstances spread the disaster's effects far beyond Texas. The area is a center of the petroleum industry and chemical manufacturing, which led to fears about fuel availability, chemical releases, and disruptions in the supply chains of many industries. [23] The concern over the possible releases or even an explosion of the Arkema chemical plant dominated news headlines for days. Rescuing stranded residents from floods required aerial and water evacuations on a scale not seen before. Virtually the entire nation's helicopter search-and-rescue resources were deployed to Texas, and managing the airspace, aviation fuel, and personnel became a huge effort.

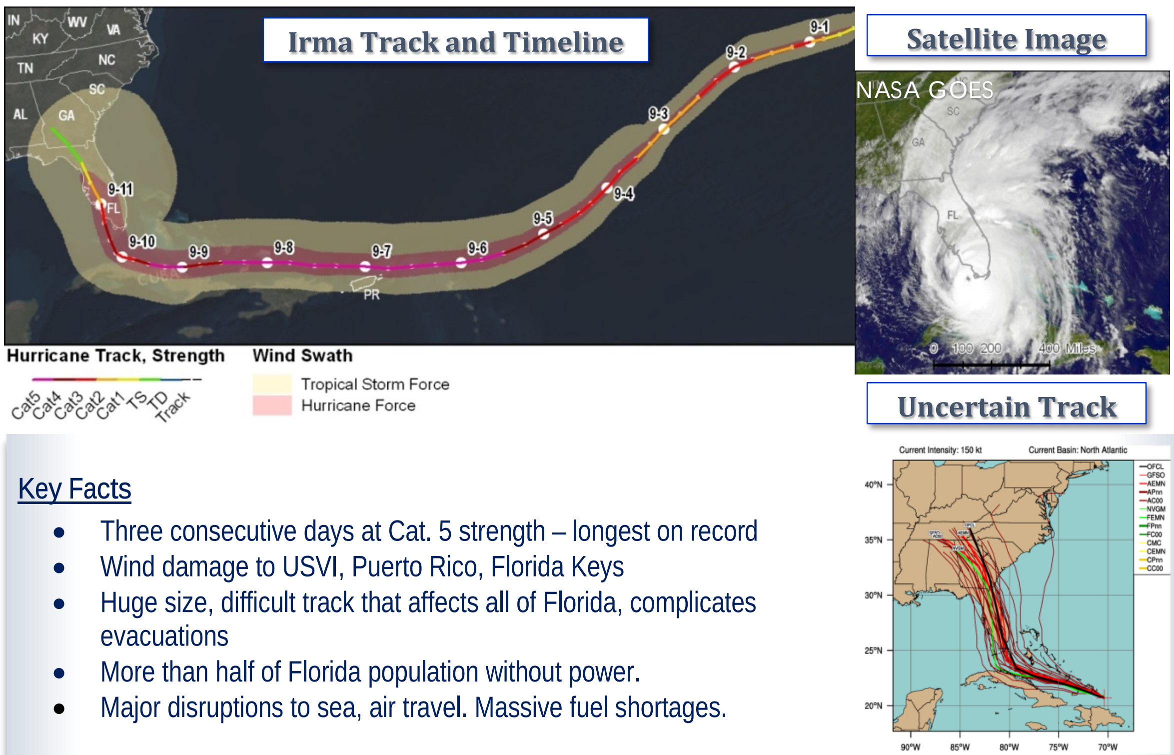
All told, the toll of the storm is estimated at more than $125 billion dollars, making it the second most costly storm in US history, after Hurricane Katrina. [21] The affected area was larger than the state of West Virginia. The response to the storm was one of the largest in history and used significant shares of all available emergency management resources. Several FEMA representatives admitted that they were fortunate that Harvey hit before the other major 2017 storms, or there may not have been enough resources to manage the scale of the disaster. A long recovery continues for southeast Texas, but even before the floodwaters had receded, the nation focused on the next storm of the season: Irma.

Hurricane Irma

As the recovery from Hurricane Harvey was in its initial stages, meteorologists and emergency managers turned their attention to a new tropical disturbance in the Atlantic. Hurricane Irma emerged off the West African coast on August 27, 2017, near the peak of hurricane season. [42] The storm would reach hurricane strength on August 31, 2017, and went on to become one of the most powerful storms in the history of the Atlantic basin. Irma was remarkable for its long duration at high intensity, large size, and wavering, difficult track that posed challenges for nearly the entire state of Florida.

As Irma approached the northern Leeward Islands on September 4 and 5, 2017, it rapidly intensified as it moved over warmer waters. With sustained wind speeds of 185 mph, Irma is the strongest hurricane ever observed in the Atlantic Ocean, and one of only five hurricanes with measured winds of 185 mph or higher in the history of the Atlantic Basin. Irma continued moving west, passing through the northeast Leeward Islands, US Virgin Islands, and just north of the islands of Puerto Rico and Hispaniola, while maintaining its Category 5 winds. While Category 5 hurricanes are rare, it is even rarer for such storms to maintain this status for such a long period of time. Irma was a Category 5 hurricane for three days. [42]

Figure 5. Hurricane Irma track and key effects



Source: CNA, NASA, NCAR

On September 6 and 7, 2017, Irma's eye passed just north of Puerto Rico, killing three people. [43-44] Puerto Rico had not seen a hurricane of Irma's magnitude since San Felipe in 1928, which killed 2,748 people in Guadeloupe, Puerto Rico, and Florida. Though Irma barely brushed the island, its strength, combined with the age and fragility of Puerto Rico's electrical system, left more than 1 million people—60 percent of Puerto Rico—without power. At least 40 percent of hospitals were functioning on generators. [24] Even before Irma hit, the head of the Puerto Rico Electric Power Authority predicted that it could take four to six months to completely re-establish service. [45] As Irma moved away, residents of Puerto Rico remained alert to flash floods as rain continued, accumulating an additional two to eight inches. [44]

Table 2. Hurricane Irma timeline

Aug 27	▪ Formation off the west coast of Africa, just west of Cape Verde Islands.
Aug 30	▪ Storm reaches Tropical Storm strength and is named Irma.
Aug 31	▪ Irma reaches Cat 1 Hurricane strength, rapidly strengthens to Cat 4.
Sep 4	▪ Irma reaches Category 4 strength. It will remain at Cat. 4 or 5 higher for five more days.
Sep 5	▪ Category 5 Hurricane Irma passes the US Virgin Islands. ▪ No power on the islands of St. Thomas (19,581 customers) and St. John (2,893).
Sep 6	▪ Irma's eye passed by just north of PR as a Category 5 hurricane. ▪ In Puerto Rico, >1 million without power (60% of island), >56,000 without potable water. ▪ At least 40% of Puerto Rico hospitals on generators.
Sep 7	▪ Evacuations ordered from high-risk areas in Florida, encouraged for vulnerable areas in FL, GA, SC. Miami-Dade county evacuation of 660,000 is largest in its history. ▪ Surge in demand for gasoline, bottled water, sandbags. Pump lines in south Florida sprawled for blocks as evacuating residents attempted to fill up. ▪ Miami-Dade County does not order evacuations for the time being, activates Emergency Operations Center, and urges residents to have three days' worth of food and water.
Sep 9	▪ Evacuation orders affect more than 6.3 million residents. Major traffic jams on interstates across Florida. 54,000 people housed at 320 shelters statewide. ▪ Irma finally makes its much anticipated turn to the northwest, into the Florida Straits. ▪ South Florida ports (Everglades, Miami) close, interrupting fuel deliveries by ship.
Sep 10	▪ Irma made landfall on Cudjoe Key, FL. The Florida Keys receive 12 inches of rain and a 10-foot storm surge. Second landfall at Marco Island at 3:35 p.m. EDT, with maximum sustained winds of 115 mph. Peak measured wind gusts of 120-142 mph. ▪ Boil water orders are issued for Collier, Lee, Broward, and Brevard counties. ▪ More than 50% of gas stations in most Florida metro areas lack fuel or power. 70%, 64%, and 60% of stations offline in Gainesville, Miami, and Tampa/St. Petersburg metro area, respectively.
Sep 11	▪ Irma downgraded to Cat. 1 as it moves over central and northern Florida. ▪ There were over 6.5 million customers without power in Florida—about 64% of the state, 930,000 in Georgia, and over 45,000 customers without power in Alabama. ▪ Irma weakens to a tropical storm in south Georgia in the afternoon, and further into a tropical depression while moving north across central Georgia in the evening.
Sep 12	▪ 54 Florida hospitals operating on backup generators, have limited internet connectivity. ▪ Irma enters Tennessee as a tropical depression. ▪ Port Everglades and most other ports re-open, resume fuel deliveries to south Florida.
Sep 13	▪ More than 50% of gas stations are open and have gas in all Florida metro areas. ▪ 3.7 million customers (36% of state) still without power.
Sep 18	▪ Between 82% and 95% of gas stations operating in major Florida metro areas.
Sep 19	▪ Power restoration in Florida reaches 99%.

Sources: [20-21, 24, 42-44, 46-65]

As Puerto Rico was pounded by Irma, evacuations were ordered from high-risk areas in Florida. Palm Beach County announced a mandatory evacuation for communities south of

Lake Okeechobee late Thursday, September 7, 2017. The mayor of Miami-Dade County activated the emergency operation center and urged residents to have three days' worth of food and water. Government officials in Florida, Georgia, and South Carolina called for people to evacuate vulnerable areas, triggering a scramble for the essentials—gasoline, water, sandbags, and so on. A shortage of gasoline and bottled water grew more acute in the wake of Hurricane Harvey, as the production of Houston oil refineries shrank and fuel and water were diverted to Texas. Lines in South Florida sprawled for blocks as evacuating residents attempted to fill up.

Early in the morning of September 10, 2017, while crossing the open waters of the Florida Straits, Irma re-intensified to Category 4 with 130 mph winds, and peak wind gusts of 142 mph. As Irma hit Florida, tropical storm force winds extended outward up to 400 miles from the center, and hurricane-force winds extended up to 80 miles. Hurricane-force wind gusts were reported along much of the east coast of Florida, from Jacksonville to Miami. Storm surge flooding also occurred well away from the storm center, including the Jacksonville area. Irma damaged ninety percent of the homes on the Florida Keys, where it first made landfall. Water main breaks led to boil water orders in several counties, including Collier, Lee, Broward, and Brevard counties. Irma knocked out electricity to 6.7 million customers, 64 percent of all accounts in the state. As Irma advanced across Florida it gave rise to severe flooding, storm surges and tornadoes and as it continued to weaken, Irma's remnants were felt in Georgia and South Carolina.

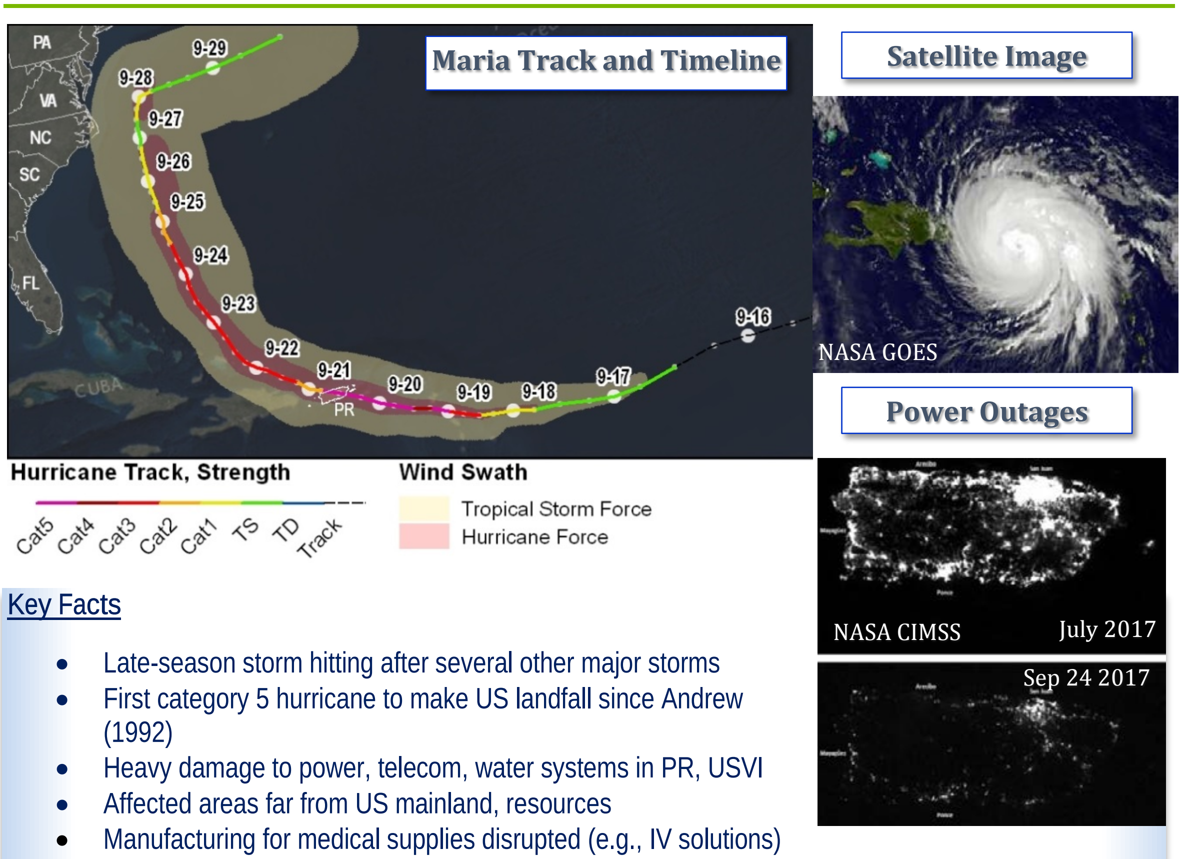
Hurricane Maria

On September 13, 2017, exactly one week after the fierce, 100 mph winds of Hurricane Irma ravaged through Puerto Rico, a trough of low pressure started to form in the Atlantic again. The storm would become Hurricane Maria. As a hurricane, Maria is notable for intensity, the short time that had passed since Irma, and the devastating effects the storm had as it made a direct hit on Puerto Rico. It is the first Atlantic hurricane to make landfall on US soil at Category 5 strength since Hurricane Andrew in 1992.

On September 17, 2017, just three days before landfall, the National Weather Service categorizes the storm as a hurricane and warns that it will likely be very dangerous for Puerto Rico and the US Virgin Islands. In the following days the storm continues to strengthen, and on September 19, a day before landfall in Puerto Rico, Hurricane Maria fluctuates between a Category 4 and Category 5 storm as it passes over the island of St. Croix in the U.S. Virgin Islands. On Puerto Rico, 60,000 to 80,000 customers still lack power from the winds of Irma that swept through two weeks prior. To gear up for landfall the next day, 2,756 people relocate to shelters.

At 2:00 AM September 20, 2017, Hurricane Maria destroyed the small US Virgin Island of St. Croix. The storm decimated the communications and power grid across the island, leaving 25,000 customers without power. Just hours later, at 6:15 a.m., Hurricane Maria made landfall just south of Yabucoa Harbor, Puerto Rico. The storm is at this point considered a Category 5 hurricane and has winds over 157 mph. Puerto Rico received more than 30 inches of rain. The storm moved across the island at 10 mph and downgraded to a Category 2-3 hurricane by 8:00 p.m. that night. The entire island—all 1,569,769 customers–was without power. The chief executive of Puerto Rico's public power utility declared that Puerto Rico's electrical infrastructure has been "destroyed." The island is covered in darkness.

Figure 6. Hurricane Maria track and key effects



Source: CNA, NASA, NHC

The next day, September 21, rain continued to inundate Puerto Rico. Power is still out over the entire island and President Donald Trump issued a state of emergency for Puerto Rico. All airports and ports remain closed. The following day, September 22, two days after Maria hit Puerto Rico, the power is still out over the island. The only facilities that have power are using generators, but those are slowly running out of fuel as well. Walmart realizes that its store generators are within two days of running out of fuel and makes a request to FEMA to provide fuel for their 48 most critical locations.

Table 3. Hurricane Maria timeline (Sep 2017 – Mar 2018)

Sep 13	▪ Formation in the Atlantic Ocean.
Sep 17	▪ Storm reaches hurricane strength and named Maria.
Sep 18	▪ Maria strengthens to Category 5 with winds at over 160 mph.
Sep 19	▪ Puerto Rican government operating 500 shelters for 4400 people and their pets. ▪ Storm reaches US Virgin Islands at Category 5 intensity.
Sep 20	▪ At 2:00 AM, hits St. Croix in USVI, knocking out power to 25,000. ▪ At 6:15 AM, landfall in Yabucoa harbor, Puerto Rico, at edge between Cat. 4 and 5. ▪ By noon, virtually all of Puerto Rico without power. ▪ Maria weakens to Category 3, then 2 as afternoon and evening pass.
Sep 21	▪ 100% of Puerto Rico without power (1.57 million people). ▪ President Trump declares state of emergency. ▪ All ports in Puerto Rico, USVI remain closed.
Sep 22	▪ San Juan airport reopens on a limited basis for military, relief flights. ▪ Walmart and other retailers on generators running out of fuel, request it from FEMA.
Sep 23	▪ San Juan port re-opens, San Juan airport and hospital connected to power. ▪ Communications infrastructure hard hit: 1,600 cell towers down. ▪ Relief supplies arrive at port, food, water, cots, and especially generators distributed. ▪ USVI water systems (St. Thomas, St. Johns) and airports (St. Croix) re-energized.
Sep 26	▪ St. Croix's Seven Season water production facility returns to normal operation. ▪ Puerto Rico power restoration slow, 11 of 69 hospitals functioning normally. ▪ 44% of Puerto Ricans without drinking water service.
Sep 27	▪ Puerto Rico estimates initial death toll at 16.
Sep 28	▪ Electricity restored to 4% of Puerto Rico. ▪ Crews work to repair communications network in PR, USVI. ▪ 10,000 shipping containers of supplies crowd PR ports. Jones Act waiver issued by DHS.
Sep 29	▪ 56 of 69 hospitals open in Puerto Rico, only one fully functional.
Oct 1-3	▪ 36% of Puerto Rico has cell service. ▪ 759 gas stations (out of 1,120) are open across Puerto Rico. ▪ 65% of big-box stores have reopened. ▪ USNS *Comfort* arrives at San Juan port.
Jan 1	▪ Potable drinking water service restored to 86% of Puerto Rico.
Mar 18	▪ 89% of Puerto Rico has electricity.

Sources: [21, 66-78]

On September 23, the main port of San Juan reopens and 1.6 million gallons of water, 23,000 cots, and dozens of generators arrive on 11 ships. Authorities were concerned that the 90-year old Guajataca Dam could fail, so the 70,000 people who live nearby were immediately evacuated as a precaution. Puerto Rico Electric Power Authority (PREPA) works with the US Department of Energy (DOE) and FEMA to distribute fuel to Puerto Rico and the US Virgin Islands. The San Juan Airport and hospital regain power.

Over the course of the next few days Puerto Rico continues without power, but FEMA and the US Department of Defense (DOD) are able to provide generators and fuel to keep the critical infrastructure online. More ports and airports open across Puerto Rico and the US Virgin Islands, allowing for supplies and generators to be brought in. On September 25, DOD provides 2,600 employees to support response efforts in the US Virgin Islands. The US Navy Ship *Comfort* arrives in San Juan on October 3 to provide additional medical support. Shipping containers containing water, food, supplies, and fuel for Puerto Rico and the US Virgin Islands begin piling up at ports and warehouses.

By January 2018, 86 percent of Puerto Rican residents have potable water. FEMA, DOE, and PREPA work to provide power across Puerto Rico and the U.S. Virgin Islands. Cell phone companies work together to get cell service back to the islands. Over the coming months, Puerto Rico's power grid is slowly repaired, but by April 2018, the grid is still not back to 100 percent and a small accident caused yet another island-wide blackout. Puerto Rico and the US Virgin Islands, with private and public help, are doing everything they can to restore services to citizens and prepare for the 2018 hurricane season.

The storm also caused supply chain effects that cascaded to the mainland and around the world. Puerto Rico is a hub of manufacturing for a range of pharmaceuticals and medical goods, with at least 40 manufacturing facilities, 13 of which produce drugs that have no other supplier. Most notably, Baxter operates three large manufacturing facilities for sterile saline solutions (i.e., IV fluids). After Maria, all of these facilities lost power, and reduced production to what can be achieved with generators. In October 2017, the Food and Drug Administration urged FEMA, Puerto Rico's governor, and PREPA to prioritize power restoration to these facilities above all others. It takes until early January 2018 to return the facilities to full operation.

CASE STUDIES TO EXPLORE THE EFFECTS OF HARVEY, IRMA AND MARIA

The 2017 Atlantic Hurricane Season caused a multitude of impacts on communities from Texas to Saint Croix. The storms' affected areas are too large, and the impacts too complex to do a comprehensive examination of the effects on supply chains. Instead, this report presents a series of focused case studies that investigate particular elements of supply chain impacts for the storms and affected areas that best illustrate the salient issues.

CNA research teams visited all of the affected areas including Texas (Houston and the Coastal Bend), Florida (Jacksonville, Orlando, and South Florida), Puerto Rico (San Juan, Comerio, and Yabucoa), and the US Virgin Islands (Saint Croix). As with all field research, CNA teams discovered unexpected findings and surprising stories, and had some preconceptions validated, and others nearly completely overturned. The case studies are organized thematically, and use the most illustrative examples to highlight the key supply chains of interest: food, fuel, and public water supply. While the focus of the case studies is generally on one storm, one affected area, and one supply chain, there is real world complexity that is a part of the story. The HIM storms caused failures in all of these supply chains, so public sector replacement supply chains, generally termed "the relief channel," are a key part of the story. Several of the case studies illustrate how existing supply chains interact with each other, and how the relief channel interacts with them. In several instances, we also included a smaller vignette case study to accompany the prime case study to illustrate similar or complementary findings for other storms or affected areas.

Of all of the supply chain effects, we observed the greatest challenges in Puerto Rico. The analysis begins with an examination of the complex situation in Puerto Rico after Maria had passed. Case Study 1, "Retail Resilience in Puerto Rico" examines the surprising resilience of the retail sector supplying food and fuel. As a companion piece, Case Study 2, "Static on the Relief Channel," investigates how food deliveries from the federal government created both real and perceived impacts on the retail food sector in Puerto Rico, and caused spillover effects into other supply chains. Case Study 3, "Resupplying Metro Miami", shifts the focus to Florida and Hurricane Irma, specifically to look at how fuel availability affected the transportation of food and other goods over time (before, during, and after the hurricane's direct effect on the state). In Texas, despite being a major petroleum hub, the most significant supply chain effects concerned public water suppliers. Case Study 4, "Harvey Turns On (and Then Turns Off) the Tap", provides an in-depth look at how Hurricane Harvey affected water suppliers, and what hindered and helped their ability to recover.

While the first three case studies covered individual storms and specific supply chains, the next case study take a more general view, and uses shorter mini-cases to examine supply chain issues grouped around similar themes. Case Study 5, "Constraints in Optimized Networks", takes a focused look on bottlenecks in supply chains in a variety of forms, and uses four examples from Florida and Puerto Rico.

Table 4 summarizes the case studies with respect to their subject, the storm, the affected area, and supply chains of concern. The colors presented at the left of the table serve as a quick reference to the relevant pages in the assembled report.

Table 4. Case studies presented in this report

#	Case Study Subject		Storm	Area	Supply Chains
1	Retail Resilience		Maria	Puerto Rico	Food, Fuel
2	Static on the Relief Channel		Maria	Puerto Rico	Food
3	Resupplying Metro Miami		Irma	Florida	Fuel, Food
4	Water Networks after Harvey		Harvey	Texas	Water
	Box: Irma and the Florida Keys		Irma	Florida Keys	Water
5	Constraints in Optimized Networks	Retail Cross-dock	Irma	Florida	Food
		Fuel Networks	Irma	Florida	Fuel
		Ports	Irma, Maria	Puerto Rico	General
		IV Manufacturing	Irma, Maria	Puerto Rico	Medical

Case Study 1: Retail Resilience in Puerto Rico

Hurricane Maria made landfall just south of Yabucoa, Puerto Rico, at dawn on Wednesday, September 20, 2017. It was a strong Category 4 storm with winds exceeding 150 miles per hour. With Thursday's dawn Jose Perales, manager of Ralph's Food Warehouse, made it through flood and debris to check the store. His typically 20-minute drive took over 40. In several places the store's roof was gone. He guessed that 30 percent of his inventory had been ruined by rain. But the diesel generators had kicked in as intended.

By early Wednesday afternoon, the Mi Gente grocery, 2,000 feet high in the mountains of Naranjito and Comerio, south of San Juan, was reeling from hot wind and rain. The owner, Rene Lopez, had locked up on Tuesday as word spread that landslides had already closed Route 167 along the Rio de la Plata into San Juan. Sometime after he left, the wireless tower connecting the ATM and credit card machine to the outside world fell hard. Eventually the store went dark. It would not be reconnected to the grid for another six months. The store stayed locked through that first day and night.

Both Ralph's and Mi Gente—and many more—are supplied from the state-of-the-art warehouse and distribution center[3] operated by B. Fernandez & Hnos. in Bayamon, just west of the Port of San Juan.[4] On Tuesday, they consolidated their trucks, trailers, and containers in the freight yard. The same steel phalanx was organized at Puerto Rico Supplies Group immediately to the north, Jose Santiago Food Service Distributors immediately to the south, and at V. Suarez just across Route 5. The Goya processing and distribution center was just a few hundred feet south across Route 28. As he supervised preparations, Angel Vasquez, President of B. Fernandez, wondered how many people could be fed with the food being held just by his company and those of his neighbors (and competitors).

Less than 500 feet behind the B. Fernandez freight yard is the Puma fuel terminal and racks. Tuesday morning, scores of tankers had refueled by moving smoothly through 12 bays. But

[3] In contemporary supply chains, there is typically a distinction between a warehouse and a distribution center, but at B. Fernandez, the two functions have arguably been hybridized.

[4] See the Case Study 1 Appendix for an overview map of all of the referenced facilities.

Wednesday morning was as quiet as Christmas. Trucks and truckers bunkered down at home. More than two million barrels of gasoline and diesel were ready,[5] but the racks were closed until Maria finished her whirlwind visit. Wednesday morning, Maria made an especially violent call on the fuel terminal and racks at Yabucoa, disrupting the source for roughly 20 percent of Puerto Rico's fuel until October 3, 2017. [79] Wednesday afternoon, Rodrigo Zavala, Puma's CEO Americas, looked out his home windows at the destruction descending around him. His house was shaking. Rodrigo worried about Puma's glass-encased headquarters overlooking the terminal. Could even the hurricane glass resist this?

Far away in Washington, DC, the night watch gave way to the day watch at the FEMA National Response Coordination Center (NRCC). The NRCC had stood up as Hurricane Harvey popped up in the Western Gulf of Mexico on August 25, 2017. It continued operations as Hurricane Irma hit, Hurricane Jose had threatened, and now as the island of Puerto Rico was swallowed whole into Maria's maw. Jeff Dorko, FEMA's Assistant Administrator for Logistics arrived early to catch the departing chief of the night watch. "What are you seeing?" Jeff asked. His colleague responded, "Mostly the whole place go dark. The grid is going down hard."

Along the north shore of Hispaniola, three ocean-going barges four days out of Jacksonville anchored as close to land as they could. This is where they would ride out the powerful waves extending for hundreds of miles in front of the hurricane's forward movement. The forecast called for Maria to turn northwest; if so, the cargo of "FEMA freight" would be safe and ready for unloading at San Juan. On board were tons of water, shelf-stable food, blue tarps, and more. The same complement of supplies had been delivered by fleets of trucks to survivors of hurricanes in Texas and Florida. What a month.

GRID UNRELIABILITY AND SUPPLY CHAIN RESILIENCE

Contemporary supply chains are dependent on—and usually interdependent with—the electrical grid, telecommunications systems, road and fuel networks, and other sometimes-surprising aspects of push and pull factors. Grocers, for example, depend on power systems for lighting, payment processing, climate control, and refrigeration. The Puerto Rican electrical grid is not reliable. Since 2014, Puerto Rican electricity consumers have experienced service interruptions at a rate of four-to-five times the average for the US mainland. [80] A November 2016 "Experts Report" stated that the Puerto Rican electric utility's "generation and transmission facilities are in a state of crisis." [80]

[5] Before the storm, Puerto Rico usually consumed about 155,000 barrels of fuel per day, according to EIA.

Grocery stores, food processing, and many other elements of consumer demand and supply require reliable water service, but the water sector itself needs power to operate. Over 95 percent of Puerto Ricans are public water customers. The network consists of over 20,000 miles of pipe and 114 filtration plants. In some areas, the water system benefits from large surface reservoirs and gravity feeds. But the island's mountainous interior also features long pipelines that climb over 2,000 feet from water treatment facilities. Water is heavy. Significant power is needed to pump volume up and sometimes over mountains. Most mainlines include back-up electrical generation. Prior to Hurricane Maria, 1,348 emergency generating units (EGUs) were deployed across the system. Another 269 EGUs were deployed during the long-term grid outage. Expenses associated with EGU deployment and operations equaled more than 60 percent of total 2017 water authority expenses. [81]

Shippers, wholesalers, and retailers rely on communications systems for logistics management, order fulfillment, inventory management, and processing payments. Puerto Rico has been an early adopter of wireless technologies for personal communication, Electric Data Transfer and business-to-business transactions. Since 2008, the number of wireless subscribers in Puerto Rico has grown from 2.54 million to 3.23 million (out of a current population of 3.4 million). More than 50 percent of internet traffic in Puerto Rico is generated by mobile devices, compared to a US average that has recently ranged from 32 to 42 percent. [82] This widespread adoption of mobile internet has facilitated significant business-to-business digital processing. Puma, for example, now facilitates bulk fuel purchases through an entirely digital process.

Most telecommunications infrastructure in Puerto Rico is engineered to persist with temporary loss of the electrical grid. Following Hurricane Irma (two weeks prior to Maria) approximately 63 percent of Puerto Ricans experienced several days without electricity. [48] But the Federal Communications Commission reports that in the area of Puerto Rico hardest hit by Irma, 45 percent of cell towers continued to operate and in less than four days, the outage had been reduced to 26.9 percent of cell sites in the impact zone. [83] Since the advent of mobile communications, quick recovery has been the common experience. This was not the case in the aftermath of Hurricane Maria.

In contemporary supply chains, demand pulls supply. Since the 1980s, pull signals have become mostly telecommunications signals. In the last 7 to 10 years, the signals have increasingly become bits and bytes flowing across the internet. In calendar year 2016, Puerto Rico recorded $37.4 billion in total retail sales. Approximately 20 percent of retail sales are transacted using credit, debit, or electronic benefit transfers. In 2016, roughly $5.6 billion was expended at food stores. [84] Approximately 40 percent of all food purchases are made with the Department of the Family's Electronic Benefit Transfer (EBT) card, also known as the PAN card. [85] There are more than 35,000 point-of-sale terminals in Puerto Rico. Even most cash transactions eventually depend on telecoms (which depend on electricity). In 2015, there were 1,064 ATMs in Puerto Rico. [86]

Responding to consumer pull, the commercial sector exchanges its own business-to-business digital signals. For example, when a fuel distributor places a digital order with a fuel supplier, it is digitally scheduled to receive fuel and digitally pays for fuel. This seamless processing keeps the flow of trucks moving smoothly through the racks and pushes supply toward demand.

Over the years, as the Puerto Rican grid incrementally deteriorated, key elements of demand and supply networks attempted to mitigate their dependence on the grid. Many residential and commercial customers invested in back-up power generation. Residential back-up typically takes the form of 250-watt gasoline-fueled generators sufficient for a few essential services, especially home refrigeration. Much larger diesel-powered generators are utilized by grocery stores, fuel retailers, and other commercial operations. None of these back-up systems are designed to operate continuously over many weeks. Many of the largest diesel generators require regular maintenance every 500 hours or so. [49] Continuous operation also requires regular refueling. Without continuous fuel and appropriate maintenance, generators fail and require specialized expertise to repair or restart.

Puerto Ricans have experienced and expect annual hurricanes. They have grown accustomed to occasional loss of the grid. When the Category 3 Hurricane Georges hit in1998, less than 20 percent of Puerto Ricans utilized mobile phones. Today it is over 88 percent and business-to-business communications has followed.

As Hurricane Maria toppled power transmission towers crossing south to north through the mountains of Puerto Rico, a wide web of dependencies fell with them.

FIRST WEEK AFTER LANDFALL: FUEL, TRANSPORT, AND CASH COMPLICATIONS

On Saturday, September 23, 2017, Jose Perales stood inside his hot, dim, but once-again clean and dry store. The roof was patched, the spoiled stock removed, and three generators were humming (well, one was growling). Most employees were back at work. The line of customers waiting in the parking lot extended the length of a football field. Local police stood by, but the crowd was patient. The assistant manager unlocked the doors at about 7:30 a.m. Customers purchased water and canned meat, and they especially wanted Coca-Cola. The demand for Coca-Cola surged and stayed high for weeks after the storm. “Something sweet for a sour time,” Jose decided. The Coca-Cola supply truck was the first vendor to show up after the storm.

Other suppliers—including B. Fernandez—began delivering to Yabucoa on Monday and Tuesday. “We were prepared to load trucks on Sunday, but most of our customers could not receive until Tuesday and several were not able to receive until Thursday,” Angel Vazquez explained. On Monday, Ralph’s Food Warehouse headquarters in Las Piedras sent one of their procurement staff to Caguas, where they had heard a cell signal was available. She was able to tell B. Fernandez and other wholesalers that the Ralph’s in Yabucoa was ready to receive. In Puerto Rico, most grocery products are Direct Store Deliveries (DSD) from wholesalers. Most of the wholesalers are in the San Juan metro area almost 50 miles from Yabucoa.

“As a rule, the smaller the store, the quicker the recovery,” Angel Vazquez (B. Fernandez) observes. “Our largest customers have the most sophisticated systems and were, as a result, the most disrupted by long-term outage of the grid. Our smallest customers, up in the mountains—even though they had been hit really hard—were the first to open. They also immediately adapted their orders. Less beer. Lots of canned meat. We sold more Spanish canned fish than ever before.”

As a year-round cost-containment procedure, B. Fernandez purchases fuel for its independent truckers from the nearby Puma fuel rack. It is dispersed at the warehouse from its own 10,000-gallon tank and sold to the delivery fleet at cost. As a result, the wholesaler’s trucking partners did not experience any fuel shortages during the post-storm period. Many others did experience significant fuel shortages.

The island-wide failure of the electrical grid resulted in simultaneous population-wide initiation of back-up generators. Luis Sanchez, President of the Puerto Rican Licensed Electricians Association, estimates there were more than 100,000 residential electrical “plants” in place pre-Maria. [87]

Most of these are smaller, under-5,000-watt generators with fuel tanks of less than 10 gallons designed to run for 10 to 12 hours with enough power to operate a refrigerator, house lights, small appliances and recharge cell phones. Even many larger commercial EGUs have fuel reservoirs only sufficient for three-quarters of one day.

“Most generator back-ups were installed to mitigate short-term spot outages. Very few were consciously trying for long-term grid replacement.” Rodrigo Zavala, CEO of Puma Americas, (and a resident of Puerto Rico) explained, “There was plenty of fuel, but there was not sufficient fuel storage at the point-of-consumption. Almost everyone needed daily refueling. Suddenly refueling one million additional households once or even twice a day is not feasible.”

In recent years, Puerto Rico has consumed roughly 2.5 million gallons of gasoline per day [88]. In the immediate aftermath of Maria, demand jumped more than 40 percent. Even as late as December, when more than 60 percent of grid customers had been restored, average daily gasoline consumption was more than 25 percent above normal. [89]

The increase in fuel demand was essentially simultaneous across the entire island. By Monday, September 25, 2017, a few more than 100 (of 1,100) gas stations were open. Nearly 10 percent of available National Guard troops were assigned to several San Juan metro area stations to encourage calm and public order. Observers counted 91 fuel tankers making deliveries on Monday, usually with security escorts. [90] Two of five major fuel racks were closed. The other three were operating at less than prior capacity, due to the loss of digital processing capabilities and a reduced number of tanker trucks arriving to be loaded.

Attempting to extend available retail supplies and treat customers fairly, many gas station operators rationed purchases to $10 or $15 per person. While this may well have defused social tension in the long lines, it also made the lines longer, as many consumers would empty their jerry cans and quickly return to the line, increasing and accelerating expression of demand.

On September 29, 2017, the Secretary of Consumer Affairs (DACO) made retail rationing illegal. "Now there is even more need for gasoline for power plants. The most common hold very little gasoline, to operate eight or 10 hours, and people have to replenish almost daily," Secretary Pierluisi explained. [91] Removing arbitrary limits on consumer purchases reduced overall consumer cycling. Curfew was also extended by two hours, giving the system more time to meet demand, and by the end of the first week almost 700 gasoline stations had opened. On September 28, the governor exempted fuel distributors from the curfew, allowing nighttime deliveries. By the beginning of the second week after landfall, the lines at gas stations were much less dramatic. The increasing range of consumer options and operating hours allowed the fuel distribution system to achieve much more balanced, sustainable, and assured through-put. By October 3, 2017, the Puerto Rican fuel distribution system had reclaimed preexisting capacity and was distributing roughly 30 percent more than it was before the storm. [79]

According to the US Census Bureau, there are about 19,000 people in Puerto Rico involved in moving material of all sorts. [92] There are about 13,000 truck drivers. [93] According to the US Bureau of Labor Statistics, there are roughly 8,000 drivers of heavy trucks and 5,000 drivers of light trucks and delivery vans. [94] All were in some ways victims or survivors of Hurricane Maria. Most took two or three days to do immediate repairs and attend to personal priorities. By Monday, September 25, 2017, many truckers were prepared to return to work, but there were serious impediments.

