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 [1], 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 [2]. 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 [3]. At the peak of outages, at least 61 public water supply (PWS) systems were damaged or offline, affecting nearly 223,000 people [4]. Cumulatively, Texans experienced more than 6 million person-

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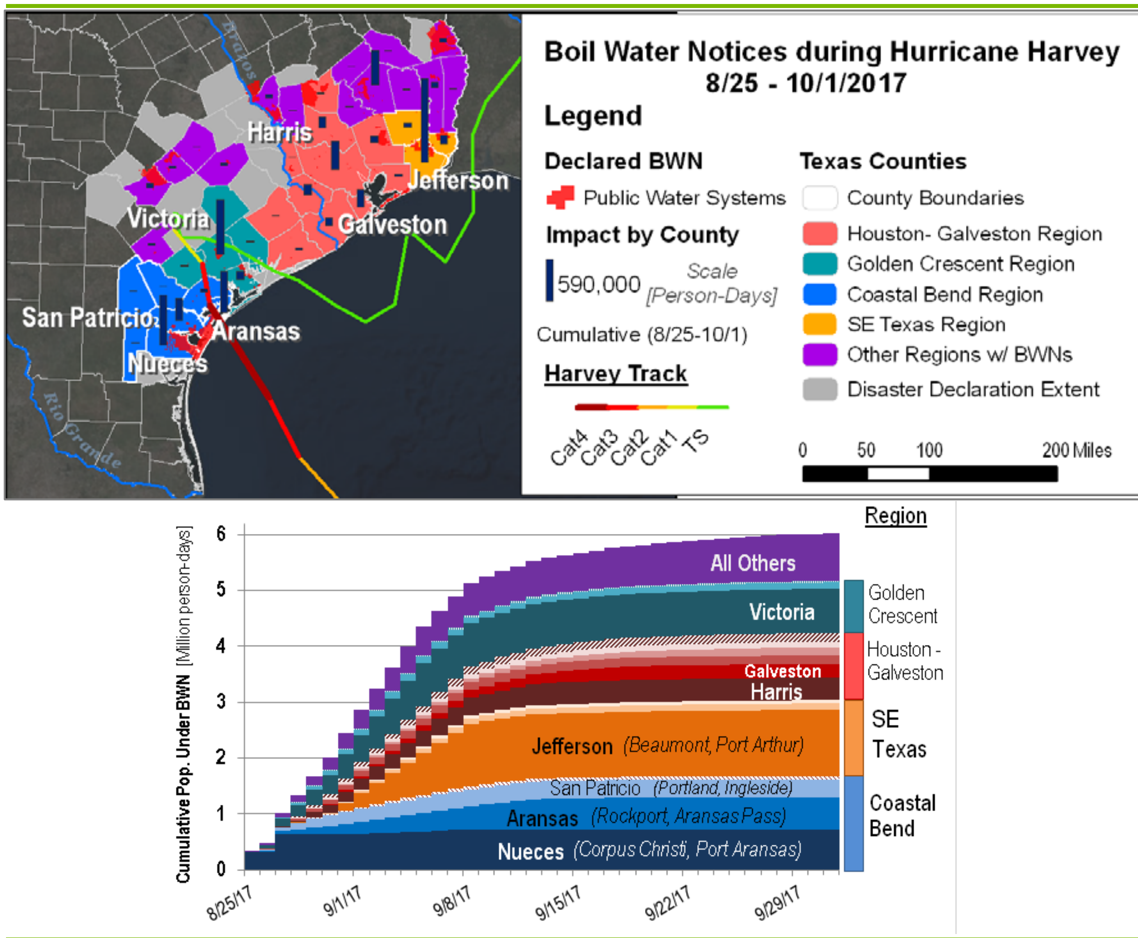
days[1] of water restrictions because of Harvey. Figure CS4-1 shows the cumulative impact BWNs in the affected areas as a map (left) and as a cumulative plot (right).

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

[1] 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.

