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The Narrows on the Blanco River.

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Best Management Practices to Mitigate Contamination of Karstic Aquifers from Emergency Fire-Control Runoff

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Editor-in-Chief's Note: The following article proposes best management practices for actions to mitigate contamination of karstic aquifers from emergency fire-control runoff. This article is a program update to Schindel and Rosen (2021), which focused on first-line-of-defense best management practices to be taken by firefighters and hazardous material team members to prevent runoff that may carry contaminants from entering aquifers. The update that follows focuses on second-line-of-defense best management practices to be taken by teams of additional emergency responders, planners, and technical experts if first-responding firefighters and hazardous material team members suspect that hazardous materials may have entered an aquifer. Both articles present best management practices and implementation information in a format useful for application in training curricula and development of emergency response standards to protect water supplies, public health, and the environment before, during, and after an emergency event. Readers of the update will need to refer to Schindel and Rosen (2021) for background and contextual information on the overall work, including why best management practices and associated training and tools are necessary; the significance of best management practices for karstic aquifer protection; the relevance of the work beyond the Edwards Aquifer; and the costs and benefits of implementing best management practices.

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Abstract: We propose best management practices to increase karstic aquifer drinking water supplies' resilience to potential hazardous material impacts where first responders and public safety officials suspect emergency firefighting runoff has entered the subsurface in the aquifer recharge zone. Karstic aquifers are unique because of their direct openings to the land's surface, which allows contaminants in runoff or other surface waters to rapidly enter the subsurface and impact aquifer water quality. In the United States, 20% of the land surface is karst, and about a third of the groundwater used for drinking comes from karstic aquifers. Proposed best management practices emphasize on-site, real-time evaluation of the transport and fate of HAZMAT that may enter the subsurface and focus on water quality sampling, runoff and groundwater flow modeling, nontoxic dye tracing, and related studies for use in planning before and during an event and after emergency response has ended. We recommend best management practices for evidence-based screening of high-risk sites to facilitate placement of hazardous material sampling devices and emergency responder deployment. The best management practices, tools, curricula, and training described combine with earlier work by the authors to provide a comprehensive menu of actions to (1) help first responders prevent or limit flushing of hazardous material into a karstic aquifer; (2) help emergency management officials understand the consequences of contamination and issue data-driven geographically focused health and safety risk communications; and (3) help provide health and safety officials with relevant science- and data-based information that can help mitigate human and environmental health risks.

Keywords: Best management practices, Edwards Aquifer, karst or karstic aquifer, water quality, firefighting HAZMAT runoff

Terms used in paper

Acronym / Initialism	Descriptive Name
BMP	best management practice
EAA	Edwards Aquifer Authority
EPA	U.S. Environmental Protection Agency
ESTI	Emergency Services Training Institute
GIS	geographic information system
HAZMAT	hazardous material
MCL	maximum contaminant level
NFPA	National Fire Protection Association
SAFD	San Antonio Fire Department
VOC	volatile organic compounds
WUI	Wildland-urban interface

INTRODUCTION

Work on developing community-level response and mitigation plans to increase the resilience of karstic aquifers to impacts from hazardous material (HAZMAT) in runoff from firefighting has been underway since the Texas Legislature directed such action in 2007 (Senate Bill 1477, 2007). This directive came in the aftermath of a fire in a large debris pile that burned for three months where runoff from fire control threatened water quality in the Edwards Aquifer near San Antonio (Hamilton, 2011; Wright, 2007).

This program note continues and updates previous work published in the Texas Water Journal to develop emergency response best management practices (BMPs) to protect the water quality of the Edwards Aquifer (Schindel & Rosen, 2021). Schindel and Rosen (2021) described the nature of karstic aquifers, potential inadvertent consequences of firefighting over aquifer recharge and contributing zones, and proposed BMPs for firefighting in karstic terrains. Those BMPs focused on first-line-of-defense actions to prevent or limit potentially HAZMAT-carrying firefighting runoff from reaching and entering the subsurface at sensitive recharge zone sites (Emergency Services Training Institute [ESTI], 2021; Rosen & Gary, 2020; Rosen & Maxwell, 2020; Schindel & Rosen, 2021; Schindel et al., 2023). This work included developing tools, methods, curricula, and training for firefighters and HAZMAT first responders. However, the BMPs and associated work products may also be suitable for use by state, county, city, municipal, and government employees and their contractors responsible for planning for, responding to, or regulating HAZMAT spills in karstic watersheds before, during, and after disaster and fire-related response.

The special practices proposed here are critically important to protect water quality—not only in the Edwards Aquifer in San Antonio where we conducted our work, but also at other locations reliant on water supplies in karstic aquifers. In the United States, as much as 20% of the land surface is karst, and about a third of the groundwater used for drinking comes from karstic aquifers (Schindel et al., 1996). Up to a quarter of the global population depends entirely or partly on freshwater from karstic aquifers, with associated watersheds covering about 7–12% of the world's land surface (Ford & Williams, 2007). Karstic aquifers are highly vulnerable to contamination because of their direct communication to the land's surface, fast transport velocities, and limited ability to filter contaminants (Green et al., 2006; Schindel, 2019). Runoff can rapidly enter the subsurface carrying contaminants through fractures, faults, sinkholes, and caves. Spills can be caused by natural disasters such as flooding, wildfire, high winds, and lightning, and by fire control during these disasters. When disasters strike in places storing or supporting HAZMAT transport, contaminants can quickly impact water quality over a large area of the aquifer and greatly threaten public safety and the environment.