Many roads remained impassable. In urban areas, even where roads were clear, traffic lights no longer functioned. Communications were minimal or non-existent, so what was open, what was closed, and the condition between here and there was very uncertain. Many independent truckers surveyed the long lines at the small number of operating gas stations, worried about running out of gas, and often decided they needed to know more before restarting their regular routes. There was plenty to do at home.

Not much moved—not nearly enough moved—for the first five days after landfall. The regular flow of food, fuel, and much more was seriously disrupted by lack of electricity, lack of communication, debris in the road, bridges out, complications with fuel distribution and the myriad challenges of immediate recovery. But by the end of the first week, each of these impediments was gradually overcome. On Thursday, September 28, 2017, B. Fernandez and its trucking partners moved seven times the ordinary daily volume. It was the beginning of a surge that continued through mid-December and beyond.

By the close of the first week after landfall, the pre-existing supply chain demonstrated considerable resilience under duress. But some places were entirely cut off. The Mi Gente grocery store, owned by Rene Lopez, stands at a rural crossroads between mountainous Comerio and Naranjito. It is usually less than 20 miles to the wholesalers in Bayamon. Looking northeast with binoculars from nearby high ridges, you can find the warehouses. But for the first few weeks following Maria's rain and wind, those 20 miles seemed to be 200 or more. Roads into San Juan were blocked by multiple landslides and wash-outs until September 28, 2017 (eight days after landfall).

Friday is usually the big day for food deliveries. Trucks could not get through on September 22, 2017. But customers did. They mostly purchased canned goods and ice. The store limited each family to three cans and two bags of ice. Still, by the end of Friday the ice was gone. The store had frozen meat to sell until Thursday, September 28, 2017, when the generators ran out of diesel. Rene was unable to refuel his generator for two days. Over $30,000 worth of meat and other perishables was lost. In late September, he did not imagine depending on his generator for six more months.

With fuel, Rene's diesel generator supplied power. The cash register kept track of sales. But for the first month, only cash could be used. The ATM and the point-of-sale terminal depend on a rooftop tower to exchange EBT and other digital signals. The antenna had blown down in the storm. After a few days it was erected again, but the relay tower in Barranquitas did not respond. On Friday, September 29, Rene was able to drive into Bayamon to place orders and bring back cases of essential products in his own truck. He continued this process of personal pick-up and self-delivery for over two weeks.

Most people paid cash. But over 60 percent of the Mi Gente's customers usually pay for groceries with their PAN card[6]. Many of these customers quickly ran out of cash. In some cases, Rene Lopez resurrected the practice of "fiao" or "Don Fiao," [95] the granting of temporary credit. During the first month, regular customers without cash made small purchases using store-credit to be repaid when PAN cards could be accepted again, or other resources were available.

At 8:00 a.m. on Saturday September 23, 2017, the US Coast Guard reopened the Port of San Juan. Shortly after 10:00 a.m. one of the barges that had anchored off Hispaniola began to unload. Over the next six days, over 700 loads of FEMA freight—including more than 1.3 million shelf-stable meals and huge quantities of bottled water—arrived. The *El Rey*, another vessel, would arrive on October 2, 2017 with 100 fuel trucks loaded with 275,000 gallons of diesel and 75,000 gallons of gasoline. As FEMA relief supplies arrived at port, they were quickly trucked to 11 staging areas around the island where they supplemented emergency supplies already stored in Puerto Rico. [96]

In Washington, Jeff Dorko and his FEMA Logistics colleagues worked to enable a minimum of 1.5 million meals per day in Puerto Rico. They aimed to feed, water, and provide essential life-saving services to 20 percent of the population. Some were arguing that even this was not enough. On September 25, 2017, the Puerto Rico Department of Housing and Governor's office requested six million meals per day for the following three weeks, with gradual reductions over the following nine weeks. [97] This request anticipated 60 percent of the population would not be supported by preexisting supply chains. In any case, FEMA was pushing every calorie and ounce of water it could procure toward the Port of Jacksonville and any other place there was a vessel sailing or an airframe flying into Puerto Rico.

No one in Washington knew about the Ralph's store opening in Yabucoa or the Mi Gente store in the mountains. Had anyone at FEMA Headquarters ever heard about B. Fernandez, a 125-year-old fixture of the Puerto Rican food chain? At the Joint Field Office (JFO) opened at the San Juan Convention Center, local emergency management personnel recognized B. Fernandez and even knew its warehouse location. But they did not know it was making food deliveries at seven times the normal rate eight days after landfall. The JFO was more likely to know that Puerto Rico Supplies, next door to B. Fernandez, had lost its warehouse roof. They were more likely to know which stores could not open because they had no diesel. The JFO was focused on hospitals with no fuel for back up generation. Bad news travels fast. Good news tends to be much more discreet, especially in a crisis.

[6] The analogous mainland program is SNAP (Supplemental Nutrition Assistance Program) AKA as food stamps.

ONE MONTH AFTER LANDFALL: NETWORK RECOVERY, REDUNDANCIES, AND INTERVENTIONS

"*Sistema! Sistema! Sistema!*" Ana shouted. Carlos and Rene came running. Every day since they had repaired their antenna the Mi Gente grocery had checked to see if they had signal. On Wednesday morning, October 18, 2017, there was a return pulse from Barranquitas. Ana danced behind her check-out counter. Carlos laughed. Rene's eyes teared up. Finally, customers could use their bank cards and PAN cards again. The ATM would recognize them again. Many were glad to get reacquainted. Well before the end of the day, the ATM was out of cash.

There was still no ice. No more fresh or frozen meat. No fresh vegetables. But the bread trucks were delivering again. The B. Fernandez truck brought cases of Spam, canned chicken, and previously unknown canned products from Mexico and Spain. Deliveries were not yet predictable. There were new drivers behind the wheels of the trucks. They told Ana that several of the usual truckers had taken higher-paying routes delivering relief supplies between the docks and government staging areas. Some were even working as translators and navigators for electrical repair crews from the mainland.

The Mi Gente store could now exchange electronic data, but Rene was still driving several miles to use his cell phone to place orders. One month after the storm, 16 of 18 cell towers in Comerio were non-operational. In Bayamon and San Juan, about half of the cell towers were back online. Island-wide, about 33 percent of cell sites had come back. This provided mobile connections for about 61 percent of the population. [98]

Thirty days after landfall, roughly 20 percent of Puerto Ricans were reconnected to what was being called the grid. But the south-to-north transmission system was still in tatters, several substations were barely operational, and for many parts of San Juan the source of electricity was not any of the long-time public power plants but temporary, recently installed mega-generators.

Those reconnected did *not* include Ralph's Food Warehouse in Yabucoa, the Mi Gente in the mountains, B. Fernandez in Bayamon, or even the Puma Terminal next door.

Connected to the grid or not, by mid-October, all the major fuel terminals were operating at or well above prior output: Puma and Total in the San Juan metro area, Buckeye in Yabucoa, Corco, and Peerless in Tallaboa. Eighty percent of gas stations had reopened. There were still some lines. Consumers were still sensitive to keeping their gas tanks close to full. The private generator set still had to be refilled daily. But in most places, most of the time, supply and demand had found a new equilibrium.

"Fuel demand spiked and remained at far above normal into November. We—meaning the entire fuel sector—always had sufficient fuel on the island. But our distribution capacity was not sufficient for the new demand. Even worse, in the first several days, some of our competitors could not dispense fuel. We had an enormous challenge creating a paper-based replacement for our digital queuing and purchasing process. So system throughput was significantly constrained just when demand was loudest," is how Rodrigo Zavala summarized the first two to three weeks.

The fuel supply chain in place before Maria focused on fulfilling demand for electric generation by the Puerto Rico Electric Power Authority (PREPA) and for surface transportation. These two requirements accounted for roughly 90 percent of all fuel products consumed in Puerto Rico. [88] In the aftermath of the hurricane, demand by PREPA precipitously declined while demand by thousands of residential and commercial back-up generators soared.[7] The equipment, personnel, and schedule required to service the prior source of demand was not identical to that required by the new source of demand. Prior demand was a predictable pull by a single source. New demand was an unprecedented level of need being expressed at hundreds of local gasoline retailers, even as those same retail locations continued to supply the fuel needed for surface transportation. Two previously separate "pulls" were now combined. The lack of sufficient storage by the private generator set produced rapidly cycling demand that drained retail stocks much more quickly than the surface transportation pull. This required distribution assets to refill the retail locations much more often, perhaps three times as often, than previously. Refilling capacity is especially limited by the number and volume of fuel delivery trucks, number of drivers, and number of fuel racks (and truck bays) available.

In the first several days after the hurricane at least three of five major racks were not operating. Driving time for fuel trucks was limited because it is unwise to operate large vehicles full of fuel after sunset where streetlights are dead and roads have been seriously damaged. These space and time constraints were further narrowed by the loss of digital processing at the fuel racks, which required much more time to serve each truck.

"But by one month in," Zavala says, "there was already excess capacity on the island, both in terms of supply and distribution. On September 21 (the first day after landfall) the system probably needed 100 more fuel distribution trucks to meet the surge requirement. Thirty

[7] PREPA uses fuel oil, diesel and natural gas for generation. The private generator set is mostly gasoline and diesel based. As a result, some of the assets used to fulfill demand for PREPA could not be immediately converted to new demand.

days later, 250 to 300 trucks had been delivered. Impressive response. But over-supply creates its own difficulties and distortions." In early October, the Public Service Commission of Puerto Rico offered a five-hour course that awarded over 2,000 provisional certificates to transport fuel. [99] But according to Rodrigo Zavala, 200 would have been entirely sufficient. That ten times as many earned the temporary certificate highlights the wild gyrations that several parts of the demand and supply network experienced.

To ensure movement of relief supplies, FEMA contractors were ready to pay premium prices to truckers. This expedited the movement of the relief supply chain even as it complicated, and arguably slightly suppressed, the ability of the grocery and construction supply chains to surge. Even other public-sector supply chains were affected. Carlos Contreras Aponte, Secretary of the Highway and Transportation Authority complained to Reuters that his agency was facing serious limitations repairing the road network because "our truck drivers, many have been hired by other companies." Reviewing his repair requirements, the President of the Water Authority said, "We'll never have enough trucks." [100]

Having lost some of their trucks and truck drivers while trying to respond to demand well above normal, many beverage, grocery, and other wholesalers could not keep shelves fully stocked. Seeing empty shelves reinforced the consumer's sense of uncertainty and increased demand. Seeing empty shelves where there should have been water was especially disconcerting. [101]

By October 20, one month after landfall, more than 70 percent of Puerto Ricans had access to public water. [102] But water quality was widely questioned. Even before the hurricane, many Puerto Ricans preferred to drink bottled water. Coca-Cola, PepsiCo, and Cristalia all maintain large capacity bottling plants in Puerto Rico. Before the storm, these and other on-island operations had supplied nearly all local demand with DSD.

During the first month after landfall, while many of these water companies doubled production, they found that demand had more than doubled [103]. Some of this demand came courtesy of FEMA contracts. "In retrospect we should have stayed away from local bottled-water producers and focused on bulk water and bringing in supplies from the mainland," one FEMA official commented. "While the on-island contract made some financial and logistical sense, it screwed up local supply and demand. We basically took product out of the commercial channel, moved it into the relief channel, and probably ended up distributing it less widely—and at a much greater overall expense—than if we had sourced elsewhere for emergency needs and let the preexisting channel respond to retail demand. We contributed to empty store shelves and this had predictable effects on consumer behavior."

Faced with scarcity and uncertainty, consumers hoard [101]. Automobile drivers fill up their tanks when they are already three-quarters full. Grocery shoppers purchase six cans of Spam because they are not sure of future supplies. Hospitals nervous about running out of diesel call three commercial providers, their local mayor, and the governor's office, trying to increase their odds that one supplier will show up in time. "In effect, many hospitals were sending pull-signals into the supply chain that multiplied actual need by three or four or more. No distribution system will ever catch-up with that kind of false signaling," Zavala notes. A 2018 study of Puerto Rican consumer behavior found that for 12 weeks after the hurricane, the frequency of grocery shopping soared from an average of slightly more than one store visit per week to 11 shopping trips per week [104]. Part of this is explained by the loss of at-home refrigeration and cooking capability. But it also reflects a fear of missing out in a time of profound uncertainty.

"Given the cost of repairs, the extra expense of diesel, and all the extra hours worked, the store probably lost money in October," the manager of Ralph's Food Warehouse in Yabucoa says quietly more than six months later. "I really don't recall. That was not my priority. I was just trying to keep things running. We've done fine since. There has been huge customer demand from the very beginning. Our customers are happy to come here."

Unlike the Mi Gente in the mountains, the roads connecting Yabucoa to San Juan were quickly reopened. The store is less than one mile from the intersection with the four-lane Route 53 toll-road. Regular deliveries resumed the week after the hurricane. Ice and meat were the most difficult to get. But in early October, the Yabucoa store was the first of 12 Ralph's stores to receive big deliveries of both high-demand products. "I hugged my assistant manager when he told me about the meat," Jose Perales said. "Ralph, the owner, did not believe me at first."

"Toward the end of the second week, maybe Thursday, our fuel delivery did not arrive as scheduled," Mr. Perales remembers. "I was worried we would lose all the progress we had made. But the mayor, he gave us some diesel from the truck FEMA had sent to Yabucoa. So, we made it through okay."

The day after the emergency fuel delivery, a team from Osnet in Humacao came to install a new piece of technology that allowed the Yabucoa store to once again process bank cards and PAN cards. "So, in just one day I went from fearing everything was falling apart to being very happy. Using their cards again allowed customers to get what they needed."

Only two weeks after landfall, the Ralph's in Yabucoa restored the power of plastic sooner than many other grocery outlets. The Mi Gente was more typical in not being able to conduct electronic data transfers before the fourth week. But in any case, by October 24, 2017, 95 percent of PAN beneficiaries were purchasing food with their EBT benefits. [105] Four thousand new families had also applied to participate in PAN since landfall. [106]

PAN beneficiaries have incomes that fall below the federal poverty threshold. Over 65 percent of PAN beneficiaries have zero monthly income. Another 31 percent have monthly incomes that are less than half the federal poverty threshold. Food costs in Puerto Rico have been estimated at 9 percent higher than the US mainland average. In 2015, the monthly benefit ranged from $112 for a single-person household to a maximum of $776 for a household of eight. [107]

Jesse Levin is a founder of Tactivate and an "expeditionary entrepreneur" especially committed to effective proactive disaster response. He arrived in Puerto Rico on September 26, 2017. "My task was to get out into the field and listen to understand the systemic challenges hindering effective recovery and look for a solution that would support local capacity to solve the discovered challenge." He initially headed for the mountainous interior and eventually spent extended time in both Oracorvis and Barranquitas. "While most of the resources in the response were directed at remedying the effects of Maria, we were looking for the system failures leading to causation. In Puerto Rico it happened to be the EBT food accessibility challenge." Jesse recognized that long before Maria, more than 40 percent of the population depended on their PAN card to eat. The grocery retail network was coming back fast and seemed to have access to product. The only thing standing between that food and hungry people was loss of electronic data transfer connections.

Jesse was acquainted with Steve Birnbaum, a communications specialist who was already working with FEMA and others in Puerto Rico. Steve considered several workable solutions, pitched a couple of possibilities to FEMA, the Puerto Rico Department of the Family (which administers PAN), and other response players. Trying to move fast, Jesse used his credit card to buy the necessary equipment. Jesse and Steve recruited a technical crew from Focused Mission to install satellite-in-the-box units at 13 grocery stores.

From Jesse's arrival to completing the initial installations took about three weeks. Once the equipment was in hand, each installation required less than two hours. "It would have gone a lot quicker if we didn't try to shop the solution to the appropriate channels and just acted ourselves sooner," Jesse says. The satellite connection allows the point-of-sale machine to communicate with the transactions processor, bypassing the usual grid-dependent terrestrial networks. Total direct costs were roughly $33,000. Other work-arounds were also deployed. Osnet gave Ralph's the ability to connect through a private terrestrial network. SkyTec provides connections using radio frequencies.

By the second week in October the grocery supply chain in Puerto Rico was well on its way to restoring demand pull. Once point-of-sale terminals could be used, the over 45 percent of the population who use PAN EBT cards was immediately reengaged. The same work-around systems allowed other consumers to use their credit and bank cards. As was the case with the

Mi Gente in the mountains, ATM networks were also coming back, even while the grid remained mostly down.

By the end of October, about five percent of PAN beneficiaries remained outside the reach of grocery and related private sector supply chains. That equates to 85,000 to 90,000 people detached from their regular source of food, which is a significant challenge anywhere…at any time. Further, there was another segment of the population that was in need even if they were next door to a fully operating grocery store. PAN serves the poorest of the poor. Restoring the ability to use PAN was a huge strategic step. But in the aftermath of Maria, many self-sustaining Puerto Ricans were suddenly not employed.

The median annual household income in Puerto Rico is $19,606. Just over 40 percent of households make under $15,000. These are almost all served by PAN. Another 29 percent of households make over $35,000 (more than 16 percent make over $50,000). This leaves roughly 30 percent of households that are not part of the PAN system and who probably have limited cash reserves. [92] Fifty-seven percent of Puerto Ricans have no savings. [108] The longer the crisis—and loss of employment—the more likely this 30 percent will need food assistance. As noted, just in the first month after Maria, there were 4,000 new applicants for PAN.

In the first 30 days after Maria's landfall FEMA procured, shipped, and provided an average of 600,000 meals and 742,000 liters of water *per day*; delivered more than 3.6 million gallons of diesel and nearly 129,000 gallons of gasoline; provided 42,000 tarps and installed 439 blue roofs plus providing financial, personnel, and logistical support for the power restoration, debris removal, health delivery, and other critical response missions. [109]

These resources were delivered at the request of the Commonwealth of Puerto Rico. "They ask. We do everything we can to respond. That's our mission," is how Jeff Dorko describes FEMA logistics. In many cases, Puerto Rico's "ask" originated with one or more of the 78 mayors. The mayor of Yabucoa was not the only one who got a fuel truck. The mayor of Comerio specifically asked for help with water purification. The US Army Corps of Engineers dedicated a team to help with this task and set up operations just a few curves down the mountain road from the Mi Gente grocery.

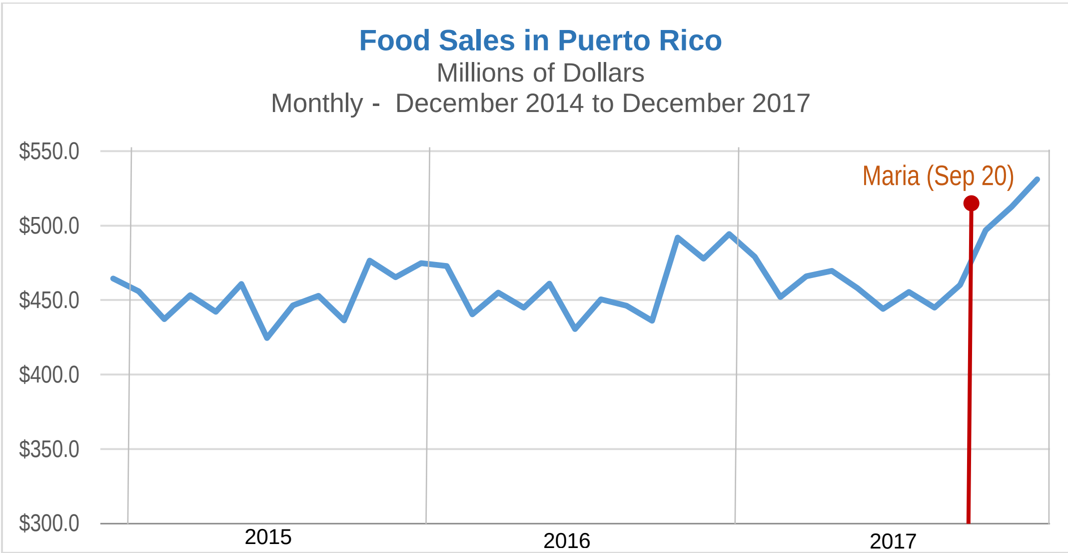
At the JFO in San Juan, any indication of private sector recovery was welcome news. But mostly they heard about impediments. There was very little strategic sense that one month after landfall, the Puerto Rican grocery supply chain was about 90 percent recovered and, by volume-sold, was operating at well above pre-storm throughputs. The government-to-government pull and push of the relief channel does not necessarily reflect the pull and push of preexisting—or recovering—demand and supply chains. Often the two networks are separate and parallel. Occasionally they collide.

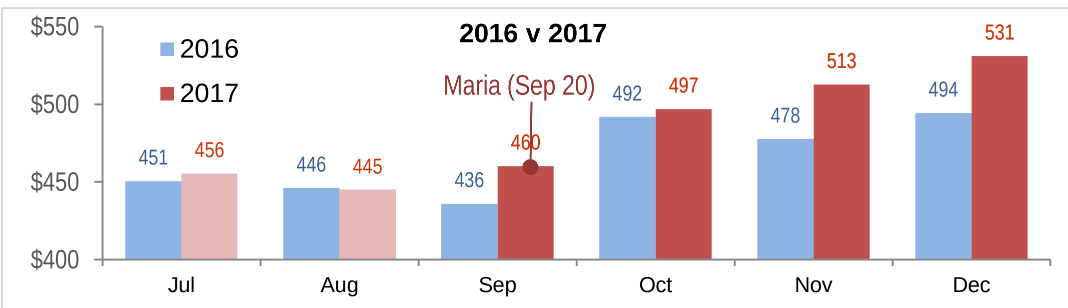
THREE MONTHS AFTER LANDFALL: A FUNCTIONAL SYSTEM ENGAGING DEEP UNCERTAINTY

Puerto Rico has experienced negative or flat economic growth since 2005. [110] Puerto Rico's population had declined by roughly 10 percent in the 14 years *before Hurricane Maria*. [111] Relocation to the mainland and elsewhere has continued. [112] Given this context, for the last decade many broad measures of economic activity have tended to produce a sense of déjà vu. For example, total retail food sales for July 2008 were $454.8 million. In July 2017, retail food sales were $455.5 million. [84] There are seasonal and monthly variations. As in the remainder of the United States, retail sales are usually highest in November and December. For Calendar Year 2016, the strongest grocery retail results were in December, with $494.2 million.

Before 2017's stormy September—do not forget Irma—comparative food sales were just slightly stronger than in 2016. Then, in the aftermath of two hurricanes, grocery sales surged [84] (See Figure CS1-1). December 2017 food sales were the strongest month since December 2009. This commercial pull and push was happening despite most of the grid still being out and the rest unreliable, even with challenges sourcing product, various distribution bottlenecks, much higher unemployment, the impact of fuel purchases on consumer disposable income, and tons of free food flowing.

Figure CS1-1. Monthly food sales in Puerto Rico spiked after Maria. Overall trend (top), and 2016 versus 2017 monthly comparison (bottom).





Source: CNA, Government Development Bank of Puerto Rico (2017) [84]

The retail fuel sector experienced similar results: August: $857 million; September: $856.5 million; October: $912.7 million; November: $838.2 million; December: $967.8 million. [84] December sales for the retail fuel sector were the best in three years, even with historically low pump prices. Consumer confidence in the Puerto Rican fuel sector was so strong that in early November, the Commonwealth stopped providing regular updates on fuel supplies. [113] No one was worried anymore.

Despite its own very strong sales, many in the grocery industry believe even better was possible. "The supply chain was very uneven, rough, unpredictable all through November. We could not get many of the products we wanted or the volume we needed," Jose Perales reports. “Too often our customers were buying what we had to sell, not what they wanted to buy.”

“I could not get vessel space for goods I regularly bring from the mainland,” Angel Vazquez explained. “FEMA food and more had higher priority. So, we (B. Fernandez) increased buying from Mexico and Europe where I could surge flow with much more confidence. Because we regularly buy and sell many international products, it was easier for us than others to diversify our inventory mix.”

“We also lost up to 10 percent of our trucking capacity,” the President of B. Fernandez reports. “Several independent truckers went to work moving relief supplies. To fill the gap and increase volume, we helped a small trucking company purchase eight pre-owned trucks. In exchange he hired drivers and guaranteed long-term service to B. Fernandez and our customers.”

“Consumer uncertainty was so high that I perceive almost everyone was ready to buy almost anything until sometime in mid-December. There were just too many signals of ongoing disruption. But once the water aisles in the grocery stores were regularly restocked, the market finally began to calm down. Lots and lots of water in the aisles was the signal shoppers finally found to be reassuring,” Vazquez suggests.

Many wholesalers report the available flow of products from the mainland has remained well-below pre-hurricane levels even into the new hurricane season. “It is still difficult for us to get products. Before Maria, we had inventory for 14 to 20 days, but now only 7 or 8,” Ricky Castro, owner of Castro Cash & Carry told the *El Nuevo Dia* newspaper. [114] The newspaper reporter adds, “Demand has skyrocketed and is higher than the capacity of the ships… the struggle to find vessel space is shared with dozens in the construction and other industries.”

Problems persist. Preparedness for the new hurricane season is weakened. But it is also worth recognizing that even with all the disruption, the grocery supply chain delivered many more calories in the fourth quarter of 2017 (and since) than it has at any time in the last decade (even when there were many more customers).

Ana had shouted, “*Sistema! Sistema! Sistema!”* The cashier at the small grocery store on a mountain in central Puerto Rico shouted, “The system! The system! The system! We are once again connected to the system.” Then she danced.

Ana does not know many of the technical details. But she does understand consumer behavior signaled through that data link pulls supplies to the mountaintop. Until that critical connection was fixed, the Mi Gente was excluded from the system of demand and supply. Outside that system, expressing demand and receiving supplies is difficult and probably not sustainable given current structures. Once that connection was healed, the Mi Gente store and its customers were also on the mend.

A big part of the "system" in Puerto Rico is Evertec. When Osnet reconnected the Ralph's in Yabucoa, every PAN transaction and most other bankcard transactions were processed by Evertec. Same story when Jesse, Steve, and the Focused Mission team reconnected their baker's dozen of grocery stores. Evertec was Ana's ghostly dancing partner.

Here is how Evertec describes itself [115]:

> Our broad suite of services spans the entire transaction processing value chain and includes a range of front-end customer-facing solutions such as the electronic capture and authorization of transactions at the point-of-sale, as well as back-end support services such as the clearing and settlement of transactions and account reconciliation for card issuers.
>
> These include: (i) merchant acquiring services, which enable point of sales ("POS") and e-commerce merchants to accept and process electronic methods of payment such as debit, credit, prepaid and electronic benefit transfer ("EBT") cards; (ii) payment processing services, which enable financial institutions and other issuers to manage, support and facilitate the processing for credit, debit, prepaid, automated teller machines ("ATM") and EBT card programs; and (iii) business process management solutions, which provide "mission-critical" technology solutions such as core bank processing, as well as IT outsourcing and cash management services to financial institutions, corporations and governments.
>
> We provide these services through scalable, end-to-end technology platforms that we manage and operate in-house and that generates significant operating efficiencies that enable us to maximize profitability.

While Puerto Rican grocery and fuel sales increased in the fourth quarter of 2017, most other retail sectors saw a significant decline in volume. This was reflected in Evertec's performance. "Total revenue for the quarter ended December 31, 2017 was $99.6 million, a decrease of 2 percent compared to $101.9 million in the prior year. The decrease in the quarter was driven primarily by the impact of reduced volumes caused by the significant hurricanes in the third quarter of 2017 partially offset by the acquisition of PayGroup." [116]

On May 2, 2018 Evertec reported: "Total revenue for the quarter ended March 31, 2018 was $110.3 million, an increase of 9 percent compared to $101.3 million in the prior year. Revenue growth in the quarter reflected the impact of the acquisition of PayGroup as well as elevated sales volumes in Puerto Rico driven by post-hurricane recovery activity, federal relief and benefit programs and insurance proceeds. [117]

Data from Evertec gave Department of the Family what it needed to work with Jesse and Steve to identify grocery stores that had historically been major PAN transaction sites but were still dark in the aftermath of Maria. That's where the satellite-in-the-box installations were targeted.

Evertec data was also indirectly being used at the JFO. Shortly after landfall, the JFO established a Business Emergency Operations Center. There was no preexisting structure, but a full-blown private-public function quickly emerged. Early on, FEMA developed a Food Availability Index to help assess specific status in each one of the 78 municipalities. The index consisted of the following information:

- Each community's Social Vulnerability Index
- Percent of people pre-storm using PAN Cards
- Whether or not PAN transactions are currently being made.
- How people accessed food prior to Maria
- How many gas stations were open?
- How often are they refueled?
- How many grocery stores are open?
- Do the grocery stores have refrigeration?
- Are the grocery stores on grid or generator?
- If on generator, how often are they refueled?
- How often are the grocery stores resupplied?

"Because the Federal Coordinating Officer was concerned about the amount of funding being spent on food, and because we did not want a false dependency on FEMA supplied food, and because we wanted to support the private sector in Puerto Rico, we created this "Food Acquisition Index" to determine how much and where food needed to go on the island. Prior to this, FEMA was operating under pressures from the media, political pressure, and the requests from the government of Puerto Rico—all at the detriment of the private sector," said Rob Glenn, FEMA's Director of Private Sector. He added, "FEMA was able to have fact-based conversations with the mayors to discuss the decision to stop sending FEMA food into their municipalities. Having this data-driven knowledge was incredibly helpful."

By statute and policy, FEMA's relief channel responds to pull as expressed by state and local governments. Strategy and operations have been organized around this government-to-government pull. FEMA logistics and NORTHCOM and other federal players want to push as much as they can as quickly as they can to fulfill this pull. A previous FEMA Administrator is often quoted as crystalizing this strategy as, "Go Big, Go Fast." The full quote is actually, "Go Big. Go Early. Go Fast. Be Smart." [118]

The Food Availability Index is an example of trying to be smart by moving beyond government-to-government pull to understand what is happening in the whole community, the real economy, the preexisting and—hopefully—recovering or effectively adapting demand and supply network.

PRELIMINARY ANALYSIS – TOWARD UNDERSTANDING SUPPLY CHAINS

In the midst of enormous and persisting challenges, water, food, and fuel supply chains in Puerto Rico demonstrated considerable—some might say amazing—resilience. The speed, scope, and scale of both recovery and adaptation meant that within four weeks of landfall, over 90 percent of residents were fulfilling fundamental needs through the strategic capacity of preexisting systems.

There was, however, no systematic process by which municipal, commonwealth, or federal authorities could be confident of this recovery and adaptation—or accurately map where and when the recovery and adaptation was not happening—or strategically target public sector interventions to facilitate recovery and adaptation.

Instead, federal, commonwealth, and local authorities focused primarily on deploying an effective relief channel for mass feeding and other direct assistance to all survivors. As a matter of statute, policy, and strategy, this relief channel assumed the failure or near-failure of the preexisting demand and supply chain. The relief channel was organized to replace, not to supplement or gap-fill preexisting strategic capacity. It did not have—and probably cannot have—this replacement capacity; fortunately this capacity was not needed. The relief channel did deliver vital water, food, and other assistance to hundreds of thousands of Puerto Ricans.

In contrast with contemporary demand and supply networks—Ana's *Sistema*—the relief channel is a "push" function that only vaguely perceives consumer or system pull signals. The receiving government is the source of pull for the relief channel. Often, the receiving government does not know the capacity, capabilities, or status of preexisting supply chains. On September 25, 2017, when the request for six million meals per day was generated, very little was moving in Puerto Rico. But within three days of that request, commercial movements surged. Within three weeks, the transformation of preexisting demand and supply chains was dramatic. But these changes are—especially in the fog of crisis—not always obvious. As a result, the predetermined relief channel push continued, regardless of its effective response to human needs or network effects.

FEMA professionals who had served or are serving in Puerto Rico—many of whom are military veterans—occasionally say something like, "We are doing a messy job of saturation bombing when we need more effective precision targeting." The Food Availability Index was the most consumer-oriented aspect of the relief channel, and it was applied more to reduce or stop push, rather than decide where, when, and what to push. Some FEMA professionals—and others—are, in retrospect, especially concerned that the energy and attention given to "saturation bombing" could have been much better applied to filling other needs where there was insufficient preexisting strategic capacity. Blue roofs, satellite communications, and fuel racks are often mentioned as examples.

Rapid assessment teams are deployed to impact zones. But their mission is often less to assess the status of preexisting supply chains and much more often to determine where and how to direct the relief channel. There could be a process by which the relief channel is guided to where preexisting networks have failed. There could also be a process by which the relief channel extends support to restoring key elements of the preexisting network.

In Puerto Rico—as in any extreme event—several bottlenecks were created or amplified. Post-Maria, the capacity and capability to push groceries recovered quickly. The capability to pull groceries with the PAN card (and other bank cards) was mostly lost. Once this bottleneck was recognized, several comparatively quick and inexpensive solutions were deployable. But the relief channel did not seem able to recognize—or respond to—this strategic opportunity.

In Puerto Rico—as in many prior disasters—fuel distribution emerged as a fundamental problem to be solved. As a matter of statute, policy, strategy, and operations, the "fuel mission" has mostly been defined as fuel for the relief channel. Significant efforts are made to avoid complicating commercial recovery. But little attention is given to helping preexisting fuel distribution capacity or capabilities recover or adapt. Again and again, long lines of fuel tankers form around the racks rather than making their deliveries. Can this recurring pattern be effectively understood and operationally engaged?

How can the relief channel[8] develop sensing capabilities that would allow it to track and target where the preexisting supply chain's strategic capacity has failed or is failing? Is there a role for local, commonwealth, and federal authorities to gap-fill and reinforce the pull and push capabilities of preexisting strategic capacity? Rather than behaving only as a relief channel, can the public sector role be reconceived to be more of a strategic adaptation function?

The experience in Puerto Rico suggests that this non-traditional role could be a crucial capability-multiplier for serving dense populations surviving an especially hard-hit and an extended period of failed critical infrastructure. Puerto Rico has demonstrated several strategic soft spots where non-recovery of preexisting capacity was experienced or

[8] See Case Study 2 for a much more complete examination of the relief channel in Puerto Rico.

threatened. Electronic data transfer, trucks and truckers, and fuel distribution were especially threatening. Are these—and other—threats particular to post-Maria Puerto Rico or systemic? Based on the outcomes of Harvey, Irma, and other large-scale disasters, there is evidence to suggest systemic implications.

Contemporary demand and supply networks are complex, adaptive systems and, in many ways, common-pool resources. [119] There are large numbers of stakeholders. No one is in charge and, in a typical meaning of the word, no one can be in charge. But there are opportunities for shared understanding, strategic intention, and operational influence.

Monitoring Flows, Applying Filters, and Choosing Targets

How is shared understanding cultivated? How is strategic intention formulated? How could operational influence be exercised?

Because the situation after Hurricane Maria in Puerto Rico is an especially extreme event, it is potentially an especially helpful case study. Vulnerabilities, dependencies, and interdependencies that can remain obscure in less extreme contexts are much more obvious in Puerto Rico.

This case study—focusing mostly on food and fuel in post-Maria Puerto Rico—is only one of many potential angles of analysis. But based on multiple experiences in Puerto Rico, and after Irma in the Caribbean and Florida, and after Harvey in Texas and Louisiana, and informed by many prior events, CNA research teams believe it would be helpful for every jurisdictional level and major stakeholder to have the following:

An accurate (and regularly updated) strategic understanding of the volume of pull and push for water, food, and fuel being delivered by the private, pre-existing (i.e., not relief channel) demand and supply networks. This would necessarily involve the role of transportation and workforce components across these elements. We are calling this **flow**.

An ability to recognize significant changes in flow and the source of such changes. There are preexisting data and information resources. There are key players who can report these changes. There are observable outcomes that could be combined to provide this strategic insight. We are calling these **filters**.

A practical ability, cultural predisposition, and legal authority to target actions that would maximize flow of water, food, and fuel to support survivors of a catastrophic event by facilitating restoration of private supply chains and strategic capacity and gap-filling where flow from preexisting strategic capacity cannot be restored or is insufficient to fundamental human needs. A strategically informed process of choosing **targets** is most likely to ensure those in need are served and that preexisting strategic capacity effectively recovers or adapts.

Flows, filters, and targets would considerably enhance whole-of-nation readiness for New Madrid, Cascadia, or San Andreas events.[9] In each of these crises—or when a CAT-5 hits Miami, a pandemic swirls, or in a host of catastrophic contexts—having a strategic grasp of flows, filters, and targets will allow the system to maximize surviving capacity and capabilities. We do not have this ability today.

A powerful destructive force hit what was essentially the entire *sistema* serving Puerto Rico. A dense population dependent on distant supplies and interdependent technologies survived to face months of grid unavailability, system unreliability, recurring network-disruption, and—as of late June 2018—a new hurricane season. It was—and remains—a precarious situation.

There are good reasons to argue that the situation in Memphis is at least as precarious in the aftermath of a New Madrid seismic event. There are reasons to argue that the situation is even more precarious for the Puget Sound region in the aftermath of a Cascadia event. In each of these and many other densely populated places, there is not a current readiness to perceive changes in demand and supply, recognize the implications of such changes for near-term population health (or long-term economic recovery), and take effective strategic action.

