9-30-2023

Best Management Practices and Standards, Training, and Tools to Increase Resilience of the Edwards Aquifer Water Supply During Emergency Fire Control

Institute for Water Resources Science and Technology

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BEST MANAGEMENT PRACTICES AND STANDARDS, TRAINING, AND TOOLS TO INCREASE RESILIENCE OF THE EDWARDS AQUIFER WATER SUPPLY DURING EMERGENCY FIRE CONTROL

Report Prepared for:
The City of San Antonio

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September 30, 2023

In 2019 the Institute for Water Resources Science and Technology at Texas A&M University-San Antonio began work funded by the Proposition 1 Edwards Aquifer Protection Venue Project to develop Best Management Practices (BMPs) for protecting Edwards Aquifer water supplies from inadvertent contamination by HAZMAT in water runoff during emergency response-related firefighting. Results of this work are now available for your use. Technical information is available for use in developing and updating emergency response planning documents (i.e., City of San Antonio Hazard Mitigation Action Plan and the Bexar County Emergency Management Plan), educational curricula can be used for training and public outreach, and BMPs along with associated tools are now available for on-site and post-event management and hazard mitigation. These have been developed for use in Bexar County and other areas where the aquifer is susceptible to contamination from disaster response on the land's surface. The following provides brief background. Attachments and linked materials provide detailed information.

Project Sponsors: The funding agency for this work is the City of San Antonio and the source of funding is the voter-approved Proposition 1 Edwards Aquifer Protection Venue Project. Additional support was provided by the Edwards Aquifer Authority.

Project Cooperators: Edwards Aquifer Authority; Institute for Water Resources Science and Technology, Texas A&M University-San Antonio; Texas A&M Engineering Extension Service, Fire and Emergency Services Training Institute; San Antonio Fire Department, and; Texas Parks and Wildlife Department.

Documentation:
BMPs for use in first responder training curricula and instruction, and for use in developing plans, standards, and specialized techniques and tools for use by first responders before, during, and after emergency response.

> Part 1 attached document: BMPs to prevent pollutants from entering the aquifer during emergency response. "Best Management Practices for Firefighting in the Karstic Edwards (Balcones Fault Zone) Aquifer of South-Central Texas." Authored by Geary Schindel and Rudolph Rosen. Published in 2021 by the Texas Water Journal.
>
> Part 2 attached document: BMPs to aid disaster responders where HAZMAT is suspected to have entered the aquifer during emergency response. "Best Management Practices and Standards, Training, and Tools to Increase Resilience of The Edwards Aquifer Water Supply During Emergency Fire Control." Report to the City of San Antonio. Published in 2023 by Texas A&M University-San Antonio.

Education and training manual: "Run-Off Control for Karst Environments, Participant Manual" FPHAZ220 TRv. 3.2.21. Available from the Emergency Services Training Institute, Texas A&M Engineering Extension Service, College Station, TX.

Emergency Responders Guide to Protecting the Edwards Aquifer.
https://digitalcommons.tamusa.edu/water_videos/1/

BEST MANAGEMENT PRACTICES AND STANDARDS, TRAINING, AND TOOLS TO INCREASE RESILIENCE OF THE EDWARDS AQUIFER WATER SUPPLY DURING EMERGENCY FIRE CONTROL

August 31, 2023

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II. Introduction and Background

As much as 20% of the land surface in the U.S. is karst and 40% of the groundwater for municipal and domestic consumption comes from karst aquifers. The U.S. Environmental Protection Agency (USEPA) has recognized karst aquifers as the groundwater type most vulnerable to contamination from hazardous material (HAZMAT) and other pollutants (Schindel et al, 1996; USEPA 2002). Karst is defined by Ford and Williams (1989) as a "[t]errain with distinctive hydrology and landforms arising from a combination of high rock solubility and well-developed secondary and tertiary porosity." Karst is characterized by the presence of sinkholes, swallets (sinking streams), springs, and caves.