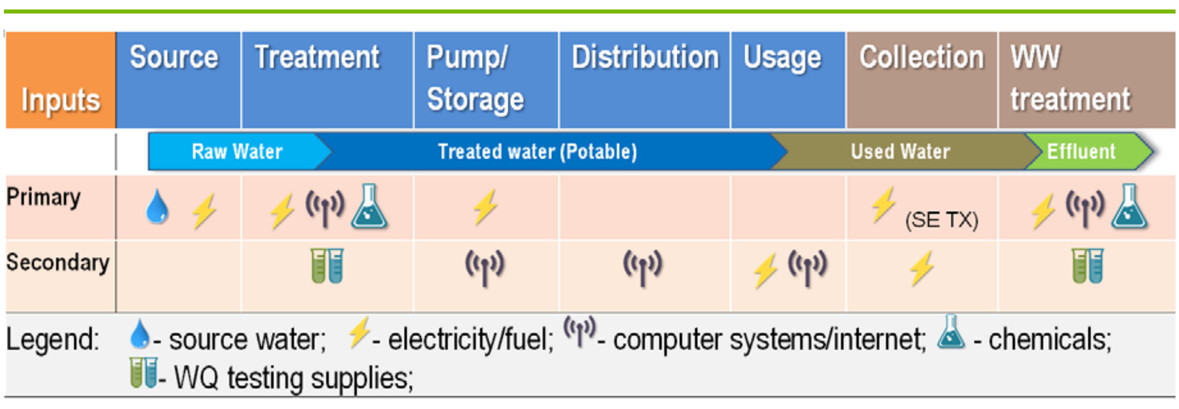
Water has a unique supply chain because it is at once: 1) needed in large quantities; 2) very heavy; and 3) low value relative to its weight. Economic delivery of water depends on significant infrastructure systems operating and working in concert. To illustrate this point, consider a single pipe, 12 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[2] 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

[2] 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 [5].
- Many water treatment, pumping, and, especially, wastewater facilities have to be near waterways, which make them vulnerable to flooding [6].
- 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

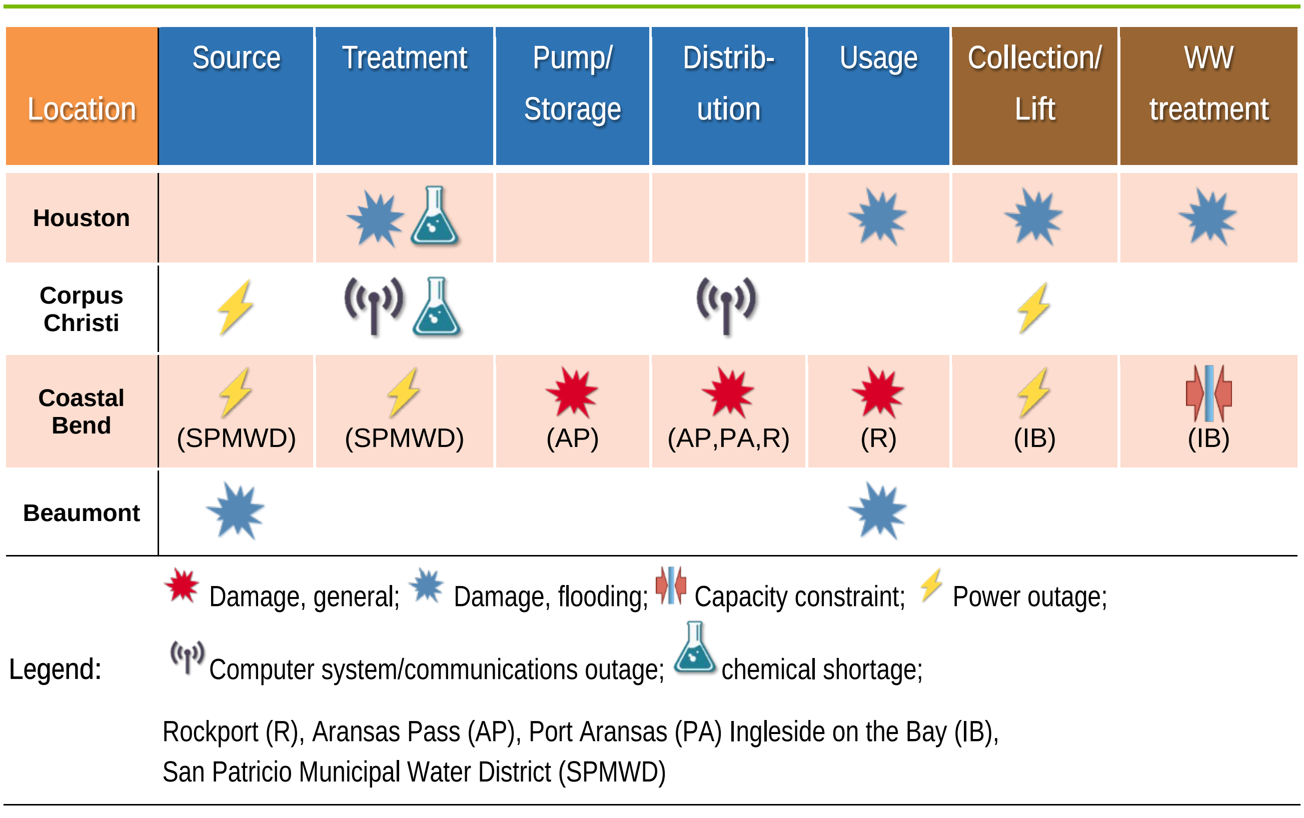
Water systems depend on all portions of the system (i.e., water's supply chain) working in concert. The source has to be accessible, the treatment plant has to be working, the pumps have to be operating, the distribution lines have to be intact and holding pressure, and the wastewater systems have to 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 [1]. 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