Even now, with the results of post-Maria Puerto Rico fresh in our minds, there is a tendency for preexisting concepts and procedures to reassert their authority. Especially with the urgency of the crisis now superseded, there is a tendency to focus on what can be controlled and to increase the resources under control, even if—maybe especially because—we just went through an experience where catastrophic risk was mostly outside our control and supply networks surged in ways we barely understood.

While the accumulating evidence from Harvey, Irma, Maria, and more suggests there is good cause to be skeptical of prospects for control, there are plenty of opportunities for enhanced understanding. The CNA research team especially recommends the following lines of inquiry:

Is it possible to accurately characterize the complex, dynamic, interdependent network of demand and supply on which dense populations depend? Can this characterization practically inform the conception, preparation, and implementation of effective system-supporting—even system-amplifying—strategies? Based on our recent research related to Harvey, Irma, and Maria, we perceive this is possible, but specifying and building such a characterization is non-trivial.

[9] Three catastrophic earthquake scenarios in Missouri, the Pacific Northwest, and California, respectively that the emergency management community is preparing for with exercises and simulations.

While engaging the first question, **who or what are the most valuable indicators of network fitness and output?** Are there recurring categories of vulnerability, failure, or constraints that can be identified in advance for specific attention and potential mitigation? Based on our recent research, we believe there is particular potential in identifying the persistence or loss of consumer “pull” and the current status of distribution or “push” for water, food, and fuel. Other network elements should be engaged, but these two aspects of pull and push seem especially promising.

To the extent these first two lines of inquiry have authentic strategic value in serving human needs in catastrophic contexts, **what statutory, policy, doctrinal, fiscal, and strategic shifts are needed to incorporate and implement the implications of flows and filters?** What is needed to do effective targeting? Potentially even more difficult, are there cultural predispositions within the emergency management profession or more broadly within the public-private domain that must be changed to make real progress?

CASE STUDY 1 APPENDIX: MAPS AND FIGURES

Figure CS1-1. Area map of Puerto Rico with Key locations labeled, and inset of the Bayamon Food Corridor.

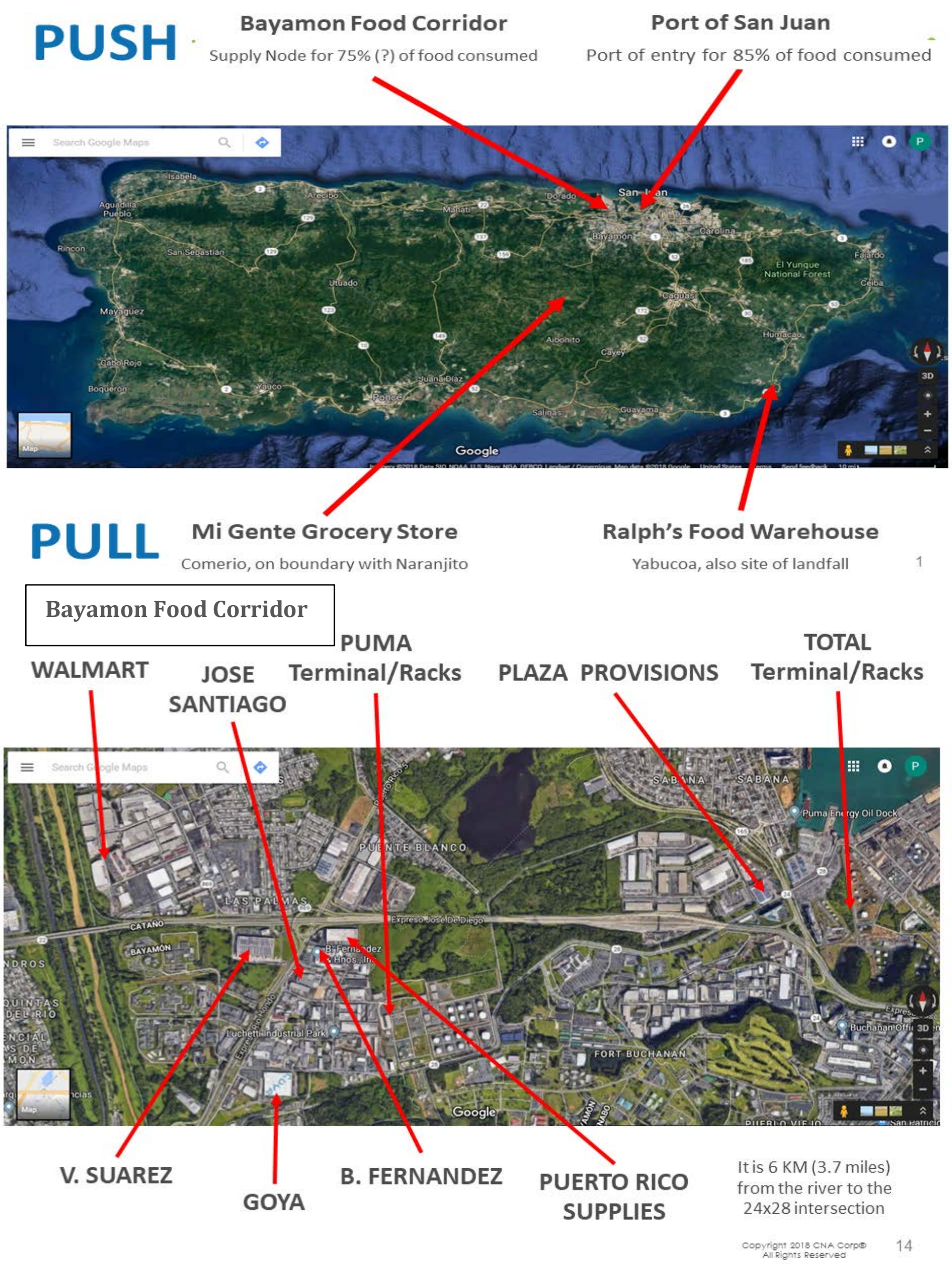


Figure CS1-2. Total retail food sales in Puerto Rico, 2009 – 2017, in million $.

PUERTO RICO ECONOMIC INDICATORS
Retail Sales
Food Stores
(million $)

Go to Index

GOVERNMENT DEVELOPMENT BANK
Economic Analysis Division

FISCAL YEAR *	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
JULY	454.8	488.9	513.5	447.1	453.5	435.0	444.6	446.3	450.5	455.5
AUGUST	437.2	470.0	513.9	440.5	456.5	436.5	456.7	452.9	446.2	444.9
SEPTEMBER	446.4	460.3	489.7	414.8	442.1	426.7	434.4	436.2	436.0	460.2
OCTOBER	468.8	469.5	481.0	427.3	442.6	431.9	464.0	476.4	491.9	496.8
NOVEMBER	485.7	491.8	482.2	437.6	428.0	439.3	450.7	465.2	477.7	512.6
DECEMBER	522.0	536.1	512.9	466.5	462.3	455.6	464.4	474.7	494.2	531.0
JANUARY	466.4	455.7	432.1	444.1	434.9	441.3	455.9	472.9	479.1	
FEBRUARY	458.7	443.7	435.7	431.4	426.8	426.5	437.1	440.4	452.0	
MARCH	472.8	467.5	454.9	451.7	444.7	458.7	453.2	455.1	465.9	
APRIL	460.8	483.0	440.7	452.6	431.6	438.8	442.1	445.0	469.7	
MAY	475.2	493.9	441.0	409.0	439.6	445.4	460.7	461.0	457.9	
JUNE	462.7	483.9	429.9	445.3	429.6	431.1	424.4	430.5	444.1	

Source: Government Development Bank of Puerto Rico [84]

Case Study 2: Static on the Relief Channel

In mid-September 2017, all the news channels in Washington, DC, and across the country had shifted from the flooded homes in Houston, and the crowded highways and empty gas stations in Florida to the incredible power of Category 5 Hurricane Maria as it was on a collision course with Puerto Rico. Not long after the images from Houston faded, Hurricane Maria devastated the islands of Puerto Rico and St. Croix in the US Virgin Islands on September 20, 2017. Within nine days, televisions across the country were inundated with images of the San Juan Mayor, Carmen Yulín Cruz, pleading: "We're dying here. We truly are dying here. I keep saying it: SOS. If anyone can hear us; if Mr. Trump can hear us, let's just get it over with and get the ball rolling." [112] This coverage received the ire of the President, who responded in retorting tweets. US mainland public perception was further driven by other media reports that indicated the island's supply chain had totally failed. Some volatile headlines in the days and weeks following landfall included the following:

Figure CS2-1. San Juan Mayor Carmen Yulín Cruz on CNN pleading for resources

Source: CNN, September 29, 2017

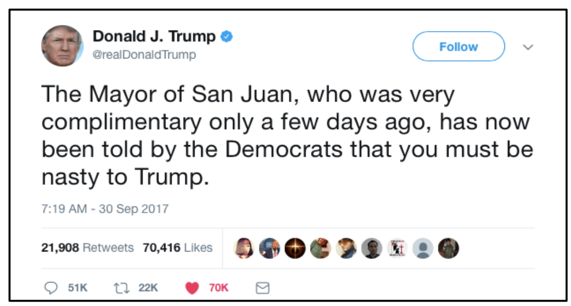


Figure CS2-2. President Trump tweets in response to the Mayor of San Juan

Source: Twitter

- *CNN*, September 26: No gas. No food. No power. Puerto Ricans fear their future
- *USA Today*, September 30. By the numbers: More than half of Puerto Rico still without drinking water
- *Business Insider*, September 29: Hurricane Maria decimated Puerto Rico's food supply

The concerns were real, but there was more to the story—omissions or blind spots had a profound effect on the response to Hurricane Maria. In the midst of enormous and persisting challenges, water, food, and fuel supply chains in Puerto Rico had actually demonstrated considerable resilience. The speed, scope, and scale of both recovery and adaptation of the citizens meant that within four weeks of landfall, over 90 percent of residents were fulfilling fundamental needs through the capacity of preexisting systems (or temporary/ad-hoc replacements). There was, however, no systematic process by which local, commonwealth, or federal authorities could be confident of this recovery and adaptation, or accurately map where and when the recovery was not happening. The perception of shortfall and human suffering argued for a massive response from the nation to help its fellow American citizens in Puerto Rico.

This response fit with the Federal Emergency Management Agency's (FEMA) whole community approach to emergency management and Administrator Brock Long's vision for the agency as presented in the new Strategic Plan: *a prepared and resilient Nation is a shared responsibility and, while recognizing FEMA's essential role, meaningful improvements will occur only when we work in concert across Federal departments and agencies, as well as with leaders from state, local, tribal, and territorial governments and non-governmental organizations and the private sector*. [3]

FEMA's approach for disasters in the United States has been to provide all potentially necessary resources as quickly as possible to ensure that lives are saved, even if it means risking waste—an approach that came about after decades of responding to many large-scale disasters such as Hurricane Andrew and Hurricane Katrina. The previous FEMA Administrator, Craig Fugate, was often quoted as crystalizing this strategy as, "Go Big. Go Early. Go Fast. Be Smart." [118]

Anticipating that existing supply chains will fail, FEMA, and specifically it's Logistics Management Division, helps manage the "relief channel" – a replacement supply chain to provide needed goods. The "push" of emergency supplies like food, water, and blue tarps typically occurs early in a response, before there is good situational awareness at the local level. The "pull" of needed resources occurs when the local government has completed damage assessments and began to request specific aid from FEMA. The objective of this push/pull process during a response is to be effective in fulfilling immediate and lifesaving needs and to reduce the flow of resources gradually as things "return to normal." The cost of the upfront push is often degraded efficiency, but it is a risk that the federal government has been willing to accept during disasters, when lives are at stake.

Having a "pull" signal from disaster victims, indicating what they actually need and want, is a more economical and practical solution. Private sector retailers use these demand signals to run their businesses on a daily basis. But local businesses are often disrupted in emergency situations and are unable to receive and convey consumer demand when power and communication are down. The "push" of goods from the public sector (as well as from well-meaning volunteers), while focused on supplementing private systems in the face of these breakdowns, can also be superfluous and unintentionally disruptive to the private sector.

FOOD MISSION: PUERTO RICO

Sitting in his office at the Puerto Rico Emergency Management Agency (PREMA) late one evening in May 2018—eight months into the recovery from Maria—Heriberto Sauri, Director of Puerto Rico Homeland Security Office, reflected on the hurricane, "We were most worried about fuel and food. Most of the food in Puerto Rico is imported from the states or other places." Indeed, approximately 85 percent of grocery products consumed in Puerto Rico arrive at the Port of San Juan. In addition, there is only a 30-day supply of grocery products on the island at all times because Puerto Rico has an inventory tax from the Puerto Rico Treasury Department, which limits the amount of inventory companies can stockpile. In 2016, roughly $5.6 billion was expended at food stores.[84] Notably, approximately 40 percent of all food purchases are made with the Department of the Family's Electronic Benefit Transfer (EBT) card, also known as the PAN card. [85]

Most residents were not ready or prepared for Hurricane Maria. Supplies were scarce and the power grid was already damaged from Hurricane Irma, which skirted the island two weeks prior, knocking out power to 1 million people. [43] Most did not have the resources on hand to prepare for such a large storm. In the rural parts of the island, few had cash readily available to pay for supplies and most depended upon electronic access to their public benefits. [85] Poverty levels overall in Puerto Rico are more than 40 percent, and in some areas like Yabucoa, where Maria made landfall, the poverty levels are even higher, at 65 percent. "People generally are not able to keep large sums of cash around in preparation for a disaster," according to Jerry Medina an Emergency Medical Technician in Yabucoa.

At 6:15 a.m. on September 20, 2017, a disaster came nonetheless. Hurricane Maria made landfall just south of Yabucoa Harbor, Puerto Rico, as a Category 5 hurricane with winds over 157 mph. Puerto Rico's electrical infrastructure was destroyed. The entire island—all 1,569,769 customers and 3.4 million people—was without power. "I don't remember anything that didn't collapse besides the will of the people," said Hector Pesquera, Secretario de Seguridad Publica.

Disasters outside the continental United States are a major challenge because of logistics, cultural issues, and the time it takes for systems to gear up. Typically, in events on the mainland, there are several options for resourcing needs from across the country. Supplies can be trucked from nearly anywhere in the country through a system that is predictable, efficient, and effective. On islands, the systems for supply chains are not as responsive, may have particular aspects absent (e.g., a 30-day food supply), and may be less resilient to disasters themselves (i.e., limited numbers of ports of entry, trucks, storage places, operators, and logisticians). In addition, the time it takes to ship from Florida to the island Puerto Rico (and indeed to further islands such as St. Croix) incurs a longer time for the system to engage and get up to maximum output—and that is if the system works well.

In some ways, FEMA was well-prepared to surge goods to Puerto Rico. As the massive response to Harvey in Texas, and to Irma in Florida had started winding down, the relief channel was operating at a high capacity, and primed to redirect supplies to Puerto Rico.

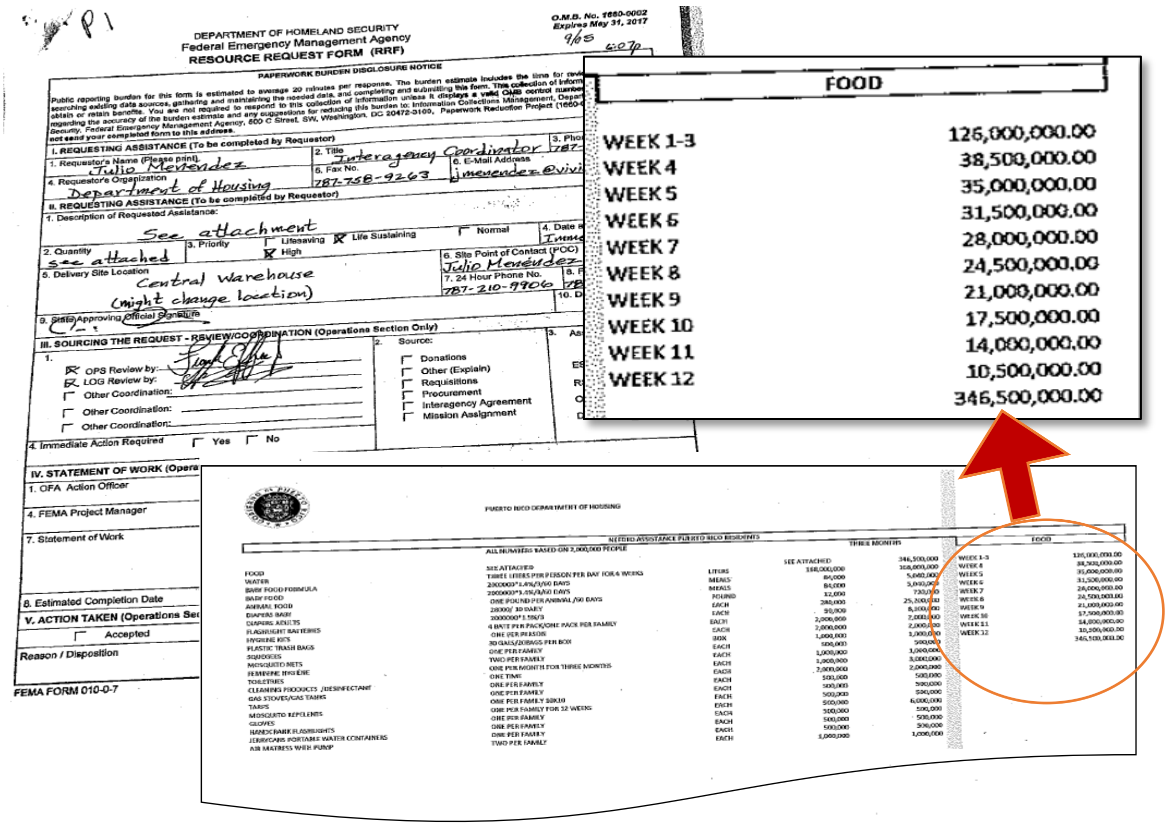
Sending in Food - the Push Begins

Hurricane Maria left the island with no power, no communications, significant flooding and damage, and blocked or washed out roads that isolated many communities. In Washington, DC, FEMA Logistics worked to enable a minimum of 1.5 million meals per day in Puerto Rico. Based on their initial estimates, they aimed to feed, water, and provide essential life-saving services to 20 percent of the population on the island. This goal made sense in terms of realistic system capacities and constraints. Then, on September 25, 2017, FEMA Region 2 received a Resource Request Form from Julio Menendez, the Interagency Coordinator for the Puerto Rico Department of Housing, on behalf of the Governor's Office, asking for immediate aid for 2 million people on an island with 3.4 million people. Mr. Menendez specifically requested 346,500,000 meals over a 12-week period. For the first three weeks after landfall, his request was for 6 million meals per day (see Figure CS2-4). [120]

Figure CS2-3. Devastation in Ultuado, Puerto Rico

Source: Hector Cruz, Emergency Management Director, Ultuado

Figure CS2-4. Resource Request Form seeking six million meals per day

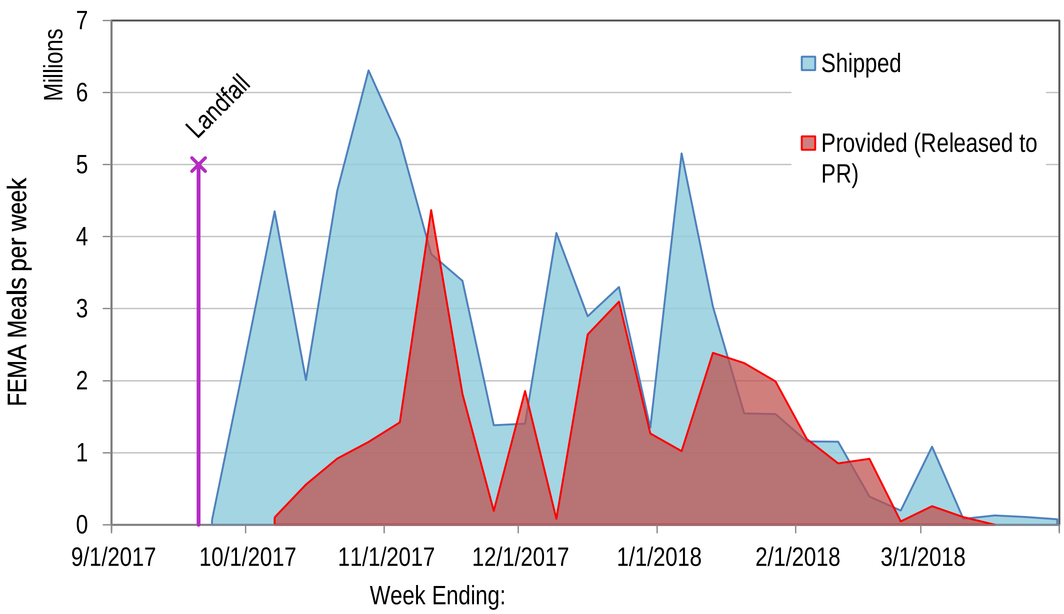


There are several paradoxes in understanding the FEMA food mission in Puerto Rico. The total food provided was massive, record-breaking for FEMA, and likely more than needed. Yet, it was still small when viewed in the overall context of the islands' total consumption. From September 20, 2017 through March 31, 2018, FEMA shipped 62,062,317 meals to Puerto Rico [121], and provided[10] 30,486,710 meals to the government of Puerto Rico [122]. In only one week did FEMA actually ship more than 6 million meals total (one-seventh of the 6 million per day request). This was the largest food mission in FEMA's history; yet for the island's population, it equated to about nine meals per capita over six months (or 1.5 meals per person per month).

[10] Meals "provided" refers to meals that are released to the government of Puerto Rico at one of the destination facility cities in one of Puerto Rico's 12 emergency management zones. From these facilities, the government of Puerto Rico, local governments, local FEMA managers or contractors manage distribution to the general population.

Another paradox is that the food deliveries were at once rapid and also too late, and the deliveries did not seem to follow the track of the storm. Figure CS2-5 shows that food started arriving quickly after landfall, but the distribution of food released to Puerto Rico does not really ramp up until October. The food is most needed in the initial weeks after landfall, but food provided to the population does not peak until mid-November. A possible explanation is that it takes a long time to ship food from the mainland to Puerto Rico, and distribution of food was significantly hampered by local issues with transporting goods.

Figure CS2-1. **FEMA meals shipped and provided to population during Hurricane Maria Response in Puerto Rico.** [121-122]

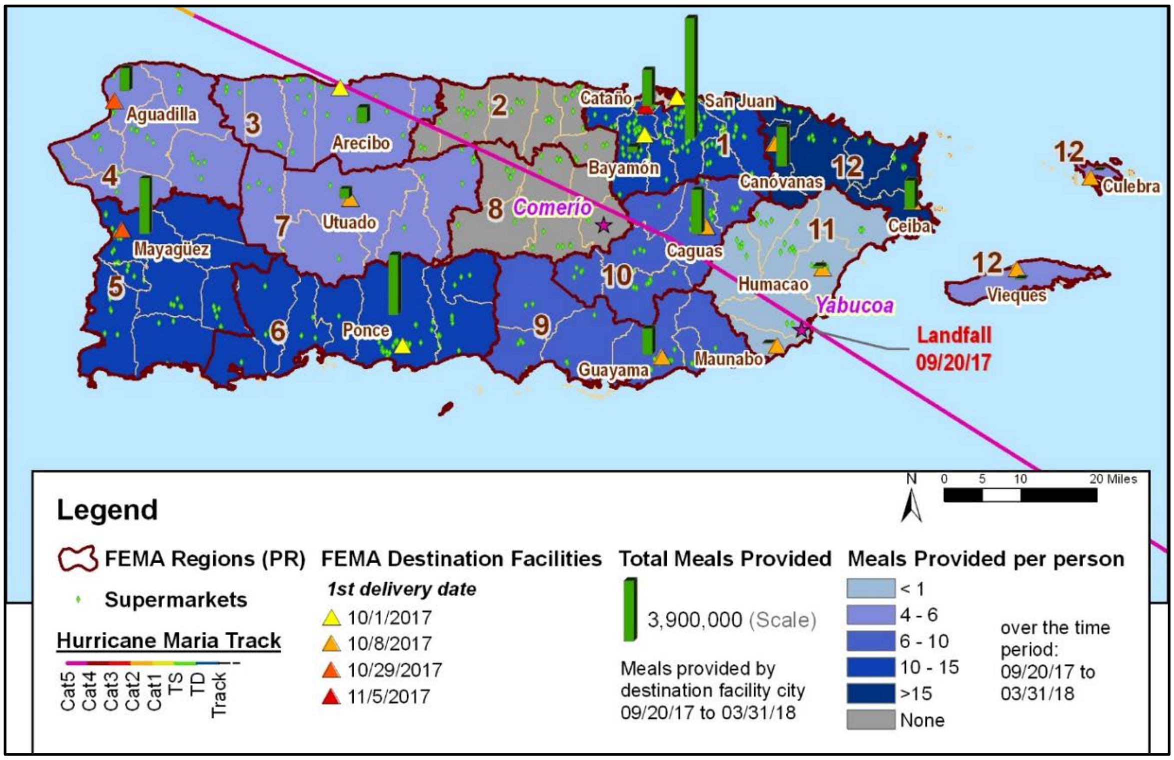


Source: CNA based on data from FEMA

Figure CS2-6 indicates when FEMA food deliveries first arrived to an area and shows the total amount delivered through the end of March 2018. Cities with ports such as San Juan, Ponce, and Arecibo receive and release food the earliest. The total food provided by zone is normalized to 2016 populations. This distribution of the meal rations across the island was not equal. Interestingly, the per capita food deliveries seem to be inversely proportional to distance from the hurricane track. Notably, Zone 11 (including Yabucoa, where Maria made landfall), received the least. Zones 2 and 8 had no food provided from their destination facilities according to FEMA data (though 23,724 meals were shipped to Comerio). A possible explanation is that those zones likely received transfers from facilities in neighboring zones (e.g., Caguas, Bayamon).

In total, 10,559,752 meals (or 35 percent) went Zone 1, with 7,880,640 meals (or 26 percent) being released to the destination facility in San Juan [122]. The population of San Juan is 355,074, which means that the San Juan facility released on average, 22 meals per capita over the six-month period.

Figure CS2-2. FEMA meals provided, by emergency zones [122]



Source: CNA. Data Source: FEMA

What is unclear is whether the food distribution matched or mismatched with population needs and how much of the distribution was based on subsequent Resource Request Forms. Angel Vazquez, President of B. Fernandez & Hnos, explained, “As a rule, the smaller the store, the quicker the recovery. Our largest customers have the most sophisticated systems and were, as a result, the most disrupted by long-term outage of the grid. Our smallest customers, up in the mountains—even though they had been hit really hard—were the first to open.” Accessibility may have played a role in the distribution as well. For example, Mr. Medina noted that for the first 45 days after Maria, Yabucoa received aid and food from the National Guard in Ceiba, not FEMA. They were not able to communicate with PREMA for a month to even make their requests and needs known.

Concerns over crowding out the local businesses

Among the local public sector a narrative developed that FEMA's response actions had a negative effect on the island's food supply chains and economy. Reflecting on the monumental task of delivering over 30 million meals to the island, Heriberto Sauri, Director of Puerto Rico Homeland Security Office, said, "The federal government acts as a parent to feed Puerto Rico. People didn't have to go to supermarkets for months because of the food FEMA provided. But this doesn't help Puerto Rico get its economy back on track."

This sentiment was echoed in the mountains in the interior of the island. Amaury Figueroa, the Emergency Management Director for the Municipality of Naranjito, said, "Instead of going to the super market for groceries, people preferred to stand in lines to get their food from FEMA. For two months, FEMA interrupted the supply chain for the local markets. When our stores reopened, the lines for FEMA food began to decrease, but they were still there because that food was free. Our mayor had to ask FEMA to stop supplying food to help out our local stores."

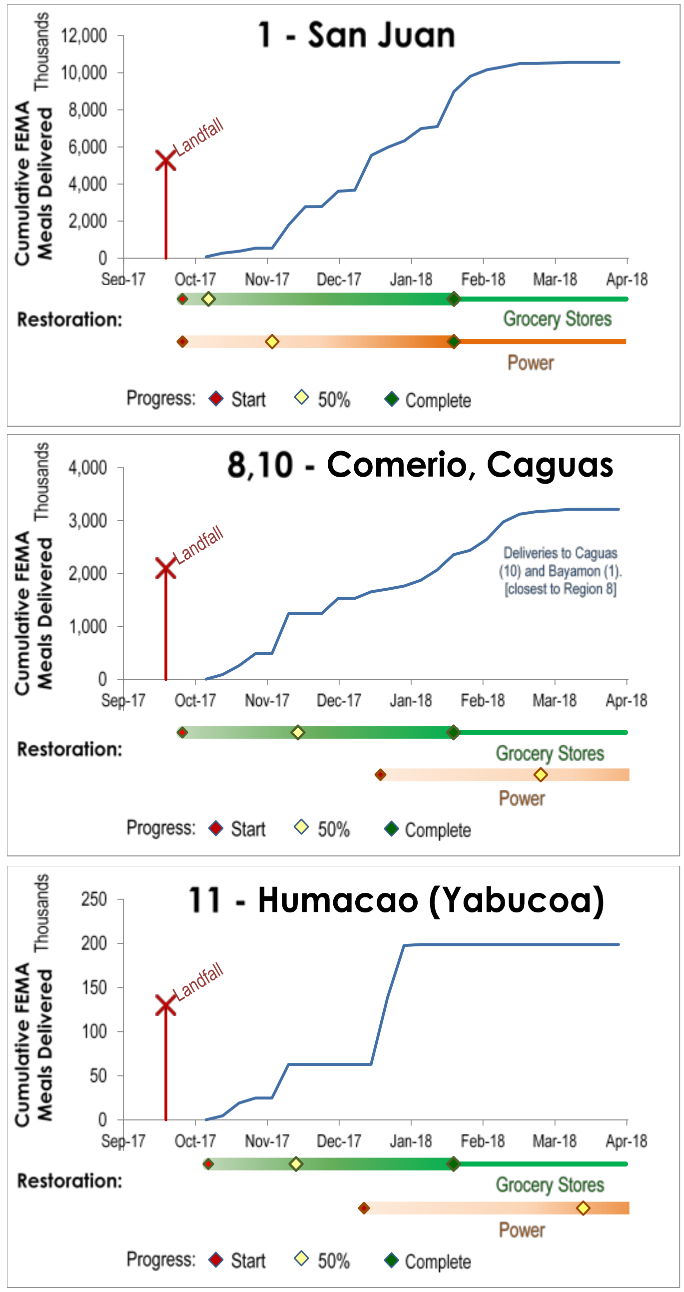


Figure CS2-3. FEMA food deliveries released to the Puerto Rico government relative to the restoration of services

Looking at three regions in Puerto Rico—San Juan, Comerio, and Yabucoa—Figure CS2-7 denotes when grocery stores reopened after the storm in comparison to when FEMA began delivering meals. In two of three regions, grocery stores were already open in the region prior to FEMA's first deliveries.

Mr. Medina in Yabucoa said, "We stopped requesting food in January 2018 because the PAN cards were working and people could buy groceries at the grocery stores," further noting that the local grocer, Ralph's Food Warehouse, went six months without power, but was open because it ran on generators. Figure CS2-7 for Yabucoa accurately reflects what you would expect when the pull signal is restored (especially PAN card transactions) soon after the power was turned back on: the push stopped.

By contrast, Zone 1 (containing San Juan), saw a huge ramp-up in FEMA meals even after the majority of communities in the area had grocery stores open and power restored. San Juan proved to be the center of the glut. While most of the destination facilities released nearly as many meals as were shipped, the facility at San Juan received over 36 million meals, and released roughly 8 million. This accounts for much of the 32 million meal difference between the total meals shipped (62,062,317) and provided (30,486,710) for all of Puerto Rico. [122]

So what effects did this glut of food have? Were the grocers actually harmed? Had the island reached its capacity to absorb food, or had something else happened?

Although the amount of food sounds massive, there are several indications it did not really overwhelm the existing food supply chain. As stated previously, the number of meals actually released amounted to only 1.5 meals per person over six months across Puerto Rico. When asked about the effect of FEMA's food mission on his store, Jose Perales, manager of Ralph's Food Warehouse in Yabucoa, smiled, shrugged his shoulders, and said, "The free food had almost no impact on our sales. People came here to buy what they wanted to buy. Then they stood in line for the free food because it was free. Some they ate; most they put away for next hurricane season. In any case, it did not impact what they bought from me." A grocer in Comerio complained about FEMA's effect, but his actual sales were approximately 20 percent higher in October 2017 and continued to be higher through at least April 2018. A bigger issue in Puerto Rico was access to cash and PAN benefits because of the lack of power.

Further evidence from the private sector shows that food was available in Puerto Rico and grocery stores opened quickly and experienced surging sales. In December 2017, Puerto Rico realized its strongest food sales in eight years (see *Case Study 1: Retail Resilience in Puerto Rico*). The total food sector sales for Puerto Rico in the wake of Maria are [84]:

- August 2017: $444.9 million
- September 2017: $460.2 million
- October 2017: $496.8 million
- November 2017: $512.6 million
- December 2017: $531.0 million.

The “free food” had not meaningfully harmed sales. Yet, even if the food supply chain was not overwhelmed, there were substantial impacts related to the push of goods. There are also significant lingering questions. Why was so much more food ordered than was used in the first place?

UNDERSTANDING THE PUSH – CAUSES AND SPILLOVER EFFECTS

Fundamentally, FEMA Logistics is in the business of fulfilling requests for aid in the form of emergency supplies, especially food, water, fuel, tarps, generators, etc. Puerto Rico, after Hurricane Maria in particular, provided several challenges that make this process difficult.

On May 23, 2018, eight months—almost to the day—after Maria made landfall, the Joint Recovery Office in Guaynabo, Puerto Rico, is bustling. The circular floorplan feels like carefully organized chaos. In the midst is R. Scott Erickson, the Chief of Logistics, who is responsible for executing a near-impossible task of managing an enormous amount of commodities onto an island with severely damaged infrastructure and limited ports of entry. If any person is up for the job, Mr. Erickson appears to be it. He’s intense, energetic, and commanding. He leads a team of logisticians who come across as down-to-earth, no-nonsense professionals who just want to get the job done despite months of grueling hours and harsh working conditions.

Figure CS2-4. Emergency ration meals in a home in Yabucoa

Source: Ben Nieves, owner, ISP

Mr. Erickson and his team have a firm grasp on the situation and the criticism they face on the island. “FEMA was giving away food and water until the 18th of May. There was no incentive to go to the store and buy food because FEMA was delivering grocery boxes with whole meals in it. In most cases, they don’t appear to need it; they are taking it because it is free,” he explained, adding, “When we cannot validate a requirement, it probably tells the story.” He also speculated that people are hoarding food in preparation for the next disaster, a reminder to everyone of the upcoming hurricane season beginning in a little over a week (on June 1, 2018).

The team understood how the situation unfolded and got out of hand. First, there were no communications on the island right after the hurricane, so there was minimal situational awareness and Puerto Rico could not make its requests. Because there were no initial requirements, FEMA began to push material based on estimates made by staff at headquarters. Second, there were two different teams placing these orders within the overall relief system—FEMA and Emergency Support Function 6, Mass Care. The two groups did not communicate clearly and, as a result, more commodities were sent than required. "Instead of coming up short, FEMA over-flooded the supply chain with product. A big issue is you can't move product once it floods an island. There are insufficient locations and resources to take the products," he explained. FEMA Logistics was challenged with the volume of supplies piling up at the port. The port had significant issues, many unrelated to FEMA, and his team struggled with the containers because of inadequate labeling.


Figure CS2-5. Food deliveries in Ultuado, Puerto Rico

Source: Hector Cruz, Emergency Management Director, Ultuado

Anything coming to the island was designated "Disaster Relief." They often did not know what was inside a container until it was opened. At one point, there were 2,000 containers holding bottled water sitting in the port, with no associated requirement. "The supply chain is only as good as the last link in the chain. If there is no one to consume the product it just sits and backs up. We should not push food faster than it can be consumed; we had to throw away 2 million meals that spoiled or were damaged," said Mr. Erickson.

Mr. Erickson recommended the following idea, "Instead of FEMA moving products, let's do vouchers and let the private sector supply the food. Currently, there is no incentive for the private sector to come to the table and assist if FEMA is going to pour massive amounts of free food on the population anyway." However, he noted that the private sector was not able to meet their contract requirements when given the opportunity in some isolated cases. The voucher recommendation is compelling because as shown in Figure CS2-9, grocery stores were open, and many residents – especially those relying on EBT cards – just needed a way to pay for food in stores that lacked power (and connectivity) to process electronic transactions.

One lingering question Mr. Erickson continues to ask is, "if most grocery stores were open, why were the Emergency Managers and Mayors still asking for food and water help? At six months in, we were still getting requests in for truck-loads of food and water from individual municipalities. Up until two weeks ago, Mayors were still asking for food and water."

Whispers from many interviewed across the island indicated, “It’s good politics to hand out free food.”

So, FEMA had delivered food as requested—more than needed, but too little to meaningfully impact the island-wide food supply. Nevertheless, the surge of FEMA supplies did have very real and cascading impacts on other supply chains on the island.