Our interest in these complex and poorly understood water supply aquifers is to develop science-based Best Management Practices (BMPs) and tools for before, during, and after response to an emergency that may involve HAZMAT. These BMPs and tools are intended to help first responders, health and safety officials, and community leaders increase the resilience of karstic groundwater supplies to the direct and indirect impacts of natural and human-caused disasters. In some cases the BMPs involve developing and assembling underlying information, such as data on surface and groundwater flows, through research that will inform tools (e.g., models) that responders can use during or after emergency events. The focus of this work is on control or mitigation of HAZMAT-contaminated runoff during emergency firefighting. The karstic Edwards Aquifer in Central Texas is the focus of our work (Figure 1). It is one of the most prolific and important karst aquifers in the United States. This aquifer is the primary water source for more than two million people in the City of San Antonio and neighboring urban, industrial, military, and agricultural areas.

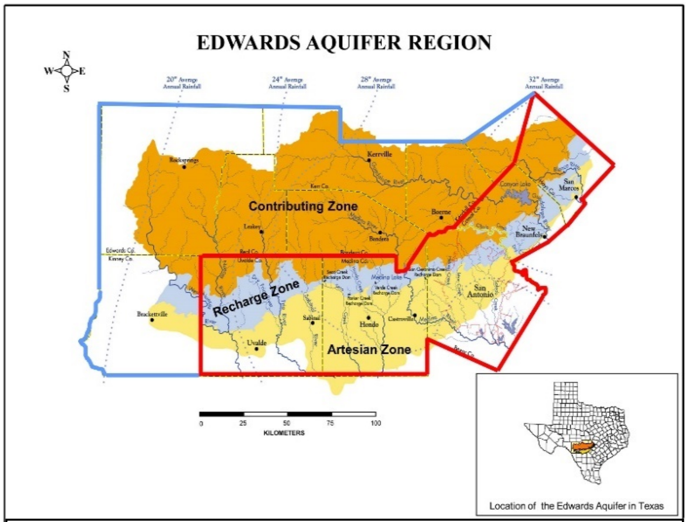

Figure 1. The Edwards Aquifer region showing locations of the contributing, recharge, and artesian zones.

A. Karst Water Supply Aquifers Have Low Resilience to Impact from Natural and Human-Caused Disaster

Karst aquifers are unique because of their direct openings to the land's surface that allow contaminants in runoff or other surface waters to rapidly enter the subsurface and impact aquifer water quality. Water and contaminants can rapidly enter the aquifer through caves, sinkholes, fractures, faults, and sinking streams (swallets). Openings occur and enlarge over time because karst watersheds are underlain by limestone or other highly soluble rock types that are partially dissolved over geologic time by chemical reactions with slightly acidic rainwater (Rosen 2014; Schindel 2019). These openings are often called "sensitive karst features" that may be readily visible or hidden beneath soils and vegetative debris. The dissolution process creates extensive interconnected openings in the rock with high levels of permeability. After entering the subsurface, water can flow quickly through the underground openings with velocities as high as hundreds of feet to miles per day. Runoff associated with HAZMAT spills, sanitary sewer line breaks and flooding, and fire control during disasters can rapidly enter the subsurface carrying contaminants through these karst openings. This becomes a high risk and threat to aquifer water quality where flood, high winds, lightning, wildfire, or other natural or human-caused disasters impact locations storing or supporting transport of HAZMAT, such as warehouses, gas stations, dry cleaners, home improvement and garden centers, highways, railways, and rail yards.

Of equivalent threat to aquifer resilience from disaster is the indirect, unintended consequence of fire-control runoff carrying HAZMAT. Rapid groundwater flow through karst aquifers can quickly carry HAZMAT and firefighting products to water wells and springs. In addition, some HAZMAT can volatilize and form explosive or hazardous vapors that can migrate to the surface and into structures, because karst openings can provide passageways for water or vapors to migrate significant distances. Contaminants can quickly degrade public and private wells used for municipal, industrial, and agricultural water supplies, and may even impact surface waters (Johnson et al. 2010; Mahler 2000; Schindel 2017, 2018; White 2018). It is difficult to determine groundwater flow pathways and velocity of contaminates, or to fully remove them once in the aquifer.

