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Best Management Practices for Firefighting in the Karstic Edwards (Balcones Fault Zone) Aquifer of South-Central Texas

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Abstract: Karst aquifers are vulnerable to contamination from hazardous pollutants that can harm drinking water supplies, species inhabiting aquifers and springs, and other karst water resources. This paper presents best management practices (BMPs; Appendix I) designed for use by first responders and for use in developing training curricula and tools to assist first responders in protecting karst water resources. Training and tools based on the BMPs will help first responders prevent or reduce runoff of potentially hazardous materials that can rapidly enter an aquifer during firefighting and other responses to emergencies in locations where hazardous materials are stored, such as in retail centers, warehouses, industrial and agricultural facilities, and in vehicles and rail cars along transportation corridors. Emergencies can include fire caused by accident or arson, terrorist attack, flood, high wind, lightning, and explosion in structures and transport vehicles. BMPs are provided for preplanning, response during an emergency, and cleanup after an event. Future work will include these BMPs in first responder training curricula and a georeferenced database that will include recommendations for protective action in areas containing karstic features (Appendix I) where hazardous materials may be present.

Keywords: best management practices, Edwards Aquifer, karst aquifer, water quality, aquifer recharge zone

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Terms used in paper

Acronym/Initialism	Descriptive Name
BMP	best management practice
DNAPL	dense non-aqueous phase liquid
EAA	Edwards Aquifer Authority
FFPs	firefighting products
GIS	geographic information system
RM	released material
RQ	reportable quantity

INTRODUCTION

In 2007, the Texas Legislature directed the Edwards Aquifer Authority (EAA; Appendix I) to work to protect the water quality of the karstic (Appendix I) Edwards Aquifer from the impact of fire control in the Edwards Aquifer's recharge zone (Senate Bill 1477). The Legislature was responding to concern over potentially catastrophic aquifer pollution events that can occur in the recharge zone during fire control or other emergency responses where hazardous materials (Appendix I) are present. The event that prompted action by the Legislature was a fire called "Mulchie" that burned for three months in an eight-story high, thousand-foot-wide, mulch and debris pile on the edge of the Edwards Aquifer's recharge zone near San Antonio.

The mandate from the Legislature called for reducing impacts on aquifer water quality from fire control activities in the presence of hazardous and other polluting materials in the Edwards Aquifer's recharge zone. This includes locations where there are existing threats to water quality due to on-site storage, production, or transport exchanges of hazardous materials, as well as along transportation corridors such as roadways, rail lines, and airports.

Work by the EAA on developing techniques to protect water quality has been underway since that time. This paper describes the development of best management practices (BMPs) to protect karstic watersheds and important groundwater resources from potentially catastrophic hazardous materials releases. Hazardous materials can enter karst aquifers directly or be mixed in water or other fire suppressant runoff from firefighting in response to emergencies. Examples of emergencies that could jeopardize the water quality of the aquifer include fires caused by accident or arson, terrorist attacks, floods, high winds, lightening, and explosions in structures and along transportation corridors where hazardous materials are being stored or transported. Locations that may contain hazardous materials include retail centers, manufacturing and agricultural facilities, warehouses, and in vehicles, rail cars, and pipelines.

These BMPs are a critical component of a more comprehensive project now underway to develop training curricula using the BMPs as a basis for first responder instruction and for developing plans and specialized techniques and tools for use by first responders. These will include a georeferenced database and user interface that will provide data displaying sensitive karst areas, direction of water flow across the landscape, and embedded recommendations for protective action. We expect the BMPs, curricula, training, and tools to serve as a model national standard for emergency response in karst watersheds.