Supply Chain Impacts in Puerto Rico – Where the Push Did Make a Difference

FEMA’s food mission did not prevent grocery stores from opening or from selling their product. It did not crowd out supermarkets. In fact, sales had surged. The quantity of food moved into Puerto Rico was large, but at the same time, met only a small portion of the islands’ total caloric needs. Nonetheless, the huge push did have a variety of direct and indirect effects on other supply chains via effects on transportation systems, and other (i.e., not retail food) economic sectors. Mr. Sauri explained, “FEMA obstructed the private sector because FEMA had priority for supplies that were transported on boats and trucks. The port even segregated the barges by who pays more. FEMA would pay more money so delivering their supplies became priority. Ultimately, FEMA made the private sector another victim, not their partner.” Mr. Pesquera echoed this concern, “Our private sector complained that FEMA took over the ports and incoming supplies. FEMA’s presence took over everything.”

“I could not get vessel space for goods I regularly bring from the mainland,” Angel Vazquez explained. “FEMA food and more had higher priority. So, we (B. Fernandez) increased buying from Mexico and Europe where I could surge flow with much more confidence. Because we regularly buy and sell many international products, it was easier for us than others to diversify our inventory mix.”

“We also lost up to 10 percent of our trucking capacity,” the president of B. Fernandez reports. “Several independent truckers went to work moving relief supplies. To fill the gap and increase volume, we helped a small trucking company purchase eight pre-owned trucks. In exchange he hired drivers and guaranteed long-term service to B. Fernandez and our customers.”

The water supply chain was another story. FEMA’s intervention in the bottled water market had a much larger effect than for food. In the case of bottled water, FEMA’s push did suppress the private sector supply chain. Mr. Erickson said that there are currently (as of May 2018) 21 million bottles of water sitting under a blue tarp in Puerto Rico that FEMA has now excessed to the commonwealth, adding, however, “it doesn’t help the economy.”

According to Mr. Sauri at PREMA, "Puerto Rico has two or three companies that can produce and bottle water and they had water and power. What they lacked was the raw materials to manufacture the caps, which were stuck at the port. These companies went weeks without producing water bottles because their containers in the port were not considered a high priority and not released. FEMA bringing in more water and other commodities created a cycle of goods getting stuck at the port."

Eventually FEMA did contract locally for bottling water; however, it had a negative effect on local supply and demand. "We basically took product out of the commercial channel, moved it into the relief channel, and probably ended up distributing it less widely—and at a much greater overall expense—than if we had sourced elsewhere for emergency needs and let the preexisting channel respond to retail demand," a FEMA official said, adding, "We contributed to empty store shelves and this had predictable effects on consumer behavior."

The displacement of bottled water out of the stores—creating empty shelves—increased the public sense of disruption that kept hoarding behavior so high well into December. According to Mr. Vazquez of B. Fernandez, "Once the water aisles in the grocery stores were regularly restocked, the market finally began to calm down. Lots and lots of water in the aisles was the signal shoppers finally found to be reassuring."

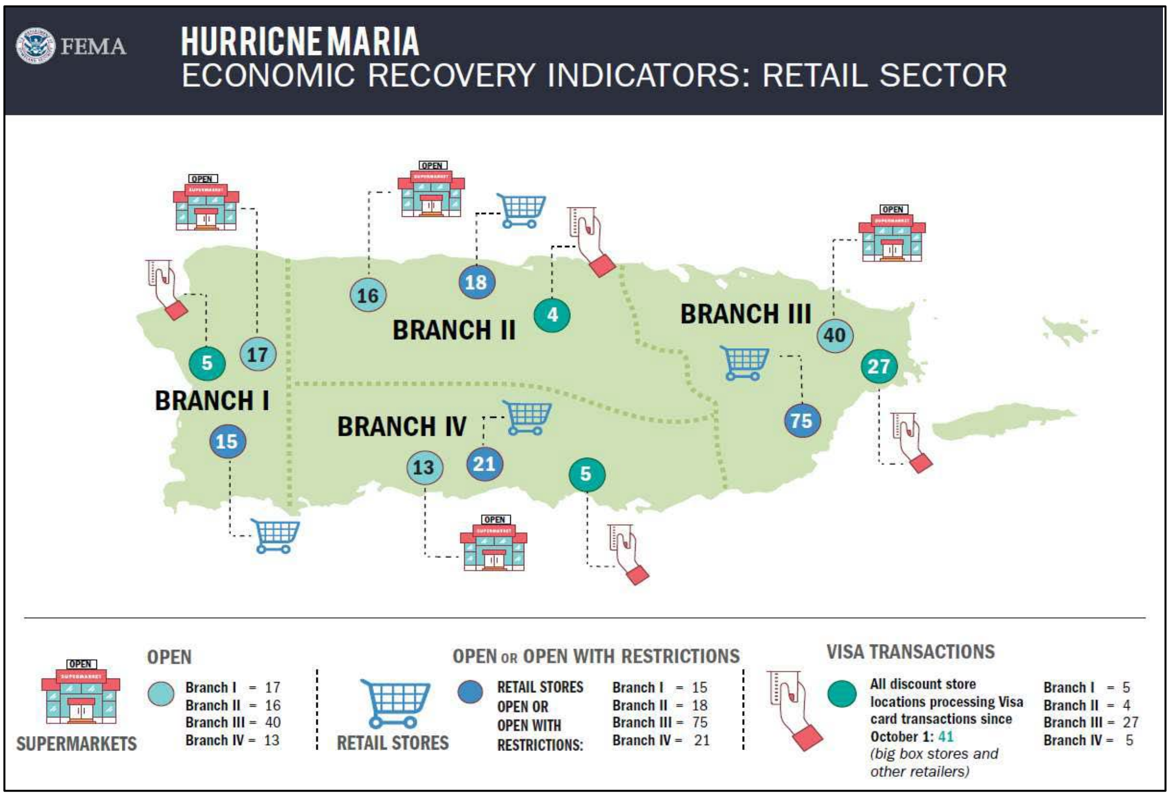
Finding the Pull Signal through Situational Awareness

Federal, commonwealth, and local authorities focused primarily on deploying an effective relief channel for mass feeding and other direct assistance to all survivors. As a matter of policy and strategy, this relief channel assumed the failure or near-failure of the preexisting demand and supply chain. The relief channel was organized to replace, not to supplement or gap-fill preexisting strategic capacity. The overwhelming push appears to be a combined effect resulting at first from a desire to fill an anticipated need when communication was cut-off, followed by fulfilling continuing requests for aid without accurate situational awareness of the private sector supply chain.

Situational awareness practices are generally linear and prescriptive and are not designed to look for unintended consequences or interdependencies. Situational awareness relies on observations and validation from the field, mostly from local, state, and federal response workers, and from the local private sector system if it is mature and capable of coordination. However, since the destruction following Maria was so widespread, this was a gap. Challenges in building and validating holistic situational awareness arose from a lack of access, lack of communications, and lack of effective processes from PREMA to build an accurate picture of local capabilities and needs, and to build a reliable picture of how the private sector was responding to those needs.

In an effort to bridge this gap and improve visibility into local businesses, FEMA helped to bring visibility of the private sector into the EOC, establishing the Business EOC (BEOC) on September 27 and 28, 2017. Figure CS2-10 shows the level of information the BEOC provided to FEMA leadership on the status of the private sector, particularly on the amount of open grocers in each area and access to electronic transitions—all good indicators that the supply chain was surprisingly resilient.

Figure CS2-10. Food retailer status presented to the FCO on 10/22/2017



Source: FEMA

Ultimately, in response to the ambiguity about food, FEMA created a “Food Acquisition Index” to help assess the specific status in each one of the 78 municipalities and determine how much and where food needed to go on the island. Prior to this, “FEMA was operating under pressures from the media, political pressure, and the requests from the government of Puerto Rico—all at the detriment of the private sector,” said Rob Glenn, FEMA’s Director of Private Sector. The Food Availability Index is an example of trying to be smart by moving beyond government-to-government pull to understand what is happening in the whole community, the real economy, the preexisting and—hopefully recovering or effectively adapting—demand and supply network.

As an effort to boost situational awareness specifically related to the food supply chain, however, the Food Acquisition Index failed to influence decisions made both in the field and especially in headquarters about FEMA's continued delivery of food—including both usable and unsuitable leftover food from Texas—as the supply chain was coming back online. While the BEOC undoubtedly had positive effects, its work did not link commonwealth and FEMA situational awareness or drive decision-making and the calibration of requirements with ongoing feedback loops.

The private sector has an important role in helping FEMA to build situational awareness. With a more complete picture of food supply chain systems reopening, the private sector could have greatly helped transition from FEMA's "push" model, which provides life-saving resources immediately following a disaster, back to the normal "pull" model where demand for goods drives supply and distribution decision-making.

Mr. Figueroa, the Emergency Management Director in Naranjito, said of the private sector in his municipality, "The private sector failed. They didn't have the generators or cisterns of water they needed. The local cafeteria only had a 200-gallon cistern that ran out of water in one day. They didn't have enough inventory. They thought they would be helped within three days, so they didn't maintain enough inventory to last any longer than three days." He noted one exception, "One bakery, Marina, surprised us. They had diesel, water, and a large inventory. They were open within 24 hours and lasted for seven days. They were the only business open for seven days."

PRELIMINARY CONCLUSIONS

The situation in Puerto Rico after Hurricane Maria was austere: information was sparse, communication was nearly impossible, and ambiguity prevailed. At the end of September, it appeared that very little was moving through the supply chain on the island. Within three days of Puerto Rico's request for 6 million meals per day, commercial movements of goods surged. Moreover, within three weeks, the local supply chain system was adapting to the situation and was able to provide commodities to local grocery stores. But FEMA's "free" goods and water were simultaneously flowing into the island. Eventually, the requirement for 6 million meals was recognized as too much and was reduced, but this could have occurred much sooner in the response if the information linkages were made.

A different approach to push/pull could have prevented the negative perception of the "free food and water" from the push of too many commodities, and alleviated the actual supply chain issues caused by it. The push of food and water onto an island with limited transportation options, led to cascading impacts most readily witnessed at the port where the release of containers was backlogged. In addition, the local public sector developed a reactive narrative around food disruption that was inaccurate, but created a tension nonetheless. As a result, both levels of government struggled with their roles in the food mission, but their resources would have been better served focusing on facilitating transportation and fuel deliveries, which both proved to have broader, positive effects on lifesaving.

Case Study 3: Fuel and Food—Resupplying Metro Miami

On Thursday, August 31, 2017 after a full week of rain, Houston's skies finally cleared. Over 39 inches of rain—more than a typical year—had fallen. Floodwaters began to drain. Remnants of Harvey churned slowly northeast. Meanwhile west of Cape Verde, Hurricane Irma was finishing her first full day at hurricane strength, achieving Category 3 (sustained winds over 111 mph) just before midnight. Conditions favored further strengthening. Spaghetti models were widely splattered, but Miami was certainly in play.

The Miami metropolitan area is the effective terminus of a dense economic corridor that begins at Boston, 1,500 miles north. Interstate 95 is the spine of this system, with average daily traffic exceeding 72,000 vehicles and sometimes surging to more than 300,000. Average daily truck traffic is over 10,000 and daily truck-counts that are triple the average are not uncommon. [123] The five million residents of metropolitan Miami ("Metro Miami") live near the end of a 400-plus-mile-long peninsula, clustered inside a 30-mile-wide strip between the ocean and the Florida Everglades. The city of Miami has a population density of more than 12,000 people per square mile. Getting food and other supplies to Metro Miami while most of its residents were evacuating highlights several supply chain issues, especially related to fuel.

PRE-EVENT DEMAND PULL

Given the dramatic media images out of Houston and the projections for Irma, many residents of Miami and most of South Florida spent some of their sunny Labor Day Weekend (September 2–4) stocking-up on hurricane supplies. Florida retailers—especially grocers and home improvement stores – were hard-pressed to keep up with burgeoning demand.

Truck traffic into Miami from Orlando and farther north increased throughout the first week in September. The annual average daily truck traffic for the most heavily used routes ranges between 9,000 and 12,000 trucks per day. [124-125] On Thursday, September 7, the same sensors reported truck counts three to four times the average.

A few hundred trucks delivering into metro Miami that week belonged to Cowan Systems, a third-party logistics operator headquartered in Baltimore, Maryland. Cowan's customers in South Florida include BJ's Wholesale Club. According to Steve Wells, Cowan's Executive Vice

President, several retail customers significantly increased deliveries starting the last week in August. “The Florida inventory build for hurricane season starts as early as May. But Harvey added urgency,” he said.[126] Water, groceries, and building materials made up most of the late August and early September loads.

Despite these preparations, consumer demand in front of Irma exceeded delivery capacity for several key products. On Tuesday, September 5, Reuters reported [50]:

> *Annisa Ali, 45, who just moved to Oakland Park, Florida, from New York City, said she was having a hard time finding water at local stores. “Last night, I went to Walmart. No water. I went to Target. No water. Now I’m here. No water,” Ali said at a grocery store in Wilton Manors, Florida. James Foote, a 56-year-old handyman in Fort Lauderdale, said he was unable to find any plywood to nail over windows at a local home supply store on Tuesday. He said more wood was expected to be delivered on Wednesday.*

At this point, most product shortages were the result of finite trucking capacity.[11] Most distribution centers had sufficient stocks of bottled water, toilet paper, batteries, and other shelf-stable product categories. But there were not enough trucks and drivers to meet surging demand. There is only so much mobile square feet available per route, only so many truck drivers, and the space between distribution centers and stores remains the same.

BJ’s Wholesale Club (with more than $11 billion in annual turnover), headquartered in Westborough, Massachusetts has 31 retail outlets in Florida, including a baker’s dozen in Metro Miami. The network is served by a 460,000-square-foot warehouse with a 173-door cross-dock near Jacksonville. Cowan Systems is co-located with its customer at this particular facility. BJ’s has a highly optimized supply chain that quickly delivers inventory to its large retail locations (typically over 100,000 square feet). Most inventory is expected to turn over within 30 days. “We don’t just have customers, we have members,” Trevor LaChapelle, Vice President for Global Transportation, explains. “They hold us to a higher standard and we want to be held to a higher standard. Demand was high both before and after Irma, especially for water. But we kept water in stock, even when we had to move it 1,200 miles from bottler to Club.”

Statistically, it can be argued that there is no “surge capacity” in US supply chains in general. Before Hurricane Harvey, the national vanload-to-truck ratio was close to five-to-one. By the time Irma was done, the ratio was more than seven-to-one. By January 1, 2018, the national ratio had hit ten-to-one.[127] Some regions have even wider ratios. What this means is that

[11] There are reports of individual suppliers being short on bottled water in early September because they had surged bottled water supplies into East Texas as part of the Harvey response.

any surge in demand is supplied by displacing previously targeted loads. Instead of surge capacity there is swapping-out how existing capacity is deployed.[12] Many of these loads are carried by "foreign power"[13] diverted—often at premium prices—from distributing other products to other places.

"We don't usually carry water from Pennsylvania to Florida," Steve Wells said. But when the supply of bottled water in Florida began to come up short, BJ's rounded-up and we loaded-up water all across the mid-Atlantic." Generators were also being hauled long-distance. It can take a full 24 hours or more to move a load from Scranton to Miami. While product is enroute BJ's works with Cowan to specifically target delivery locations, depending on last-minute demand. "The lane (I-95) is the same. But loads and routes and schedule can totally flip," Wells explains.

Similar swaps were happening across many product categories and a wide geographic area involving dozens of trucking companies and their customers. Vans originally scheduled to carry house shingles into Houston became vans carrying water into Homestead. "Foreign power" coming back empty from Houston picked up plywood in Atlanta and headed south toward Tampa. "Driving empty is a sin," Cowan's Steve Wells emphasizes. Dispatchers, brokers, procurement teams, store managers, and many more all work their digital and personal networks, aggregating last-minute loads to maximize all the capacity available to supply all the demand possible.

PERSISTENT UNCERTAINTY WITH PERCEIVED HIGH RISK

By **Tuesday, September 5**, Irma had become a Category 5 storm, with 175 mile-per-hour winds. It was the most powerful Atlantic mid-ocean hurricane ever recorded. [51] On September 7, the Caribbean islands of Barbuda, St. Martins, Saint Bart, and St. Thomas experienced horrific hits. More than one million residents of Puerto Rico lost power. [43]

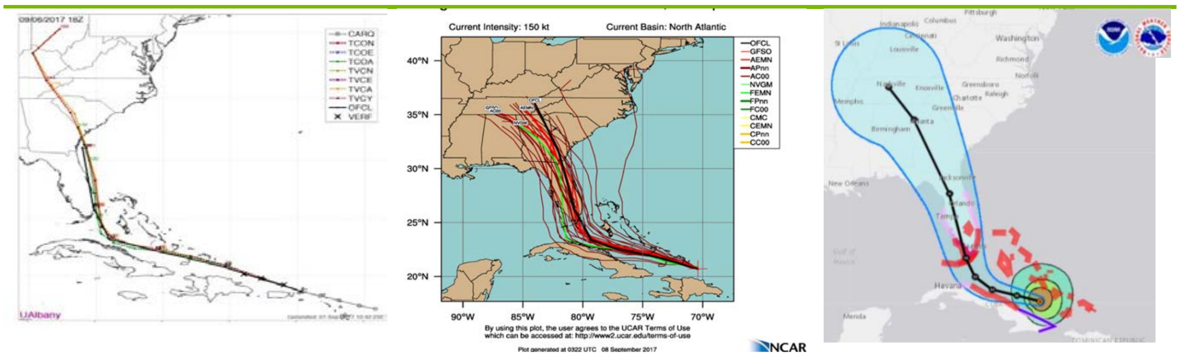
The forecast map for Miami remained uncertain. Eventual impact would be determined mostly by when Irma turned north. Some computer models forecast an early turn, keeping Irma just offshore and subjecting the entire I-95 corridor—Miami to Jacksonville—to a buzz

[12] In this context it may be worth remembering Churchill's question to the French High Command early in the German Blitzkrieg. "*Où est* la masse de manoeuvre?" he asked in bad French. "Where is the strategic reserve?" is a possible translation. Marshall Gamelin's reply, "Aucune!" (none) is exactly our current situation.

[13] "Foreign Power" is the trucking term for actual truck-tractors (source of power) moved from their usual area or operation to an atypical area of operation

saw of maximum sustained winds and storm surge. Other models had Irma barreling through the Keys and slowly paralleling Florida's Gulf Coast. In a newspaper column, Troy Moon wrote, "Hurricane Irma's Cone-Of-No-One-Has-A-Clue had the storm potentially coming our way. Or another way. Or some other way. The colorful storm models showing all the tracking predictions were as messy, looping, and entangled as one of my old Spirograph creations." [52]

Figure CS3-1. **Irma's track shifts from a consensus Atlantic landfall on Sep 6 (left), amid considerable uncertainty in the track (center), to a Gulf Coast landfall in the Sep 8 forecast.**



Sep 6, 6 p.m. | **Sep 7, 6 p.m.** | **Sep 8, 11 a.m.**

Sources: NCAR, NOAA, NHC

On **Thursday, September 7,** Miami-Dade and Monroe County (Florida Keys) announced mandatory evacuations [128]. On September 8, mandatory evacuations are expanded to include several Gulf Coast jurisdictions and areas around Lake Okeechobee [129].

EVACUATION IMPACTS RETAIL DEMAND AND SUPPLY

Eventually, more than 6.5 million Floridians were told to evacuate. Given the geographic scope of hurricane risk—and persistent uncertainty—consumption surged across the entire Florida Peninsula. As early as September 6, the *Tampa Bay Times* reported [53]:

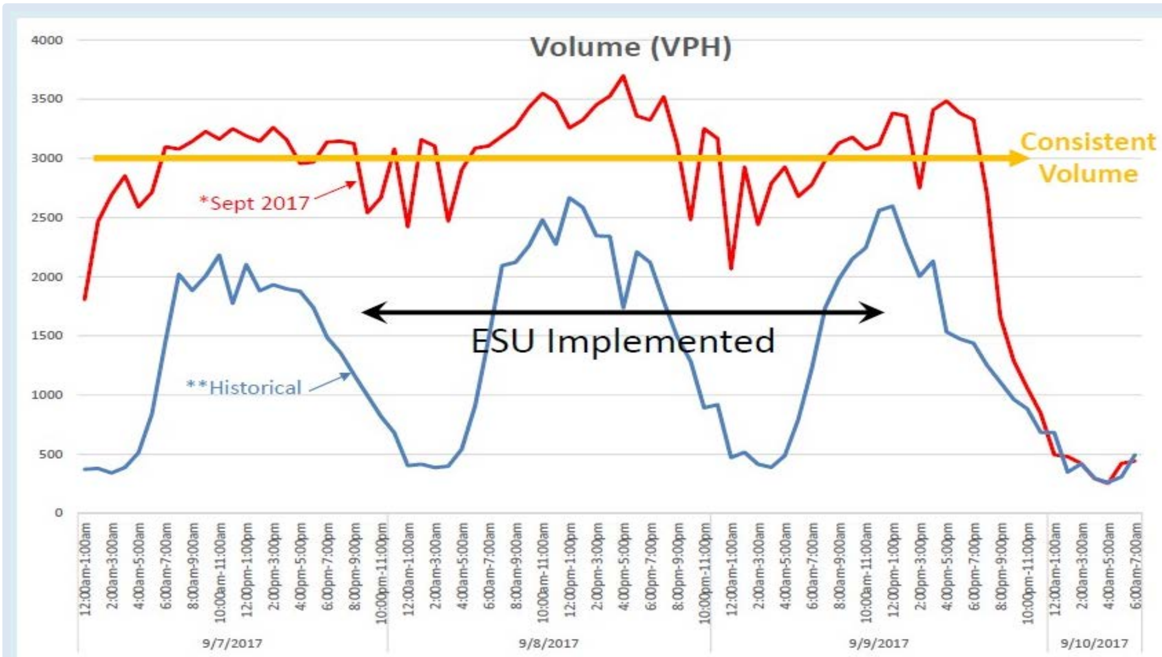
> *Retailers across Tampa Bay are trying to replenish supplies like bottled water, plywood, and other merchandise that is flying off the shelves at stores across the region. Some Publix supermarkets are limiting bottled water to two packages per person or four per family in an effort to share supplies evenly. Some local gas stations are reportedly selling bottled water packages for $8 a pop.*
>
> *"Our warehouse and distribution centers' water supply is at full capacity and stores are receiving deliveries throughout the day and night," said Dwaine Stevens, a*

> *spokesman for Publix. "We're monitoring the storm track and working with our warehouse and distribution centers to ensure our stores have water, batteries, hurricane supplies, and essentials to serve our customers. Supplies are ordered early so warehouses are well stocked should a storm threaten during hurricane season."*
>
> *(continued) Walmart and Amazon are reporting shipping delays for online orders due to overwhelming demands. Walmart stores have suspended all grocery pick-up services at stores in Florida for the duration the storm, said Regan Dickens, a spokesman for Walmart. He added that Walmart has sent 800 truckloads of bottled water to Florida, which began arriving at local stores last night. Walmart stores are restocking shelves by the hour, with the greatest need coming from the southern areas of the state and extending north.*
>
> *"While some stores may sell through product quickly, our supply chain and merchandising teams are working to ensure stores are replenished as quickly as possible," said Matt Harrigan, a spokesman for the Home Depot. "We began shipping pre-staged loads of hurricane supplies from distribution centers to stores in the potential strike zone late last week and we'll continue to do so through the end of the week."*

By Thursday, September 7, congestion caused by evacuation traffic is further complicating supply chain operations. "Going south into Miami was okay, even easier than usual. But making the return was a real pain," Steve Wells said. "I don't understand why Florida never used contra-flow. The usual four or four-and-a-half-hour trip from Miami to Jacksonville took over seven hours by Wednesday/Thursday." [126] On Thursday, the Florida Department of Transportation reported volume on northbound interstates at three to four times normal. [130] On Friday, it was worse. On Friday morning, Florida Governor Rick Scott says in interview after interview, "If you're in an evacuation zone, you've got to get out; you can't wait." The governor warns that evacuees need to be out of evacuation zones by midnight Friday. After that, high winds will make it too dangerous to be on the roads. [54]

Figure CS3-2 demonstrates the evacuation volumes between September 7 and September 10, 2017, for one monitoring location on I-75. [46] The total volume of vehicles-per-hour (VPH) is indicated with the red line. The blue line is total VPH for the same location averaged over time. Emergency Shoulder Use (ESU) is when Interstate shoulders were authorized for traffic use on September 7–10.

Figure CS3-2. Evacuation volumes in vehicles per hour, 9/7-9/10 (one location on 1-75 north)



The *Miami Herald* reported:

> *Thousands of Floridians found themselves in hours of gridlock or slow-moving traffic on Friday as they sought to head north and flee Hurricane Irma's wrath. The exodus was so much so that Interstates 95 and 75 were backlogged not only in parts of central and northern Florida, but also into southern Georgia, too. That prompted Georgia transportation officials to issue a 4 p.m. advisory telling drivers to expect an extra four hours on a trip from the Florida line to Atlanta — almost double the normal travel time.*

Some of Friday's congestion results from increasing concern that Irma could now become a Gulf Coast event. As shown on the maps below, many mid-week forecasts tended to emphasize the threat to the Atlantic Coast. The forecast track began to shift on Thursday and into Friday. **On Friday, September 8, 2017** at 11:00 a.m. (Eastern) the National Weather Service released a forecast anticipating an early Sunday morning landfall. By 5:00 p.m. on Friday the National Weather Service included even more of the Gulf Coast in its projection of storm surge and strongest sustained winds. [131] Storm surge ranges of eight to twelve feet were forecast for the Naples and Fort Myers region, and three to five feet in Tampa Bay.

As the Gulf Coast forecast became more foreboding, northbound traffic on I-75 north of Tampa began to reach the same concentration levels as I-95 north of Miami. Congestion was especially heavy between Wildwood and Ocala, where the Florida Turnpike connects Metro Miami to I-75 toward Atlanta.

According to the Florida Department of Transportation, between September 6 to 9, "I-75 northbound in the Ocala area experienced an hourly traffic volume with a 1,236% increase over the same day the previous year and experienced pockets of severe congestion." [46]

By Friday afternoon, September 8, northbound traffic on both coasts was generally four to five times normal volume. At many places, long lines formed at fuel stations. On what was thought to be its last deliveries before landfall, Cowan Systems had just over 100 vanloads to deliver into Metro Miami. Less than 15 percent of products made it to their destination that Friday. Most South Florida retailers were closing at sunset to allow employees to evacuate. "Lots of bare shelves needed restocking, but traffic was so bad we could not get to receivers before dusk," Wells remembers. "Several trucks had to be turned around full and join the crowds inching north." [126]

EVACUATION IMPACT ON FLORIDA'S FUEL SUPPLY

Double the time it takes to travel between Miami and Jacksonville and you almost double the diesel or gasoline consumed. Even as early as Thursday night, Cowan's carriers were no longer able to top-off their tanks in most of Miami or anywhere farther south. On Friday morning, Gas Buddy reported that 40 percent of gas stations in Miami and Palm Beach County were out of supply. Tampa was not much better, with nearly 35 percent of stations shuttered. Orlando still had more than two-thirds operating. The worst case was Gainesville, north of Orlando, where nearly 60 percent of retail fuel outlets were empty. [55] One of the reasons contraflow was not implemented was the result of an effort to resupply fuel into evacuation departure zones and northbound corridors. During a Friday news conference, Governor Scott explains, "We still need southbound lanes to get needed gas and supplies down to shelters and families that need it in southern parts of the state…. Contraflow also inhibits our ability to get emergency vehicles to people that need them." [55]

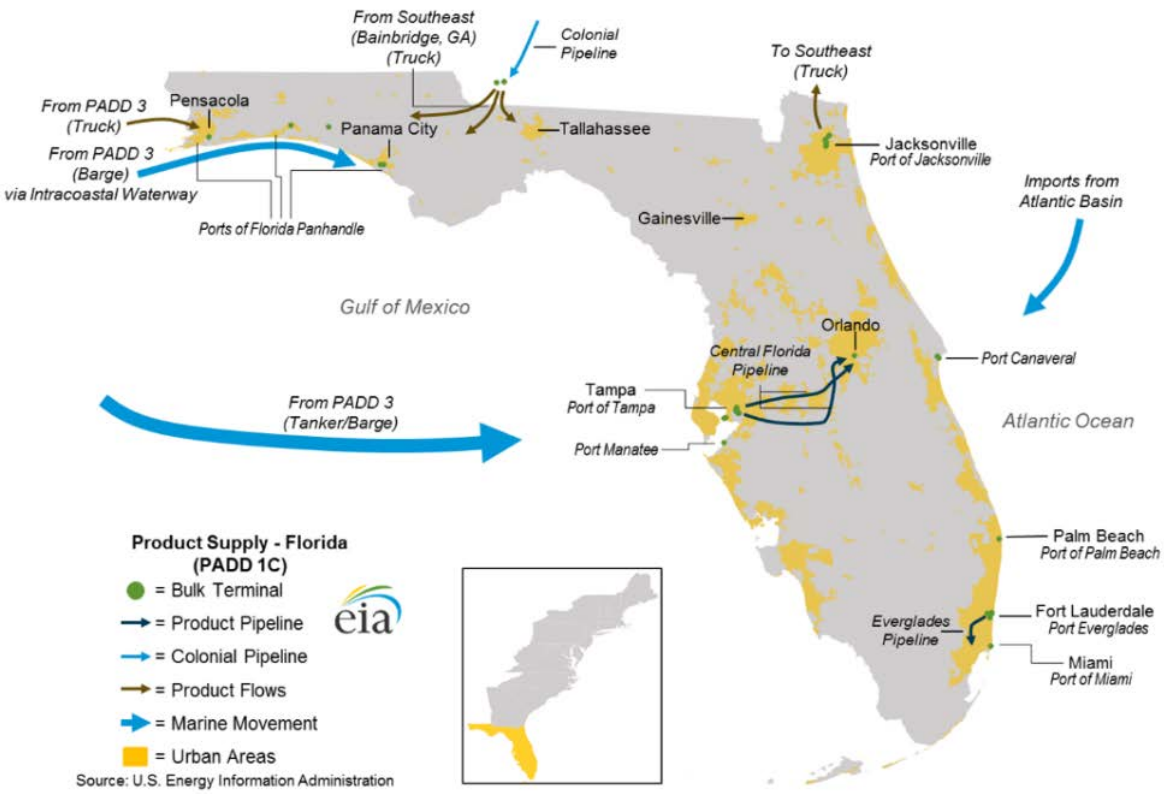
The supply chain for fuel includes sourcing raw petroleum (crude oil), refining into motor fuels at refineries; transporting to bulk storage facilities; transporting to retail fuel distributors; and, finally, dispensing at retail stations for use by vehicles. Florida does not have any appreciable petroleum production or major refineries. As is the case in many Southeastern states, most of the fuel that Florida uses is produced at refineries along the Gulf coast of Texas and Louisiana. The fuel supply chain in Florida is also different than most states because it has few pipelines, relies heavily on petroleum ports, and has relatively few petroleum product terminals.

Florida's fuel network especially depends on three big nodes[132] (see Figure CS3-3):

- Tampa Bay Port: over 273,000 barrels per day. Fuel arrives by barge from refineries near Houston. The fuel terminal is operated by Kinder-Morgan. It includes 1.8-million-barrel storage capacity and pipeline connections to the Taft terminal near Orlando.
- Port Everglades (Near Miami): over 298,000 barrels per day. Fuel arrives by maritime means from a variety of domestic and international sources and is distributed to 12 different petroleum companies serving South Florida. In 2017, 661 petroleum ships docked at Port Everglades.
- Bainbridge (Georgia) Terminal (near Tallahassee): over 150,000 barrels per day arrives via the Colonial Pipeline from refineries near Houston.

Maritime fuel deliveries are made to other Florida ports and, especially in North Florida, fuel is sourced by truck from various out-of-state sources. But according to a 2016 report by the U.S. Energy Information Administration, these three nodes provide more than half of the transportation fuel consumed in Florida. [133] All three include commercial fuel racks located at bulk terminals (i.e., petroleum product terminals) to supply tanker trucks. Also note in Figure CS3-3 that there are relatively few bulk terminals across the state, including some major metro areas (e.g., Gainesville, Fort Myers) with none.

Figure CS3-2. **Fuel supply network in Florida. [133] Florida depends on petroleum ports and offloading from the Colonial Pipeline at Bainbridge, GA for its supply. There are relatively few pipelines to move fuel within the state.**



Source: U.S. Energy Information Administration

There were sufficient fuel stocks on hand to meet demand during the Irma evacuation, but the level of "demand congestion" exceeded the delivery capacity of tanker trucks available. The number of fuel retailers and the distance of fuel retailers from fuel racks is constant. The number of fuel tankers operating on the routes between retailers and racks is mostly constant. Some increase in demand can be met by increasing hours of operation. But even this can be constrained by state and federal regulation. The wider the geographic scope of surge, the less any system can scale to serve it. A demand surge of 400 to 500 percent will drain a typical week's worth of retail fuel storage in less than a day. Given the innate limits of the fuel distribution system in Florida, this level of surge will always result in retail points of distribution running out of fuel.

One locus of demand for fuel in the days before Irma's Florida landfall was the Pilot Travel Center (Store #90) at the intersection of I-95 and the Florida Turnpike, near Fort Pierce (see Figure CS3-4). Across the street is a Love's Travel Stop. About two miles north is the competitive tandem of another Love's and a Flying J (owned by the same company as Pilot). This concentration of retail supply is well-suited to this junction 225 miles south of Jacksonville, 130 miles north of Miami, 150 miles east of Tampa, and about three miles west of the Atlantic Ocean. Pilot/Flying J, headquartered in Knoxville, Tennessee, is the largest retailer of diesel fuel in the United States. Pilot is also a regularly contracted source of diesel fuel for the Cowan Systems fleet.

Figure CS3-4. Critical fueling station – Pilot Store 90

UNCERTAINTY PERSISTS AS IRMA ARRIVES

As late as Friday evening, threat-vectors for Irma remained fungible. Just before midnight on Friday Weather.com posted the following [134]:

> *Key uncertainties still remain in the forecast for Irma's eventual impacts along its future path.... Irma is a large hurricane, so, despite the uncertainty in its track, impacts will be felt in a large area along its path.... Irma will remain an intense hurricane, at least Category 4, as it makes landfall in South Florida on Sunday, with potentially devastating impacts. The hurricane will then go on to affect much of the peninsula, with severe impacts extending into parts of central and northern Florida. Life-threatening storm-surge inundation will occur along coastal areas north and east of Irma's path. Hurricane-force winds (74+ mph) that are capable of causing structural damage and widespread power outages will also occur. Flooding rainfall and isolated tornadoes are threats as well. Irma has a large wind field so tropical-storm, even hurricane-force winds might reach both the west and east coasts of Florida, even outside of the cone. This includes Miami, Naples, Fort Myers, Fort Lauderdale, Tampa–St. Petersburg, and Orlando.*

On **Saturday, September 9,** Irma became the second recorded Category 5 hurricane to ever hit Cuba. At least ten people were killed and over a half-billion dollars damage was done.

About one hundred miles east of Havana, Irma finally made her long-anticipated right turn, angling sharply northwest.

In Florida, the highways were packed as tens of thousands continued to move north. A Tallahassee newspaper reported on the Governor's Saturday morning news conference[135]:

> *With a sense of urgency in his voice, Gov. Rick Scott bluntly told millions of Floridians in a mammoth evacuation zone to leave or take shelter immediately today, as Hurricane Irma's high winds began battering the Keys.*
>
> *"The storm is here," Scott said at a briefing in the Sarasota Emergency Operations Center. "This is a deadly storm and our state has never seen anything like it. Millions of Floridians will see major hurricane impacts with deadly storm surge and life-threatening winds."*
>
> *The governor said 25,000 south Floridians had already lost electricity when he held his 9 a.m. briefing.*
>
> *Irma weakened to a Category 4 hurricane after striking northern Cuba overnight, but was forecast to strengthen back to Category 5 — with winds of more than 150 miles an hour — in the warm Straits of Florida waters as it curves north to the Keys... "You need to leave now," Scott said, enunciating each word slowly for emphasis. "Do not wait, evacuate — not tonight, not in an hour, you need to leave now."*
>
> *"I want to be clear," Scott said, "we are under a state of emergency. This is a catastrophic storm. It's bigger than our state."*

At the Pilot Travel Center near Ft. Pierce, Floridians had been following their Governor's advice. On Wednesday and Thursday, September 6 and 7, Store 90 experienced demand volume four to five times normal. Each day the store sold as much gasoline as is usually sold some weeks, supporting the evacuation north from Miami. Diesel volumes were about triple daily averages. Fuel was being delivered by multiple vendors from various locations as quickly as it could be procured.

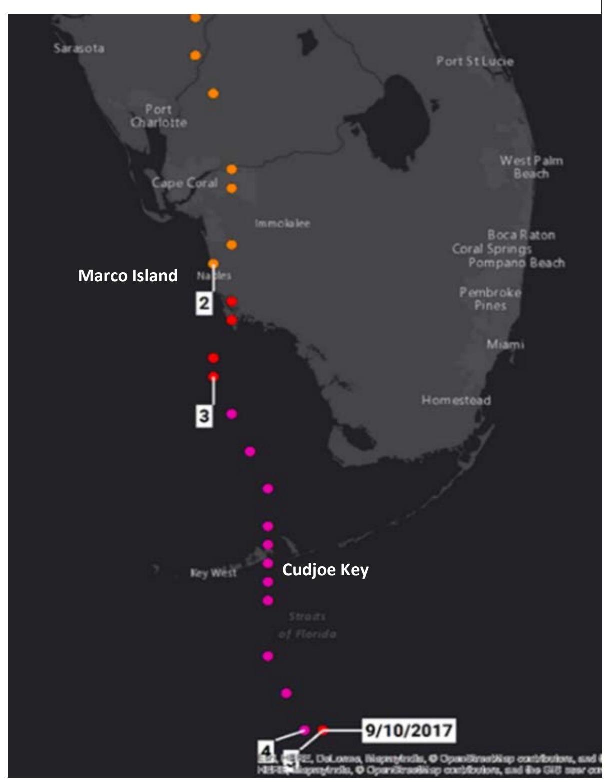
On Friday morning, September 8, Store 90 was not refueled. By early afternoon it was out of gasoline. By late afternoon it was out of diesel.