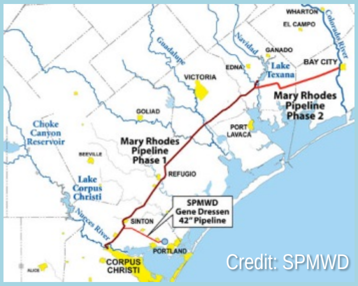


Source: CNA

Examples of water supply chain impacts

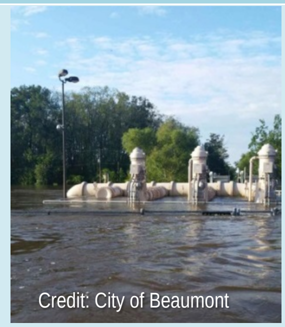
The following sections provide more detail on the specific issues experienced in these areas by phase of the water supply chain.

Source

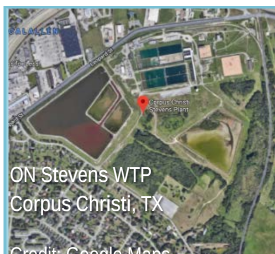


Aug 26 - The Mary Rhodes pipeline loses power at one of its primary pump stations, temporarily limiting the raw water supply. The loss of power lasts less than 24 hours before repairs can be made [7]. The pipeline brings raw water from Lake Texana to the City of Corpus Christi and the San Patricio Municipal 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) [8]. The distribution system loses water pressure, resulting in a city-wide outage and the issuance of a BWN. [9] On Sep 1, a temporary pump allows for the withdrawal of some water from the river [10], 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 [11], but many residents get water from the local supermarkets that remain open.



Treatment

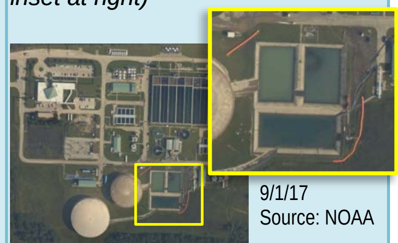


Aug 25 – Corpus Christi briefly loses power at the O.N. Stevens water treatment plant (WTP), which takes down the Supervisory Control and Data Acquisition (SCADA) system, meaning the water treatment process is not controlled effectively. The power returns quickly, but the SCADA system takes 24 hours to be rebooted. Although the water quality is believed to be fine, a BWN is issued for one day as a precaution [7].

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 [7].

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 [5]. (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)

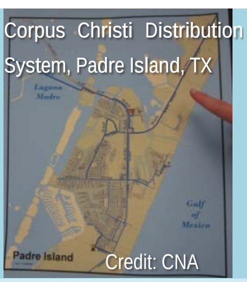


9/1/17
Source: NOAA

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


Credit: City of Aransas Pass

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


Credit: CNA

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 [5]. 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

Credit: Google Maps

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 [12].

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 [13]. 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 [14]. In several areas, Houston Water staff also found large sewer lines washed away by flooding [5].

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 [15]. 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[16]. 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. [15] 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 [16]. 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. [15-16] 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. [15]

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 [15]. 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 1. 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. [12]

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 [17]. 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 [15].

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. [18]

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. [7]

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 [19]. John Herrera, District Manager of Nueces County Water Control Improvement District #3,[3] 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" [20]. 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. [21]

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

[3] 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. [7]

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 [16]. 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 [1]. 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 [1]. 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. [5]

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 [5], 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 [1].

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 [11]. 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. [21] 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 [22], 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 [23]. The hospital was not flooded, had power, and its emergency room stayed open [24]; 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 [24].