KARST SYSTEMS AND RISK TO WATER QUALITY

In the United States, 20% of the land surface is karst and 40% of the groundwater used for drinking comes from karst aquifers. The U.S. Environmental Protection Agency has recognized karst aquifers as the groundwater type most vulnerable to hazardous contaminants and pollution (Schindel et al. 1996; USEPA 2002). Karst aquifers are unique because of their

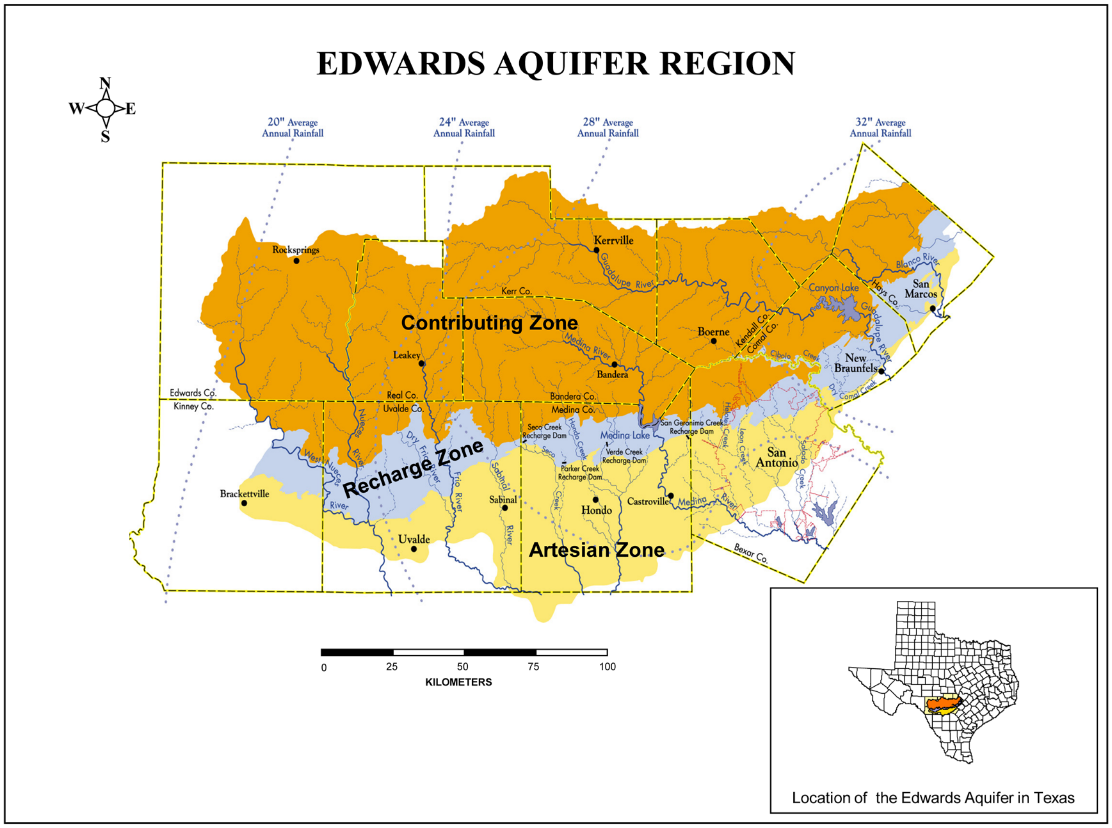

Figure 1. Location of the Edwards Aquifer of Southcentral Texas and the contributing, recharge and artesian zones (Illustration: Edwards Aquifer Authority).

direct connections to land surfaces that allow contaminants to rapidly enter the subsurface and aquifer. Karst watersheds are underlain by limestone or other highly soluble rocks, such as dolostone and gypsum. These rock types are partially dissolved over geologic time by chemical reactions with water (Schindel 2019). The dissolution process creates interconnected openings in the rock, thereby increasing its porosity and permeability. Karst terrains (including the surface and subsurface) are characterized by the presence of sinkholes (Appendix I), sinking streams (Appendix I), caves (Appendix I), interconnected voids, subsurface streams, enlarged fractures and faults, and other conduits (Appendix I) for water movement, including springs that discharge water to the surface. Karst groundwater systems can be the source for large springs that form the headwaters of large river systems. Openings, such as caves or cracks in limestone at the surface, allow direct exchange of surface water with the subsurface and groundwater, providing for little or no filtration or biological treatment of potential contaminants in the water. Water can move quickly in karst aquifers with velocities as high as thousands of feet to several miles per day. These conditions allow for rapid transport and spread of contaminants that may harm the quality of public and private water supplies (Appendix I) and may even impact surface water. Contaminants released into the aquifer can also imperil sensitive cave and aquatic ecosystems that are home to endemic and endangered species.