Friday evening the Pilot Travel Center closed. It had no fuel and few shelf-products remained. McLane, the store's principal shelf-products vendor, had cancelled its Friday delivery. McLane did not resupply Store 90 until Friday, September 15. The store manager had secured five rooms at the Fairfield Inn, walking distance from the store, where the manager, assistant manager, and three employees rode out the storm.

At the BJ's/Cowan terminal near Jacksonville, 124 trucks were loaded and had their gas tanks full. On Saturday, crews stayed out of harm's way. But depending on conditions, the plan was to begin making runs into Metro Miami as early as Sunday night, trying to resupply stores that had not received their scheduled deliveries on Friday. BJ's had more than 100 "Hurricane Trailers" preloaded and staged with all the supplies typically needed after a storm and when the power is off. For this purpose, BJ's maintains a trailer pool in its Jackson freight yard. The BJ's cross-dock is designed to push product forward fast. There is very little space to hold inventory. "We shed our congestion risk by quick transfer of inbound to outbound or outbound-ready," Trevor LaChapelle explained. "We don't have much room at the cross-dock. If we can't get to our Clubs or our Clubs are unable to receive, we move product into outbound trailers. Our trailer pool is not efficient, but it is the least inefficient of relief valves available to keep flow moving or ready to move."

On **Sunday morning, September 10,** Irma made landfall on Cudjoe Key, 100 miles southwest of Miami, as a Category 4 hurricane (see Figure CS3-5). On Sunday afternoon at 3:35 p.m. the hurricane makes a second landfall at Marco Island and tracks north, again with 130-mile-per-hour winds. According to the National Weather Service, "Sustained hurricane force winds extended well inland over the southern Florida Peninsula. At Government Cut off of Miami Beach sustained winds of 65 knots at an elevation of 23 meters occurred, and a wind gust of 97 knots was measured at Deerfield Beach. Nearly all of the inland observations in the Miami-Dade and Broward County metro area reported sustained winds just below hurricane force."[136]

Figure CS3-3. Path of Hurricane Irma



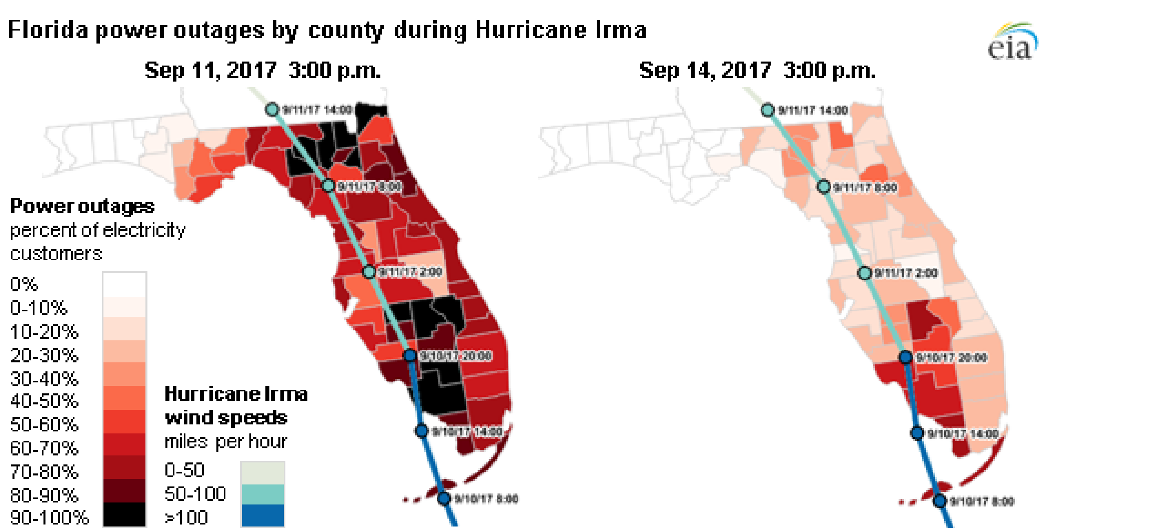
Storm surge near landfall was recorded at up to 10 feet above ground level. But elsewhere on the Gulf Coast surge ranged mostly between three and six feet. Extensive flooding in Miami was not all surge related. More than eight inches of rain fell in Miami, with some places totaling 15 inches over September 9–11.

According to the National Oceanic and Atmospheric Administration [136] :

> The combined effect of storm surge and the tide produced maximum inundation levels of 4 to 6 ft above ground level for portions of Miami-Dade County in southeastern Florida, especially along Biscayne Bay. A [U.S. Geological Survey] USGS storm- tide sensor at Matheson Hammock Park in Miami measured a peak water level of 5.75 ft NAVD88 (5.6 ft MHHW), consistent with a high water mark of 5.1 ft above ground level which was surveyed in the park. The NOS (National Ocean Service) tide gauge on Virginia Key recorded a peak water level of 3.7 ft MHHW. Significant flooding occurred in downtown Miami; however, the flooding was likely caused by a combination of heavy rainfall and urban runoff, wave overwash becoming trapped behind seawalls, and seawater coming up from below through the city's drainage systems.
>
> *Note: NAVD88 – North American Vertical Datum of 1988. MHHW – Mean Higher High Water.*

By Sunday night, at least four million electric customers had lost power, including more than three-quarters of those living in the Metro Miami area. (see Figure CS3-6). More than 20,000 Florida Power & Light (FPL) utility workers with equipment had been predeployed for the restoration process. [137] Still, for many residents, it took more than a week for their grid access to be restored.

Figure CS3-4. Four million customers in Florida lost power by September 11th, including over 1.5 million in Miami-Dade and Broward County.



Source: US Energy Information Administration, National Hurricane Center, Florida DEP

The Pilot Travel Center near Ft. Pierce lost electricity around noon on Saturday, presumably from downed power lines. The possibility of quick restoration disappeared when the electrical substation serving Pilot's Store 90 lost grid connection at 7:15 p.m. The store is prewired with a transfer switch to quickly connect to a portable generator, but there is no permanently installed power generator.

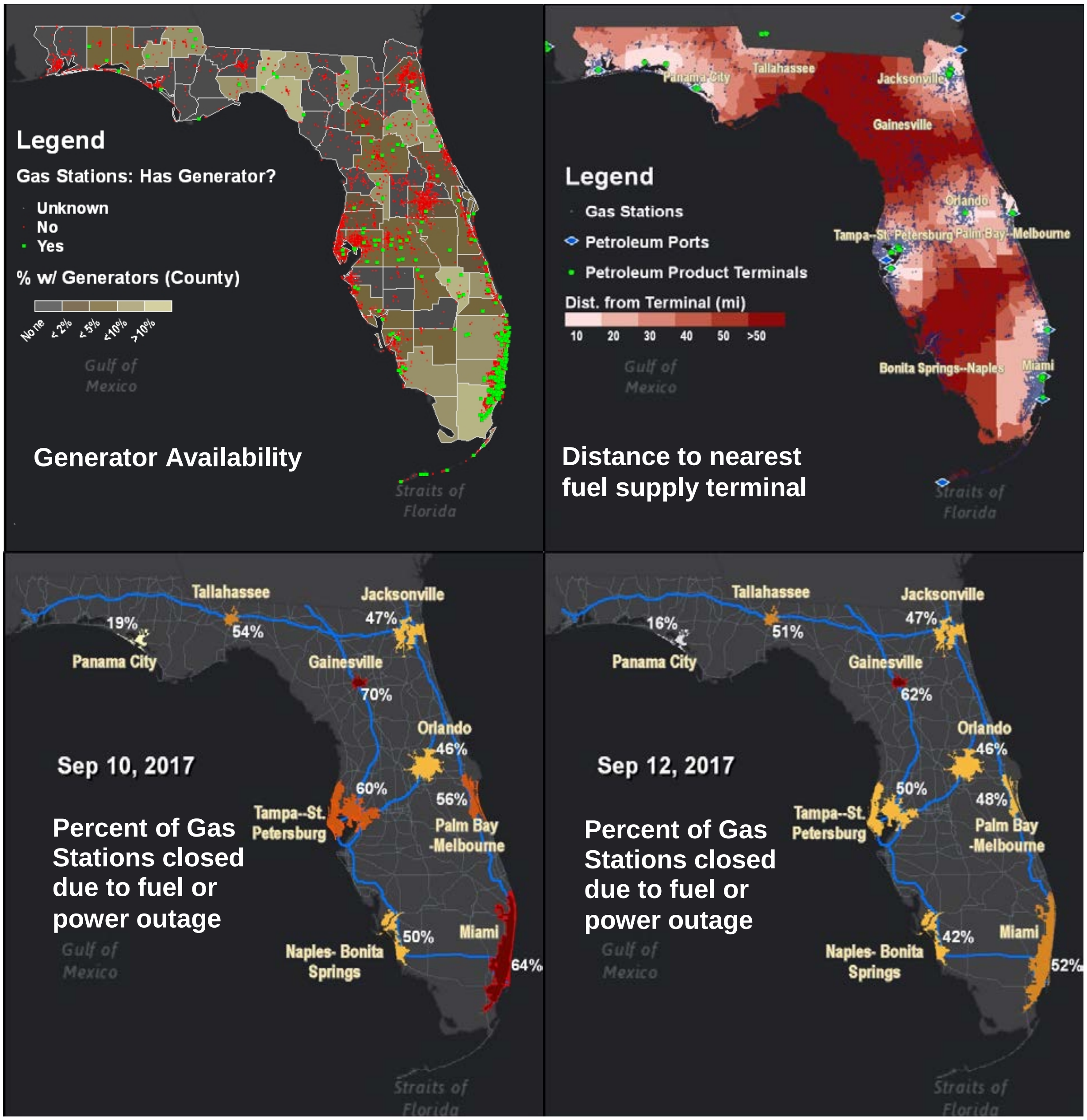
Store 90 is connected to the electrical grid through the Fort Pierce Utilities Authority (FPUA), whose electric service area encompasses roughly 35 square miles and serves approximately 28,000 customers; the utility delivers roughly 45,000 MWh of power per month. This power is sources through three 138 kV interconnections with Florida Power & Light and one 138 kV interconnection with Vero Beach Utilities. FPUA owns and maintains approximately 266 miles of overhead lines, 151 miles of underground electric circuits, and over 20,000 poles and 5,600 transformers. Store 90's manager had never been contacted by county or state emergency management or utility officials regarding priority restoration of power, nor had he ever contacted them.

Fueling stations have three essential needs in order to operate: fuel delivery, power to run pumps, and a method of processing payments. During hurricanes, power often goes out, and without backup generators, stations cannot run their pumps. Less than 5 percent of Florida gas stations have backup generation capability, though generator prevalence varies by county. Fueling stations are also vulnerable when deliveries are interrupted.

According to the National Weather Service, Hurricane Irma hit the Ft. Pierce area especially hard Saturday night and into the early morning hours of Sunday, September 10 with wind gusts of 100 miles per hour and sustained winds of over 70 miles per hour**.** More than 21 inches of rain was recorded at the Ft. Pierce water plant. When the store manager returned shortly after dawn on Sunday, water was near knee-deep in most of the truck bays, and some water had penetrated the store (despite baffles and other protective measures). Store personnel focused on clearing debris from retention pond intakes and cleaning the interior of the store. While significant draining occurred on Sunday, a few inches of standing water continued to cover the truck lot until mid-week. There was no significant wind-damage at the store. Cellular telephones continued to operate as usual. The Pilot Travel Center remained disconnected from the electrical grid on Monday, September 11. Yet there was progress: at 3:52 p.m. on Monday, the area's substation was reconnected.

A snapshot of the various power challenges facing Florida is provided in Figure CS3-7—specifically, generator prevalence at retail gas stations by county (top left); mean distance from nearest petroleum product terminal by U.S. Census Bureau block group (top right); percent of gas stations out of service by metro area after Irma's landfall on September 10 (bottom left); and percent of gas stations out of service two days later, on September 12 (bottom right). [92, 125, 138-139]

Figure CS3-7. Florida's retail fuel network experienced shortages because some areas had few stations with generators (top left), many stations are far from bulk terminals (top right). The outages by metro area are shown for Sep 10th and 12th.



Sources: CNA, EIA, FL DEP, GasBuddy. [92, 125, 138-139]

On Sunday, there had also been heavy rain over Jacksonville and most of northeast Florida, but shortly after midnight Cowan Systems dispatched 20 trucks for Miami, 350 miles down I-95. This was a reconnaissance operation: Depending on what was discovered, more than a hundred trucks were ready to head south before dawn on Monday. Cowan was not the only carrier probing Metro Miami.

The drivers found the roads in good shape and the BJ's Wholesale Clubs in Miami were ready to receive, even though all depended on backup electrical generation. Yet the drivers were unable to find any refueling locations. Many of the truck stops had been drained of fuel before landfall and had not been refilled since. On Sunday night, none of the truck stops on I-95 between Jacksonville and Miami were reconnected to the grid and not all had backup generators.

Figure CS3-8. FPUA Facebook post from 5:42 p.m. on September 11, 2017.

Fort Pierce Utilities Authority
September 11, 2017 ·

FPUA Update - Electric
Fort Pierce Utilities Authority is continuing to assess damages. Due to the length and severity of the storm, approximately 23,700 FPUA customers and three of FPUA's substations were without power. Power has been restored to all three substations and approximately 6,200 customers. Power is being restored to main feeders and then to lateral lines. Restoration crews are focusing their restoration efforts on critical customers, Health Care facilities, Nursing Homes, Wastewater Facilities, and other Health and Safety Systems/Facilities. Once critical customers are restored, FPUA restoration efforts will restore power to the greatest number of customers in the least time. Care is being taken to restore power efficiently while continuing to ensure safety for both customers and lineman.
Currently, restoration efforts include FPUA's 14 internal linemen working extended shifts. Mutual Aid crews from Michigan are expected to arrive this evening and will provide 22 additional lineman to assist in restoration efforts. In addition, 15 tree trimmers are assisting with vegetation management to facilitate efficient power restoration. We appreciate your patience.

Wastewater
FPUA's Water Reclamation Facility on South Hutchinson Island lost power from approximately 11:00 PM, September 10th, until 1:00 PM September 11th causing the deep water injection well to be inoperable. This necessitated a release of treated effluent into the Indian River. This poses no threat to the human population or wildlife.

In well-moving traffic most heavy-duty trucks will get 6.8 to 7.2 miles-per-gallon (mpg). 300-gallon tanks on each truck are typical. This gives each truck roughly 2100 miles between fill-ups. But during the week before Irma's landfall, traffic congestion had reduced mileage to as low as 4 mpg, or only 1,200 miles between fill-ups. A round-trip between Jacksonville and Miami is 700 miles. Because Cowan had topped-off tanks before Irma, its fleet could confidently complete one roundtrip to Miami, but nothing more would be possible until refueling was assured.

Monday morning, September 11, arrived with no observable change related to grid restoration or fuel availability along the I-95 corridor (see Figure CS3-8). During Harvey, Cowan EVP Steve Wells had started sharing information with a supply chain analyst volunteering at FEMA headquarters. Late that morning, he sent an email outlining his concerns in Florida:

Appears we are in the worst shape in Jacksonville and Orlando. No power, flooding.

Surprisingly, Miami and Tampa—we are in good shape so far. Nothing major to speak of in terms of damage.

No word from the Fort Myers area, or south of Miami (Homestead). This area is of concern.

Some drivers (I'll estimate about 50% of the workforce) are able to come to work later today; but we have no fuel source at this point. All trucks are full of fuel but will only last about 1,000 miles of transit. We'll chew that up in 1-1/2 days.

Therefore, because fuel is an uncertainty—we are holding back inbound trucks (in North & South Carolina, destined for Florida) and delaying start up until tomorrow sometime—once we can determine that we have good access to fuel. Fuel seems to be the only thing holding back reactivating operations at this point.

According to the U.S. Energy Information Administration, "Power outages in Florida rose slowly on September 10, but they increased rapidly overnight as Hurricane Irma traveled up the state. About 15% of customers were without power at noon on September 10, and power outages peaked at 3:00 p.m. on September 11, affecting 64% of customers."[65] Along the I-95 corridor, outage percentages of over 80 percent were common.

On Monday afternoon, mutual aid utility crews on their way to support FPUA ran out of fuel in northern Florida. FPUA employees and equipment were sent to refuel the Michigan-based mutual aid trucks.

At FEMA's National Response Coordination Center (NRCC) in Washington DC, observations, information-exchange, and priority-setting discussions with Florida officials continued Monday afternoon. BJ's Wholesale Club is not the only distributor with major nodes between Jacksonville and Lake City, where less than 60 miles separate I-75 and I-95. Many of the long-haul truck fleets serving Metro Miami had been pulled back to Orlando or Jacksonville. All were facing fuel limitations similar to those on Cowan's fleet. At 8:15 p.m. on Monday evening, the following analysis was distributed inside FEMA headquarters:

We perceive that a significant proportion of private fleets are staged near Jacksonville or farther north to avoid Irma. We have specific and first-person reports from operators of these private fleets that they are delaying resupply of metro Miami and other locations because of the lack of fuel between Jacksonville and Miami…

We are concerned that unless resupply of metro-Miami begins in earnest tomorrow (Tuesday) or Wednesday at the latest that demand will far exceed supply in the metropolitan region.... potentially re-initiating hoarding behavior that will diminish existing supplies even more quickly. A similar situation may exist in Ft. Myers and Naples. In prior disasters, public foraging has sometimes unfolded into civil unrest.

At the intersection of I 95 and Florida 70 there is a Pilot Truck Stop and Love's Truck Stop. There is a Gator Truck stop a few miles north. Can these locations be rapidly *prioritized for power restoration? Can these locations be rapidly re-energized using mobile generators? Are there other locations with existing truck stops that are better suited for rapid restoration of power?*

If one of these efforts to re-energize is effective, is there enough capacity in federal and state fuel reserves to support a private sector refueling depot at these locations? For how many trucks?

There are considerable uncertainties here. But the threat of insufficient supply of the metro areas will grow more and more dire the longer re-fueling is not available.… If we can get the power restarted somewhere appropriate, THEN we can seriously tackle fuel ... if the ports and fuel distributors have not already solved the problem.

About 30 minutes after the Monday night note was distributed inside FEMA headquarters, Cowan's Steve Wells wrote to his FEMA contact:

I have 25% of my Florida-based drivers willing to work tonight. Tomorrow, I have commitments that the number will increase to 50–60% attendance. However,… I can't send them too deep into Florida … because there is nowhere to fuel.

So they are in a holding pattern right now and limited to only deliver to select locations (which have power and are able to receive goods) in North Florida and Georgia. We have reluctantly abandoned any hope of sending trucks south of I-4 tonight.

I am sitting on 124 loads of supplies in Jacksonville as we speak, with another 50+/- loads in route. I am holding the 50+/- loads in route in Atlanta GA, and just outside Fayetteville NC.

Until I have certainty on the ability to get fuel, I won't move these trucks—it's too much of a risk right now. We have a 6 a.m. internal discussion planned, and may release those trucks at that point.

One plan we have is for the drivers staged in GA and NC to run into our terminal in Jacksonville switch trucks – dump theirs off low on fuel, and hop into others which are full of fuel (I fueled all my trucks in JAX [Jacksonville]/ topped off prior to the storm).

Then we will run until we exhaust fuel supplies. We have loaded these trucks up with water and food in the bunks so the drivers can survive on the road for 3-4 days if they get stuck. This is the current plan to service South Florida tomorrow night maybe. Not the #1 choice for me.

I spent the whole afternoon searching for vendors who could deliver fuel to our fleet in Jacksonville or if we could go to them to fuel up. No luck.

If I could just get about 8000 gallons of fuel in Jacksonville, it would be golden to move a ton of freight—gives me about 50,000 miles of run time. I am sitting on generators, water, batteries, food, tarps … etc. What I would consider critical items.

In my opinion – tomorrow [Tuesday, September 12] is a do-or-die day for the Feds. Either they jump in and problem-solve this or the wheels will come off the cart *because we are going to have a bunch of parked trucks by tomorrow night when we run out of fuel. And the supply chain comes to a grinding halt.*

Monday night, September 11, NRCC staff did "jump in" to ensure truck stops along I-95 were re-energized and refueled. This involved working closely with the State of Florida's Emergency Operations Center on power restoration and with the Defense Logistics Agency on making sure federal fuel supplies could be available if necessary. But even as Tuesday morning dawned there remained several broken links—and considerable uncertainty—between Jacksonville and Miami.

The I-95 corridor in Florida gets its fuel primarily from Port Everglades near Miami, Taft Terminal near Orlando, Port Canaveral on the Atlantic Coast east of Orlando, and the Port of Jacksonville. All these locations were hit hard by Irma. The Coast Guard closed Port Everglades to maritime traffic on Friday. Canaveral and JAX were closed on Saturday. Taft Terminal is supplied via pipeline from Port Tampa Bay, which was also closed on Saturday [45].

Port Canaveral is the smaller piece of the I-95 Corridor's fuel capacity, handling about half the fuel flow of JAX, about 25 percent of Taft, and only about 10 percent of Everglades. But to fill the gap between Jacksonville and Miami on Tuesday, September 12, the terminal and racks at Port Canaveral were crucial.[14] Tanker trucks began queuing at Canaveral early on September 12. The racks opened at dawn. Over the next 48 hours, more than 750 fuel tankers were filled.[15] It was a big help that in May 2017 the racks had been expanded from six bays to ten. At Tuesday noon the Coast Guard opened Port Canaveral to restricted commercial vehicle traffic, specifically to receive an incoming fuel vessel. [140]

On most days Pilot Store 90 at Ft. Pierce, 90 miles south of Port Canaveral, sells more diesel than any other Pilot or Flying J in Florida. Sitting at the intersection of I-95 and the Florida Turnpike, the truck stop is typically very busy. But Tuesday at dawn Store 90 was still dark and empty.

From Labor Day forward, Pilot's headquarters in Knoxville, Tennessee was in constant contact with tanker truck operators at every rack in Florida and across the Southeast to refill its operations. In normal times, Pilot/Flying J serves its stores with its own fleet of more than 900 tanker trucks. But in the days before and immediately after Irma, Knoxville was procuring and dispatching fuel wherever and however it could. From Monday night into

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[14] Port Canaveral is unique among Florida ports in importing a majority of its fuel from non-US sources.

[15] Florida Ports Council, Hurricane Preparedness. The tanker truck throughput was about 10 percent above normal days.

Tuesday morning, FEMA, the Florida Division of Emergency Management, the Defense Logistics Agency, and Foster Fuels (the DLA fuel contractor) were engaged in parallel efforts focused on the I-95 corridor. Early Tuesday morning an intergovernmental plan was ready to be executed for tanker trucks to be dispatched from a staging area in Alabama late in the morning. FEMA was also working to locate and transport generators necessary to pump the fuel.

On **Tuesday morning, September 12,** the Flying J Truck stop, two miles north of Store 90, was reconnected to the grid at about 8:00 a.m. Flying J shares the same main feeder line as the local hospital and jail. Shortly after the Flying J was re-energized it received a fuel delivery from a Pilot fuel tanker. The same tanker truck delivered fuel to Store 90 even before it had power. Other tankers followed. By about 2:00 p.m. on Tuesday, September 12, Store 90 was reconnected to the electrical grid and reopened. The FPUA Director of Operations says that both reconnections were scheduled in accordance with pre-storm priority plans focusing entirely on immediate life-safety issues. The strategic importance of Store 90 was not locally known. Supply chain resilience was not part of local decisions.

Mid-morning on Tuesday at Cowan's Baltimore offices, Steve Wells got a call from a Pilot executive in Knoxville: fuel had just become available at Ft. Pierce. Steve called BJ's headquarters in Massachusetts and the Cowan team at the BJ's cross-dock outside Jacksonville. Over 100 trucks full of water and food started moving south on I-95.

There were still plenty of problems. Trucks were not allowed to deliver to BJ's in Ft. Lauderdale because of curfew. The traffic southbound on I-95 was crowded with returning evacuees, reducing the average mpg by nearly 30 percent. "We had one truck run out of fuel and practically coast into the Ft. Pierce Pilot. Really close calls," Steve Wells recalls. Resupply of the Tampa region was delayed until Wednesday by continuing lack of fuel on the Gulf Coast.

But by Tuesday afternoon, most Miami-area BJ's and most other grocery retailers—supplied out of Orlando or Jacksonville or wherever—were well stocked and ready for customers.

PRELIMINARY ANALYSIS

The risk to resupplying Metro Miami on Tuesday, September 12, 2017, was much greater than generally recognized. Extraordinary measures by several decision-makers were necessary to avoid a possible shortfall. Most of these measures were taken independently of one another and were unknown to the decision-makers involved. The failure of any single measure could have resulted in resupply being further delayed. The consequences of such a delay cannot be confidently projected.

Every day—disaster or not—supply chains consist of many moving parts. No matter how well calibrated the various system components are, there is friction, failure, and surprise. Disasters multiply uncertainty. Uncertainty amplifies the system's dissonance. Thousands of independent, rather random choices made to reduce uncertainty accumulate to produce the reality then experienced. Taken together, these individual choices are difficult to undo and can sometimes cascade unpredictably.

Nonetheless, pre-existing networks do tend to persist. Roads and, especially, bridges are difficult to replace quickly. Supply nodes—ports, warehouses, distribution centers, truck stops—emerge over time in relationship with the transportation network. Supply nodes, together with transportation links, establish the system's capacity and—often unintentionally—impose constraints on capacity.

Congestion exposes constraints. Demand congestion, as when millions are evacuated up a peninsula, will expose otherwise hidden constraints on road, fuel, and other networks. Supplying five times the normal demand for bottled water will expose rate-limiting factors that are not usually obvious in system operations on ordinary days. Supply congestion—as when inbound product accumulates faster than outbound product can be distributed—can be as complicating.

When there is more pull (demand) than usual, contemporary supply chains stimulate equal or greater push (supply). Suddenly increased volumes moving through finite time and space will find—sometimes even create—impediments to flow. In worst cases, such impediments can debilitate entire networks. Reducing or removing emergent bottlenecks is much of what supply chain management does on the best days, and this skill is even more valuable on the worst days. Doing this in a disaster—with the grid down, telecommunications disrupted, populations on the move, and dealing with deep uncertainty—is a significant challenge.

In many cases, the emerging constraint is not recognized until too late. During September 10–12, 2017, the lack of fuel on I-95 and its supply chain implications were recognized in time. A possible mitigation measure—refueling and re-energizing Store 90—was recognized late on September 11, but it was not too late. Several separate mitigation paths coincided over about six hours on September 12.

In Washington, Tallahassee, and Knoxville, several people and different organizations were pushing to secure fuel for Store 90. Pilot/Flying J were calling all their regular and several new vendors. FEMA was working federal sources. At Canaveral, Everglades, and Taft, hundreds of truckers—who were also storm survivors—queued up. Emergency electrical generators were turned on. Purchase orders were processed. Trucks filled with fuel were able to travel open roads. Would the tanker that filled Store 90 have been there in time if the fuel racks at Canaveral had not been expanded their capacity by two-thirds in May?

In Washington, Tallahassee, and Ft. Pierce, several people and organizations were pushing to reconnect Store 90 to the grid or get a generator in place. Would Store 90 have been re-energized on September 12 if the Michigan mutual aid crew had not been able to arrive on September 11? Would the system have been restored in time if, since 2006, FPUA had not invested in significant storm hardening of its distribution network?

In Baltimore, Westborough, Jacksonville, Miami, and many other places, several people and organizations were pushing to dispatch trucks full of food and water south on I-95. They needed open roads and fuel. They got what they needed just in the nick of time. Is it meaningful that in this one case the fuel arrived thanks to pre-existing commercial arrangements and the power to pump the fuel was reconnected through the SOPs established well in advance by the local electric utility?

Does this suggest that effective SOPs are more likely to impact network outcomes than the best crisis response? If so, does this raise the question of whether the single largest distributor of an essential commodity in an essential network should be quite so vulnerable to a predictable disaster? Can systemic constraints—strategically important constraints—be identified in advance and, if so, how can these constraints be mitigated in advance?

The questions are authentic and the answers are not obvious. But this case and the preponderance of evidence from similar cases emerging from Hurricanes Harvey, Irma, and Maria do strongly suggest the following:

Essential network characteristics are knowable. Fuel terminals and racks, logistics clusters, and other dense nodes of supply and demand can be identified in advance. High-volume links, lanes, and junctions are usually well known. Knowing before a crisis emerges the laydown of channels and places by which and through which food, fuel, pharmaceuticals, and other key "lifelines" flow can be helpful.

Critical points in networks are knowable. Working ahead of a crisis, the network can be assessed for critical points. These are often likely candidates to become systemic constraints. Once identified, mitigation measures can be implemented or prepared or, at least, prioritized.

Complex systems are susceptible to influence. A complex adaptive system—such as a large demand and supply network—cannot be "controlled," especially in a crisis. But with sufficient awareness of the network and its crucial features, network participants can collaborate to reduce risk and enhance system throughput, especially to address pre-identified vulnerabilities or opportunities.

To be a less abstract, Pilot Store 90, at the intersection of I-95 and the Florida Turnpike, is a rather obvious candidate to be either a system constraint or a system enabler. In any large system there will be several such candidates. At the very least, they can be mapped to enable visual comprehension of their place in a network. Once they have been mapped some effort can be made to prioritize. Once they have been prioritized, measures can be considered to mitigate the risk. In the specific case of Pilot Store 90, a permanent backup generator is not out of the question. The truck stop is not currently on the list of FPUA's "Essential Customers." It would be conspicuous on a list consisting mostly of medical facilities. Should the other three truck stops in the FPUA service territory be given equal attention? Again, the answers are not obvious, but given the place of Pilot Store 90 as set out in this case, surely the questions are worth persistently asking.

CASE STUDY 3 APPENDIX: MAPS AND FIGURES

Figure CS3-9. Hurricane Irma's wandering track. Source: TheWeatherChannel

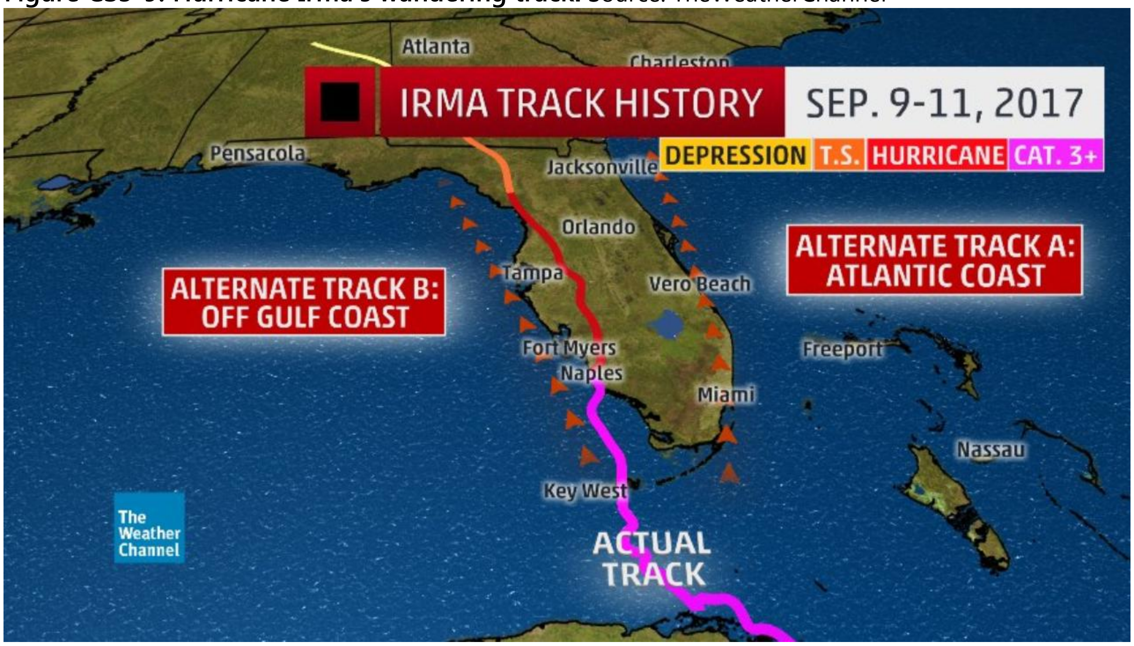
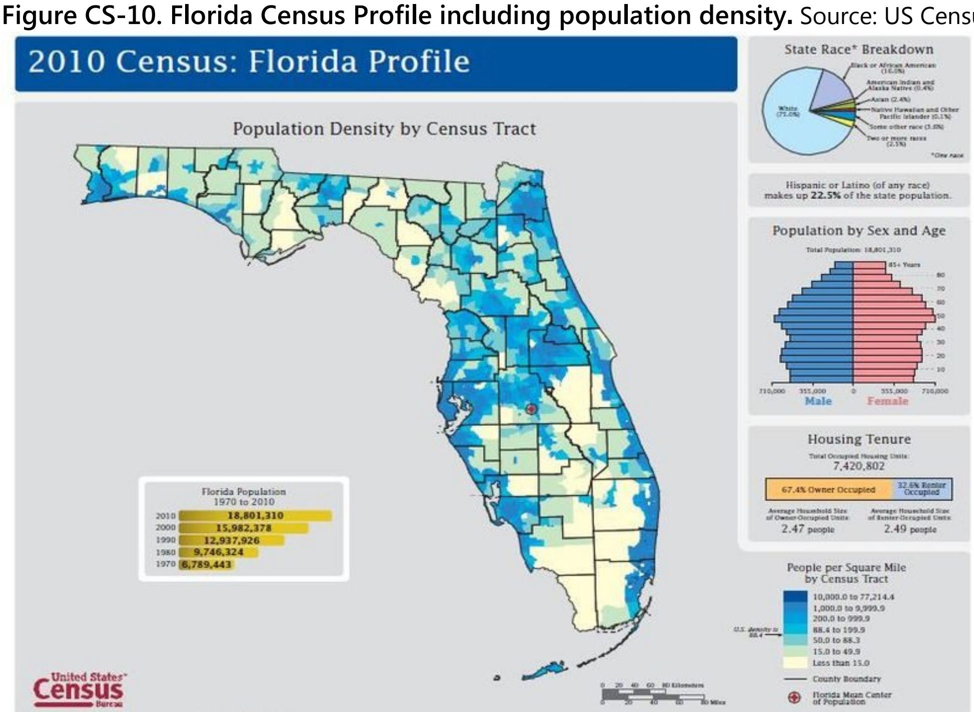


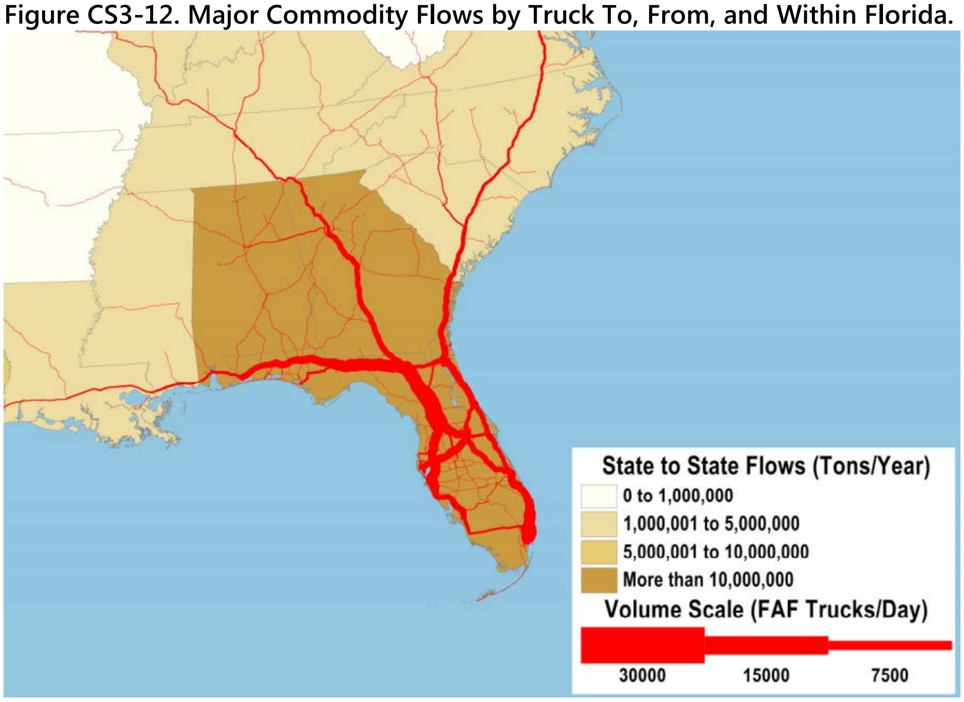
Figure CS-10. Florida Census Profile including population density. Source: US Census Bureau.