NEW PROPOSED BMPS FOR AQUIFER PROTECTION

Work described herein recommends added protection of karstic aquifers by proposing second-line-of-defense BMPs to help disaster responders address instances where HAZMAT in fire-control runoff is suspected to have entered the subsurface. Proposed second-line-of-defense BMPs emphasize on-site, real-time evaluation of the transport and fate of HAZMAT that may infiltrate into the aquifer. They focus on water quality sampling, runoff and groundwater flow modeling, nontoxic dye tracing, and related studies and on-site application. Application of these proposed BMPs will require involving technical experts who may have little or no prior experience working on emergency response or with emergency management teams. Proposed BMPs will also require research on developing and applying new tools and evidence-based screening of high-risk sites to help facilitate BMP planning, coordination, and deployment. For example, research on HAZMAT flow and transport will be needed to inform some of the proposed BMPs in the event of a catastrophic spill affecting the Edwards Aquifer. Data on HAZMAT flow and transport modeled for other types of aquifers are not readily transferable to karst. Even information developed in a different karstic aquifer may not be transferrable to the Edwards Aquifer because flow through karst is so complex and variable (Quinlan & Ewers, 1985; Schindel, 2019; Schindel et al., 2001, 2004, 2005; Smith et al., 2005). As a result, we include BMPs, recommended actions, and supporting and cautionary notes on developing and assembling information, such as data on runoff and groundwater flow for the Edwards Aquifer. This information can inform tools (e.g., predictive models) that responders can use during and after emergency events. To help facilitate this, our proposed BMPs also recommend establishing ready access to technical experts and researchers who can support response efforts and gather essential data before, during, and immediately after a HAZMAT event. We emphasize anticipating high risk locations, planning and preparing for potential HAZMAT events, and supporting HAZMAT event response by first responders and technical specialists, as well as by health and safety officials after most—or all—firefighters and first responders have departed from the immediate disaster site.

Rapid population growth, presence of HAZMAT in storage and transit in San Antonio, weather instability, urban encroachment into farm and ranch lands, wildfire, and flash floods are factors that have created an urgent need to increase the resilience of the region's karstic drinking water supply to contamination from unintended consequences of disaster and disaster-related emergency response. While our work focuses on BMPs proposed for application in the Edwards Aquifer region, the BMPs are generally applicable anywhere karstic landscapes encompass direct points of entry to an aquifer and where HAZMAT-containing runoff may threaten the quality of aquifer water supplies of municipal, public, and private wells.

We hope to increase the resilience of karstic drinking water supplies to disaster-related emergency and fire-control activities through the application of science-based BMPs.

BMPs are typically developed for use by water-quality experts to serve as standards for action and for developing tools to be used in the course of responding to stormwater runoff, floods, sewer line breaks, or other management issues or emergencies involving water (e.g., in the case of this work, to develop BMPs for use where fire-control runoff may carry HAZMAT). BMPs standards are often used in local, state, and federal planning, training, and regulatory materials. These are commonly described as "firefighting product control measures" in emergency training manuals, standards, and curricula (National Fire Protection Association [NFPA], 2022). We use the term "best management practices" for firefighting to also cover the term "firefighting product control measures."

BMPS TO MITIGATE KARSTIC AQUIFER CONTAMINATION FROM EMERGENCY FIRE-CONTROL RUNOFF

The BMPs in this section are proposed to aid disaster response planners and responders to address instances where first responders and public safety officials suspect that HAZMAT in fire-control runoff may have entered the subsurface. The BMPs are organized into the three categories—pre-event, during event, and post-event—commonly used in emergency response training materials (NFPA, 2022) and by the ESTI in their manual for karstic environment runoff control (ESTI, 2021). Table 1 provides a quick reference for the proposed BMPs.

Pre-Event BMPs

- Develop location-specific models for predicting runoff flow and aquifer vulnerability at sites suspected of being at risk of HAZMAT contamination during disaster response fire control or from direct impacts of disaster.[1] This should

[1] For the San Antonio region, the Edwards Aquifer Authority [EAA] has developed a georeferenced database and user interface for many areas at high risk of HAZMAT contamination during disaster response fire control. This tool provides data displaying reported HAZMAT contents and storage locations, many openings to the karst aquifer (sensitive areas), water flow direction across the landscape, and embedded recommendations for protective action. This tool supports application of BMPs and can be developed for use in other locations.

Table 1. Summary list of BMPs to increase resilience of karstic aquifer drinking water supplies to potential impacts from HAZMAT suspected of entering the subsurface in the contributing and recharge zones.

Pre-Event BMPs
Develop location-specific models for predicting runoff flow and aquifer vulnerability
Determine the short- and long-term contaminant risk potential in the aquifer
Develop models to estimate potential flow characteristics and fate of high-risk HAZMAT
Develop plans to preposition and use sensors and nontoxic dyes
Develop site-specific predictive models of HAZMAT transport and fate at sites with high contamination risk
Provide specialized curricula and training to personnel
Develop visualization and predictive tools for on-site use
Develop a clear communication protocol and contact list
Develop pre-event public communication plans
Implement regular training for emergency response team members
Implement regular inspections and reviews of tools and plans for implementing BMPs and HAZMAT control
Review and improve BMPs at least once every 5 years
BMPs for During Event Response
Employ on-site surface mitigation techniques and tools
Employ location-specific information and models for predicting runoff flow and aquifer vulnerability
Deploy nontoxic dyes
Estimate contaminant transport and fate
Report the nature of HAZMAT release to appropriate authorities
Inform disaster responders, public health and safety officials, and water providers about the potential transport and fate of released HAZMAT
Post-Event BMPs
Continue sampling runoff, surface water, and groundwater as long as necessary to complete dye tracing and testing
Take remedial action as needed based on event-related data
Issue health advisories or other disaster-related communications-based, event-related data
Use event-related data to refine information on HAZMAT transport and fate
Develop an action plan for employing active remediation techniques at high-risk and at-risk sites in the aftermath of a HAZMAT runoff event

include mapping runoff flow, locating containment sources, and identifying unprotected drainage features in areas of greatest risk. Models and available information should include an assessment to assist planners in placing and deploying BMPs.