The Edwards (Balcones Fault Zone) Aquifer

The Edwards (Balcones Fault Zone) Aquifer was the first sole-source aquifer designated in the United States and currently serves as a primary source of drinking water for more than two million people in San Antonio and surrounding areas (Schindel et al. 2004). San Antonio is the seventh largest city in the United States and serves as a major hub for medical, military, technology, and transportation industries. The Edwards Aquifer is noted for some of the largest production wells in the United States, as the source of water for the two largest springs in the Southwest, and for rapid groundwater velocities in the recharge zone (Schindel 2019). The Edwards Aquifer and associated springs are also home to numerous rare endemic and listed endangered species. The aquifer is the primary source of water for municipal, agricultural, and industrial use in South-Central Texas. The aquifer spans over 2 million acres stretched across 180 miles and five counties (Figure 1). This karst aquifer and associated watersheds will serve as the model for application of BMPs, training, and tools to protect water quality.

Like all karst aquifers, the Edwards Aquifer is highly vulnerable to contamination from surface activities. Liquids or solids mobilized by precipitation or flooding, releases of hazardous materials, firefighting products and runoff, or septic waste from sanitary sewers can quickly enter the subsurface and result in degradation of groundwater and surface water resources. This can then result in contamination of public and private water supplies (Johnson et al. 2010; Schindel 2018; Schindel 2019a) and impact species habitat.

Water Quality and Quality of Life at Risk

San Antonio is the first major urban area along the transportation route between Laredo, the largest inland port of entry in the United States, and the rest of the country. Significant quantities of many kinds of hazardous materials are stored in or transported through the city and region due to the nature of local industries and the volume of goods passing through. The release of hazardous materials has occurred in the past, and future releases are inevitable given the scale of development and nature of activities over the Edwards Aquifer's contributing and recharge zones. The same may be said for many karst watersheds elsewhere in the United States.

Private and public water supplies using groundwater commonly only use chlorination as the major component of their water treatment system. Hazardous materials released into water supply systems during emergency response can result in Safe Drinking Water Act standards to be exceeded and may require expensive treatment systems or outright abandonment of a well. This can cost private or municipal owners millions of dollars to either treat contaminated water or replace their water supply. Given the potentially high direct and indirect dollar cost of even a single catastrophic release of contaminants that impact the quality of a municipal water source (Appendix I), first responders need to be supplied with the training and tools needed to protect aquifer water quality during emergency response activities.

BEST MANAGEMENT PRACTICES

BMPs are actions designed to be taken in the course of responding to floods, sewer line breaks, or other emergencies involving water (e.g., in the case of this work, response to fire emergencies) to minimize negative impacts on public health and the environment. While BMPs are typically developed for use by water quality experts, the BMPs presented herein were designed to be readily usable in emergency management curricula and training courses for first responders involved in emergency management, hazardous materials response, and fire control. However, the potential benefits of BMPs to protect the aquifer during an emergency response extend beyond just protecting water quality, even during a single emergency event. Benefits include protecting quality of life, the local economy, the environment, and threatened and endangered species that depend on the aquifer. These BMPs may also be applicable for use by state, county, city, municipal, and government employees and their contractors responsible for responding to or regulating spills and releases of hazardous materials. The BMPs described herein can be applied anywhere across the aquifer's contributing and artesian zones (Figure 1).