Figures CS3-11. Florida's Strategic Intermodal System (SIS) highways.

Source: Systems Planning Office, 2013

Figure CS3-12. Major Commodity Flows by Truck To, From, and Within Florida.



Source: US Department of Transportation, Federal Highway Administration, Office of Freight Management and Operations. [Freight Analysis Framework Version 4.3](#) (2017)

Figure CS3-13. BJ's BJ's Wholesale Club warehouse, cross-dock, and freight yard near Jacksonville, Florida. Cowan Systems is co-located at this complex. (top) BJ's Wholesale Club locations in south Florida (bottom).

Case Study 4: Harvey Turns on (and Then Turns Off) the Tap

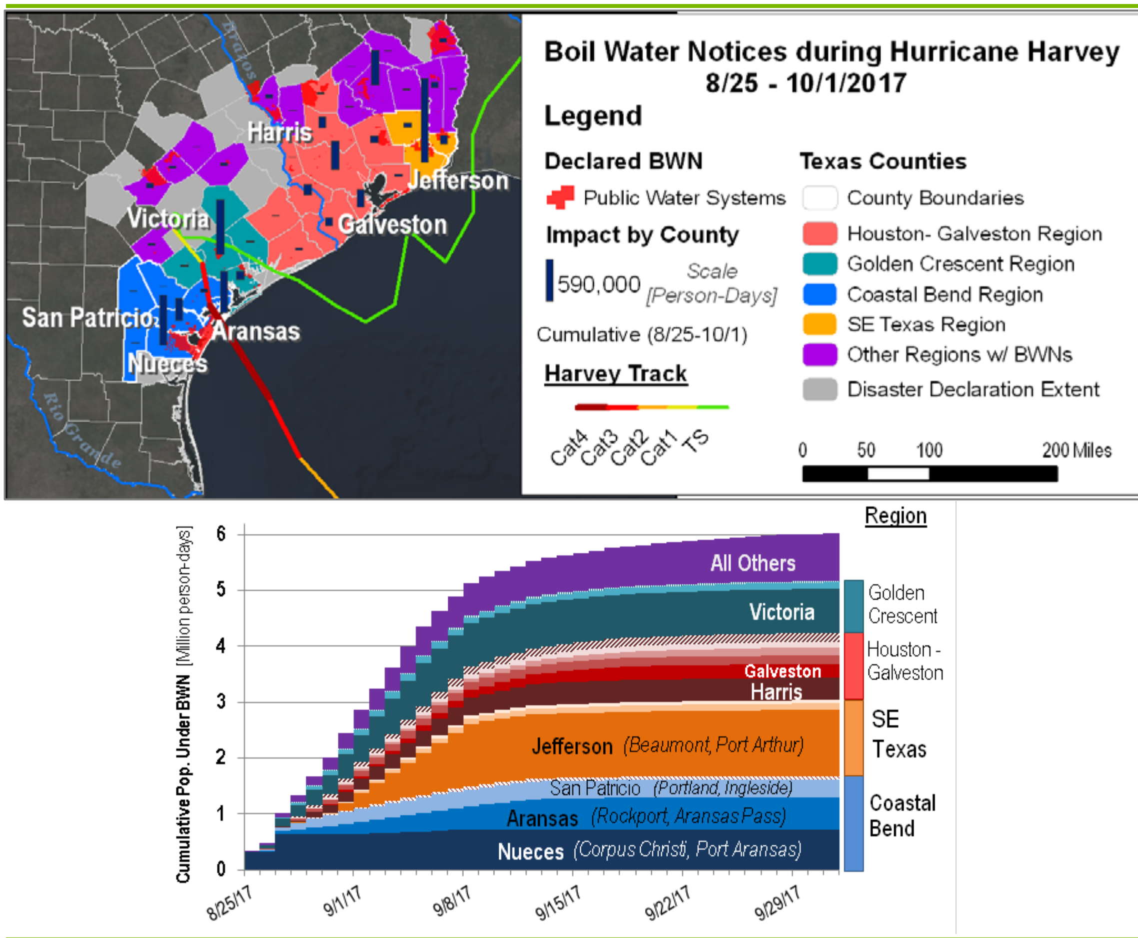
As Tropical Storm Harvey crossed the Gulf of Campeche on August 22, 2017, weather forecasters began sounding the alarm that it may turn into a hurricane again. Few could foresee the intensity of its winds or the magnitude of rainfall it would bring to southeast Texas. By nearly any measure, the amount of moisture that Harvey dropped on south Texas was historic. Rainfall totals over five days exceeded 60 inches in several places, and the storm dropped 27 trillion gallons of water across southeast Texas and Louisiana. With so much water everywhere, it was particularly ironic that water—safe, treated, and fit for human consumption—became a precious commodity. Texas more typically experiences droughts that challenge its water providers' ability to provide sufficient supply. In this case, the huge amount of moisture dropped on Texas caused even greater issues for a large number of water providers who experienced difficulties reliably delivering water to their customers.

Water became a significant factor in the management of Harvey, but also one that the emergency management community had limited ability to influence. Even tracking the current status of water service became a significant issue for emergency managers. Although the Texas section of the American Waterworks Association (AWWA) was tracking the status of water providers in nearly real time [141], state and federal emergency managers had difficulty determining which utilities were having issues, and even knowing where the utilities were located. Ultimately, federal (Department of Homeland Security and Environmental Protection Agency) and state agencies (Texas Department of Emergency Management, Texas Commission on Environmental Quality) developed a list of latitude and longitude coordinates to track the status of water service in the disaster area [142]. From a supply chain perspective, there was relatively little the emergency management community could do to help water providers. The utilities needed specialized expertise and experience, and they sought help from their peer utilities to repair their systems.

The scale of Harvey's impact on water providers was massive. In total, nearly 915,000 Texans dealt with some reduction in their water service (i.e., from a boil-water notice (BWN) to a full outage) based on Texas Commission on Environmental Quality (TCEQ) data [39]. At the peak of outages, at least 61 public water supply (PWS) systems were damaged or offline, affecting nearly 223,000 people [16]. Cumulatively, Texans experienced more than 6 million person-days[16] of water restrictions because of Harvey. Figure CS4-1 shows the cumulative impact BWNs in the affected areas as a map (left) and as a cumulative plot (right).

During a water disruption, BWNs can become a nuisance for most residents and businesses, while more serious water outages can quickly make neighborhoods, or even whole towns, uninhabitable. Even BWNs can cause significant ripple effects. For example, hospitals and grocery stores, among other businesses, depend on water meeting all regulatory standards to function at full capacity.

Figure CS4-1. Population affected by BWNs by county, cumulative duration, in person-days. (August 25–October 1, 2017)



Source: CNA, based on data from TCEQ

[16] Figure calculated by multiplying length of outage in days by service population for each water system. This means the 915,000 affected persons were out of water for an average of roughly seven days.

Harvey moved incredibly slowly through Texas, giving it time to cause many types of impacts across the state. Three primary areas of focus illustrate the range of impacts residents experienced. (See the overview map in Case Study 3 - Appendix A.) First, the Coastal Bend region experienced Harvey's landfall as a Category 4 hurricane. The Coastal Bend includes Corpus Christi and the waterside communities located in Aransas, Nueces, and San Patricio counties, notably Rockport, Aransas Pass, and Port Aransas, which were directly in Harvey's path at landfall. As the storm turned and became a historic flooding event, Houston experienced challenges in maintaining water service as waters rose around Harris County. Finally, Jefferson County (especially the City of Beaumont) experienced perhaps the most catastrophic of Harvey's flooding from rain and the rising of the Neches River.

WATER – A PECULIAR SUPPLY CHAIN

Providing reliable water service depends on a very particular supply chain of infrastructure and management systems that must work together to deliver water to homes. Unlike most commercial supply chains, water systems do not rely on trucks, trains, or boats to deliver goods. Instead, utility commodities, like electricity, natural gas, and especially water, depend on functioning infrastructure for delivery, and their supply chains cannot be easily reconfigured—they have to be either repaired or rebuilt.

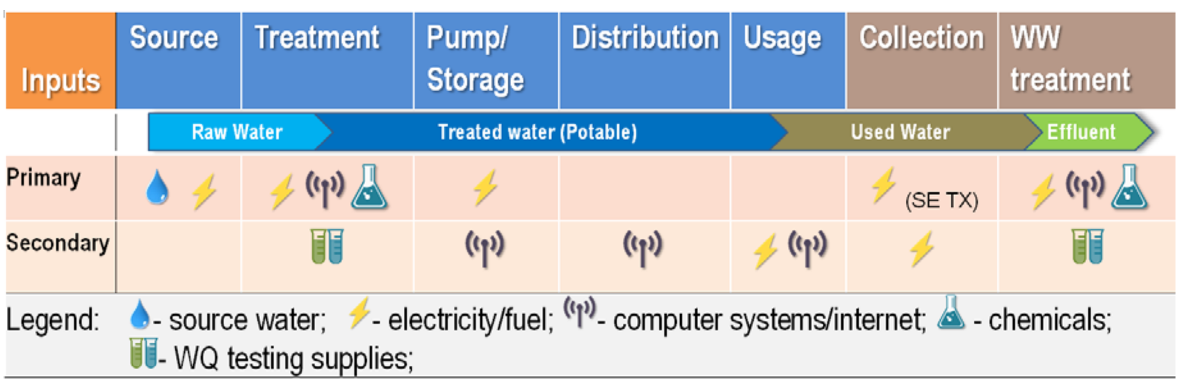
Water has a unique supply chain because it is at once: 1) needed in large quantities; 2) very heavy; and 3) low value relative to its weight. Economic delivery of water depends on significant infrastructure systems operating and working in concert. To illustrate this point, consider a single pipe, 12 inches in diameter, carrying water a distance of five miles at a reasonable five miles per hour. This pipe moves more than 2.5 million gallons of water per day (MGD). To replace this one pipe, imagine a large tanker truck holding 8,000 gallons and driving the same five miles at 65 MPH. (Add only 10 minutes per trip for filling and draining the water.) It would take a little more than 4 trucks running continuously (more than 300 truckloads per day) to replace the one pipe. Now imagine the pipe is 24 inches in diameter, carrying 10.1 MGD; 17 trucks making a total of 1,270 deliveries would now be needed. For a 36-inch pipe, 38 trucks would be needed, making a total of 2,856 deliveries per day.

Water service depends on moving quantities of water to where it is used and protecting the quality of water during transit. The most efficient way to do that is by pushing water through pipes and keeping those pipes pressurized, which requires several steps along the way both to manage quality and ensure delivery. The following section explains those steps, with a particular focus on the vulnerabilities and dependencies for each step.

General Supply Chain Dependencies for Water Systems

As explained in the introduction, water systems depend on a series of connected infrastructure to perform several sequential water service functions. These functions can basically be broken down into five stages, which include: 1) source and transmission, 2) treatment, 3) pumping and storage, 4) distribution, and 5) usage. If wastewater service is also considered, the supply chain continues with 6) wastewater collection, and 7) wastewater treatment and effluent discharge. Each of these stages in the supply chain can experience failures that can result in an inability to provide water service. All of these stages depend on infrastructure, which can be damaged, but many of the infrastructure components also have inputs needed for operation. In general, these inputs include power, chemicals, and computer systems. Depending on the facility, some of these inputs may be "primary" dependencies, where a failure may cause an outage in water service very quickly (less than 24 hours). Others may be "secondary" dependencies, without which the water system can operate for several days, although perhaps at a reduced capacity. Figure CS4-2 illustrates the phases of the water supply chain—the transformation of the product from raw water to treated water to used water[17] to treated effluent. The strong and secondary dependencies are shown for each phase, but the degree of dependency may vary by water system.

Figure CS4-2. Water supply chain primary and secondary dependencies on key inputs by stage



Source: CNA

[17] Used water is the preferred term used by the water industry instead of wastewater because it recognizes that water (even if not fit for drinking) is a resource and not simply a waste product.

Because water is so heavy and difficult to move, the local hydrology and topography have a huge impact on the way water systems work. This is certainly true in Texas. The next sections cover some of the particular vulnerabilities seen in Harvey's impact area.

Water System Vulnerabilities in Southeast Texas

The challenges faced by water systems typically stem from a combination of water sourcing, climate, and topography. The defining features of southeast Texas are that it is quite flat and has a hot, humid-subtropical climate. From a source perspective, there are multiple small to moderately sized river basins that drain to the Gulf Coast, but few large rivers bringing reliable surface water flow. Because of these conditions, many water utilities in the area face some of the following challenges:

- Large surface water sources are not common due to small watersheds, so there is a reliance on either groundwater or pumping water from far away sources, which requires power.
- Surface water sources are typically quite turbid (i.e., have a lot of silt and sediment), so treatment requires regular filter back-washing and significant amount of chemicals. Turbidity increases during storms as water and sediment are churned up.
- The heat and source water quality make it difficult to store large quantities of finished (i.e., treated) water for fear of violating regulations on disinfection byproducts [143].
- Many water treatment, pumping, and, especially, wastewater facilities have to be near waterways, which make them vulnerable to flooding [15].
- Because of the flat topography and low elevation, most wastewater systems depend on lift stations (i.e., wastewater pump stations) instead of gravity to keep sewage flowing to wastewater treatment plants.

All of these challenges came into play as Texas water systems coped with the impact of Harvey. In particular, water systems in Texas are vulnerable to power outages because they rely on pumping for groundwater wells, pipelines to move source water over distance, and pumping water to pressurize distribution systems. Because Texas is so flat, wastewater management is more dependent on power than in many other areas of the county. While most sewer systems around the country can rely on gravity to bring sewage to treatment plants via the collection system, many Texas utilities need lift stations to pump it to treatment plants instead.

HARVEY CHALLENGES EVERY PART OF THE WATER SUPPLY CHAIN

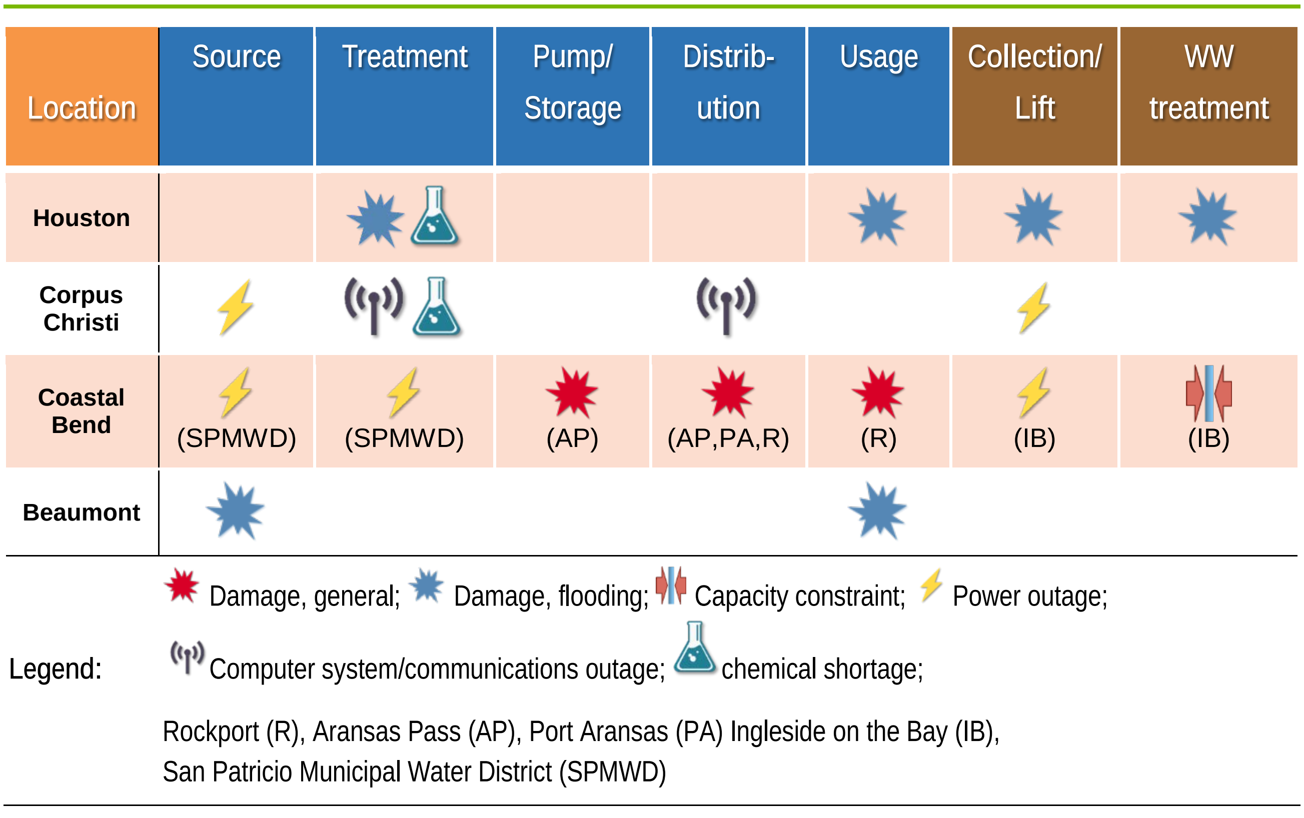
Water systems depend on all portions of the system (i.e., water's supply chain) working in concert. The source has to be accessible, the treatment plant has to be working, the pumps have to be operating, the distribution lines have to be intact and holding pressure, and the wastewater systems have to be able to collect and treat water. Failures in any component can cause water systems to fail or suffer a reduction in service quality. Hurricane Harvey provided examples of nearly every part of the water supply chain experiencing failures, or at least significant challenges. From source to wastewater treatment, water service providers experienced infrastructure failures (or near failures) for a variety of reasons ranging from flooding and wind damage, to power outages, to running out of chemicals.

There are degrees of failures for water supply. In emergencies, quantity and the ability to move water is more important than quality [141]. The most severe type of failure is a total loss of supply from failure either of a water source, water treatment plant, or major water transmission lines. More frequently, water systems face issues that result in less than a complete outage or that potentially impact water quality. Some of the more common types of water supply issues include:

- **Loss of supply** (quantity) – Inability to move water to customers means that there is no water available for any use. Potential causes include total loss of source water, severe damage to transmission pipes or water treatment plant, severe power outages affecting treatment and pumping, or major breaks in distribution system.
- **Loss of pressure** (quantity and quality) – Inability to maintain required pressure in distribution system can cause diminished ability to provide water for fire suppression, and will trigger a requirement to boil water. Potential causes include loss of power to pumping stations, damage to pumps or storage tanks, and breaks in the distribution system.
- **Treatment effectiveness** (quality) – Water is available but does not meet regulatory quality standards. Potential causes include source water contamination, water treatment process failures, or loss of ability to monitor or test quality. Impacts can vary widely between recommendations to avoid water for sensitive populations to a complete ban on use. Not all contaminants can be removed by boiling water.
- **Other restrictions** – There are regulatory, policy, or other reasons for not being able to use water. Potential causes could be mandated water conservation or requests to reduce water use because of sewage capacity constraints.

Figure CS4-3summarizes the supply chain issues encountered during Harvey by the part of the water system disrupted, the water system or region impacted, and the cause of the impact. Although Harvey affected water systems in many parts of Texas, we focus on four key water systems or regions: Corpus Christi, a collection of water systems in the Coastal Bend region where Harvey first made landfall, the City of Houston, and the City of Beaumont. The types of impact include direct damage either from wind or flooding, disruptions to key inputs like power or chemicals, and other issues.

Figure CS4-3. Challenges (failures and near failures) to the water supply chain during Harvey

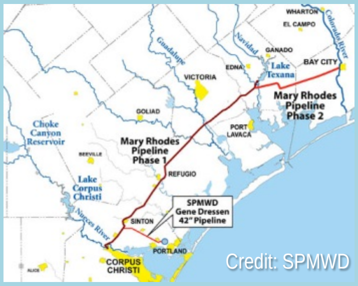


Source: CNA

Examples of water supply chain impacts

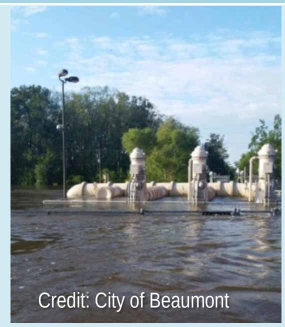
The following sections provide more detail on the specific issues experienced in these areas by phase of the water supply chain.

Source

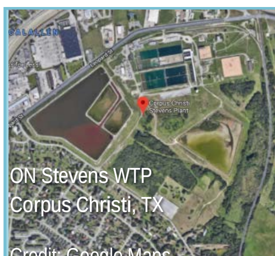


Aug 26 - The Mary Rhodes pipeline loses power at one of its primary pump stations, temporarily limiting the raw water supply. The loss of power lasts less than 24 hours before repairs can be made [144]. The pipeline brings raw water from Lake Texana to the City of Corpus Christi and the San Patricio Municipal Water District (SPMWD), which is the provider of treated water for many Coastal Bend communities. Corpus Christi has other water sources, but the SPMWD would have been severely constrained had the outage persisted.

Aug 31 – Beaumont loses its primary raw water supply on the Neches River due to inundation and also loses access to its secondary source (wells in Hardin county) [145]. The distribution system loses water pressure, resulting in a city-wide outage and the issuance of a BWN. [146] On Sep 1, a temporary pump allows for the withdrawal of some water from the river [147], but the city remains on a boil water advisory, which will last until Sep 9. The city sets up a bottled water distribution point on Sep 1 [148], but many residents get water from the local supermarkets that remain open.



Treatment

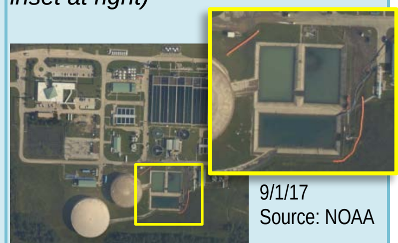


Aug 25 – Corpus Christi briefly loses power at the O.N. Stevens water treatment plant (WTP), which takes down the Supervisory Control and Data Acquisition (SCADA) system, meaning the water treatment process is not controlled effectively. The power returns quickly, but the SCADA system takes 24 hours to be rebooted. Although the water quality is believed to be fine, a BWN is issued for one day as a precaution [144].

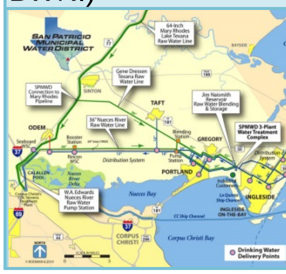
Aug 29 – Corpus Christi realizes it is running low on treatment chemicals, specifically caustic soda (i.e., sodium hydroxide), which is used for pH regulation. It has less than a 7-day supply, and normal suppliers are unable to make deliveries. Corpus Christi uses the Texas Water/Wastewater Agency Response Network (TxWARN) to request contacts with alternate suppliers and is able to receive chemicals in time [144].

Aug 27 – At 6:00 PM, flood water surrounds and submerges the Northeast Water Production Plant (NEWPP). The plant still functions but is running out of time before it needs to backwash filters, and it has nowhere to discharge the backwash. Houston Water staff work the phones to identify suppliers of portable coffer dams (to surround the backwash ponds and create sufficient storage space). The plant comes very close to failure on Aug 28, but the coffer dams are located, and pumps brought in to keep the NEWPP operating [143]. (Even if the NEWPP had been shut down, it is likely Houston had sufficient treatment capacity at other plants to keep water flowing, but would have likely needed a BWN.)

Houston NEWPP –
Sep 1, 2017
(Orange coffer dams still visible in inset at right)



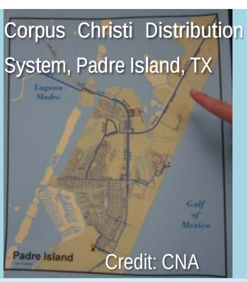
9/1/17
Source: NOAA



Aug 26 – SPMWD loses power at its main water treatment plant, and issues a BWN for its customers, including many towns in the area that purchase treated water. The affected communities include Rockport, Aransas Pass, Port Aransas, and Ingleside, among others. The BWN lasts just three days for SPMWD but continues much longer in the other communities.

Credit: SPMWD

Pumping, Storage, and Distribution



Corpus Christi Distribution System, Padre Island, TX

Credit: CNA

Aug 26 – Port Aransas is completely lacking in utilities. On Padre Island, the main 20-inch diameter water supply line bringing treated water purchased from Corpus Christi to Nueces County WCID#4 broke. It was repaired within roughly 24 hours. (Port Aransas has a second main distribution line from SPMWD, which remained in operation, although with a BWN.) It is likely that Port Aransas would still have lost pressure in the distribution system due to other water line breaks, loss of power, and other issues, even without this line break.

Aug 25–29 – Communities in multiple Coastal Bend communities (Port Aransas, Aransas Pass, Ingleside) deal with multiple water line breaks in their service areas due to downed trees and other storm-related damage. Although the water supplier of treated water for these towns (SPMWD) lifts its BWN by Aug 29, fixing the issues in the distribution systems keeps BWNs in these towns in place for several more weeks. Port Aransas lifts its BWN on Sep 8, Aransas Pass on Sep 11, and, finally, Rockport on Sep 13.

Credit: Jim DeVisser, CCFD

Aug 26 – Aransas Pass finds its main water tower has toppled during Harvey. Breaks in the distribution system and loss of power cause a system-wide water outage that probably would have occurred even if the tower had remained standing. Aransas Pass also has ground-level storage tanks. It took until Sep 11 for Aransas Pass to return to normal operations, after officially implementing a BWN on Aug 27.

End Uses

Aug 26 – Rockport and other Coastal Bend communities find that many of their customers have water leaks inside their properties due to storm damage breaking plumbing and fixtures. Utilities from around the area, including Nueces County WCID#3 and the San Antonio Water System, send crews starting on Aug 27 to help local public works departments shut off water service at the meters to allow the distribution system to build pressure.

Aug 28 – Flooding in Harris County forces thousands in the Houston area to evacuate quickly. Few shut off their water as they flee. Weeks and months later, many residents receive extremely high water bills from Houston Water. The explanation: flood water had caused dishwashers, refrigerators, and washing machines to float, thereby breaking their pipe connections to the plumbing system [143]. Houston Water has no choice but to continue water service to these properties until flooding subsides because shutting off service to neighborhoods would risk damaging and contaminating the distribution system.


Credit: DOD

Wastewater

Aug 27 – Ingleside on the Bay finds it has lost power at several pump stations and its main sewage lift stations. It makes a request to the FEMA to provide generators, and through the US Army Corps of Engineers (USACE), six generators are provided. The request is made on Saturday, the crews arrive on Monday for a power assessment, and the generators are installed on Tuesday. But the town still cannot use its water. Ingleside on the Bay receives water from the SPMWD and sends sewage to the City of Ingleside's treatment plant. The City of Ingleside's plant is near capacity, and it refuses to take sewage from Ingleside on the Bay. Thus, the mayor is forced to keep water restrictions in place because of sewer-capacity restrictions. Ingleside on the Bay lifts its restrictions on Sep 6, four days after the City of Ingleside and one week after SPMWD [149].

Aug 31 – Houston depends on a decentralized network of over 300 lift stations and 39 plants for wastewater treatment. Seven of the plants flooded during Harvey, including two for over a two-week period [150]. The Turkey Creek Wastewater Plant (pictured) was one of those flooded and, as a result, Houston Water asked customers in the plant's collection area to limited their water use to toilet flushing, laundry, bathing, and dishes to limit untreated sewage releases [22]. In several areas, Houston Water staff also found large sewer lines washed away by flooding [143].

Credit: City of Houston

RESPONSE AND RECOVERY: EXPECTED AND UNEXPECTED DEPENDENCIES

"Expect the unexpected" has become almost a cliché in disaster management circles. For the water systems in Texas, there were literally unexpected dependencies needed to repair their systems. While power, chemicals, and internet service are known dependencies of water systems during normal operations, there are different needs to repair a water system that has been damaged and return it to service.

Some of the needs are anticipated by water systems, but Harvey highlighted how quickly unexpected needs can arise. Most water systems recognize that, at some point, they might need to repair parts of their distribution system or replace equipment that fails. Thus, water systems keep a certain amount of pipes, valves, replacement parts, and other equipment on hand, and they are generally in close contact with suppliers in case they need to order more. Water systems also have personnel (staff or licensed contractors) and equipment (e.g., trucks and excavators) available to complete repairs. In many cases, critical facilities like water and wastewater treatment plants, or very large pumping stations, may have back-up power generation capability. Harvey illustrated that there are limits to resiliency. It also demonstrated how quickly unexpected needs can arise to hinder restoration of service.

Roofs, Radios, Radials, and … Bug Spray?

In the Coastal Bend, the water distribution systems were surprisingly intact relative to the scale of the wind damage experienced, because the pipes were buried. The distribution systems in Rockport, Aransas Pass, and Port Aransas were still challenged and losing pressure because of severed service connections and a lack of power for pumping, not to mention the toppling of the Aransas Pass water tower. The first priority for a water system is water quantity, closely followed by ensuring that the distribution system can hold pressure. In the first days after landfall, that meant sending out work crews to find and repair line breaks and shut off service connections to storm-damaged buildings with broken internal plumbing. But sending out public works crews was no easy task.

“Roofs…and radios,” said Captain Lynn Pearce, the Emergency Management Coordinator for Aransas Pass, when asked what was most needed in the first 48 hours after Harvey’s landfall. Harvey had devastated so many buildings across the area that it was difficult to set up an emergency operations center (EOC) because the primary and many secondary locations had holes in their roofs and water inside [151]. Eventually, makeshift EOCs were established, and the public works staff could go to work. But before they could pay attention to the water system, the first priority was road clearing and helping the first responders with health and safety checks and fire watch, a critical task when there is no fire suppression capability[152]. To send crews out in the field, several items are required: personnel, radios, vehicles, fuel, and tires. All of these were in short supply. In particular, personnel were busy, and many of the vehicles in the area were storm damaged.

A major problem early in the storm was a complete lack of communication. “Everything you thought you had was gone” said Rick McClester, Emergency Management Coordinator for Aransas County. In Aransas County, eight redundant forms of communication (e.g., landline phones, cell phones, satellite phones, internet, etc.) were inoperable. [151] In addition to being a means to request resources, radios are absolutely critical for work crews going into the field for safety and coordination. In Port Aransas, a group of intrepid firefighters from the Corpus Christi fire department made the long overland journey via Mustang Island and brought radios with them on August 26. Initially, a daisy chain of radio communications linking Port Aransas to the Corpus Christi fire department and then the Corpus Christi city EOC were the only way to put in requests for resources [152]. Throughout the region, there were not enough radios, and many were damaged in the storm. Gradually, and from a variety of sources, the communities acquired the radios necessary to be able to send public works crews into the field.

Outfitting the vehicles used by the public works crews was the next problem to overcome. Enough vehicles had survived the storm to (mostly) support the needs of public safety and public works. However, it proved difficult to keep them on the road. Most communities were able to request and obtain fuel through State of Texas Assistance Requests (STAR), so fuel was not an issue after the first few days. The roads were littered with shards of wood, nails, broken glass and other storm damage debris. Very quickly, the trucks on the road started succumbing to flat tires. In Port Aransas, first responder and public works vehicles were going through more than 100 tires per week. [151-152] Completely out of spare tires, and with no other options, they were forced to salvage tires from storm-damaged vehicles left behind by evacuated residents. Rick Adams, the Port Aransas Emergency Management Coordinator, thought this issue was so critical to the response effort that he developed a contract with a local tire shop to provide patch kits and tires during future emergencies. He recommended other communities do the same. [151]

Even when the crews had radios, vehicles, and fuel, they still had challenges working in the field to complete damage assessments and repair water systems. After Harvey's rainfall, mosquito populations exploded. Working outside in swarms of mosquitoes became a major challenge for work crews, and protective clothing and insect repellent were necessary. Stan Upton, Refugio County Emergency Management Coordinator, reported that the mosquitoes were so thick that they actually plugged vehicle air intakes and even clogged radiators [151]. By August 28, many of the Coastal Bend communities had to request aerial mosquito spraying to be able to conduct basic public safety and public works functions.

Figure 5. CS4-4. Water pooled in Port Aransas is a breeding ground for mosquitoes (left). The Port Aransas Fire Department roof is mostly intact, but the building sustained damage (center). Used tires in Aransas Pass (right).

Source: Jim DeVisser, Corpus Christi Fire Department (left and center); CNA (right)

Generators – Power as a Key Input for Water Systems

Power is required to operate WTPs and pumps. Without power, water systems quickly lose the ability to treat and distribute water. Elevated water towers can provide something of a buffer in case of short power outages (generally 24 to 72 hours) because they keep pressure simply by using gravity. Without power, however, pumps cannot refill them. Thus, WTPs and pump stations require emergency generators to ensure continued operation during disasters that cause power loss.

Harvey demonstrated that electricity is a critical input for water systems for pumping and for wastewater lift stations. Generators were essential to keep systems in operation in many areas.

Ingleside on the Bay, a small community in San Patricio County, was one of the only communities in the Coastal Bend to request a generator from FEMA for its water system. Jo Ann Ehmann, the mayor of Ingleside on the Bay, put in a request for six generators on Saturday, August 26, and by Monday, August 28, 2017, FEMA had deployed the generators with engineers from the USACE to evaluate the power needs and connect the generators to pumps. Mayor Ehmann noted that the engineers, however, "had a bit of a problem hooking them up; they were too big." Many of the lift stations had a smaller power draw than expected. The generators were eventually installed by Tuesday, August 29, and ran for five days by Mayor Ehmann's recollection until power was restored. [149]

Generator sizing is a considerable issue for water systems. Water facilities can range in size from very small, like the lift stations in Ingleside on the Bay, to enormous water treatment plants. Portable generator systems cannot power a large plant like Houston's NEWPP; backup generation capacity has to be installed before an event. Although many critical water facilities like treatment plants do have backup power generation, smaller facilities like pump stations and lift stations often do not because of the expense and maintenance required.

Generators are incredibly useful for enabling resilience, but there are many considerations a water system must take into account before hooking them up. They are not really plug-and-play systems. Justen Noakes, Director of Emergency Preparedness for H-E-B, a grocery chain in Texas, outlined some of these considerations for local governments at the 2018 Coastal Bend Hurricane Conference [153]. They include the following:

- **Cost** – Generators are expensive, ranging from $30,000 to $600,000 per unit.
- **Power needs assessment** – Generators have to be selected and sized appropriately based on expected load and utilization, operating voltages, phase of power, etc.
- **Sourcing and hook-up** – Generators can be purchased, leased, rented, or held in reserve, but if there is not a contract in place before a disaster, it can be difficult to get them. (One generator supplier noted he does not believe there were enough generators in the country to meet the demand he observed during Harvey.) Additionally, most generators require a licensed electrician to hook them up safely.
- **Maintenance and fueling** – Generators need regular maintenance and plans in place for fueling. If generators are not maintained or run dry on fuel, generator repair technicians will have to come to the site to re-prime and start the generators. Fuel delivery plans also need to be in place.
- **Site planning** – Portable generators are heavy, need airflow, and have hot exhaust. It is important to carefully plan the location to have a stable base, sufficient airflow, no overhanging trees or lines, and enough cable to connect generators to their load.

Many of these considerations became evident during the response to Harvey. In Aransas Pass, there was little issue ordering 28 generators (for a variety of public facilities) through STAR. Unfortunately, as Captain Lynn Pearce, the Aransas Pass Emergency Management Coordinator, recalled, the generators arrived without electricians to hook them up, or fuel, so it took several days to get them running. Stan Upton, the Refugio County Emergency Management Coordinator, noted that the permanently installed generators at several facilities failed due to a lack of maintenance. The seals on the exhaust flaps had deteriorated, and heavy rain flooded the generators, rendering them unusable [151].

Familiar Helping Hands – Mutual Aid Proves Critical

Water systems have very particular needs when it comes to managing disasters, and often those needs are met by others in the water industry, or in related industries. Water systems in Texas had the benefit of being able to turn to their peers and industry contacts for help, and, thus, unburdened the relief channel. [20]

In the Coastal Bend area, water systems and their professional associations helped other water systems. Corpus Christi's water department had several needs early on and sought help through the TxWARN, an informal coalition of water providers organized under the auspices of the AWWA. Corpus Christi requested generators initially, and then requested assistance with finding providers for water treatment chemicals before they ran out. [144]

In the communities of Rockport, Aransas Pass, Port Aransas, and Ingleside, the damage assessment and triage process required more personnel than they had available. A few days after landfall, crews from other water utilities started arriving to help with shutting off meters to damaged properties and other tasks. San Antonio Water System sent 24 personnel and 12 trucks to help in Port Aransas [154]. John Herrera, District Manager of Nueces County Water Control Improvement District #3,[18] said, "We were really blessed…We never lost power, never lost pressure, our pumps kept working…We sent a few guys over to Rockport to help out. Mostly, they were going around shutting off service to houses and properties that were vacant" [155]. Between help from peer utilities, and STAR requests processed through the Texas Department of Emergency Management, water systems needed little federal assistance. FEMA logistics management division in Region VI confirmed that they responded to very few, if any, requests for assistance by water utilities in the Coastal Bend region. [13]

Water systems helped each other in other ways, too. Corpus Christi, for all of its issues with power failures, SCADA system failures, and chemical shortages, was back to normal operations within a few days after landfall. As one of the larger water systems in the area, it operates its own water quality testing lab. Many of the water systems in the area were on BWNs but relied on sending water samples by courier to private testing labs. Regulations are

[18] Nueces County Water Control Improvement District (NCWCID) #3 serves Robstown and the surrounding area to the west of Corpus Christi and should not be confused with NCWCID#4, which serves Port Aransas.

designed to be quite cautious when it comes to public health. A drop in pressure, or loss in SCADA systems, is sufficient to trigger BWN as a precaution even when there has been no chemical detected above mandated human health limits. When it comes time to lift the BWN, however, the state requires a set of water quality tests conducted at a certified lab facility to verify there is no risk to human health. In normal circumstances, many smaller water providers collect samples and then ship them to certified laboratories, but the turnaround can be several days. Corpus Christi invited these systems to bring their water samples to the Corpus Christi lab instead, where they could have testing complete in a matter of hours. This ability to share resources likely cut days off the boil water restrictions for several communities in the Coastal Bend. [144]

CASCADING AND RIPPLING IMPACTS AS WATER SYSTEMS GO DOWN

A reliable water supply is an input to a wide variety of supply chains and emergency support functions. Just as water systems have a strong dependence on the electric grid, many other facilities have a strong dependence on an operating potable water service.