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 [25]. 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. [26]

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 [17]. 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. [27]

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. [27] 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. [28] 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. [28]

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. [28] 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. [29]

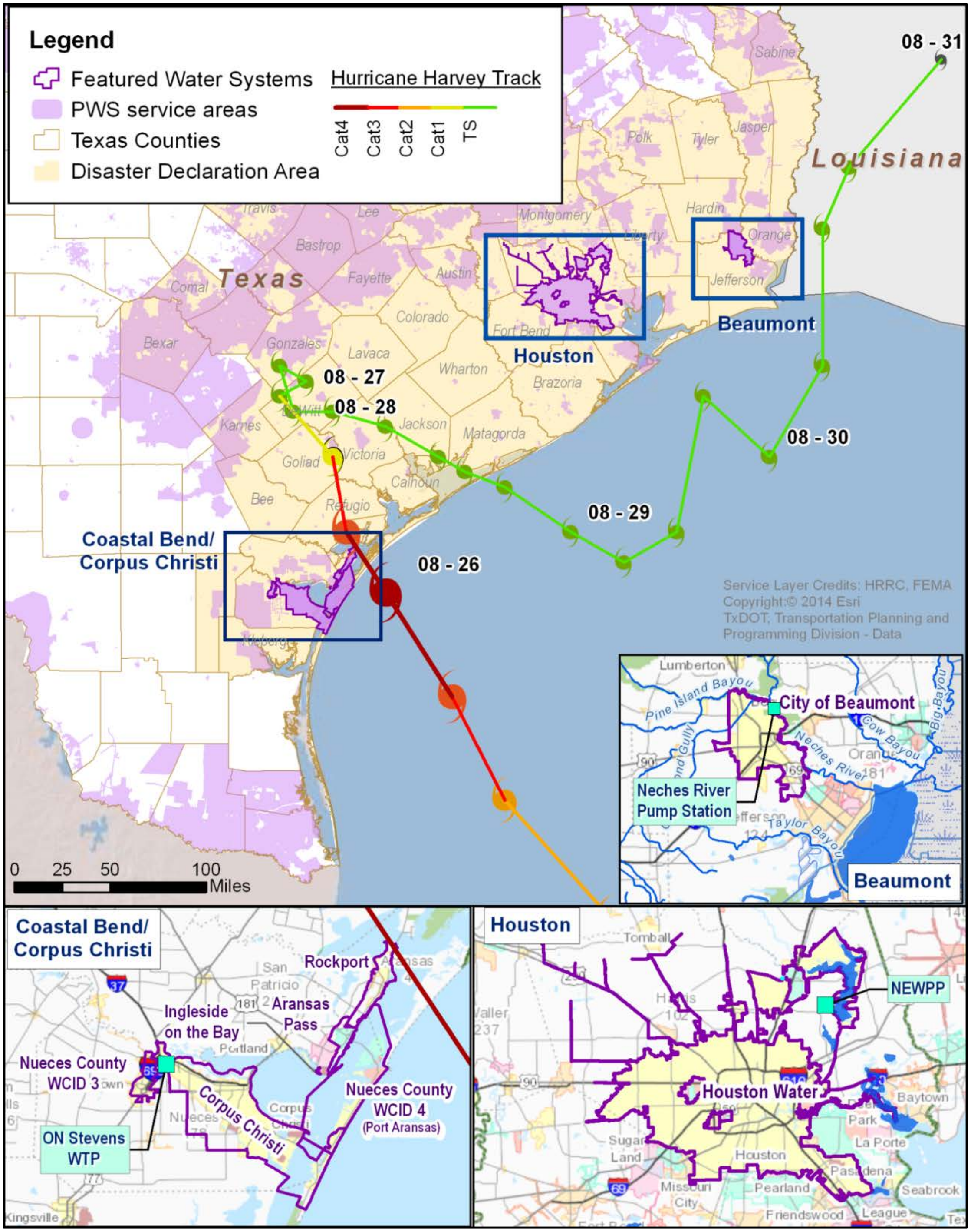
Gradually, FKAA and residents fixed the breaks and closed off the leaks and the system reached adequate pressure. Only when the system pressure was steady, and tests had verified the water was safe for human consumption, could the boil water notices end, and the distribution points be closed. [28]

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

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Additional case studies related to issues of Supply Chain Resilience emerging from the 2017 Hurricane Season are available at: www.cna.org/supplychainresilience

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