The BMPs presented in this paper are based on well-established scientific information for karst areas. These BMPs were reviewed by an expert panel familiar with water quality protection in the Edwards Aquifer and development of emergency response training curricula for hazardous materials and fire control (Schindel 2019b), and thus could serve as a national standard for responding to the release of hazardous materials in karst watersheds.

Emergency firefighting activities and critical pathways

Runoff associated with spills of hazardous materials, sanitary sewer spills including overflows and discharges, and fire control runoff can rapidly enter the subsurface through a variety of pathways (p. 5) on or near the location of the spill or runoff. Rapid groundwater velocities in the recharge and contributing zones (Johnson et al. 2010) can cause released materials (RMs; Appendix I) and firefighting products (FFPs; Appendix I) to move into a public or private water supply within hours or a few days after entering the subsurface. In addition, RMs can volatilize and form explosive or hazardous vapors that can migrate into structures. Released materials and associated runoff should be managed through addressing the nature of potential contaminants and the various pathways runoff can take to enter the aquifer or affect water quality before, during, and after an emergency response.

The nature of hazardous materials

Contaminants commonly take three forms when they enter groundwater. The first form is contaminants that are insoluble in water, existing in suspension or depositing in the substrate. Deposited, insoluble contaminants may remain sequestered in soil or groundwater or become suspended during high-flow events. They may remain a source of low-level contamination over extended periods of time.

The second and third forms are contaminants that are soluble in water. These contaminants are either lighter than water—light non-aqueous phase liquids (LNAPLs)—or heavier than water—dense non-aqueous phase liquids (DNAPLs; Appendix I)— once their solubility is exceeded. LNAPLs can float on the surface of the groundwater and volatilize , becoming a gas.

An LNAPL gas can migrate into sewer lines and into buildings through crawlspaces and cracks in foundations resulting in explosive or poisonous atmospheres. Gasoline is a common example of an LNAPL that can create an explosive condition if exposed to an ignition source (Quinlan et al. 1991).

DNAPLs are heavier than water and will sink. They may be redistributed by turbulent flow in the groundwater, where they may resolubilize and reenter the water column. Common examples of DNAPLs are polychlorinated biphenyls and perchloroethylene.

Contaminants that are soluble in water may exceed drinking water standards as defined under provisions of the Safe Drinking Water Act (Safe . . . 1974). Contaminants of all types can be extremely difficult and expensive to investigate and remove from a public water supply source and may require abandonment and replacement of the supply. Contaminants can also affect species that depend on aquifer water quality.

Pathways for contamination

The many caves, sinkholes, fractures, faults, and other sensitive features characteristic of karst terrains described earlier provide direct pathways and allow rapid discharge of runoff into groundwater. Likely most such sensitive features remain hidden, are buried near the surface under shallow soil, and have yet to be discovered. Hidden features have not yet been recorded in a Geographic Information System (GIS; Appendix I) resource or in other available sources (Rosen et al 2020). Unrecorded sensitive features may only become apparent on-site during emergency responses or after contaminant release events have occurred. In addition, many recharge features, known and unknown, are located within drainage ways (Appendix I) and may be obscured by gravel, cobble, and other types of sediment. These features may not be directly visible or leave any discernable evidence of their existence on the surface, but they will readily receive and convey water inflow to the aquifer.