- Determine the short- and long-term risk potential in the aquifer for legacy and emerging contaminants considered hazardous and persistent in the natural environment (Guiseppi-Elie, 2020; U.S. Environmental Protection Agency [EPA, 2024a] Emerging Contaminants and Federal Facility Contaminants of Concern). For contaminants of most concern locally, pathway-focused human health risk assessments should be conducted, with results used to develop response protocols, such as for risk communications, as needed (Randrianarivelo et al., 2019).
- Pre-identify which HAZMAT will be incident- or site-specific. Lists of chemicals associated with different industries, facility types, and specific facilities are currently available for this purpose (EPA, 2024b; EPA, 2024c).
- Develop plans to preposition and use sensors to sample for contaminants and to track nontoxic dyes during emergency events.[2] These plans should include a comprehensive map and access guide for sampling points in the aquifer and initiating efforts to increase the number and accessibility of locations where sampling can take place, especially in areas downgradient of high-risk sites. For sites of suspected high aquifer vulnerability and high contamination risk, potential sampling sites should be designated for sensor locations, for sampling groundwater for dye and contaminants, and for specialized sampling. For example, if highly volatile substances such as gasoline are involved in a spill, then wells, caves, and the basement or ground floor of buildings should be tested using air-monitoring equipment such as an volatile organic analyzer or explosimeter. For high-risk sites, runoff control barriers or sampling/testing materials can be prepositioned. Existing stormwater or dye monitoring and sampling locations should be used when available.
- For sites suspected of being at high risk of contamination, develop site-specific predictive models to estimate the transport and fate of a site-specific or generalized HAZMAT that could enter the aquifer during firefighting. Models can be used to develop visualization and predictive tools that can then be used on site during disaster response to help responders assess on-site safety needs and anticipate contaminant transport and fate to mitigate threats to aquifer water quality. Using dye tracing in the development and verification of models is recommended.
- Provide specialized curricula and training to appropriate personnel who can be deployed during emergency response to conduct nontoxic dye tracing, well sampling (i.e., monitoring points for dye/contaminants), and data analysis. Identify and train technical specialists who can be deployed to support emergency responders by conducting sampling at monitoring points, performing laboratory analysis, monitoring sensor data, and assessing HAZMAT transport and fate.
- Develop a clear communication protocol and contact list to be used in the event of suspected HAZMAT release during firefighting. The protocol and list should include all official authorities normally advised of HAZMAT emergencies, such as the Texas Commission on Environmental Quality, EAA, San Antonio Water System, and other municipal supply systems as well as all local authorities, governments, community organizations, and potential volunteer groups that either need to be informed or can assist in response and community action.
- Develop pre-event public communication plans with a focus on risk communication (FEMA, 2021; FEMA 2023), including appropriate language options built on best fact-based information available.
- Implement regular training for emergency response team members on BMPs applicable to where they work, with training to include HAZMAT control protocol in karst areas and review of HAZMAT storage locations, sensitive sites for water runoff entry to the aquifer, and locations/positioning of water runoff retention and detention areas.
- Implement regular inspections and review of materials, equipment, and structures relevant to local use of BMPs and HAZMAT control.
- At least every 5 years, BMPs should be reviewed and improved, as needed, based on new emergency response experiences and as new scientific data or practical use information is acquired.

[2] Nontoxic dyes act as surrogates for contaminant transport when the dyes are injected into aquifer waters at or near a location where runoff carrying HAZMAT is suspected of entering the aquifer. After dye is injected, points of access to the aquifer (i.e., monitoring points) are sampled repeatedly over time, and water samples and activated charcoal receptors are tested for dye presence. Monitoring points include monitoring wells, water supply wells (public and private), springs, and other direct openings into the aquifer where water can be readily sampled for dye and contaminant presence. Dyes used to track contaminant transport and fate in karst aquifers are commonly called “tracers,” and the technique is commonly called “tracer testing” and “dye tracing.”

BMPs During Event Response

- Whenever appropriate during event response, on-site surface mitigation techniques should be deployed as a first line of defense. These may include runoff control dams, adsorbents, runoff diversion to detention and retention basins, and other measures described in our earlier work (ESTI, 2021; Rosen & Maxwell, 2020; Rosen & Gary, 2020; Schindel & Rosen, 2021; Schindel et al., 2023).

Event runoff that may contain contaminants should not be flushed into a ditch, ravine, dry streambed, or flowing freshwater stream in an to attempt to dilute contaminants. Contaminated runoff that remains accessible on the surface should be remediated or removed as soon as possible.

- If and where possible, apply location-specific information and models to predict runoff at sites identified as having high aquifer vulnerability and high HAZMAT contamination risk. When lacking detailed site-specific information or when in doubt, it is best to assume that the aquifer is vulnerable at the emergency event site, and manage accordingly.
- If appropriate and possible, within at least 24 hours of a potentially significant spill—due to the high volume or risk level of contaminants involved—deploy nontoxic dyes to trace contaminant transport and fate. Dye tracing during disaster response can be used to collect real-time data, in early screening tests to focus sampling for detection of contaminants and to help verify predictive models and expert assumptions. Results from dye tracing can also be used to plan and direct appropriate responses to public health and mitigate environmental impacts. Dye tracing is not recommended for low-volume or low-risk spills.
- If appropriate and possible, where HAZMAT is suspected to have entered the aquifer, estimate contaminant transport and fate using a hydraulic-flow model, existing hydrologic studies, expert opinion, and on-site visualization and predictive tools. If relevant, use the results of dye tracing to inform the models or help verify assumptions and predictions from models.
- As soon as possible after a HAZMAT release is suspected, report the nature of the release to appropriate authorities and follow the communication protocol established as a pre-event planning BMP.
- Inform disaster responders, public health and safety officials, and water providers about the potential transport and fate of specific contaminants that are suspected or known to have entered the aquifer as a result of the disaster or in the course of disaster response and firefighting. Provide information to the affected public as appropriate (FEMA, 2021; FEMA 2023).[3]

Post-Event BMPs

- Sample appropriate wells and aquifer openings as long as necessary to complete testing for contaminants and monitoring at dye tracing points. Where relevant, continue sampling and analysis of spill site runoff and surface waters recharged by the aquifer. Depending upon local conditions, it may be advisable to continue sampling at monitoring points for weeks or months.
- Issue health advisories or other disaster-related communications, as appropriate, based on data and the communications protocol.
- Data from monitoring point sampling, dye tracing, and other information from a disaster or release event should be used to refine information on site-specific HAZMAT transport and fate. These data may be used by first responders and public health and safety officers, as well as to inform communications, best practices, and planning for future events.
- Develop an action plan for employing active remediation techniques at high-risk and at-risk sites in the aftermath of a HAZMAT runoff event. Some examples of remediation techniques include identifying wells that can be used as areas for runoff containment, bioremediation, vapor removal, and groundwater "pump and treat" methods.

