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Impacts of emergencies on water and wastewater systems in congested urban areas

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The impacts of emergencies on society and structures are often reported in the media, but the impact of these emergencies on the water and wastewater system is less publicized. The safe operation of these systems is critical during hazardous events and the recovery process to ensure safe and clean water for the public. This need is magnified in congested urban areas where the number of people affected is greatest. A critical aspect to the safe operation of these systems during emergencies is a timely response by municipal leaders. Municipalities must develop plans to prevent and/or mitigate the damage to water systems during emergencies, which will speed the recovery process when these events occur. This paper discusses the impacts of hurricanes and flood events on the water and wastewater systems of densely populated urban areas and presents measures that could be taken to prevent and mitigate the impacts of these events in the future.

The impact of sudden-onset emergencies on the well-being of society and the integrity of residential and commercial structures is typically well-documented in the media. A less visible impact that affects the safety and health of the public is the safe and continuous operation of the water and wastewater system. Emergencies such as earthquakes, hurricanes, tornadoes, and floods can destroy these systems, pollute drinking water supplies, and prevent the safe treatment of drinking water and wastewater streams. These impacts are magnified in congested urban areas where the number of people affected is greatest.

In the past few years, several sudden-onset emergencies such as hurricanes on the Gulf coast, earthquakes in Haiti and Pakistan, and tsunamis in the Indian Ocean have had a significant impact on an extremely large number of people. While many of these events are typically unavoidable, it is important that cities and municipalities have plans in place to ensure their water systems remain safe and operational. This includes distribution and supply of potable drinking water to healthcare facilities, emergency responders, and the general public, as well as proper treatment of wastewater to ensure water bodies are not polluted (Welter et al., 2010).

The impacts on these systems due to hurricanes and flood events in congested areas can include damage to above ground treatment facilities, pollution of source

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water, and damage to buried infrastructure systems. To effectively mitigate these types of emergencies, several congested urban cities, such as New Orleans, have now implemented local hazard mitigation plans (Seldes, 2010). These plans contain guidance on planning for hazards, identifying vulnerable areas, and implementing mitigation plans to deal with emergencies as they arise.

This paper will discuss the criticality of safely operating water and wastewater systems, the impacts on those systems due to hurricanes and flood events, and presents prevention and mitigation techniques used by some urban cities. This paper does not address earthquakes and tsunamis, but the San Francisco Emergency Response Plan (2011) and San Luis Obispo County Emergency Plan (2005) are examples of plans specific to those types of events.

Criticality of Water and Wastewater

The need for clean water is a common notion that most people recognize globally. People need clean water to live healthy lives and this need can be magnified in an emergency, where water may be scarcely available. There are also numerous critical emergency services that rely on water and wastewater services to operate (EPA, 2010). These services include water for firefighting, sterilization of medical devices, hydration of emergency personnel, and service for emergency shelters, and the protection of water sources to prevent contamination and pollution during emergencies is critical (EPA, 2010).

Some alternative emergency water supply delivery modes include: mobile water treatment units; water delivery by tanker truck; and field bottling operations (Rest, 2007). For mobile water treatment or tanker trucks to be effective, coordination with the local regulatory agency beforehand is essential to resolving pre-planning issues such as testing of the treated water and certification of the equipment and operators (Rest, 2007). These types of actions can be challenging in congested urban areas due to the magnitude of the need for water service and the effects of traffic congestion as large portions of the population evacuate the area before or during an emergency.

Impacts due to Hurricanes and Flood Events

The following is a summary of the non-traditional mechanisms that cause damage to water and wastewater systems during hurricanes and flood events (Chisolm, 2007). Some examples are provided from the effects of Hurricane Katrina that struck the city of New Orleans, Louisiana, a congested urban city, and other gulf coast cities in 2005. Damage can generally be categorized as either short-term or long-term impacts. Short-term impacts include damages that are directly related to storm forces and conditions. The main conditions related to hurricane events, which can lead to water system damage, include wind and storm surge, while inland flood event damage is usually associated with low-and-high velocity flooding.