Without water service, it is difficult to support a residential population. There is no practical way to move enough water to replace a municipal water supply fully. Plus, fire suppression is needed. In Port Aransas, in the first days after the storm, even with an evacuated population, fire watch became one of the highest priorities for first responders [152]. There was no means of fighting fires, so vigilance became paramount, and it took personnel and vehicles from other tasks. For small communities, a recovery can be staged over several weeks without full water service if enough resources can be brought in to support needs for human consumption, sanitation and hygiene, and fire control. For large water systems, there is almost no choice to be made—water is virtually indispensable.

In major metropolitan areas, the line between disaster and catastrophe can be quite fine when it comes to water service. Water systems must function as relatively optimized systems. It is impractical to store large volumes of water in case of emergency for two main reasons: storage is expensive, and treated water cannot be stored more than a day or two, as its quality starts degrading. Most water systems have at most between 24 and 72 hours' worth of finished water storage feeding the distribution system. Water systems without elevated storage may lose pressure in their systems in 3 to 24 hours if their pumps lose power [141]. This is a small window of time either to patch the water system or order a full scale evacuation. Large water treatment plants are therefore virtually indispensable. In case of damage to the plant, it has to be fixed by whatever means necessary. There are no off-the-shelf solutions for providing a facility able to treat water for millions of people. According to

Kevin Morley of AWWA, the largest mobile treatment options can provide up to 1 million gallons per day. In comparison, Houston's water system treats 449 MGD on average [141]. The only options are to get the plant working again, buy water from neighboring water systems, or evacuate.

As with many disasters, Harvey could have been worse, but no one really knows how much worse it could have been. If the NEWPP had been completely submerged, or some major water distribution lines broke, or if all of Houston lost power (taking down most pump stations), the impacts of Harvey would have been unimaginable. With so much of Houston under water, fixing the system would have been extremely difficult until the water receded. Throughout the event, the Deputy Director of Houston Water, Yvonne Forrest, kept her focus on keeping the water flowing by any means necessary. "Safety first, but *please*, don't let my plant go down," Forrest told the NEWPP manager. It took a concerted effort by staff and even private citizens to keep the NEWPP operating. Dozens of staff worked on locating and acquiring the portable coffer dams needed to keep the plant's filter backwash basins operational. Transporting the portable coffer dams to the plant proved to be another challenge, as floodwaters covered most roads in the area. A determined private citizen in a truck voluntarily circled the plant for hours trying to locate the most viable route into the facility to get personnel and equipment to the plant. [143]

Although there was never a point at which a city-wide failure of water service was truly imminent, there was no readily available contingency plan. "You can't plan for a Harvey," said Yvonne Forrest, "We've planned for a repeat of an Ike [as far as flooding is concerned]. Harvey was totally different, and I'm not sure how you can plan for it." Houston was never under a mandatory evacuation order [143], but a major water system failure could have made one necessary— while more than half of the city was underwater. The logistics of conducting such a large evacuation— with the "first-mile" by water for many—and then providing water to the population would have been daunting. For that matter, Kevin Morley was uncertain whether FEMA, or anyone, knows how much water would be needed to support Houston's population. Based on back-of-the-envelope calculations for 4 million people, he figured the number of bottles needed for basic drinking water and minimal hygiene would reach into the billions in the first few days [141].

In Beaumont, fears of a sudden water outage became reality on August 31, as 118,000 people lost access to water when the main water intake pumps were inundated by the Neches River. The system never completely went dry, but it did lose pressure, and there were reports of a sudden surge for bottled water at area grocery stores [148]. FEMA's Logistics Management Division for Region VI noted that there was no issue transporting sufficient water to meet requests made by the state for the City of Beaumont. [13] The first delivery of FEMA water arrived in Beaumont on September 3, 2017, and two more deliveries were made on the

September 5 and 9. In total, FEMA delivered almost 184,000 liters of water to Beaumont. For perspective, at the World Health Organization's recommended minimum of 20 liters per person per day for water and sanitation [156], supplying a population the size of Beaumont would require 2.36 million liters per day (equal to 0.62 MGD). Thus, the total FEMA water delivery to Beaumont over six days met slightly more than 1.2 percent of the population's minimum daily need. Of course, there were many other water sources for Beaumont, including retail outlets, charitable organizations, and even neighboring towns. In the end, Beaumont's water system had temporary repairs made by September 1, and much of the city had limited public water access by September 3 when FEMA-supplied water started arriving.

The cascading impacts of Beaumont's loss of water service caused a greater challenge than figuring out how to supply drinking water to the population. Although most residents can manage to boil water effectively for a few days, some critical facilities cannot. In particular, medical facilities—including hospitals and dialysis centers—may have to stop operating unless they have onsite means of maintaining water treatment. In Beaumont, the loss of water supply prompted a partial evacuation of Baptist Beaumont Hospital [18]. The hospital was not flooded, had power, and its emergency room stayed open [157]; the sole reason for the evacuation was the loss of water supply, which prevented the treatment of acute care patients. From roughly 12:00 AM on September 1, to 9:55 PM that night, the hospital had to evacuate over 300 patients, and at least 210 of those were air evacuations [157].

Beaumont's EOC, located at the city's courthouse, was also affected by the loss of water. The staff used the EOC for both working and sleeping, so a loss of water, especially for sanitation, threatened the city's ability to manage the disaster. Further disrupting the work of emergency managers, the lack of water service also forced the evacuation of Beaumont shelters holding 1,400 people [23]. As in many other cases, it was the water industry, using its specialized equipment, that provided a temporary solution. Aqua America, a private utility company that manages many small water systems in Texas, provided two tanker trucks permitted to transport potable water to supply water to the Beaumont EOC and other Beaumont sites. The trucks faced a perilous 500-mile drive through Louisiana to reach Beaumont since so many roads were blocked. The tankers picked up water from neighboring towns with fully functional water systems, and then delivered water to Beaumont, often multiple times per day for about 10 days. [19]

Finally, even a service reduction short of an outage like a BWN can have more mundane impacts on a return to normalcy. Grocery stores may have to stop offering fresh produce, meat, and baked goods. H-E-B, one of Texas's largest grocery companies, actually keeps mobile water treatment units to deploy to areas under BWNs [153]. Affected restaurants, hotels, and other commercial establishments cannot operate normally, and in some cases may have to reduce their hours or delay re-opening. And the entire population that makes up a community's workforce will be less effective as they spend additional time and effort boiling water or using bottled water for their daily routines.

SUMMARY AND PRELIMINARY ANALYSIS

Water service is dependent on a very particular supply chain made up of connected infrastructure components, each stage of which is vulnerable to failure during disasters. Harvey illustrated examples of failures (or close calls) for nearly every stage of the water supply chain, and ultimately caused over 6 million person-days of water service restrictions (BWNs or worse). Water service providers are generally quite resilient, and generally have most of the specialized tools and resources they need to repair their systems; they can also turn to their peers for help. But Harvey tested their abilities, and exposed some unexpected dependencies and vulnerabilities. From the stories told by the water utility personnel that lived through Harvey, here are some of the key resources that were critical for recovery:

- **Communications equipment** – A sufficient quantity of functioning radios are necessary to send repair crews into the field. The ability to communicate with local EOCs is also important for requesting assistance.
- **Dry storage space for managing operations** – Setting up a base for operations is critical during initial response, and after a Category 4 hurricane, these spaces are in short supply.
- **Generators** – Multiple stages of the water supply chain depend on power, particularly treatment and pumping facilities. Water treatment plants should have backup power supplies. If pump stations and lift stations do not have permanently installed generators, bringing in portable generators is easier if the utilities have done a power assessment before the disaster hits.
- **Mosquito control** – Field crews and their vehicles can be slowed after rain pools and stagnant floodwaters cause dramatic growth in mosquito populations. Both personal use repellents and aerial spraying can be beneficial for enabling field crews to do their work.
- **Experienced personnel** – Most utilities do not have sufficient staff on hand to conduct damage assessment and repairs for events that affect an entire system. Reaching out to neighboring utilities for that experience sped the recovery process for several utilities in Texas. Another key need was electricians to install generators.
- **Tires** – After hurricanes with significant wind damage, debris can damage tires for vehicles. Spare and replacement tires and tire patch kits were a critical need for crews to be able to repair water systems.
- **Specialized vehicles** – In addition to basic work trucks, several specialized vehicles proved useful in managing the impacts on water systems. These include:
    - Potable water tanker trucks – Some facilities need bulk water instead of bottled water. Trucks need special permits to safely haul water that is fit for human consumption.

- Sewer cleaning trucks – When sewerage systems get backed up (perhaps due to a power outage at a lift station), sewer cleaning trucks are needed to empty the system. Most include both a vacuum with a tank to remove the sewage and a water jet to break up blockages.
- High-water vehicles or boats – With water and wastewater facilities often near water bodies, they are prone to flooding. Sometimes, access even to undamaged facilities may require passing through flooded roads.

- **Water treatment chemicals** – Regular deliveries of treatment chemicals can be disrupted during disasters, and daily usage can increase as source water quality declines. Identifying alternate suppliers of chemicals can help avoid shortages.
- **Water testing laboratories** – Lifting BWNs requires water testing performed by a certified laboratory to confirm water is safe to drink. Identifying local certified laboratories within a short drive of water treatment facilities can speed the lifting of restrictions.

In summary, water systems play a critical role in disasters by providing water to affected population, but also by allowing critical facilities (e.g., hospitals) to continue operating normally. Furthermore, a functioning water system reduces strain on emergency responders who would otherwise be assigned to fire watch. The biggest issue, though, is one of scale. There is simply no practical way the relief channel can provide sufficient water to meet even minimum basic needs for densely populated areas. In most cases, failures come with little warning, and there is generally storage in the system for a few hours to days. Not enough time to evacuate a large cities.

So, public water supply disruptions are a race against time. Can the system be repaired before storage runs dry, before further damage occurs to distribution systems, before back-up supply wells or emergency connections are exhausted? The very particular supply chain for water systems means that specialized expertise is needed, and water systems have built a system of mutual aid agreements to ensure access to specialized resources and personnel. Often, water systems won't require federal assistance during the disaster if they can get it from the state or industry partners. That doesn't mean the federal community can't be ready to assist. A few key resources such as generators, fuel, radios, treatment chemicals, or mobile water testing laboratory might be the difference between a water system having a brief outage or multi-day crisis. Better communication can ensure that emergency responders have as much as warning as possible in the case of potential failures.

Bottled water is one of the most visible signs of disaster response. Fear eases when bottled water fills the grocery aisles. A running faucet with water that is the safe for human consumption (or a toilet that flushes) may be one of the most important early signs of disaster recovery.

DISPATCHES FROM IRMA

Hurricane Harvey was not the only storm that caused issues for water systems—Hurricane Irma also caused water issues, particularly in the Florida Keys.

Irma Hits the Keys, but Doesn't Cut Them Off

During Irma, Florida's water utilities were largely spared the widespread issues that Hurricane Harvey brought, with a few notable exceptions. The Florida Keys' drinking water is supplied by the Florida Keys Aqueduct Authority (FKAA), which operates a drinking water treatment plant near the tip of the Florida peninsula. FKAA serves water to the Keys via a pipeline (or "aqueduct") that was originally built by the US Navy to serve the Naval Air Station Key West. FKAA also operates some small reverse osmosis plants on the western Keys to provide additional supply. All of the Florida Keys' major utilities follow the path of the bridges and causeways that connect the Keys to one another and the mainland. These key links are vulnerable to a powerful hurricane such as Irma with a significant storm surge. With the prospect of being completely cut off from all utilities and transport of goods, it is easy to see why the Keys were under mandatory evacuation orders. [158]

As Irma approached Florida on September 6, 2017, it appeared that the eye of the storm might pass right through the eastern-most Keys on its way into the Miami area. This track could have easily severed the Keys from the mainland. Instead, the track kept shifting farther and farther westward, and Irma finally made its turn to the north, making landfall at Cudjoe Key and continuing to the Gulf Coast of Florida. Miami was spared the worst of Hurricane Irma, and so were the Keys. The damage from wind and storm surges was serious. Power was out virtually everywhere. A majority of the buildings were wind-damaged, flooded, or both. [158] But the bridges were mostly intact—and so was the pipeline.

The key pipeline was functioning, but much of the distribution system was not. Multiple line breaks and broken piping inside buildings was leaking water faster than FKAA could pump it through the pipeline. Irma had affected the entire length of the Keys. While the major pipelines and storage were still intact, the small service lines serving neighborhoods and houses were shredded. The primary culprit appeared to be tree roots that broke pipes as the trees toppled during wind and flooding. [159] None of the islands was spared.

The Response – Pushing on a (Leaky) Chain

In a complex hydraulic system like a distribution system, pressure regulation is not trivial, even under normal conditions. When the system is de-pressurized, it is a gradual process to build pressure back, requiring significant triage along the way to find and close leaks. A pipe network can build pressure only if more water enters the network than leaves it. So FKAA had to limit water service to many of the Keys while it repaired the breaks. [159]

FKAA faced a challenge, though. Completely cutting off water would require a replacement supply chain of trucks bringing bottled water and would also require many extra public safety vehicles for fire watch that would require fuel, which was in short supply across Florida. Instead, FKAA chose to partially cut off water service both geographically and temporally. [159] Many neighborhoods and developments received water service only a few hours a day. On the more western Keys, FKAA did not provide water service to most of the islands' neighborhoods, but instead set up water filling stations where returning residents could pick up water. [160]

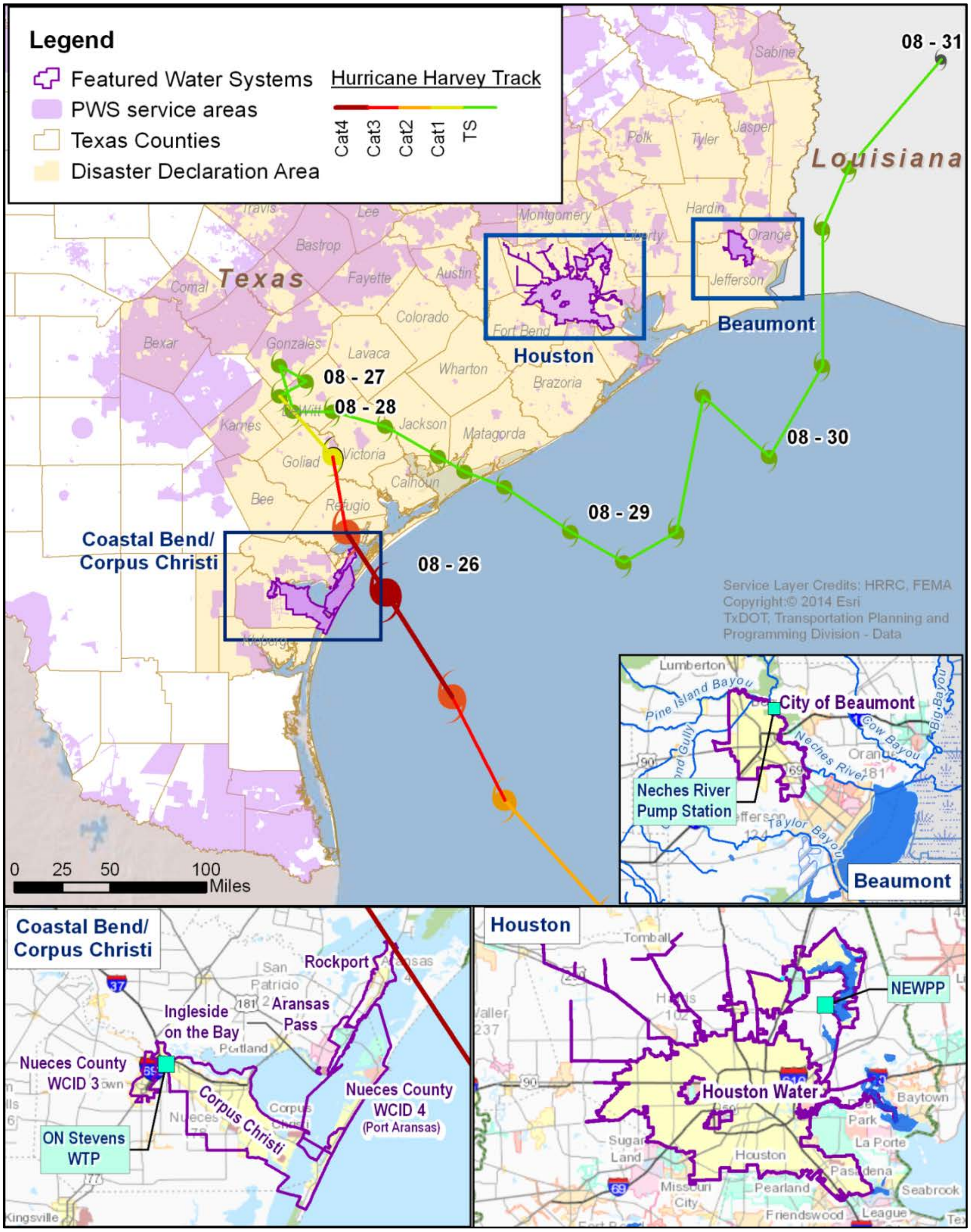
Gradually, FKAA and residents fixed the breaks and closed off the leaks and the system reached adequate pressure. Only when the system pressure was steady, and tests had verified the water was safe for human consumption, could the boil water notices end, and the distribution points be closed. [159]

The peculiarities of water system supply chains were on display. The main pipelines had never been completely severed and there was no viable replacement, so FKAA had decided to keep pushing supply as close as possible to demand nodes rather than take the whole system down. Even though repairs may have been faster without maintaining flow, and certainly less water would be lost, keeping the water moving while figuring out how to stop the bleeding was the logical choice.

Figure CS4-5. FKAA announcement of water filling station availability during Irma recovery.

Source: Facebook, Florida Keys Aqueduct Authority

CASE STUDY 4 APPENDIX: AREA MAP



Credit: CNA. Data Sources: TCEQ, FEMA, Public Utility Commission of Texas
PWS – Public Water System; WTP – Water Treatment plant; NEWPP – Northeast Water Production Plant

Case Study 5: Constraints in Optimized Networks – Evidence from the 2017 Hurricane Season

The Mathews Bridge reaches 146 feet above the St. Johns River, leaving lots of room for ships moving past Jacksonville and into the Atlantic. From high in his emerald green Prostar rig, Joe Albright[19] scans the cranes to his left that line the river at the Port of Jacksonville (JAXPORT). This morning, he has a short haul of groceries for Atlantic Avenue. This afternoon, he is scheduled to deliver to Blanding Boulevard.

In square miles, Jacksonville, Florida, is the largest city in the United States. With 880,000 residents, it is the most populous city in Florida.[20] Long before Mickey Mouse arrived in Orlando, well before Miami was imagined, Jacksonville was a major transportation hub. As late as 1920, the population of Duval County (Jacksonville) was more than double that of Dade County (Miami). [161] Joe came to the area to serve on the USS *Forrestal*, met a local girl, and raised his family here.

In 2017 more than 1.3 million containers were loaded at JAXPORT. [162] Jacksonville is the largest maritime center in Florida. Both CSX Transportation and Norfolk Southern operate major intermodal terminals in Jacksonville. All rail traffic serving Florida transits through Jacksonville. Interstate 10, originating in Santa Monica, California, terminates in Jacksonville at I-95 (which originates at the Canadian border and continues to just south of downtown Miami). The annual average daily traffic (AADT) count for the I-95 bridge crossing at Jacksonville is over 155,000. At the I-295 bridge, the AADT is more than 125,000. [163] The Mathews Bridge mostly connects Jacksonville to its beaches, less than 20 miles east. Still, its AADT is more than 67,000. In 2012 Jacksonville's wholesale trade was valued at over $18 billion, and its retail trade was nearly $12 billion.

[19] "Joe" is a composite of several people active in the Jacksonville transportation sector

[20] US Census Bureau 2016 Estimates: Miami: 453,000, 55.25 square miles. Jacksonville is 875 square miles

When Joe drove for Crowley, he mostly moved containers back and forth from huge barges arriving and departing the port. With Cowan Systems, he drives vans back and forth from the huge 170-plus door cross-dock BJ's Wholesale Club that operates on the western edge of Jacksonville. The American Community Survey estimates more than 13,000 people in Jacksonville are involved in "material moving." [164]

Along the St. Johns River, there are several docks and fuel jetties. Crowley, TOTE, Trailer Bridge, and other shippers use Jacksonville as their principal port serving the Caribbean. For example, 80 percent of the groceries consumed in Puerto Rico are shipped out of Jacksonville. [165] Several fuel farms and five active fuel racks also line the river's bank. According to the US Energy Information Administration, about 10 percent of the fuel consumed in Florida flows through Jacksonville [133]. From downtown to Blount Island, there are roughly 10 densely packed miles of critical infrastructure and key resources. Taken together, this port can seem to be a very big network node. With a wider lens, the Port of Jacksonville is only the neck between huge upstream sources of supply and downstream needs and wants.

Farther west, there is another 10-mile stretch along the I-10 (either side of the intersection with I-295) that has emerged as a critical link in the retail food and fuel (and likely other) supply chains. In addition to BJ's cross-dock, there are large distribution centers for Publix, South East Grocers, Zephyr Dairy, UPS, Southeast Toyota Distributors, Henry Schein, Owens & Minor, and several other major suppliers. Kangaroo and Pilot truck stops are also located here. Jacksonville touts its role as the "gateway" to Florida. According to the US Cluster Mapping Project at Harvard University, 30 percent of the Jacksonville area economy serves markets outside Northeast Florida and Southwest Georgia. [166-167] Medical devices are among the top-10 product categories that Jacksonville trades outside its region, an asset reflecting the city's important connection with Puerto Rico. While Jacksonville is the 49th largest economy among US metropolitan areas, it is the 23rd largest trader of medical devices. This concentration of maritime, surface transportation, and related assets concentrates considerable potential *and risk* in the Jacksonville region.

Geographic and functional concentration is not unusual. There is some evidence that supply chain concentration is increasing. [168] Yossi Sheffi, an MIT scholar of supply chains, has written [169]:

> *Logistics clusters offer their members other advantages, most of which are rooted in the interchangeability of transportation and logistics assets. The basic logistics operations: storage, removal, transportation, tracking, delivery, etc. are similar regardless of the item being handled. Consequently, transportation and logistics assets can handle packages containing a large variety of goods in a standard manner. Furthermore, rail cars, containers, trailers, barges, and airplanes all come in standardized sizes and capacities, dictated by regulations, international standards, or prevailing conveyance designs. Thus capacities, reach, and velocities are similar regardless of the*

company logo on the tractor's door, ocean shipping container side, or airplane tail. Both of these factors mean that companies in logistics clusters can share certain assets, allowing them to serve their customers better than firms not participating in a cluster and allowing them to better adjust to fluctuating business volume.

These advantages are of crucial importance as supply and demand networks attempt to serve increasing density and expectations of rapid delivery.

In the last 50 years, the population of Florida has increased from 6.8 million to over 20 million. Since 1970, Jacksonville's metropolitan area population has increased from 612,000 to 1.6 million, Tampa's has increased 1.1 million to 2.8 million, Orlando's has increased 523,000 to 2.4 million, and Miami's has increased 1.3 million to 5.5 million. This rate of growth and this level of densification requires high-volume, high-velocity supply chains. To also supply demand at affordable prices—even intensely competitive pricing—arguably requires supply chains that are highly optimized, meaning they deliver what customers are ready to buy when and where they will buy it.

The use of Advanced Planning and Scheduling (APS) concepts and technology emerged in the late 20th century with the availability of real-time transaction data and the computing power to more accurately predict patterns of consumer demand. Data analysis and modeling have allowed supply chains to be better organized around the temporal and spatial character of demand, significantly reducing inventory and transportation costs. APS—especially in its attention to production planning—has also driven much more detailed mapping and management of supply chain components and dependencies to enhance the speed and accuracy of delivering what is needed, where it is needed, when it is needed. In recent years, a tension has emerged within planning/scheduling about whether to optimize for predictability or to optimize for unpredictability. But in either case, optimization is intended to shape supply system behaviors to accurately anticipate and serve demand.

Hurricanes, earthquakes, and other calamities play havoc with traditional notions of predictability. The 2017 Hurricane Season was especially challenging. The response of the Jacksonville logistics cluster to Hurricane Irma and Hurricane Maria revealed both its strengths and weaknesses. The following are four examples of adaptation involving grocery, fuel, maritime, and medical goods networks.

These brief case studies reflect a risk that recurred during the 2017 Hurricane Season. Demand and supply networks are often described as having an hourglass structure.[170-172] Demand can be conceived as the lower bulb in an hourglass "pulling" supply. This structural observation can also serve as an operational analogy: many contemporary supply networks are organized to deliver just in time—just when the consumer is ready and able to buy. Considering a wide array of hourglass structures, one recent study notes, "The presence of these critical modules at the waist (the ‘constraints’) limit the space of all possible outputs that the system can generate.” [172] During the 2017 Hurricane Season, the real capacity of crucial networks was again and again reduced to what was happening—or too often *not* happening—at the neck of these perceived hourglass structures.

BJ’S WHOLESALE CLUB CROSS-DOCK

Five days a week, Joe drives up Pritchard Road through the wetlands and pines from which the Trout River forms. The BJ’s Wholesale Club warehouse, cross-dock, and freight yard sit about 600 feet south of Pritchard, part of the 3,300-acre Westlake Park developed by Norfolk Southern.

BJ’s Wholesale Club was founded in New England and followed its snow-bird customers to Florida. There are now 31 Clubs in Florida and five in Georgia. More are expected. The Jacksonville facility is usually called a distribution center, but it is arguably much more a cross-dock. Facing north is a 290,000-square-foot rectangular warehouse, and extending south is a long, thin 170,000-square-foot cross-dock (see Figure CS5-1). On one side, inbound product arrives from multiple vendors. On the other side, vans are allocated multiple products for specific retail locations. Like the waist of an hourglass? This is a configuration that not only facilitates high volumes, it practically enforces high velocity.

Figure CS5-1. BJ’s Wholesale Club distribution center, 4500 Director Road, Jacksonville, Florida

Source: Google Maps

"Everything we do is designed to forward-deploy as fast as possible to our Clubs. That's where the products are needed, not anywhere else," says Trevor LaChapelle, BJ's Vice President of Global Transportation. "We want to receive and sell our products even before we've paid for them."

In addition to volume and velocity, BJ's Wholesale Club also competes on variety, claiming [173]:

> *Our approach to merchandising positions us between other warehouse clubs and grocery retailers. We sell a wide range of products, combining the bulk savings of a warehouse club with a broader assortment and selectively smaller pack sizes in perishable and grocery products than our club competitors. We have more stock keeping units (SKUs[21]) than other warehouse retailers (around 7,200 versus around 4,500), which allows us to offer a greater selection while still enabling us to manage our inventory more efficiently than supermarket and mass-market competitors (which can carry 40,000 or upwards of 100,000 SKUs, respectively).*

BJ's also claims to save its members 25 percent or more on grocery purchases compared to mainstream supermarkets. Competing on volume, velocity, variety, and value is only possible when supply chains can reliably discern what is needed where and when and can deliver on target. As BJ's explains to potential investors [173]:

> *We buy most of our merchandise from manufacturers for shipment either to a BJ's cross-dock facility or directly to our clubs. This eliminates many of the costs associated with traditional multiple-step distribution channels, including distributors' commissions and the costs of storing merchandise in central distribution facilities. We route the majority of our purchases through cross-dock facilities which break down truckload quantity shipments from manufacturers and reallocates these goods for shipment to individual clubs, generally within 24 hours. Our efficient distribution systems result in reduced freight expenses and lower handling costs compared to other retailers.*

As important to BJ's operations, especially in preparing for a fierce nor'easter or a major hurricane, is the freight yard surrounding their cross-dock and warehouse. Trevor LaChapelle explains:

> *At the end of week before Irma hit on Sunday, we were getting backed up on what could be delivered. Demand was off the charts. Transit times were doubled or more because of the evacuation....Most of the time, our Clubs are the relief valves in our supply chain. They are big enough to take almost anything we can get to them, and we push hard. [BJ's retail facilities range between 63,000 and 150,000 square feet.] But the whole week after Labor Day, inbound was*

[21] Stock Keeping Units or SKUs are popularly known as barcodes. These codes identify specific products and services and are widely used in inventory management.

> *delivering more volume than we could get off the property at Jacksonville. Obviously, we've got to keep the cross-dock flowing; any disruption in that flow would be its own disaster. So, when we see flow slowing between the cross-dock and the Clubs, we move product into parked vans. We keep a trailer pool on hand just for managing this risk. Our tractor-to-trailer ratio isn't efficient. In fact, it's awful, but this keeps the cross-dock flowing, which is most important. And with Irma we were able to create specific Hurricane Trailers pre-loaded with everything Clubs really need when the grid is down. So effectively adapting to the pre-storm problem actually helped us rebound more quickly post-storm.*

BJ's and Cowan have consciously built into their high-volume, high-velocity, value, and variety optimized supply chain a relief valve to manage specifically unpredictable events. The neck of their hourglass can be expanded.

JACKSONVILLE AREA FUEL NETWORK

Joe usually fills up his tractor at the Travel Pilot Center near the intersection of I-295 and Pritchard. There's a Kangaroo Express across the street, but Pilot and Flying J give Cowan Systems a nationwide volume discount. The Cowan fleet carries twin 100-gallon fuel tanks. Trucks with two 150-gallon tanks are more common.

"Company-wide, our typical haul is about 200 miles," Joe says. "Fuel is heavy. The less fuel we carry, the more inventory we can haul. At typical speeds, our fuel tanks are good for about 2,000 miles. From Jacksonville, Miami is 700 miles roundtrip. Homestead is 760." Cowan Systems is serious about running lean. Their fleet of more than 1,700 tractors feature lighter-weight engines. Their trailers feature mostly aluminum flooring. Along with other intentional choices, a Cowan truck and trailer start about 5,000 pounds lighter than most of the competition.

Almost all of Jacksonville's fuel arrives by ocean barge, most of the time on Jones Act carriers from refineries near Houston. There are five active fuel terminals located near the convergence of the St. Johns River and the Broward River: Buckeye, TransMontaigne, MPLX, NuStar, and CenterPoint.

The Buckeye terminal is the local branch of one of the largest fuel operations on the planet. In the United States, the company operates 115 fuel terminals, with another 22 overseas. Buckeye has global storage capacity for more than 170 million barrels of fuel.[174] The Jacksonville terminal stores and sells gasoline and diesel from a six-bay fuel rack (see Figure CS5-2).

Figure CS5-2. Buckeye Terminals, LLC - Jacksonville 2617 Heckscher Drive

Source: Google Maps

There are about 400 fuel racks in the United States [175]. About 220 are attached to a pipeline. The others, like Buckeye in Jacksonville, depend on maritime vessels or tanker trucks for resupply or are located at a refinery. Racks are built to rapidly and safely fill tanker trucks. A tanker carrying 9,000 gallons can usually be filled in about 40 minutes. Many fuel stations have storage tanks with a capacity of roughly 9,000 gallons, often one for each grade or gasoline (or two for regular and one for premium if they use blending). But others, including the Pilot where Joe usually fills up, can have much larger storage capacities. The largest truck stops will often sell more than a million gallons of fuel per month. That means more than 25 rack visits per week just to keep one truck stop operating. According to a study conducted by the National Tank Truck Carriers, in 2013 tanker trucks accounted for 163,670 tractors (or 10.9 percent) of all the roughly 1.5 million over-the-road tractors in the United States.[176] Just about half of this fleet is committed to transporting petroleum products.

Buckeye has the largest rack in the Jacksonville area. But Pilot Travel Centers and other fuel retailers may, depending on price, availability, and bulk contracts, receive fuel from the Taft terminal near Orlando (150 miles), the Seaport Canaveral racks (160 miles), or even from the Colonial Pipeline racks at Bainbridge, Georgia (200 miles).

According to Genscape, a firm that monitors the energy market, "Total motor gasoline demand in Florida rose 62 percent between September 4–7 (2017) in preparation for Irma….Truck rack loadings on September 7 increased by 64 percent from one week prior, and week-to-date (September 2–7) gasoline rack demand in the state was up 32 percent compared to the previous week (August 26–31).” [177]

The week before Irma hit, the demand for fuel was difficult to meet no matter where it was sourced. “A couple of million cars evacuating north tends to disrupt the best-laid plans,” Joe observes. On Saturday September 9, according to GasBuddy, about 36 percent of Jacksonville gas stations were dry. By Sunday local outages had climbed to 46 percent. [139] Joe recalls:

> *Diesel was sometimes still available when gas was out. Anyplace that still had gas had so many cars piled up that it was tough to get a truck through the crowd. I was able to top-off at the Pilot on Friday night, but it took a while. Anyway, after that, BJ’s reloaded the van for the first post-hurricane run. This set us up for a jump-start; it cleared the cross-dock and added weight to help the van resist winds. Nice trifecta. Then we parked real tight in the yard, more wind protection. Anyway, by Saturday morning the yard was packed tight as eggs in a carton.*

Jacksonville is more than 300 miles northeast of where Irma made second landfall on Sunday morning (September 10), but by Sunday night the city was feeling her full effect. Just over five inches of rain fell on Sunday, and about four and a half inches fell on Monday. [178] Wind gusts of over 86 miles per hour and sustained winds of 50 miles per hour were recorded.

Figure CS5-3. Buckeye Terminal faces flooding on Drummond Creek

Sunday night Jacksonville started losing power. About 12,000 customers were off the grid by 10:00 p.m. By Monday evening, over 230,000 customers (places not people) had lost power. [179] Eventually, 284,000 of more than 400,000 Jacksonville Electric Authority customers were without power for some period.

The Buckeye racks had emergency generators. The electrical outage did close several retail fuel stations. On Monday September 11, flooding was even more a problem. According to Weather Underground: “Waters along the St. Johns River in Jacksonville spiked dramatically on Monday morning, due in part to runoff from torrential overnight rains of 5”-15” across northeast Florida. At 1:06 p.m., the gauge at downtown Jacksonville’s Main Street Bridge showed a water height of 5.57’, smashing the previous modern-day record of 4.12’ observed during Hurricane Dora on Sept. 10, 1964.” [24] The Buckeye racks were 11’ above flood stage. But most tanker trucks stayed parked. Joe says:

> *I live just south of BJ's and could get in on Sunday without much problem. They wanted to send some trucks to Miami to see what's up. My wife went over to help with the grandkids. I decided to volunteer to make the run. Rain was really bad down on the Treasure Coast (Ft. Pierce, Vero Beach) but otherwise not much problem. The stores were open, and we could deliver. Not many others on I-95. But we noticed that everything was dark down and back, didn't see one truck stop open, and diesel was really tight in Jacksonville. I pulled back into the yard almost half empty.*

Florida's upstream fuel stocks were fine. Despite the loss of refining capability as a result of Hurricane Harvey, the US Department of Energy reported, "As of the August 25 Weekly Petroleum Status Report, stocks of gasoline in PADD 1 (East Coast) were near the top end of the 5-year range." [24]

The energy market adapted to the loss of supply from the Gulf Coast and the spike in Florida demand. *CityLab* reports [180]:

> *Barges that normally deliver from offline Gulf Coast refineries were rerouted to New York and Philadelphia to bring gas south. Tankers from Louisiana and Mississippi steamed eastward to reach Florida in time, having been delayed by Harvey's fearsome path. One oil trader redirected two European barges destined for Africa to Florida instead…the state took in some 570,00 barrels from Europe ahead of Irma in order to make up for supplies it had lost to Harvey.*

But no matter how much supply is available, the time and space required for distribution can be insufficient for sudden surge in demand. Joe observes, "Monday there were a whole bunch of empty gas stations. The number of fuel racks did not suddenly increase. Miles between racks and the gas stations stayed the same, and some were flooded. Most truckers stayed home, so even fewer tankers. Takes a while to make up the difference."

MARITIME TRANSPORT – CROWDING AT SAN JUAN PORT

More than a week before Irma's remnants hit Jacksonville, she had already impacted the city's docks. JAXPORT is the principal embarkation point for most mainland products shipped to and sold in Puerto Rico and the US Virgin Islands. TOTE, Trailer Bridge, and Crowley are all Jones Act Carriers[22] with significant operations at JAXPORT. Transit to San Juan typically requires three to six days depending on vessel, course, and speed.

[22] The Merchant Marine Act of 1920, also known as the Jones Act, requires that all goods moving between US ports be carried by US owned, built, and crewed vessels. As a result, US products consumed in Puerto Rico must be transported by so-called "Jones Act Carriers". The Jones Act does not restrict the import of foreign goods.