ADDITIONAL CONSIDERATIONS FOR IMPLEMENTING BMPS TO IMPROVE AQUIFER RESILIENCE

Detailed considerations for implementing BMPs are described in the Supplemental Information. This is provided for readers seeking additional detail, or for readers who are or may in the future be involved in planning for or responding to emergencies where firefighting runoff may contain HAZMAT. The Supplemental Information includes recommended actions, supporting and cautionary notes, and extensive references for practical implementation of BMPs involving (1) runoff flow and aquifer vulnerability modeling; (2) dye tracing to track transport and fate of HAZMAT; and (3) evaluation of transport and fate potential of specific HAZMATs.

IMPORTANCE OF BMPS

BMPs for Full Range of Responders

The original objective of the project partners (Schindel & Rosen, 2021) was directed at training firefighters in urbanized Bexar County on means and methods to protect aquifer water quality from the potential impact of HAZMAT resulting from significant fire or other emergency events. This focused our tasks, but it is now obvious that this also limited our coverage to only a subset of emergency responders. BMPs should be extended to help guide the actions of the full range

[3] We recommend that a hydrogeologist with expertise in karst systems be consulted about potential transport and fate of specific contaminants. A person with such expertise, in particular if they have previous experience in the site of an event, will be best able to help interpret and verify aquifer physical properties along with data on potential travel times and flow paths.

of responders, such as health and safety officials, community leaders, support organizations, HAZMAT site managers, planners, permitting and regulatory authorities, and members of the community who play a role or have interest in HAZMAT emergency response and aquifer water quality protection. This would be particularly important in pre-event planning to ensure that the full range of interested and responsible parties have established roles in advance of a disaster.

BMPs Provide Response to Increasing Threat of Wildfire

The BMPs herein and in Schindel and Rosen (2021) are directly applicable to emergency response to wildfire in karstic terrains. This is significant over the Edwards Aquifer, as well as in other karst regions in the Unites States where the frequency and intensity of wildfire is increasing (Abatzoglou & Williams, 2016; United Nations Environment Programme, 2022; Zhuang et al., 2021).

For the Edwards Aquifer, the contributing and recharge zones are the areas of greatest vulnerability to HAZMAT contamination. Those zones coincide in many locations with the wildland-urban interface (WUI), which has highest wildfire risk in Texas (Texas A&M Forest Service, 2024) (Figure 1). The San Antonio Fire Department (SAFD) describes the northern reaches of San Antonio along the WUI as among the most at-risk areas for destructive wildfires in Texas, basing its assessment on information from the Texas A&M Forest Service and centuries-long efforts at fire suppression and build-up of fuels (Gibbons, 2018). The SAFD equated WUI fuel loads and topography to the wildfire threat faced by many communities in California (Gibbons, 2018). The WUI's proximity to sensitive features exacerbates the threat to the aquifer during wildfire response. Rapid population growth into the WUI and an increasing frequency of elevated fire weather conditions in Texas represent major concerns (Texas A&M Forest Service, 2024). BMP implementation training should extend to wildland firefighters and HAZMAT teams that respond to wildfires in areas that overlap or drain into karstic terrains.

BMPs as Due Diligence in Protecting the Edwards Aquifer and Drinking Water Supplies

The Edwards Aquifer was the first aquifer in the nation to be designated as a sole source aquifer by EPA, under Section 1424(e) of the Safe Drinking Water Act of 1974. This designation was made in 1975 and signifies (1) that the aquifer provides at least 50% of total water supply in its service area, and (2) that there are no reasonably available alternative drinking water sources should the aquifer become contaminated. Although the San Antonio Water System has since diversified local water supplies, the Edwards Aquifer still accounts for about 60% of its total supply (San Antonio Water System, 2023). Protecting the quality and use of aquifer water supplies is critical to the well-being of citizens, the local economy, industries, and the environment (Rosen, 2014).

San Antonio and surrounding areas serve as a major hub for medical, military, technology, and transportation industries. The city stands as the first major urban area along the transportation route between the largest inland port of entry in the United States (i.e., Laredo) and the rest of the country. Significant quantities and many different kinds of HAZMAT are stored in or transported through the city and region. HAZMAT release at some level is inevitable, given the scale of development and nature of activities over the Edwards Aquifer's contributing and recharge zones.

It is critical that first responders be supplied with training and tools that will help protect the aquifer, and—even more importantly—be prepared to use the training and tools where applicable. Public health and safety officers and community leaders need data-driven means to help mitigate the consequences of a HAZMAT event. This will require providing sufficient future funding to assemble existing data and acquire new data for optimal BMP application. This will be expensive, but the costs to prepare for a potential catastrophe will be far less than the costs to recover from a catastrophic HAZMAT event in the aquifer.

Emergency responders and responsible public leaders are encouraged to use the information we provide within their organizational structure and planning processes, coordinate among themselves, share resources, and respond to emergency events. We make no specific recommendations on how to assemble needed resources, fund recommended work, or coordinate among responsible parties, even though several BMPs may require considerable sustained effort and funding that may involve coordination, possibly sharing available resources, and dividing up tasks. It is beyond the scope of our work to offer recommendations on internal operations, management, cooperation, and public outreach by emergency response and public health and safety agencies, cooperatives, or other organizations responsible for addressing potential HAZMAT release into water supplies.

Spending and effort on preparation and acquisition of data for BMPs and BMP implementation activities can be justified as due diligence in the event of a significant HAZMAT incident. Acquiring, planning for, training to use, and using BMPs to prevent HAZMAT entry into the aquifer—and using BMPs to mitigate impacts if it does—demonstrate a high level of due diligence by responsible agencies and public officials to protect essential water supplies.