Water wells and Class V injection wells, which are used to inject non-hazardous fluids underground, are also potential conduits for contaminants to enter the subsurface of karst aquifers. Water wells include public water supply wells and privately owned and managed wells, which are common sources of water for domestic, municipal, industrial, livestock, and agricultural uses. Wells have been constructed in the past using a wide range of drilling and construction methods. Some may be fully cased and grouted to the water production zone, or they may be completed with little or no well casing or grout (i.e., an open hole). The top of the casing may be at or below land surface level. Wells may be in active use, abandoned, or unsecured. Poorly constructed or maintained wells can become conduits for surface water to rapidly enter karst aquifers (Green et al. 2006). Wells may also present a physical hazard to the public and first responders. The condition of wells and potential for wells to become a pathway for groundwater contamination should be determined where possible. Well evaluation commonly requires specialized expertise and equipment. Without readily available information about a particular well, it is best to assume that the well is an open conduit to the aquifer and should be protected from exposure to RMs and FFPs. Some stormwater retention systems may also be considered Class V injection wells if they allow infiltration into the subsurface. Stormwater retention systems in the Edwards Aquifer generally are sealed with a high-density polyethylene or concrete liner to prevent infiltration from the basin. Filtration of stormwater occurs through a sand filter or other system to reduce sediment load, and the water is then passed through a piping system and into a drainage channel.

BMPs FOR REDUCING RISKS

BMPs for pre-event site planning: actions before an emergency event takes place

Predicting when and where an emergency event might take place that involves RMs or FFPs that could threaten the aquifer is not possible. However, in advance of emergency events, it is possible to identify specific sites where hazardous materials are stored, transit-sensitive areas, and areas over the aquifer that are particularly vulnerable to contaminated water runoff. Such information can be placed on a map or provided as mapped layers of information on mobile GIS displays. The following BMPs cover advanced planning to locate sites, develop plans to protect the aquifer in these sites, and communication, mapping, and training should an emergency event take place:

- Identify sites where hazardous materials are stored or cross sensitive areas that could present a risk of RMs or FFPs entering sensitive areas. Identify the specific risk if possible. Establish an order of priority to conduct pre-event planning for emergency responses at high-risk sites. Add sites to maps and visualization tools.
- In order of priority, identified high risk sites should be evaluated for potential runoff of RMs and potential for production of FFPs.
- The topography of each site should be evaluated and mapped to determine the direction of the likely flow of RMs or FFPs.
- Storm drains and water inlets should be identified and documented at each site, along with their expected outfall. Add sites to maps and visualization tools.
- Preplanning should include evaluating and documenting methods and means to capture potential RMs and FFPs before they reach sensitive features at or near vul-

nerable sites, such as caves, sinkholes, drainage ways, creeks, streams, storm and sanitary sewers, etc.

- Features at the site, such as stormwater retention basins, should be evaluated for use as temporary containment features for RMs and FFPs. These features should be added to maps and visualization tools and evaluated for the following:
  - o Whether and to what extent the outfall from basins can be closed (or otherwise contained) to prevent the outflow of contaminated liquids and other materials
  - o Whether and to what extent RMs and FFPs might rupture, penetrate, or dissolve the liner of the retention basin, resulting in the release of contaminated materials to the subsurface
  - o Whether removal of RMs and FFPs from a stormwater retention basin can take place quickly, allowing the basin to be returned to service as a stormwater retention basin
  - o Whether stormwater retention basins can be decontaminated and tested after being used to hold RMs and FFPs
  - o Whether the owner of the basin can ensure that the basin is being properly maintained so that it will operate as anticipated
- GIS resources should be used in areas targeted for pre-event planning efforts to help identify on-site topography and water flow pathways that could influence RM or FFP migration into nearby sensitive features, such as known caves, sinkholes, sinking streams, storm drains, stormwater retention basins, and active and abandoned water wells (Appendix I).
- GIS databases should be completed in order of priority, with the highest zones of risk completed first. High risk zones include highways, railroads, pipelines, regulated industrial and retail facilities, firefighting training areas, and sewage lift stations.
- Preplan ways to minimize the spread of RMs and FFPs where possible.
- Where feasible, on or near the site, preposition relevant emergency response materials (e.g., covers, rock socks, berms, booms, sandbag dams, or plastic sheeting) for use should an event take place. Prepositioning emergency response materials at strategic locations in sensitive areas may be done using a series of storage containers.
- Uplands and areas between draining features at the sites should be inspected and evaluated in advance to identify additional features that could potentially allow RMs and FFPs to enter the subsurface and impact the aquifer.
- Susceptible public and private water supply systems and irrigation systems should be identified in advance for their potential use as monitoring sites for the presence of contamination during or after an event. Contingency plans should be created to address the impact of contamination.
- Develop plans and training, and preposition materials to monitor the fate and transport (velocity and location) of liquid runoff from an emergency event through use of non-toxic fluorescent dyes. Fluorescent dyes may be injected into RMs and FFPs and monitored to estimate the fate and transport of contaminants detected in runoff. Fluorescent dyes have low detection limits and are relatively inexpensive, quick, and easy to use for tracking water movement through the subsurface and aquifer. Fluorescent dyes should be administered and tracked under the direction of a professional experienced in their use.