This is a critical matter for people dependent on karst aquifer water supplies in San Antonio as well as in other karst regions. San Antonio is the seventh largest city in the U.S. and serves 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 U.S. (Laredo) and the rest of the country. Consequently, significant quantities of HAZMAT is stored in or transported by highway and railway through the city, Bexar County, and region due to the nature of local industries and the volume of goods passing through.

III. Leveraging Previous Work and Current Efforts

In 2007, the Texas Legislature directed the Edwards Aquifer Authority (EAA) to work to protect the water quality of the karstic Edwards Aquifer from the impact of disaster-related fire control in the aquifer's recharge zone (S.B. 1477). The legislature was responding to concern over potentially catastrophic aquifer pollution events in the recharge zone during disaster-related fire control where HAZMAT may be present in firefighting runoff. Concern extends to fire-control response to wildfire, windstorm, flash flooding, lightning, and hurricane, as well as other events of a catastrophic nature both natural and human-caused. 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 (Hamilton 2011; Wright 2007).

A. Previous Work to Address the Resilience of Karst Aquifer Drinking Water Supplies from Disasters and Related Firefighting Runoff

Work on developing community-level response and mitigation plans to increase resilience of drinking water supplies to potential impact from HAZMAT in runoff from firefighting or other emergency events has been underway since the Texas Legislature directed such action in 2007 (S.B. 1477). Recent work has developed a set of best management practices (BMPs) for use in first responder training curricula and instruction, and for use in developing plans, standards, and specialized techniques and tools for first responders designed to help prevent pollutants from entering the aquifer during emergency response fire control (Schindel and Rosen 2021; Schindel et al. 2023). Training curricula and associated materials have been developed and are now ready for use (ESTI 2021; Rosen and Gary 2020; Rosen and Maxwell 2020). Tools include a georeferenced database and user interface that provides data displaying reported contents and storage locations of HAZMAT, many openings to the karst aquifer (sensitive areas), direction of water flow across the landscape, and embedded recommendations for protective action in areas of high risk to disaster. Work was initiated by a partnership formed between the EAA and Texas A&M University-San Antonio (TAMUSA) that resulted in a grant request to the City of San Antonio through the voter-approved Proposition 1 Edwards Aquifer Protection Venue Project focused on firefighting and associated HAZMAT training and response to protect the karst aquifer in urbanized areas of Bexar County. This work was funded and a partnership effort was initiated that involved TAMUSA, EAA, San Antonio Fire Department (SAFD), Texas A&M Engineering Extension Service's Fire and Emergency Services Training Institute (ESTI), and Texas Parks and Wildlife Department. Development of training curricula, BMPs, and standards generally followed the format used by the National Fire Protection Association (NFPA) in its planning and training manuals, e.g., Hazardous Materials Standards for Responders (NFPA 470). Curricula were developed by ESTI in their standard format used across 25 major training programs and 130 specialty areas to train about 220,000 emergency responders from all 50 states and 65 countries each year.

This past work increases resilience to disaster of karst aquifer water supplies by providing BMPs, standards, tools, and other solutions to reduce the amount of or prevent HAZMAT from entering the aquifer and harming drinking water supplies during fire control.

B. New Work Provides BMPs, Mitigation Standards, and Tools for use when HAZMAT is Suspected to have Entered the Aquifer

New work described herein will leverage the past work described above by developing new or revising existing BMPs, standards, training curricula, and tools to aid disaster responders in addressing instances where first responders and public safety officials suspect that HAZMAT may have entered the aquifer at a disaster site during fire control. New work will include information on developing, staging, and deploying tools first responders and public health and safety officials can use to predict and mitigate the consequences of specific suspected contaminants that may enter the aquifer. Such predictions can be used to inform mitigation decisions, understand the consequences of contamination, and issue timely data-based communications to the community. This new work maintains the original focus of the partners and the Proposition 1 funding agreement on firefighting and Bexar County, although the BMPs and materials that have been developed by the work are generally applicable in other karst landscapes and for karst aquifers elsewhere.