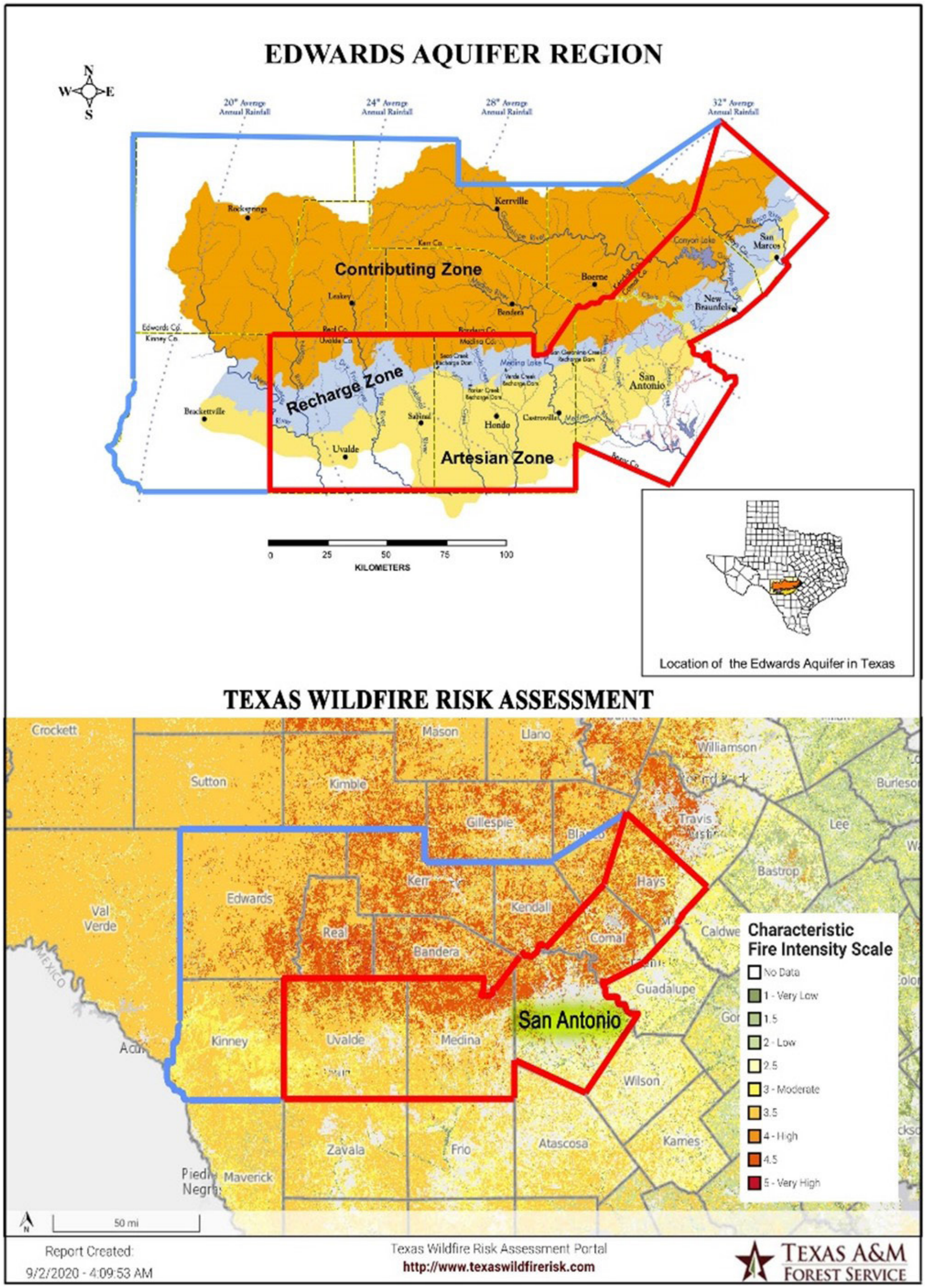

Figure 1. Top: The Edwards aquifer region showing locations of the contributing, recharge, and artesian zones. Credit: EAA (Schindel & Rosen, 2021). Bottom: The vulnerable recharge zone coincides with the line of greatest threat of wildfire along the wildland-urban interface running between San Antonio and Austin. Credit: Texas A&M Forest Service. Texas Wildfire Risk Assessment Portal (http://www.texaswildfirerisk.com).

CONCLUSIONS

The work we recommend to develop and use BMPs focuses on developing measures to help increase karstic aquifer resilience to the impact of HAZMAT that may enter the subsurface in fire-control runoff. Schindel and Rosen (2021) provide a similar complete listing and summary table of BMPs that focus on preventing entry of fire-control runoff to the subsurface. Together, the proposed BMPs described herein and BMPs previously described by Schindel and Rosen (2021) provide a comprehensive listing of means and methods to mitigate karstic aquifer contamination from HAZMAT resulting from disaster-related runoff. The BMPs offer a menu of actions to (1) help first responders prevent or limit flushing of HAZMAT into aquifer water supplies; (2) help public health and safety officials issue data-driven, geographically focused health and safety risk communications when HAZMAT is believed to have reached the aquifer and threatens municipal, public, and private water wells and supplies; and (3) help public health officials mitigate risks based on science and data to plan for and direct efforts to protect karstic aquifer water quality from HAZMAT.

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SUPPLEMENTAL INFORMATION

Additional Considerations for Implementing BMPs to Improve Aquifer Resilience

BMPs Involving Runoff Flow and Aquifer Vulnerability Modeling

Pre-Event

Identify and plot locations of aquifer vulnerability and develop models of the runoff flow regime in areas at high risk of contaminant release during emergency response (Koosha, 2019; Schindel et al., 1987; Schindel et al., 1996). Such models will help inform responders about potential aquifer vulnerability from firefighting runoff at the disaster event site. The utility and effectiveness of models can be enhanced by placing and monitoring sensors that can inform models in real time in the highest-risk locations.

During Event Response

Use runoff flow modeling to (1) predict runoff flow and make decisions about preventing contaminants from entering the aquifer, and (2) identify potential contaminant entry points when preventive measures fail, were not used, or were deemed infeasible.