Emergency event mitigation: actions during the event

During emergency events, public safety should remain the utmost priority, but with proper planning, acquisition of essential data, and efficient communication, many environmental concerns can also be addressed. Depending on the volume of material generated, flows that enter a drainage way may travel downgradient for thousands of feet beyond the event boundary. The following guidance and emergency event mitigation BMPs are recommended:

- Act as quickly as possible to:
  - o Identify the leading edge of the contaminant flows along the ground.
  - o Identify the nearest downgradient points of potential entry into the aquifer (sensitive features such as caves, sinkholes, fractures and faults, sinking streams, storm drains, stormwater retention basins, and active and abandoned water wells).
  - o Identify the best method or combination of methods for fire management, firefighting product control, and aquifer protection.
- Whenever possible, covers, rock socks, berms, booms, sandbag dams, or plastic sheeting should be used to prevent RMs and FFPs from reaching storm drains, drainage features, surface waters, other sensitive features, or other pathways into the subsurface.
- Whenever possible, no materials should be flushed into a storm drain, sinkhole, sinking stream, cave, fracture or fault, well, or drainage way.
- Use stormwater retention basins that are suitable for temporary storage of RMs and FFPs, based on compatibility and design analysis to minimize or exclude infiltration and conducted during event preplanning where available.

- Take all precautions to prevent hazardous materials and decontamination water from being discharged into streets, parking lots, storm drains, sinkholes, fractures and faults, sinking streams, caves, grass swales, solution features, wells, or other potential pathways into the subsurface.
- Use discharge pathways from the site as identified during event preplanning where available. Refer to maps or information showing water flow direction, if available. Discharges that enter a creek bed, drainage way, or other surface water conveyance will most likely enter a sensitive feature that will directly recharge the aquifer.
- Where appropriate or required depending upon the nature of the emergency and materials present, notify landowners, well owners, and relevant officials.
- Where appropriate and under the direction of trained personnel, non-toxic fluorescent dyes may be injected into RMs and FFPs during an event and monitored to estimate the fate and transport of contaminants if detected in runoff.

Post-emergency firefighting activities: Actions after release is controlled and clean up underway

These BMPs apply after a release is under control and personnel are available to conduct these activities:

- Liquids and materials contained in stormwater retention basins after an emergency event should be tested and, if necessary, removed as soon as possible and disposed of in an appropriate manner based on testing results. This is necessary to ensure that the basin can return to function as a stormwater retention basin as soon as reasonable to minimize the possibility of release of hazardous material when the basin next receives stormwater.
- Depending on the type and level of contamination in the material removed, the retention basin may require decontamination and testing before reuse.
- If the volume of RMs or FFPs released exceeds the reportable quantity (RQ; Appendix I), the Texas Commission on Environmental Quality (Appendix I), the EAA, other regulatory agencies as appropriate for the locality, and nearby public and private water supply owners and operators (within a 5-mile radius) should be notified of the RQ release and informed about any suspected contaminants in the release.