As Irma formed on August 30, there was scant time to expedite landings and cargo unloading at San Juan. The hurricane then delayed cargo movement while plowing through the northern Caribbean, hitting St. Thomas very hard and knocking out power to over a million Puerto Ricans. The Port of San Juan was closed September 5–7. [78] The Port of Jacksonville was closed September 9–13. When Maria hit Puerto Rico on September 20, shippers, stevedores, drayage drivers, and other port personnel were still working to make up for Irma's delays.

Joe's buddies still hauling to JAXPORT told him that as Maria closed in on Florida, CSX and Norfolk Southern embargoed cargo into Jacksonville, and lots of truckers were staying away, too. [181-182]

Demonstrating this delay—and the maritime system's adaptability—one of Trailer Bridge's vessels (*Chicago Bridge*) departed Jacksonville on September 1 arcing south of Cuba to avoid Irma's storm track. The vessel arrived at San Juan on September 12. The *JAX-San Juan Bridge* arrived at Jacksonville on September 5 and was held there until late on September 12. *Memphis Bridge* arrived from San Juan on September 7 and did not depart until September 15. Both vessels took the long way around Hispaniola to avoid Maria, arriving at San Juan on September 23. In early September, Trailer Bridge reactivated the vessel *Brooklyn Bridge* in anticipation of needing additional capacity to make up for these delays. [183] The vessel *JAX-San Juan Bridge* (see Figure CS5-4 below) was also sailing proximate sea lanes.

Figure CS5-4. The JAX-San Juan Bridge is a non-propelled barge, 223 meters x 32 meters

Source: TrailerBridge

In early September 2017, vessels operating between JAXPORT and San Juan included both self-propelled liners and tug barges. Crowley was sailing nine Roll-On, Roll-Off (RO-RO) barges. TOTE was serving San Juan with two LNG-powered Lift-On, Lift-Off (LO-LO) container ships. [184]

In 2015, JAXPORT had 2,200 vessel calls of all types, carrying more than 18.5 million short tons. That same year, the Port of San Juan had just over 1,500 vessel calls with more than 11 million short tons. About 7.3 percent of this throughput at San Juan consisted of groceries. [185] Both ports are key nodes connecting supply in the mainland US with demand in the Caribbean. The Port of San Juan is the most important entry point for goods coming into Puerto Rico and those continuing to smaller islands in the Caribbean. Both ports are "supernodes" because of their volume—and because their capacity to process goods has a profound impact on total throughput of dozens of supply chains for goods ranging from groceries to cars to concrete. All these goods pass through the same docks and are moved by the same cranes, whose overall capacity is more or less fixed.

Domestic shipments arriving on Jones Act carriers into the Port of San Juan are not liable for customs duties, but most items arriving at the port are liable for Puerto Rico sales and use taxes that are calculated and paid before the items leave port. Since 2014, these payments have been digitally facilitated using the Portal Integrado del Comerciante (PICO) system.

On Tuesday September 19, as Hurricane Maria tore through the eastern Caribbean, the Puerto Rico Department of the Treasury (widely referenced as Hacienda, reflecting the name of its colonial era headquarters) anticipated the PICO system could fail. It did in fact fail. But while communications systems were still operating, Hacienda conceived and distributed a temporary process to facilitate releasing certain "authorized merchandise," including food, medicines, raw material, animals, perishable goods, power plants, and goods received by bonded taxpayers. [186] The temporary procedure, also called "manual release," outlined the following requirements. The party receiving the goods must physically appear at the Office of Consumption Tax located in the Crowley facilities within the Isla Grande port zone (Crowley satellite office) and submit the following: a bill of landing, a manifesto, a copy of bonding documents, evidence of applicable payments, the name of the consignee, and the cost of merchandise.

On September 23, Trailer Bridge advised its customers in Puerto Rico [187]:

> *Department of Hacienda's electronic system remains down due to Hurricane Maria, since approximately 12 p.m. on Tuesday 9/19 no cargo has been able to be transmitted and no status has been able to be received by the carrier. Cargo that was not transmitted to Department of Hacienda prior to the system closure cannot be processed through normal electronic channels for release. We anticipate based on the devastating impact of Hurricane Maria it will be several days or longer before the electronic processes are back up and running.*

Given disrupted sailing schedules starting with Irma, many shippers used the window between the two hurricanes and after Maria's passing to surge what they could toward San Juan. When the port fully reopened on September 13, several staged fuel shipments immediately made delivery. [188] But many—even most—newly received commercial products were held at the port until taxes could be paid.

Figure CS5-5. Crowley maritime shipping lanes

There were myriad reasons why many shipments were not retrieved from the port in the first two weeks after Maria's passing, including the direct impact such a hard-hitting storm has on survivors. There are immediate issues of response and recovery that do not usually involve retrieving Bills of Landing. Given the island-wide grid loss, this would have been difficult even for those so inclined. But even with all the paperwork in hand, warehouse or retail locations could not receive goods from the port before clearing debris from the roads. With the grid (and refrigeration) non-operational, refrigerated vans were better for some products (fresh produce, for example) than hot tables or shelves. Many truckers faced a host of survivor priorities and felt uncertain about driving conditions and fuel availability.

For reasons ranging from new paperwork requirements to much more profound (and less arbitrary) impediments, congestion on the docks soon became a severe problem. More than a week after Maria's landfall, *Bloomberg* reported [189]:

> *Thousands of cargo containers bearing millions of emergency meals and other relief supplies have been piling up on San Juan's docks since Saturday. The mountains of material may not reach Hurricane Maria survivors for days. Distributors for big-box companies and smaller retailers are unloading 4,000 20-foot containers full of necessities like food, water, and soap this*

week at a dock in Puerto Rico's capital operated by Crowley Maritime Corp. In the past few days, Tote Maritime's terminal has taken the equivalent of almost 3,000. The two facilities have become choke points in the effort to aid survivors of Hurricane Maria. "There are plenty of ships and plenty of cargo to come into the island," said Mark Miller, a spokesman for Crowley, based in Jacksonville, Florida. "From there, that's where the supply chain breaks down—getting the goods from the port to the people on the island who need them."

Others in Puerto Rico claimed that Hacienda officials at the port expedited FEMA freight and ignored commercial throughput, diverting trucking resources that usually served wholesalers and retailers. Movement out of the port was below normal for much of the first three weeks after landfall.

Between unclaimed containers piling up at the port and many removed containers not being returned, Jacksonville was on the edge of not having enough containers to make new loads. Jose Ayala, vice president for Crowley's Puerto Rico services, told the *Journal of Commerce* that Crowley had "added more than 5,000 containers and several hundred chassis to make up for slower equipment turn times." [184] Puerto Rico was eating up containers already in short supply globally since early in 2017 [190]. In June 2017 the *Journal of Commerce* reported [191]:

US exporters are scrambling to find containers, with some coming up empty handed. While some of the shortage is seasonal, some of it is because of new Chinese regulations slowing container production and pressure on carriers to get empties back to Asia for import loads. Kansas City has been hit particularly hard, according to individual carrier reports that have also highlighted Dallas, Denver, Memphis, and even Chicago.

Because of Hurricanes Irma and Maria, maritime transport between JAXPORT and San Juan experienced delays. There were also several system disruptions. But there was never a fundamental shortage of supply. Rather, there was a significant surge in supply. The unevenness of flow, combined with this surge, created congestion at the port in San Juan. The surge in supply did not always match demand preferences, and there were several problems with surface transportation once products arrived at San Juan, which further increased congestion at the port.

Several months after the 2017 Hurricane Season, a shipping executive[23] walked along the docks at JAXPORT:

What happened in Puerto Rico post-Maria was probably the biggest Beer Game ever played," he said. "Think about it, the system that had been feeding 3.4 million people on September 19 was

[23] This interviewee spoke on the condition of personal anonymity and not identifying his employer

mostly still in place after landfall. All the food that was in the pre-existing pipeline was still flowing, maybe flowing around Cuba instead of direct to San Juan, but nothing fundamental had happened at JAX or the San Juan port to change anything. People just got nervous. Grid's out. Communication's spotty. Lots of stores aren't open. Truckers are absent. So, yeah, folks got nervous. At the port and on the liners and on order into Jacksonville, they've got everything they need. But they started ordering more. Demand was erratic and anxiety-driven. New sources of demand – like FEMA, Commonwealth, and Mayors – ordered a lot more on top of the plus-up already flowing. So, we're trying to push a lot more down essentially the same pipe. Was there displacement? Hell, yes. Was there a need for much better distribution of stuff on the island? Absolutely. Was more stuff needed? Not really and handling all the unneeded stuff just complicated solving the distribution problem. As usual there was a real communication and distribution problem, misperceived as a supply problem.

The Beer Game[24] is a role-play activity often included in introductory supply chain management classes. It was originally developed at the MIT Sloan School of Management. In its most common form, the game typically exposes how small changes in the pattern of downstream demand can be amplified in terms of upstream supply. Inaccurate perceptions of demand—usually related to distorted communication of demand—can create production inefficiencies, excess inventory, disrupted distribution, and ineffective fulfillment of demand. These symptoms are often referred to as the "bullwhip effect."[25] Instead of decisions based on documented demand and actual supply, uncertainty drives behavior that floods the market. In the case of post-Maria Puerto Rico, was the pre-existing neck size closer to the right size than was realized at the time?

Not surprisingly, cargo receipts by weight for the Port of San Juan were about 20 percent below normal for September 2017. But October receipts were higher than October 2016. The weight of cargo received at San Juan in November 2017 was 40 percent higher than in November 2016, and it was the most delivered in November since 2012. December cargo was 18 percent higher than December 2016 and the highest in five years. [192]

[24] The Beer Game

[25] Sloan Management Review, The Bullwhip Effect

INTRAVENOUS BAG MANUFACTURING IN PUERTO RICO

Trailer Bridge was founded to provide single-carrier, highway-with-maritime transportation to and from the mainland and Puerto Rico. The company has its headquarters in Jacksonville and sails from the southwest tip of Blount Island.

Like all carriers operating between JAXPORT and Puerto Rico, its loads into San Juan are much heavier than those sailing outbound. Its inbound flow to San Juan is four-times larger than its flow on the return trip to JAXPORT. Most of the shipping containers sailing from San Juan are empties, needed at the mainland port and farther back to refill with supplies for Puerto Rico. There are comparatively fewer products moving into JAXPORT. Each year, Bacardi alone sends about 138 million pounds of rum to the mainland. But the highest value products embarked for the mainland are usually medical goods and pharmaceuticals.

Despite overall declines in pharmaceutical production in Puerto Rico, in recent years Trailer Bridge has seen outbound volume for specific categories of medical goods increase. [193]

Figure CS5-6. Baxter IV bag

Puerto Rico produces $40 billion per year in pharmaceuticals and medical goods. This is more than the value produced by California and Indiana combined (the next two top producers of US pharmaceuticals and medical goods). According to the Food and Drug Administration (FDA) [194]:

> *Puerto Rico manufactures thirty drug products and approximately ten biological devices/biologics that are of critical importance because Puerto Rico is a primary or sole manufacturing site and these drugs do not have clear therapeutic alternatives. All forty of these products are being carefully monitored by the FDA Drug Shortage Teams; fourteen of these drugs are sourced only in Puerto Rico.*

Since 2015—and Hurricane Maria—Trailer Bridge experienced specific increases in shipping volumes for intravenous bags. Baxter is the largest US producer of these products. There are two plants in Puerto Rico that produce over 40 percent of the intravenous bags used in US healthcare. [195] A global shortage of these products began in 2014. Since then Baxter has been pushing to fill the gap, hence the increase seen by Trailer Bridge. In this case, the production capacity constrains more than the transportation capacity.

According to the New England Journal of Medicine [196]:

> *Saline is an inexpensive product—it's simply salt water—but proper manufacturing practices are required to keep it sterile, pyrogen-free, and free from particulate matter. Production demands are challenging, since very large quantities are needed: more than 40 million bags per month. Saline is required for virtually all hospitalized patients, whether as a component of a medication infusion or as a hydration, resuscitation, or irrigation fluid. Unfortunately, shortages of saline have become commonplace in recent years. Most drug shortages occur with older, generic, injectable medications that are produced by a small number of suppliers—typically three or fewer. The United States gets its saline from just three companies: Baxter International, B. Braun Medical, and ICU Medical. Most shortages are caused by a quality or production problem at the manufacturing facility—causes that apply to the current saline shortage as well.[2,3] In addition, when one supplier experiences a shortage, other suppliers often have insufficient manufacturing capacity to make up the difference.*

US supplies were further reduced by an August 2017 decision by B. Braun Medical to exit the intravenous bag market [197]. The hourglass structure of the intravenous bag market tightened at the neck—the relatively few sites that account for much of the manufacturing.

The plants manufacturing intravenous bags are located at Guayama, about 30 miles from Maria's landfall, and at Jayuya in the central highlands, one of the hardest hit areas. As was the case across Puerto Rico, the electrical grid failed. Restoration of the grid to each of these locations was difficult and especially time consuming in Jayuya. At the beginning of March 2018, half of the residents of Jayuya were still off the grid. [198]

The manufacturing facilities had emergency generating units. But these were designed and fueled to maintain operations during short-term outages, not for months and months. Further, they were large units that consumed large amounts of diesel. About two weeks after Maria, Baxter was having particular difficulty being regularly refueled. They reached out to FEMA for fuel. A FEMA official explains:

> *It was, I think, my second day in Puerto Rico. I was at the JFO [Joint Field Office] and some guy generally explained the situation and asked for fuel support. Made sense to me, and I felt like we could get them what was needed. But as I understood regulations, for FEMA to provide this support to the private sector, I needed someone to officially tell FEMA that this is a critical national facility. I asked. I pushed for maybe two more days. No answer. Then I moved on to where I could make a difference. There were plenty of other problems where I was able to be more productive. You don't even have time or energy to be frustrated."*

As far as this FEMA official recalls, no one said anything about intravenous bags. There was no mention of 40-plus percent of national production.

> *It was a big pharmaceutical and medical goods maker. That was good enough for me. I probably didn't connect the dots until early January when I happened to hear about the saline shortage back on the mainland. But even if I had connected the dots at the beginning, I'm not sure we were, at least back then, leaning forward to engage these kinds of problems. We were plenty busy just trying to keep the hospitals running and the water on.*

Nine months after the fact, a more senior FEMA official offers:

> *Yeah, we're still not there yet. We're focused down-the-supply-chain to move heaven and earth to respond to a state request to fill a gap or an unmet need. It's the most used and straightforward way we exercise our Stafford Act authorities. But understanding the up-the-supply-chain issues where we, the operators/executors, don't know what we don't know about critical infrastructure or supply chains or maybe don't know what someone else or some plan knows, that's the issue. We need to have processes, systems and relationships that let us see these things coming. That said, and with all the benefit of hindsight, I sure wish we would have worked with Baxter to get the Commonwealth to request the refueling. That's the solution that is always fastest and most effective: get the issue in front of the Governor's team so they can ask for the help.*

There had been a shortage of this critical product since 2014. One of three US manufacturers exited the market in August 2017. The single largest US manufacturer lost production capability in late September. Then, the 2017–2018 flu season was one of the worst in years. [199] Did someone say "perfect storm"?

On October 13, Scott Gottlieb, the FDA Commissioner, issued a statement that included [200]:

> *The FDA has also taken many steps to help Baxter restore operations in its Puerto Rico facilities and move critical products onto and off the island. The FDA and Baxter will continue to keep in close consultation as we monitor the challenging situation on the island. The agency is also continuing its work with other manufacturers on steps to prevent or mitigate shortages of other types of critical medical products. Among the actions that the FDA is taking—in conjunction with other manufacturers and federal and local government partners—to help restore production in Puerto Rico and maintain operations on the island is helping facilities secure fuel and manufacturing supplies, and the logistical support to move critical products onto and off the island.*

In late December—about 90 days after the hurricanes hit—power was restored to the Baxter manufacturing plants. On January 4, 2018, the FDA Commissioner reported [200-201]:

> *All the other companies that manufacture products that were on our initial list of drugs that we considered critical and at risk of potential shortages—because the drugs were largely or entirely manufactured in Puerto Rico—are now on the power grid. Many of these companies report to us that their production is increasing. While there are still many challenges that remain—for instance, the commercial power grid remains unstable in places—these developments reduce the risk of any future shortages resulting from the impact of the storm on the island's manufacturing sector.*

In June 2018, Trailer Bridge was honored by New York's Seamen's Church—along with Crowley and TOTE—for what the carriers had delivered to Puerto Rico after the hurricane. [202] What they carried *out* of San Juan to Jacksonville was equally lifesaving.

PRELIMINARY ANALYSIS

To serve dense populations, volume (or more precisely, throughput) is necessary. High velocity can be conducive to moving volume. Efficiently moving volume at high velocity often facilitates delivery at a cost/price (value) that is affordable to a higher proportion of the population.[26] Networks often assume an hourglass structure in trying to improve velocity (speed in a specific direction).

To deliver volume at higher velocities, networks are organized and emerge. As greater volume at higher velocity is achieved (i.e., throughput or flow), spatial concentration is a recurring—perhaps innate—feature of networks. Spatial concentration, volume of flow, and velocity of flow are often mutually reinforcing. [203]

How and where concentration emerges in a network has important implications for robustness, resilience, and adaptability. How and where flow is generated can be equally important to the behavior and survivability of the network.

High volumes moving at high speed to specific destinations are needed for BJ's Wholesale Club to achieve its business goals and the expectations of its customers. For this purpose, BJ's has concentrated its capacity for receiving goods from suppliers and shipping to its Clubs at one location west of Jacksonville. This location was selected, designed, and is currently operated to maximize velocity of throughput. The cross-dock is a self-constraining choice. Warehouse or other longer-term storage is strictly limited in part to enforce velocity. Comparatively cheap vans are kept on hand to provide a seldom needed relief valve. Since there are no viable replacement facilities (a structural bottleneck in the supply chain), the relief valve ensures that the throughput of the cross-dock can be maintained.

Florida's fuel network is concentrated in six large nodes, specifically petroleum product terminals.[27] This concentration facilitates economies of scale involved in transporting and storing large quantities of fuel. Each of these nodes consists of its own sub-networks

[26] Variety of choice and the so-called veracity (visibility and integrity) of the supply chain may be a comparative advantage in attracting demand.

[27] Tampa Port, Taft Terminal, Port Everglades, Port Canaveral, Port of Jacksonville, and the Colonial Terminal at Bainbridge, Georgia

featuring a method of filling the terminal storage (pipeline or offloading ships), and one or more fuel racks to fill trucks that distribute the fuel. Enormous supply is distributed to enormous demand through a proportionally narrow discharge point. The number of fuel racks—and tanker bays available at each rack—reflect a network configuration that is arguably optimized as “just right” for currently perceived and anticipated demand.[28] The relief valve for fuel racks mostly involves operating for longer hours and, up to a point, serving additional tankers. But too many tankers at the same time can also reduce overall throughput. [204]

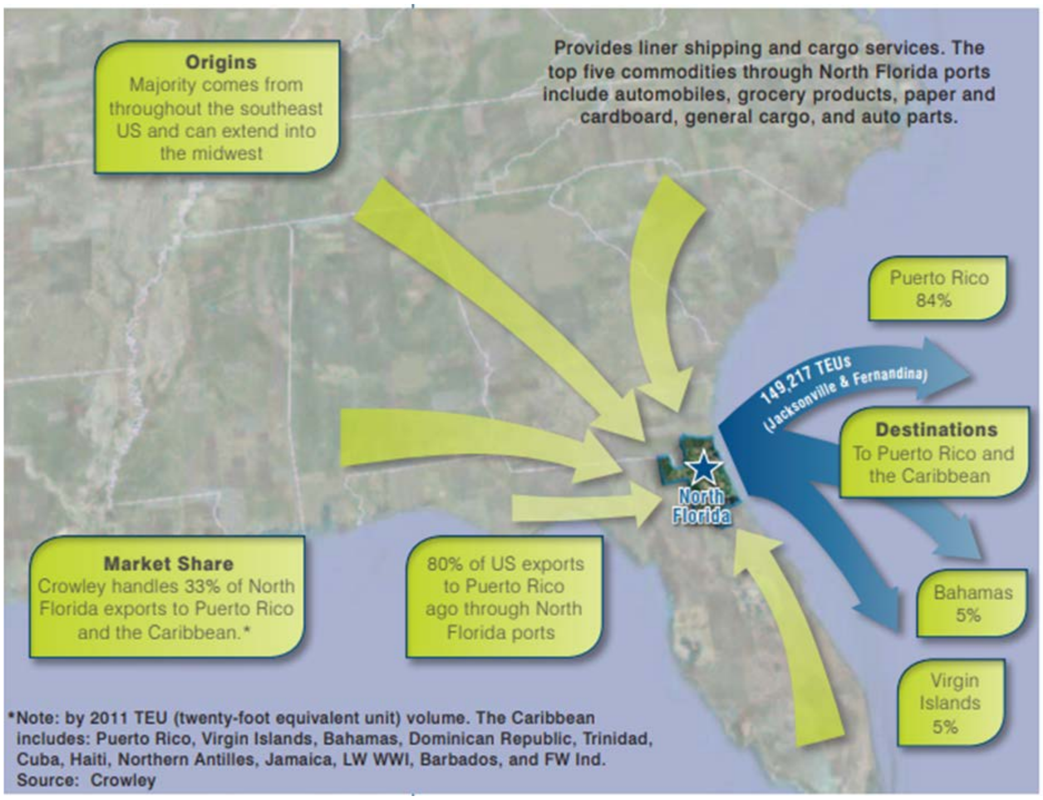
Puerto Rico’s supply network is highly concentrated at the Port of Jacksonville [205] as well as at (and near[29]) the Port of San Juan with three carriers and a comparatively small number of vessels facilitating the vast majority of supply. The strong link between Jacksonville and Puerto Rico is shown in Figure CS5-7, a schematic of the Crowley maritime network’s freight flows. As spatial concentration of volume has increased—and as regional carrier volumes have increased [206]—competition focused on velocity appears to be increasing. [207] Increasing shipping capacity is not easy or quick. Diversifying ports, origins, or entries can be even more complicated. These ports, and the supply chains for all the goods they handle, depend on the processing capacity of docks, cranes, and even bureaucrats.

Intravenous bags are needed in high volumes. Given low profit margins for the product, concentrating production is a reasonable network configuration choice. Velocity of supply from existing production has become more important as sources of volume have declined. When forty percent of volume usually serving US healthcare was suddenly shut off by the collapse of the grid in Puerto Rico, problems emerged with nearly every attempted relief valve. [208]

[28] For an interesting treatment on the role of constraints in configuration problems see: The Goldilocks Problem by Tudor Hulubei , Eugene C. Freuder and Richard J. Wallace.

[29] Outside the Port of San Juan, primarily in Bayamon, there is a parallel spatial concentration of storage and distribution capacity.

Figure CS5-7. Crowley maritime network



Source: North Florida Freight Logistics and Intermodal Framework [209]

Once concentrations of supply and demand are well-established and regular channels of movement (involving both time and space) have emerged, quick changes in a network can produce unpredictable effects. But awareness of concentrations and channels—including related risks and rewards—presents the opportunity to reduce excessive risks and develop response strategies for when risks are realized. Being able to find hourglass structures in regional and local demand and supply networks can provide helpful strategic and operational focus.

In the FEMA After-Action Report on the 2017 Hurricane Season, the agency concludes [210]:

> *The unparalleled scope and scale of the 2017 Hurricane Season underscored the need for, and identified several limitations in, implementing timely national response capabilities that are fully integrated with and supportive of private sector supply chain restoration. In 2017, public and private sector response and recovery efforts were too "stove-piped" to share timely information, too slow to consult, and as a result, often too late to synchronize stabilization efforts. The public and private sector are inextricably linked and must have shared situational awareness and the*

ability to synchronize their respective efforts to be successful. FEMA should work with its key partners to develop a more comprehensive understanding of local, regional, and national supply chains, as well as stronger relationships with critical private sector partners to support rapid restoration in response to catastrophic incidents.

Such a "comprehensive understanding of local, regional, and national supply chains" will include the role of network concentration and related constraints. In each of the four examples outlined above, significant concentration(s) of supply was connected to significant concentration(s) of demand by way of rather sparse points of discharge: cross-docks, fuel racks, and the JAXPORT to San Juan maritime shipping lane. These hourglass structures—usually sufficient to support supply and demand—can suddenly become life-threatening constraints. Recognizing the potential for such constraints and being prepared to preempt emerging constraints is an important means of synchronizing private-public stabilization efforts.

Hourglass structures are common features in hierarchical systems. They are observed both in natural and engineered contexts. Hourglass structures can assume fractal-like properties, appearing self-similar from micro-to-macro.[30] They are not always constraints. If and when the neck of an hourglass survives an extreme event, it may in fact be a crucial element in increasing system capacity.

For all these reasons, these hourglass structures can reward attention by individuals and organizations involved in disaster mitigation, preparedness, response, and recovery. Where are the hourglass structures? How can hourglass structures be pre-identified and anticipated

[30] From "The Hourglass Effect in Hierarchical Dependency Networks" by Kaeser M. Sabrin and Constantine Dovrolis*: It has been observed across several disciplines that hierarchically modular systems are often structured in a way that resembles a bow-tie or hourglass (depending on whether that structure is viewed horizontally or vertically). Informally, this means that the system generates many outputs from many inputs through a relatively small number of intermediate modules, referred to as the "knot" of the bow-tie or the "waist" of the hourglass. This "hourglass effect" has been observed in embryogenesis, in metabolism, in immunology, in signaling networks, in vision and cognition, in deep neural networks, in computer networking, in manufacturing, as well as in the context of general core-periphery complex networks. The few intermediate modules in the hourglass waist are critical for the operation of the entire system, and so they are also more conserved during the evolution of the system compared to modules that are closer to inputs or outputs. These observations have emerged in a wide range of natural, technological and information disciplines, and so it is interesting to investigate whether the so-called hourglass effect has deeper and more general roots that are largely domain independent…. If there is a change in the inputs (sources), the outputs do not need to be modified as long as the modules at the waist can still function properly. Similarly, if there is need for a new target, it may be much easier (or cheaper) to construct it reusing the modules at the waist rather than directly relying on sources. This is related to the notion of "constraints that de-constrain", introduced by Kirschner and Gerhart in the context of biological development and evolvability. At the same time however, the presence of these critical modules at the waist (the "constraints") limit the space of all possible outputs that the system can generate.*

in demand and supply networks? In the supply chain there are already analogues to streamflow gages from hydrology in place that could help us measure the volume and velocity of upstream to downstream flows. These views of volume and velocity can be used to determine where there are constraints, as well as when instead the neck is actually enhancing throughput. For example:

Demand Pull: Where are electronic transactions being made (with bank cards or electronic benefit cards)? Often more important, where are electronic transactions *not* being made?

Flow Volume and Velocity: What are traffic counts at key transportation intersections? What are traffic counts at fuel racks? How is the rack-rate for fuel behaving? What are regional (and wider) spot-market rates for trucking? What is the sailing schedule for vessels? How do the current numbers compare to recent counts and year-over-year? Where are the principal breaks in the transportation network?

Supply Potential: What are currently available fuel stocks? Did major distribution centers, warehouses, and cross-docks survive the event? Are these facilities still connected to transportation networks? Do they have key resources needed to operate (power, fuel, water, communications, personnel)?

Being able to monitor specific indicators of volume and velocity across demand and supply networks would enhance the ability of FEMA and others to effectively target disaster mitigation, preparedness, response, and recovery in case of disruption and destruction. In some cases, restoring supply potential by providing key resources or a relief valve for a glut in product that is constraining throughput can be more effective than surging a replacement supply chain.

Synthesis and Strategic Recommendations

Harvey, Irma, and Maria have reconfirmed important findings from a wide range of prior extreme events. The following points are of specific strategic importance:

- Private sector supply networks and the public sector relief channel are two mostly separate flows; they have limited visibility of each other.
- Private sector supply capacities are orders of magnitude larger than public sector relief channels.
- FEMA (and State and local agencies) have demonstrated, albeit tentatively, an ability to alleviate constraints and provide key resources that facilitate the resilience of private sector supply chains.

These three realities have been increasingly recognized at least since Superstorm Sandy. But calibrating policy and strategy to reflect these realities has been difficult. Issues of public expectations, statutory interpretation, institutional legacies, and human capital have all complicated the alignment of policy and strategy with reality. FEMA's ability—and the nation's ability—to more effectively and consistently practice supply chain resilience during disasters is still evolving.

The outcomes of Harvey, Irma, and Maria have, however, produced important policy and strategy shifts. FEMA's After-Action Review of the 2017 Hurricane Season (July 2018) [210] sets out the following:

> *The unparalleled scope and scale of the 2017 Hurricane Season underscored the need for, and identified several limitations in, implementing timely national response capabilities that are fully integrated with and supportive of private sector supply chain restoration. In 2017, public and private sector response and recovery efforts were too "stove-piped" to share timely information, too slow to consult, and as a result, often too late to synchronize stabilization efforts. The public and private sector are inextricably linked and must have shared situational awareness and the ability to synchronize their respective efforts to be successful. FEMA should work with its key partners to develop a more comprehensive understanding of local, regional, and national supply chains, as well as stronger relationships with critical private sector partners to support rapid restoration in response to catastrophic incidents. As a result, the Agency is adopting new response principles to closely align public and private sector efforts in a unified effort focused on rapid stabilization of key lifelines.*

This is entirely consistent with the implications of the case studies and the totality of the research CNA completed.

Moreover, the results of the 2017 hurricane season suggest several specific operational steps that FEMA and the broader EM community can implement and refine over time. Based on real-world experiences during the responses to and recoveries from Harvey, Irma, and Maria, the following steps will result in better-calibrated private-public collaboration in supply chain resilience:

- Identify the most at-risk densely populated areas
- Identify key nodes and links for water, food, and fuel in these at-risk areas
- Develop relationships and a sentinel system for monitoring flow through these nodes and links
- Give sustained and strategic attention to hourglass structures within supply chains
- Continue to reconceive and reform the FEMA catastrophe response strategy to facilitate and gap-fill flows that are crucial to supply chains and lifelines

Taken together, these five operational measures serve to better integrate preparedness, response, and recovery, especially for potentially catastrophic events. These operational steps set the conditions for effective response to and recovery from extreme events involving dense populations. Without this research and outreach ahead of the event, it is not possible to fully advance the resilient characteristics documented in the case studies above.

Identify the most at-risk, densely populated areas

The results of Harvey, Irma, and Maria reaffirm that population density, geographic distance, and technological dependencies are three critical aspects of anticipating catastrophic risk. Dense populations require complex dependencies to successfully deliver water, food, fuel and other key resources. Disruption or destruction of dependencies can quickly threaten supply to dense populations. The supply volume required by dense populations cannot be easily replaced by outside parties, including the government. If an affected population is surrounded by other dense populations then this capacity serving these surrounding populations can usually be redirected, but if the affected dense population is isolated from other sources, supply chain resilience is much more difficult to achieve.

Given these observations, San Juan, Miami, Honolulu, Portland, the Puget Sound region, and their surrounding metropolitan areas almost certainly qualify for sustained attention. Los Angeles and San Francisco are very dense, susceptible to catastrophic risks, and in danger of being “islanded” by their risks. Houston is not distant but given density, risk, and perhaps recent memory, it arguably belongs on the list. Less dense population concentrations may also merit special attention due to unusual risks or distance from neighboring hubs of supply. Hurricane Florence, for example, would have had an amplified effect if it had directly affected populations near Charleston, South Carolina, or Virginia Beach, Virginia.

A related, longer-term objective may be to recognize regions that process a disproportionate amount of total flow for national or global supply chains for key commodities, as these concentrations may represent strategic considerations. Puerto Rico's status as a hub of intravenous saline fluid manufacturing was a key concern for the entire medical care industry after Maria. Houston is a major hub for oil and gas and chemical manufacturing. Philadelphia and New Jersey are hubs for pharmaceutical manufacturing. Awareness of the national importance of these supply chains may help prioritize interventions after immediate needs of survivors have been met.

Identify key nodes and links for water, food, and fuel in these at-risk areas

If major utility services (electricity, telecommunications) and transportation networks continue operating in at least partial capacity, many supply chain resilience issues are alleviated. But if—for whatever reason—the electric grid experiences long-term failure, then it is especially important to understand the strengths and vulnerabilities involved in how dense populations are supplied with water, food, and fuel. Water and food will still be needed to sustain life. Surging demand for fuel will almost certainly result to provide generator power to homes and business, operate water systems, and, when possible, to support large-scale evacuations. In Puerto Rico and Florida, the 2017 hurricane season demonstrated that delays in fuel distribution can quickly unfold into urgent consequences, especially for vulnerable communities and individuals. In these situations, unmet demand will flock to any potential sources of key commodities. Even a few critical supply nodes being open can help stem potential catastrophe. What makes a node critical, though? It is situation dependent, to some degree, but there are several potential criteria: size (processing a disproportionate share of flow of certain goods, high throughput), centrality (location relative to demand), resilience (factors that make it more likely to survive disasters), accessibility, and adaptability.

Knowing the location of critical nodes often exposes opportunities for mitigation, enhanced collaboration, and effective targeting of supply, if undertaken well before the extreme event. With location, the nodes can be mapped, but full situational awareness requires a means of gathering information on the node (or key link) during a disaster. Which leads to the next recommendation…

Develop relationships and a sentinel system for monitoring flow through these nodes and links

The key nodes and links have owners, operators, customers, vendors, and many more participants that monitor some aspect of flow through nodes and links every day for everyday purposes. If FEMA can also meaningfully monitor reduction, increase, or absence of flow, it can provide the situational awareness needed to appropriately target federal, state, and local efforts to restore, redirect, or gap-fill resources. From a supply perspective, knowing which facilities are operational, which are running at limited capacity, and which are shuttered is a key piece of situational awareness. On the demand side, awareness of the status of transactions (number, type), payment processing system operability, stocks of key goods at retailers, and general population information (density, isolation), can focus aid in a timely way. By more precisely targeting what is needed—and where—FEMA can amplify its strategic capability to reestablish lifelines and support survivors. This is especially important in a catastrophic event involving a dense population that is distant from other sources of supply. But it requires relationships and trust with private industry and local government and new capabilities for sharing and validating information.

Give sustained and strategic attention to hourglass structures within supply chains

As noted previously (especially in *Case Study 5: Constraints in Optimized Networks*), there is a tendency for networks of all kinds, and supply chains in particular, to develop hourglass structures. A wide array of supplies, for example, are concentrated at ports or other nodes before being distributed to broadly diversified demand. These hourglass structures often enhance the overall system by consolidating flows of goods and information along efficient, high capacity pathways. But in extreme events, disruption, destruction, or surging demand can create severe congestion along these pathways. This so-called bottleneck effect is common across supply chains and can manifest in a variety of forms, but the common denominator is that a capacity constraint at some point in the network limits the flow of goods to a rate that is less than downstream demand for them.

We observed network structure bottlenecks where relatively few nodes or links consolidate upstream flows and process a disproportionate amount of flow, such as the IV saline manufacturers in Puerto Rico. We observed the importance of overall capacity constraints at key nodes, such as fuel racks at petroleum terminals. Further, we witnessed how even process constraints *within* a facility (receiving, transfer, outgoing) can influence overall capacity, as at the Jacksonville cross-dock. We saw how one or two key resource needs can shutter critical facilities, such as water plants without power or chemicals, or supermarkets without the ability to process electronic payments. Finally, we witnessed how some nodes and links (notably ports and key roads and bridges) have a fixed capacity to serve many supply chains simultaneously, and can become overwhelmed when flow surges for several disparate supply chains.

Bottlenecks that form around densely connected hourglass structures can have an amplified network effect. Is there a set of bottlenecks common to many regions that have recurring strategic implications? In Harvey, Irma, and Maria, fuel racks presented similar problems. In Puerto Rico and other extreme events, the delayed recovery of electronic data transfer linkages seriously complicated delivering nutritional support to survivors. In all three 2017 events, emergency generating units and related fuel distribution issues were fundamental to supply chain resilience (or non-resilience). Would it be worth investment by FEMA or others to specifically recognize and mitigate these bottlenecks and devote resources to alleviate them? Research emerging from the 2017 hurricane season suggests that such bottlenecks deserve much more deliberate consideration.

Continue to reconceive and reform the FEMA catastrophe response strategy to facilitate and gap-fill flows that are crucial to supply chains and lifelines

FEMA and federal resources coordinated by FEMA are of crucial importance in catastrophic events. But even the combined efforts of federal, state, and local resources are unlikely to be enough to hydrate, feed, and otherwise serve the essential human needs of a dense population of survivors. FEMA has recognized this reality and is just beginning to engage this reality with policy, strategy, and effective operations. The recent focus on supply chain resilience and rapid reestablishment of lifelines, with attendant focus on private-public relationships, is entirely consistent with the most important findings outlined in the case studies above. While important progress has been made, this is probably the beginning of a decade-long process of policy changes, strategic alignment, operational redesign, professional development, budget alterations, and more.

Research related to Harvey, Irma, and Maria regularly uncovered well-intended, but poorly informed decisions producing difficult outcomes. One of the most encouraging aspects of public and private sector behavior since the 2017 Hurricane Season has been a readiness to recognize reality, adapt behavior to reflect reality, and adjust policies, strategies, and plans for future behavior to match what has been learned. No matter what the catastrophic challenge, this is a constructive way forward.

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IRM-2018-U-018098-Final

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