Recommended Actions

- Identify physical sites within the karstic aquifer's contributing and recharge zones that are near karst features with high risk of aquifer contamination during firefighting and other emergency response. Examples are a warehouse or large retail facility that stores HAZMAT, such as home improvement centers that carry paints, cleaning supplies, and other chemicals (Rosen & Maxwell, 2020), and lawn and garden centers that store large quantities of fertilizers (Ward et al., 2018).
- Develop a comprehensive ArcGIS project or assemble data layers for use in geographic information system (GIS) applications. Acquire relevant data layers, including data that may be available from past and ongoing work. Principal components should include the following: (1) topography; (2) impervious cover; (3) stormwater containment structures and assigned characteristics; (4) adjoining runoff flow paths, such as culverts or creek beds; (5) location and nature of karst features, such as creek beds, caves, sinkholes, sinking streams, faults, and fractures; and (6) footprint of structures holding HAZMAT vulnerable to disaster and related fire control. Include in the GIS database the type of surface coverage, locations of stormwater containment structures, and other location-specific factors that could impact the transport and fate of HAZMAT released in runoff.
- Conduct in-depth assessments of karst features, including the nature of surface coverage, anthropogenic land use, depth to water table, soil permeability, hydrologic conductivity, caves, and sinkholes (closed contour depressions). Maps should be designed and made available to support decision-making during emergency response.
- Formulate a model of the runoff flow regime appropriate for each high-risk site. The model may be mechanistic and based on hydraulics, or it may be a reservoir model representative of the major components of runoff flow.
- Develop and make available a visualization tool using information collected in the course of this work.

Supporting and Cautionary Notes

- Runoff flow and aquifer vulnerability modeling should be conducted for specifically defined locations where there is a high risk of potential aquifer contamination during disaster response, such as (1) HAZMAT storage or transport locations near sensitive karst features, and (2) locations generally at risk of wildfire, flood, wind, or other disasters where fire control is a likely disaster response outcome. Previous work may provide comprehensive data of this nature for locations of high vulnerability to aquifer contamination in urbanized areas (Schindel & Rosen, 2021).
- Effective use of models describing runoff and groundwater flow or aquifer vulnerability will require trained technical support and skilled operators to be on-call for immediate deployment. Due to the highly technical nature of deploying models in an emergency, and the high operator skill level required, continual readiness training and availability of trained personnel is recommended. Runoff flow modeling is a unique skill set that requires expertise in calculating the volume of water from rainfall and firefighting activities. This information is used to estimate the volume of potentially contaminated water that

may require treatment, and to inform responders about the retention area size necessary to contain contaminated water runoff. This is information generally provided by a civil engineer who does flow calculation models for the design of culverts, stormwater retention basins, and bridges.

BMPs Involving Dye Tracing to Track HAZMAT Transport and Fate and Inform Models

Pre-Event

- Develop plans and criteria for using nontoxic dyes to track contaminant transport and fate in the aquifer, with deployment criteria based on the estimated volume and public health risk level of the HAZMAT suspected to have entered the aquifer.
- Obtain, store in a readily accessible location, maintain, and prepare to use appropriate nontoxic fluorescent dyes during emergency events.
- Identify and provide emergency response training to personnel who can be employed during emergency response and who have the expertise to conduct dye tracing and analysis. Identify support personnel with sufficient expertise to assist emergency responders in coordination with and support of experts conducting dye tracing work (Alexander & Quinlan, 1996; Quinlan & Ewers, 1985).
- Develop an agenda of research to use past and new dye tracing data as it becomes available to better describe water flow through the aquifer. Use these data in conceptual modeling of contaminant transport and fate.

During Event Response

Where appropriate, conduct dye tracing work and sample predetermined monitoring points for dye and contaminants.

Post-Event

Continue sampling at monitoring points as necessary. Use the data from dye tracing to inform short- and long-term response modeling, communications, remediation, and other mitigation measures.

Recommended Actions

- Dye tracing should be considered in the event of significant spills that could have catastrophic results due to the high volume of runoff that is suspected to have entered the aquifer or high risk to human health or the environment from the HAZMAT involved. Dye tracing is a highly effective means to collect flow path and time-of-travel data on significant HAZMAT spills where there may be potential public health consequences. Dye tracing is not recommended for small-scale or low-risk spills.
- In the event of suspected contaminant release into the aquifer, engage people with appropriate expertise as soon as possible to identify the HAZMAT point, provide insight into the potential amount and concentration of HAZMAT released, ascertain likely HAZMAT transport rate and fate, and help responders make a judgement on use of dye tracing to collect essential data.
- Use dye tracing as the basis of research in pre-event planning and in developing science-based action plans for use on-site and in real time. During disaster response these plans can be used to predict suspected HAZMAT transport and fate through the aquifer and into drinking water supply wells, monitoring wells, and springs. Conduct research using dye tracing to identify, map, and categorize potential monitoring points for ready use during a disaster. Include domestic, municipal, industrial, agricultural, and environmental monitoring wells and natural springs in this work.
- Nontoxic fluorescent dyes (i.e., Uranine, Eosine, Sulforhodamine B, Phloxine B, Rhodamine WT, Direct Yellow 96, Tinopal CBS-X) should be considered for use in both research and emergency response. These dyes are inexpensive, readily available, and can be detected at low concentrations.
- Dye tracing can include multiple different dyes injected into different karst features to address emergency situations where the exact entry point of fire-control runoff is unknown. This would be useful for application during or immediately after emergency fire control involving flood, heavy rain, or high wind. Commonly, as many as 30 to 60 (or more) monitoring points may be sampled to detect dyes. Dye concentration can be measured by using a synchronous scanning luminescence spectrometer.
- Identify wells and springs most likely to be impacted by a HAZMAT release and develop a water quality sampling program

to detect potential contamination, including a parameter sampling list, sample collection methods (sample bottle types, temperature storage requirements, and holding times), sample frequency, and designated laboratory for analyses.