These main mechanisms that cause damage are wind, flooding, and saltwater corrosion. It should be noted that while these condition categories are essentially different, in the event of a hurricane the damage mechanisms may be interrelated (e.g. widespread surge flooding would not occur without the extreme winds produced by the storm). Other damages may be caused by one condition, but are exacerbated by another as the result of multiple conditions. There are also some indirect short-term damages that can occur during response and recovery. Long-term impacts can occur when short-term impacts are not addressed or corrected including physical damage and inefficient recovery.

Wind damage

Wind can cause damage to both above-ground and buried components in water and wastewater utility systems. Above-ground water and wastewater facilities, such as lift stations, pump stations, and treatment plants; and elements, including hydrants, meter boxes, and valves, are susceptible to structural damage due to hurricane force winds and wind-driven debris. The City of Galveston, Texas estimated damages of US$80 m to its wastewater treatment plants due to Hurricane Ike, which struck in 2008 (Wilson, 2011).

Buried pipes in the vicinity of tree roots and embedded utility poles are also susceptible to damage. Tree roots are attracted to water and nutrient sources, which are found in wastewater and stormwater pipes. It is common to find roots growing into and around these pipes, especially when buried pipes are located along the sides of the roadway. Shallow service pipes are particularly vulnerable to intrusion of root systems.

During hurricane events severe wind conditions cause the uprooting of power poles and trees, especially those with shallow root systems such as oaks. Pipes that are intertwined in the root system of uprooted trees or are near utility poles that are pulled out can be damaged. The severity of the damage ranges from holes and breaks to the possibility of entire sections being ripped out of the ground. Older parts of town are usually the most vulnerable because the extent of root intrusion is much greater.

Flood damage

The effects of floodwaters on buried pipes can be particularly devastating in areas impacted by severe flooding, whether it is produced by hurricanes, excess rainfall, snow melt, or tsunamis. When flooding of an urban area is rapid, such as with surge floods and levee breaches, high velocity flow can erode soil away from shallow buried pipes, cause settlement of pipe lines, or create internal pressures in stormwater and gravity-driven wastewater pipes that can cause damage.

Settlement and movement of soils around pipes during periods of inundation and then drying can cause sections of pipes to become disjointed. Clay soils, which are not as porous as sandy ones, are also vulnerable to swelling. Pipes buried in this type of soil are more likely to sustain damages from external pressures caused by swelling and settlement. Internal pressure damage is most likely to occur where there are connections or joints, especially where manholes or inlets join with pipes.

Older sections of vitrified clay piping are suspected to be the most vulnerable to pressurization damage, especially at pipe joints. At these points, water is pushed through the joints and into the soil surrounding the pipe. As the pipe drains, the water in the saturated *in situ* soil flows back into the pipe, carrying particles of soil with it. Soils with a finer particle size, such as clays and silts, are especially susceptible to this type of erosion. This surrounding soil is responsible for structurally supporting the pipe, manholes, and other elements within the stormwater and wastewater networks. When the soil is removed, the affected sections no longer have sufficient beam support. As a result, these sections are more prone to settlement, which in turn leads to cracking and fractures of the pipes and manholes.

In systems composed mostly of vitrified clay, it is common to find hairline cracks that in most cases pose little threat to the service life expectancy of the pipes. However, when these defects are exposed to high internal pressures they can be widened or even completely fractured, thus compromising the structural integrity of the pipe. The severity of flood-related damages is related to the magnitude of the hydrostatic head, velocity of flows, and the length of time that the urban area is inundated.

Floodwaters also produce buoyant forces that can uplift residential type structures and equipment that are attached to service pipes. The shifting of these structures and equipment can lead to the fracturing or rupturing of rigid service pipe connections. Potable water pipes are particularly vulnerable to this type of damage, since these systems rely on pressure to maintain service and prevent contaminant infiltration. If the pressure in potable water systems falls below a certain level, boil water orders are required. Other elements related to potable water and wastewater systems, such as meters, pump stations, monitoring facilities, lift stations, and treatment plants can also sustain both structural and electrical component damage if flooded by water.

In addition to the impact of hydraulic pressures, another major adverse effect of widespread flooding in urban areas is debris blockage in stormwater systems. Because this network is responsible for the removal of rainfall from the surface, it is important that the system remains free of any obstructions. Floodwaters, especially those produced by hurricane surges, can carry thousands of tons of debris into stormwater networks as the water drains. Debris can be anything from silts to pieces of damaged structures, grease, leaves, branches, and even small machinery.