CONCLUSION AND IMPLEMENTATION

Contamination of karst aquifers can occur from natural causes, but most commonly contamination is caused by human action or inaction. The best means to secure karst groundwater supplies from becoming contaminated by hazardous or polluting materials is to prevent water or other liquids containing contaminants from reaching areas of entry to the aquifer. This paper provides a set of BMPs for use by first responders to protect the quality of water in karst aquifers from hazardous materials or other pollutants carried in runoff during emergency response actions, such as firefighting. BMPs are provided for preplanning, response during an emergency, and cleanup after an event. Ongoing work will include these BMPs in first responder training curricula and a georeferenced database that will recommend actions to protect sensitive areas where hazardous materials may be present. After implementation of curricula, first responder training, and initial implementation in San Antonio, we will evaluate the effectiveness and usability of BMPs by first responders. We hope to make improvements as appropriate based on use over time.

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Appendix I

Definitions

Term	Definition
Abandoned Water Well	A water well that is no longer in use. Abandoned water wells may not have been constructed to modern standards, maintained, or properly plugged. Abandoned wells and boreholes may provide a direct opening to the aquifer and serve as a pathway for contaminant transport.
Best-Management Practice	A set of actions designed to minimize negative impacts on public health and the environment.
Cave	A void in the subsurface rock large enough for a person to enter.
Conduit	A void ranging from about the size of a garden hose to large enough for a person to enter.
Dense Non-Aqueous Phase Liquid	A liquid that is both denser than water and is immiscible in or does not dissolve in water.
Dissolution Feature	A feature such as a fracture, fault or bedding plane parting that has been enlarged by geologic processes such as the chemical and physical action of flowing water.
Drainage Way	A rill, runnel, rivulet, gully, ditch, creek, brook, stream, river or any other feature that can convey water.
Edwards Aquifer Authority	A groundwater district in the state of Texas that was created by the 1993 Edwards Aquifer Authority Act. Its jurisdictional area includes all of Bexar, Medina, and Uvalde counties and portions of Atascosa, Caldwell, Comal, Guadalupe, and Hays counties. The Edwards Aquifer Authority is mandated to manage, conserve, preserve, and protect the Balcones Fault Zone Edwards aquifer.
Firefighting Products	Any liquid or solid material used or produced during firefighting operations.
Geographic Information System	A framework for gathering, managing, analyzing, and presenting data.
Hazardous Material	Any material that may impact public health and/or the environment.
Karst, Karstic	Any landscape and subsurface occurring in soluble rocks such as limestone, dolostone, and gypsum. Karst is characterized by sinkholes, sinking streams, caves, dissolution features and springs and rapid groundwater movement.
Karstic Feature	A cave, sinkhole, sinking stream, spring, or enlarged fracture, fault, or bedding plane parting that allows surface water or spilled liquids to enter the subsurface.
Light Non-Aqueous Phase Liquid	A groundwater contaminant that is not soluble in water and has a lower density than water therefore, it will float on the top of groundwater. Examples are gasoline and other hydrocarbons including oil.
Municipal Water Supply or Source	A water well used to provide drinking water to a community or city that is regulated under the Safe Drinking Water Act.
Public Water Supply or Source	A water supply well or spring with at least 15 service connections or serve at least 25 individuals for at least 60 days out of a year.
Released Materials	Any liquid or solid materials spilled on the land surface and generally considered potentially hazardous to the public health and the environment.
Reportable Quantity	The amount of a hazardous substance that must be released before EPA requires notification to go to the National Response Center. These quantities are based on volume. Reportable quantities are listed under 40 CFR part 302.4 under the Clean Water Act.
Sinkhole	A depression or opening in rock or soil with internal drainage. In south-central Texas, sinkholes may be as small as only a few feet in diameter and a few feet deep, or as large as hundreds of feet in diameter and tens of feet deep.
Sinking Stream	A stream or creek that loses water to the subsurface either at a discrete sink point or along its bed.
Texas Commission on Environmental Quality	The state regulatory agency tasked with maintaining clean air and water, and the safe management of waste in Texas.