- Establish a long-term research and data inventory initiative on local and regional hydrogeology using dye tracing, water level monitoring, and water quality analysis that focuses on groundwater flow paths, range of groundwater velocities during wet and dry conditions, flows to critical monitoring points such as water supply wells and springs, and estimates of concentration loading at critical monitoring points.
- Data from tracing studies using nontoxic fluorescent dyes, including data from past dye tracing work, should be used to refine any conceptual and analytical predictive modeling of HAZMAT transport and fate in the aquifer.

Supporting and Cautionary Notes

- Dye tracing is a readily available and rapidly deployable tool to use to determine HAZMAT transport and fate in karstic aquifers in real time (Alexander & Quinlan, 1996; Johnson et al., 2005; Quinlan & Ewers, 1985; Schindel et al., 2003, 2004, 2005, 2023; Smith et al., 2005). Tracing studies have been used for more than 100 years to help characterize groundwater flow in karstic substrates (Schindel et al., 1996).
- Nontoxic dyes used for tracing should be injected into a karst feature within about 500 yards of the suspected location of HAZMAT entry into the aquifer. Additional data may be obtained by injecting two different dyes at the site. One dye should be injected directly into the runoff stream suspected to be carrying HAZMAT (if still flowing), while a different dye should be injected into a separate karst feature within about 500 yards of the suspected location of HAZMAT entry to the aquifer. Dye injected into a nearby karst feature may require flush water from a water tank, fire truck, or fire hydrant to make sure that dye will enter the aquifer. Approximately 5,000 gallons of water should be used to saturate the surface and subsurface, then the dye should be injected along with an additional 5,000 gallons of water to flush the dye into the aquifer. Such flushing should not take place in areas where contaminants from the spill may be present on the surface or subsurface that could be flushed through the unsaturated zone of the aquifer into aquifer waters along with the dye.
- Overuse of dye tracing can progressively complicate future use, because each different dye introduced into an aquifer location may become distributed widely and persist for lengthy periods. To be an effective surrogate for a HAZMAT spill, the dye used to trace the spill must be uniquely identifiable. Remnant dye from past use may confound detection of newly introduced dye. Existing dyes from previous studies can be detected in background samples collected before or just after dye injection. However, dye tracing may be the best available option to use for research and tracking small-scale or low-risk spills for specialized reasons, such as for data collection. Regardless of the underlying basis for use, the decision to apply tracer testing techniques to a spill or research project should be predicated on assessment and recommendations by a qualified expert on tracer testing in karst.
- Karst hydrogeology experts should be consulted as soon as possible during the course of responding to an event where a significant quantity of HAZMAT has entered the aquifer. Such services should be secured during preplanning. While advance planning can provide information on the level of relative risk of aquifer contamination at various sites and the location of sensitive features, expert advice is essential when an event takes place in an area not surveyed for risk and at all high-risk sites. Expert support can help direct if, when, and where to initiate dye tracing on site and help provide advice on sampling at monitoring points. The following questions may be among many considered by responders, but finding answers will be facilitated by expert on-site evaluation:
    - Is the use of nontoxic dye the best way to proceed given the nature of the HAZMAT, suspected amounts of HAZMAT, and site-specific conditions?
    - Which dye(s) and how much will need to be injected at or near the suspected HAZMAT entry point so that the dye remains detectable for the distance contaminants are likely to be carried in the aquifer?
    - What needs to be communicated to water well users in the potentially affected area? For example, what is the contaminant at issue; how will users detect it in their wells; will well water become discolored by dyes; and if so, who should be made aware and what should they be told if that happens?
- Dye tracing can be used to test conceptual models to better understand groundwater relationships between rock units (stratigraphic versus hydrostratigraphic units), aquifers, and the vulnerability of potential monitoring points. Tracer studies require cooperation between the researchers and monitoring point owners, such as public and private water supply system operators and owners of small water wells. Injecting tracers into the aquifer is the most reliable and effective method to directly determine flow direction, identify potential monitoring points, estimate travel time during different hydrologic conditions, and estimate the potential concentration of contaminants at monitoring points of concern (Quinlan & Ewers, 1985; Schindel et al., 1996).

BMPs Involving Transport and Fate Potential of Specific HAZMAT in Karstic Aquifers

Pre-Event

To the extent possible, determine the short- and long-term risk potential for legacy and emerging contaminants that are (1) considered hazardous, (2) would be persistent if they entered the aquifer, (3) have hazardous and non-hazardous breakdown products that can be traced through the aquifer and remediated if possible, and (4) are known to be present at high-risk locations. This will provide insight into the fate of contaminants likely to enter the aquifer from firefighting actions during disaster response if runoff control measures fail or are not used. Predictive models of the potential fate of specific HAZMAT should be developed where conditions at high-risk locations and related aquifer characteristics allow accurate HAZMAT fate projections.

During Event Response

Use existing research, data, runoff flow modeling, expert opinion, and dye tracing where appropriate during emergency response to (1) identify and predict transport and fate of specific HAZMAT in runoff; (2) make decisions about their transport, location, persistence, and potential risk; and (3) use prepositioned monitoring points to verify predictions and issue fact-based communications to emergency responders and the public.

Post-Event

Use information on transport, fate, and testing obtained during or immediately after the event to inform short- and long-term response and inform communication plans.