It is important that debris is removed immediately after the disaster event, in order to prevent flooding during future rainfall events. It is also critical that debris on the surface be removed to prevent re-clogging of drains and pipes after the initial cleaning. One company responsible for cleaning and videoing storm sewers in New Orleans after Hurricane Katrina removed almost 300,000 tonnes of debris and bedding from a single 50-inch sewer force main that was two-thirds full so that the pipe could be relined (B. Dutruch, Compliance Envirosystems, pers. comm., 2007).

Saltwater corrosion

In the case of coastal flooding, floodwaters contain salts and other corrosion agents that cause severe corrosion in metal components, especially when they are inundated for extended periods of time. Meters, hydrants, valves, and fractured metal pipes are particularly susceptible to salt-induced corrosion. Cast iron manhole covers and frames, responsible for preventing water infiltration into the sewer system, can also be affected.

Extended periods of exposure to saltwater can significantly decrease the service life and structural integrity of metal components. In New Orleans, many of the hydrants were submerged in saltwater for weeks following Hurricane Katrina. As a result, many of them after the storm no longer functioned properly. Some of the hydrants, especially those immediately outside the levee break, fractured at the stem, which had been structurally weakened by saltwater corrosion (Dutruch, pers. comm., 2007).

Indirect short-term damages

Damages to underground infrastructure networks can also occur in the aftermath of the event. Construction crews clearing debris within affected areas can inflict significant damage to surface elements and shallow buried pipes. Hydrants, curb boxes, and other above-ground elements can be damaged by heavy equipment being used to remove debris from the sides of roadways. Curbs and storm drains are also susceptible to heavy equipment damage as well as shallow buried pipes that are not designed to withstand heavy loading. Electric companies installing new utility poles have also inflicted damage on buried infrastructure.

Long-term physical damages

Direct damages to utility networks that are not addressed soon after they occur, could lead to more serious long-term secondary impacts. Secondary damages can include sinkholes, soil voids, ground settlement, contamination of soil and ground water, contamination of potable water, and instability of pressurized pipe networks. It is possible that collapsed pipe sections and voids in the supporting soils could lead to significant settlement of the ground surface and/or the development of sinkholes.

Settlement and soil voids can significantly impact the foundations of above-ground structures and erode road sub-bases. In the case of roadways, the pavement itself could collapse under heavy traffic. Considering that many of the recovery-related vehicles are heavier equipment, the chance of sinkholes forming is even more likely. Figure 1 shows a vehicle operated by Compliance EnviroSystems that fell into a sinkhole during the effort to remove debris from the stormwater networks in New Orleans.

Other damage included leaking/malfunctioning wastewater systems that can contaminate soil, groundwater, and other pipe networks. Also, potable water networks are vulnerable if the pressure drops low enough to allow contaminants to infiltrate or siphon into the system. Low pressures in potable water networks can negatively impact industrial and commercial facilities that require large volumes of water in order to operate, i.e. food processing plants, car washing businesses, laundries, etc.

Figure 1 Sinkhole in New Orleans during cleanup
Source: Courtesy of Compliance EnviroSystems

The problem of low pressure is also a major concern for fire departments that need a properly functioning water network in order to fight fires. High levels of water lost through leaks in the potable water network contribute to an increase in water demand and the cost of treating water.

In addition to potable water treatment, leaks in wastewater pipes increase the amount of water infiltrating into the system thus increasing the volume of wastewater that must be treated. Aside from increasing the cost of wastewater treatment, increased infiltration can also lead to the forced discharging of raw sewage into waterways if the capacity of a plant facility is overloaded during a major rainfall event. If these problems persist and buried network systems are not returned to pre-storm conditions, the economic, environmental, and social impacts (i.e. increased traffic delays and vehicle operating costs) can be great (Matthews, 2010). The survival and stability of communities depend on the presence of functioning infrastructure networks.

Long-term recovery impacts

In addition to physical damages, there are also problems related to procedure and disaster preparation that significantly affect the efficiency of the recovery process. Since it is difficult to predict when the next major flood or hurricane will strike, it is important that procedures aimed at minimizing the length of the recovery period are established, thus decreasing the impact of the event on the community.

The most significant issue directly affecting the recovery of potable water, wastewater, and stormwater services immediately after the storm is the loss of electrical power. Pumps, lift stations, and treatment plants that rely on power are rendered inoperable if they are not provided with backup power systems.

Unfamiliarity with the power requirements of utility systems or an inadequate supply of backup generators prior to the event, can also lead to added delay in restoring power to pump stations. The location of electric components is also a very important factor to consider since low-lying areas, such as underground vaults and basements, are the first areas to flood and last to drain.

In addition, recovery can be inefficient if municipalities do not have a disaster plan in place that outlines the procedures that must be taken before and after a natural disaster event. Mitigation of damages and the rate of recovery depend heavily on the steps that are taken before, during, and after a storm event. Disaster preparation can include any number of steps from strategic placement of repair vehicles to installation of redundancies within utility systems in order to ensure functionality of essential elements after the storm. The management of repair operations immediately after a storm also has a direct relation to the length of time between the loss and restoration of services.

The organization of the restoration effort is vital to recovery; for example, many municipalities recognized the importance of removing debris from stormwater systems in order to prevent flooding during future rainfall events. However, even after the stormwater networks were initially cleaned in New Orleans, the clogging of storm drains and pipes continued to be a problem because debris remained on the ground surface (Dutruch, pers. comm., 2007). Rainfall runoff that occurred after Hurricane Katrina continued to carry surface debris into the network.

Prevention and mitigation techniques

A damage mitigation plan is a living document that should continuously be reviewed and amended based on experience and knowledge. Funding may be difficult to acquire for developing a mitigation plan, but some agencies, such as Miami-Dade County, Florida, provide guidance to municipalities on obtaining funding for plans (Miami-Dade, 2010). A damage mitigation plan usually consists of three main phases: preparation or planning; response; and recovery, shown in Figure 2 (Tampa, 2011). The first step in creating a damage mitigation plan is to understand what happens to the water and wastewater system during a hurricane or flood, and to identify what damage conditions are the most likely to occur in the area being considered.

For example, in Lake Charles, Louisiana, the most damaging mechanism during Hurricane Rita, which struck about a month after Katrina in 2005, was the combination of wind and trees, which was responsible for most of the breaks in the potable water network. Most of the damages (approximately 80%) occurred in the service lines connecting residences and businesses to the main lines (Chisolm, 2007). While it may be impossible to prepare for every type of damage scenario, a well thought out damage prevention plan can decrease the risk of damage to vital utility networks, shorten the time needed for recovery, and reduce the economic impact on the affected area.

Figure 2 Phases of damage mitigation
Source: Tampa (2011)

Preparation

Preparedness is the most vital phase of any damage prevention and mitigation plan. The success of the response and recovery phases depends on the quality of work and amount of effort put into preparation. It is also the only phase where all actions taken are completely within the control of local, state, and federal officials.

Vulnerability assessments

Every preparedness plan should begin with an assessment of the vulnerability of the infrastructure systems. Vulnerability depends on the condition and location of the buried networks, attached elements, and above-ground facilities, and the most likely conditions that will cause damage to each network or element.

Self-assessment tools and training are available for municipalities that can help them to identify their community's level of resilience. One such tool is Sea Grant's Coastal Resilience Index, which allows a community to assess its readiness for disasters. Training is also available through Sea Grant and other organizations and agencies (Sempier et al., 2010).

Collaboration between communities and sharing of experiences can give ample opportunities for communities to garner new knowledge, which can aid in preparation or amendment of mitigation plans. It is also important for communities to have full working knowledge of federal or higher-level government requirements, such as damage surveys and reimbursement procedures. Understanding of these processes helps communities anticipate the level of support that will be available to them, and identify any shortfalls that may occur.

Regular inspection and documentation of the conditions of underground infrastructure not only helps officials in the management of normal maintenance and rehabilitation activities, but also supports identification of utility system vulnerabilities. Older sections of piping are generally the most vulnerable to damage. Buried pipe networks are expected to age at a certain rate over their designed lifetime. Maintenance ensures that a pipeline reaches the end of its design life and rehabilitation can be used to extend the lifetime of a pipe.

While these steps should normally be carried out by municipalities, the degree of quality at which these tasks are performed can greatly affect how pipes perform under the abnormal loading induced during hurricane and flood-type events. In some extreme cases even pipes in good condition are still vulnerable to some type of damage.