Recommended Actions

- Assemble information on transport characteristics of selected legacy contaminants in the aquifer by reviewing available literature or by conducting studies that describe flow characteristics through conduit-dominated karstic aquifers. In conducting studies, HAZMAT types should be divided into broad categories, such as immiscible solvents, soluble solvents, heavy metals, micro-solids (e.g., pathogenic microbes), and radioactive materials. The properties of different categories may be used to represent commercial proprietary chemicals containing multiple ingredients. Evaluations should include transport and fate of potential HAZMAT in the aquifer. Results can be used to model the potential effectiveness of containment structures, estimate disaster resilience, and assess risk. The following are notes on transport and fate of common HAZMAT types:
  - Industrial solvents, generally volatile organic compounds (VOCs), have a low maximum contaminant level (MCL) in drinking and surface water and are often immiscible or have finite solubility in water and a high level of volatility. When VOCs enter a karstic aquifer, they can be transported long distances dissolved in water or as an entrained liquid in the form of a light non-aqueous phase liquid that has a lower density than water and will float on the top of groundwater, or as a dense non-aqueous phase liquid that has a higher density than water and will sink in groundwater. These compounds can collect in the aquifer by sorption or direct storage in karst openings. There is a risk of explosion if a VOC's gas is flammable (such as gasoline), because volatile gases trapped underground can migrate into water wells, stormwater injection wells, basements, and above-ground structures. Risks associated with VOCs should be evaluated as many of these compounds have a very low MCL that is lower than their solubility limits in water.
  - Heavy metals usually have high toxicity and a very low MCL in drinking and surface water. Their transport and fate, however, can be highly variable, as they can form complexes that exhibit differential fates during transport. The potential to form complexes and how they may affect transmission and fate in the aquifer should be assessed.
- Disasters that result in damage to sanitary sewer lines, wastewater containment facilities, or sewage lift stations can result in pathogens entering the aquifer. The volume of material released from sanitary sewage systems can be large—as much as hundreds of thousands of gallons—and can continue for days. Unlike releases on the surface of tightly packed sand, organic, and gravel soils and other substrate, where pathogens may be filtered or subject to some bacterial decomposition, karst substrate's high permeability allows material to flow unfiltered and untreated. Large volumes of contaminants, coupled with rapid groundwater velocities, can rapidly impact private and public water supplies. Mass release of pathogens into a water supply during disaster response can lead to exceeding MCLs and acute and rapid public health concerns (Mahler et al., 2000; Schindel, 2018; White, 2018).

- It may become possible to develop reliable models for contaminant transport and fate in karst for some regions with varying degrees of reliability as groundwater modeling capabilities improve for karstic aquifers. However, this will require collecting large amounts of data and testing (Hontoon, 1995; Johnson et al., 2010; Quinlan & Ewers, 1985; Schindel et al., 2003, 2004, 2005, 2023; Smith et al., 2005).

Supporting and Cautionary Notes

- Dye tracing research has revealed that karstic aquifers may exhibit a wide range of groundwater velocities and changing flow paths depending upon hydrologic conditions. Variability in flow through karstic aquifers is extremely difficult or impossible to predict through numerical modeling (Quinlan & Ewers, 1985; Schindel et al., 2001, 2004, 2005; Smith et al., 2005).
- Cores removed from karst substrates for testing contaminant transport and fate can be highly variable from one location to the next or even within the same core, often making them of little use or providing misleading data. Unlike cores used for testing flow from sand or gravel aquifers, which have relatively uniform porosity and flow characteristics, cores from karst are drawn from a substrate composed of large to small openings oriented in varied directions and dispersed across large to small distances with permeabilities that can range more than 11 orders of magnitude over distances as small as a few feet. The variability of karst makes laboratory-based testing of contaminant transport and fate subject to large error (Hontoon, 1995; Smith et al., 2005).
- There is no current technology that can remotely map the interior spaces of a karstic aquifer with sufficient information to yield reliable results. However, some general trends can be established over time and given adequate study. Data from dye tracing can be used to improve the confidence level in modeling results and help inform models on a real-time basis as more empirical data from tracing and other studies become available or are assembled. Expert opinion can help substantiate model results where corroborating data are lacking.

APPENDIX

Definitions

Term	Definition
Aquifer vulnerability	A sensitive karst feature where materials may directly enter into the subsurface in karstic landscapes and move into aquifer waters. Areas of high aquifer vulnerability include sinkholes, caves, cracks, fractures, faults, holes, and well openings.
Best management practices (BMPs)	A set of actions designed to minimize negative impacts on public health and the environment.
Cave	A natural void in the subsurface large enough for a person to enter. Generally found in soluble rock but may also occur in soils.
Conduit	A natural 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.
Edwards Aquifer Authority (EAA)	A groundwater district in the state of Texas that was created by the 1993 EAA Act. Its jurisdictional region includes all of Bexar, Medina, and Uvalde counties and portions of Atascosa, Caldwell, Comal, Guadalupe, and Hays counties. The EAA is mandated to manage, conserve, preserve, and protect the Balcones Fault Zone Edwards Aquifer.
Emerging contaminant	A substance that has a perceived, potential, or demonstrated threat to human health or the environment, or is considered a threat but for which there are not current health standards.
Transport and fate	What happens to a material that enters the subsurface, how it may or may not chemically change or be diluted, and where it travels or is deposited in the aquifer.
Firefighting product	Any liquid or solid material used or produced during firefighting operations.
Geographic information system (GIS)	A framework for gathering, managing, analyzing, and presenting data.
Hazardous material (HAZMAT)	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.
Karst/karstic feature	A cave, sinkhole, sinking stream, spring, or solutionally enlarged fracture, fault, or bedding plane parting that allows surface water or spilled liquids and contaminants in runoff to enter the subsurface.
Legacy contaminant	A contaminant composed partially or solely of a substance once used in the United States that has been banned or is no longer in use, but which may still be present in the ground and water.
Light non-aqueous phase liquid	A groundwater contaminant that is not soluble in water and has a lower density than water, meaning it will float on the top of groundwater. Examples are gasoline and other hydrocarbons, including oil.
Maximum contaminant level (MCL)	Highest concentration of a contaminant that is allowed in a public drinking water system supply.
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 that serves at least 25 individuals for at least 60 days out of a year.
Monitoring point for dye or contaminant sampling	Water wells, springs, and other direct openings to the aquifer where water can readily be sampled for the presence of dye or contaminants.
Recharge zone of the Edwards Aquifer	The area where water enters through the surface into the aquifer.
Risk communication	Information, advice, recommendations, and orders issued by officials or experts to people potentially affected by hazards or threats to life, health, or property. Use of the term focuses on forms of risk, risk thresholds, and risk assessments.

Term	Definition
Sensitive karst feature	An area of high vulnerability to the aquifer where materials may directly enter into the subsurface in karstic landscapes and move into aquifer waters. These features include sinkholes, caves, cracks, fractures, faults, holes, and well openings.
Sinkhole	A natural depression or opening in rock or soil with internal drainage. In south-central Texas, sinkholes may be less than a foot in diameter and depth, 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 safe waste management in Texas.