For example, during the 1997 Red River Flood in Grand Forks, North Dakota, pressurization induced by flooding caused hairline cracks in clay pipes to open and in some cases the pipes broke (Chisolm, 2007). Under normal conditions, hairline cracks pose little threat to the life expectancy of clay pipes, which is why such repairs are rarely taken. Because such defects only become vulnerable during extreme flood events, practical steps would be to document and monitor this condition.

A second benefit of adequately inspecting and documenting the condition of networks is that in doing so municipal officials are creating a database of information that can become very valuable after a disaster event. This data can provide evidentiary support in favour of municipalities that are filing for government reimbursement of the funds spent during the recovery effort. By comparing pre- and post-event data, officials can more easily determine the damages that were a direct result of the disaster event.

Management plan

In addition to inspecting and documenting the condition of the infrastructure elements, it is also important to have a detailed plan for managing supplies and personnel. The loss of electric power is one of the most significant conditions to consider when creating a response plan. Efforts to restore operations at above-ground facilities, such as water treatment plants and wastewater treatment plants, are crippled until power is restored.

In Lake Charles, Louisiana, city officials were forced to discharge raw sewage into the Contraband Bayou following Hurricane Rita because there was no electric power and the facility's pumps were flooded. The city also did not know the size of generators needed and was forced to rely on electrical teams to determine the power requirements. However, by the time generators were delivered, power to facilities was already restored 10 days later (Chisolm, 2007).

In the City of Slidell, Louisiana, municipal officials were not familiar with the power requirements of potable water facilities and stations and were forced to spend time immediately after Hurricane Katrina trying to determine the size and number of generators that were required. If power requirements had been known in both cities before the disaster, precious time could have been saved in the response phase and environmental damage could have been avoided (Chisolm, 2007).

Contrarily, following Hurricane Iniki in 1994, municipal officials on Kaua'i Island in Hawaii were amply prepared with water tanker trucks to supply water to communities and generators for pumps, which were used in the repair and restoration of the water system. Municipal workers organized their response efforts to restore service to critical facilities first and then made repairs to lower priority sections, beginning with the least damaged sections. Because of the municipality's successful preparations and planning, the island's water systems were restored in less than two weeks (Murphy, 1994).

Other supplies, such as repair tools, spare tyres, fuel, pipe clamps, segments of pipe, etc., should also be kept in sufficient supply or be made ready so that they will be available for response efforts. Vital electronic equipment stored in underground vaults or in weak metal buildings should be protected or sealed in case it comes into contact with floodwater or rainwater. Important files and information should be backed up or protected in a secure location. Loose objects should be secured and windows covered. Municipal vehicles, equipment, and supplies should also be placed in locations where they are not vulnerable to flood or wind damage.

Plans for the placement of both local and volunteer personnel should also be made. Municipalities should plan for the possibility that local employees and their families will be affected by the storm. Preparations should be made for providing housing and supplies to personnel who have lost their homes in the storm. Crews volunteering assistance from other states and regions should be self-reliant and bring all necessary supplies and equipment with them.

Local officials should also keep in mind that the majority of volunteer personnel are not familiar with the community they are assisting and most street signs will be damaged or blown away by the storm. This can make navigating difficult especially in large complex urban street networks. In this instance it might be good to implement GIS/GPS technology to guide crews throughout affected areas.

Response

After the storm has passed, the management and organization of the response efforts can be very difficult because of the unpredictable nature of most disasters. Before taking any action, it is important to examine the initial situation and identify the dangers that exist. Response plans should be organized in the beginning according to the severity of the situation (Shimoda, 1994).

As the response effort progresses it is vital for officials to constantly reassess the circumstances, especially as new emergencies arise. Cooperation between varying groups is crucial to the success of response efforts. Evacuation and taking control of situations that pose danger to human life (i.e. fires, broken gas lines, etc.) should be the first priority for officials responding to a disaster followed by taking measures to prevent further damage to infrastructure or human life.

Plans should be made for backup power and communications in case these networks are lost. Initial steps to clear paths through debris and repair infrastructure should focus on critical facilities, such as hospitals, fire departments, and other emergency response units. After high priority repairs have been made, the remainder of the system should then be restored (Shimoda, 1994).

Recovery

The recovery phase involves steps taken to restore utility systems to as close to pre-storm conditions as possible, which will aid in the personal recovery of the many people affected by the emergency. In may be impossible to recover completely and municipalities may be involved in the recovery phase for several years.

Recovery involves the continued repair and inspection of networks, removal of debris from the surface and stormwater networks, upgrades of system components, or even complete replacement of failed sections of utilities networks. Municipal officials should also be prepared for further damage during the recovery effort, such as heavy equipment damage, as well as long-term damage due to the increased degradation caused by the damages incurred during the hazard event.

Conclusions and recommendations

There is a great need for the application of engineering knowledge and advanced technologies in the area of hurricane/flood damage prevention and mitigation, especially in relation to water and wastewater systems. Recovery of affected congested urban communities relies heavily on the restoration of utility services. Modern technologies that assist in preventing or mitigating damages can decrease recovery time and reduce the economic and sociological impact of a disaster on an urban community. Key problems that need to be addressed include: mitigation of damage to service connections, protection of above-ground system elements, prevention of corrosion, and the management of disaster response and recovery efforts.

Service connection damage

Service connections, especially potable water, are the most vulnerable part of buried pipe networks. Mitigating damage to service pipes would significantly improve the performance of the potable water network during hurricane and/or flood events and the recovery process. From an operational standpoint, the main concerns for potable water networks are to maintain pressure, control water loss, and prevent the infiltration of contaminants. The application of automatic shutoff valves at service pipes that close when there is a sudden drop in pressure may be one solution. Installing flexible instead of rigid connections at structures could also prevent damage to service pipes when the structures shift in floodwaters.

Mitigating the intrusion of root systems into and around pipe infrastructure, or preventing the uprooting of trees during hurricanes would significantly decrease the amount of damage to service pipes. Some solutions may be to remove shallow rooted trees that are growing immediately around pipes, apply TGRs (tree growth regulators) that slow down the growth of branches and roots, anchor trees that are vulnerable to uprooting, or bury water service pipes deeper than the current cover depth which is as shallow as 2 feet (0.6 m).

Above-ground damage

Above-ground elements, such as fire hydrants and meters, are subject to structural damage both during and after storm events. The majority of damages are caused by construction crews operating heavy equipment after the storm and impact from wind- or flood-driven debris. One solution for construction type damages could be the use of a GIS based system which gives warning to construction workers if they are in the vicinity of utilities. Some software allows data to be input from the field into a simplified user-friendly GIS program and automatically downloaded wirelessly on the internet via cellular service. When used in conjunction with construction machinery, the system can function as a warning system (Chisolm, 2007).
Other damage to above-ground elements caused by the impact of wind- or flood-driven debris is probably unavoidable. However, systems vulnerable to this type of damage can be shut off prior to the storm to prevent water loss.

Corrosion prevention

Metal components, including meters, hydrants, valves, low pressure gas lines, and manhole covers and frames, are vulnerable to corrosion when submerged in saltwater. The corrosion of hydrants in New Orleans was so severe that many no longer function properly. There is a need for new preventative maintenance measures (i.e. corrosion resistant coatings) that can be used to protect these elements from future damage.

Disaster management

In addition to preventing physical damages, the effective management of recovery efforts should be a priority for municipalities located within flood- and hurricane-prone areas. In many cases the importance of establishing effective disaster plans has been realized by some municipalities when it is too late. This is why it is vital that officials learn from events such as Hurricanes Katrina and Rita, and the Red River Flood of 1997. Through garnering knowledge from these events and investigating the potential benefits of technologies, it is possible to create solutions that would make a positive impact in the areas of disaster planning.

It would be beneficial to develop software technology and disaster guidelines that can educate and inform utilities on the steps that need to be taken to set up an effective disaster plan. GPS/GIS technology could also be implemented in the coordination of response crews, so that every action that is taken can be recorded and viewed anywhere in real-time so decisions can be made quickly and response actions can be prioritized more easily. Software applications can be customized to satisfy the needs of utilities in emergency disaster situations. Managing response and recovery efforts in real time would increase efficiency and assist municipal officials in coordinating recovery efforts in a situation that is often uncontrollable and unpredictable.

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