IV. Vision of Resilience

Rapid population growth, presence of HAZMAT in storage and transit in San Antonio, weather instability, suburban expansion 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 karst drinking water supply to contamination from the unintended consequences of disaster and disaster-related emergency firefighting.

A. How We Define Resilience

For our work in karst aquifers, we define resilience as the "prevention, reduction, and mitigation of disaster and disaster-related fire-control impacts to drinking water supply, public health, environmental quality, and the economy."

B. How We Improve Resilience to Disaster

While natural disasters will continue to occur over time, we can increase the resilience of vulnerable water supplies to disaster and related events through application of science-based solutions. Resilience will increase through improved mitigation capacity and new options for emergency response by applying an added level of science-based planning, standards, tools, and BMPs for training, curricula, and disaster response that focus on modeling and on-site, real-time evaluation of the transport and fate of HAZMAT on the surface and in the aquifer. Information on fate and transport is essential to have when responding to disasters to enable rapid remedial action and for issuing science-driven and real-time data-based public safety communications about municipal and domestic water supplies.

V. Three Categories of Planning and Response

Best Management Practices 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 as standards are used often in local, state, and federal planning, training, and regulatory materials. As standards in emergency services training, BMPs are commonly described as "product control measures" in fire and HAZMAT emergency training manuals, standards, and curricula (NFPA 470). We use the term "Best Management Practices" for firefighting to also cover the term "product control measures."

The BMPs we describe fall into three main categories which are commonly used in emergency response training and planning materials: (1) pre-event, (2) during event response, and (3) post-event.

Previous work has established BMPs focused on preventing or limiting firefighting runoff that may be carrying HAZMAT from entering sensitive sites in the recharge zone of karst aquifers (ESTI 2021; Rosen and Gary 2020; Rosen and Maxwell 2020; Schindel and Rosen 2021; Schindel et al. 2023). The BMPs were developed for use by firefighters and HAZMAT first responders, although the 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 HAZMAT in karst watersheds during and after disaster and fire response.

Our BMPs and supporting materials describe techniques, training, and tools that responders can use to address the unique nature of response to disaster-related emergencies involving HAZMAT in karst systems and aquifers. We do not intend for these BMPs to direct firefighters how to do their job, how to organize themselves, how to conduct planning, or how to coordinate among themselves in emergency event pre-planning, during events, or after events. Nor do we direct or imply to direct other emergency responders, officials, and other responsible parties in agencies, governments, companies or other concerns involved in emergency response. We make no specific recommendations on how to assemble available 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. Emergency responders and responsible agency leaders are encouraged to use the information we provide in whatever fashion they are organized and however they normally plan for, coordinate among themselves, share resources, and respond to emergency events. 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. It is also beyond our original focus on firefighting and associated HAZMAT responders to extend BMPs, tools, and curricula to a wider range of first responders or uses. That is beyond the requirements of our funding agreement, and it is beyond our expertise. Such expansion is well worth pursuing, but it's not within the scope of our past and currently funded work.

A. Planning for and Deployment of New BMPs will Require Specialized Support

Previously described BMPs for use during response in karst terrains and aquifers were focused on actions firefighters and other first responders can use when planning, during, and immediately after events (ESTI 2021; Rosen and Gary 2020; Rosen and Maxwell 2020; Schindel and Rosen 2021). Proposed new BMPs, standards, and tools will primarily focus on on-site, real-time evaluation of the transport and fate of HAZMAT in the aquifer. This will involve technical expertise and tools that firefighters and other first responders do not usually have readily available. The new BMPs will focus on non-toxic dye tracing, water quality sampling, surface and groundwater flow modeling, and related studies to support development of new tools and evidence-based screening of at risk sites that facilitate better placement and deployment of BMPs. In some cases BMPs may not be formed as a typical BMP. They may appear more as activities that often occur in the background, such as research. However, there is very little work going on in the background that can provide the data needed to inform the BMPs or underpin the tools that will be of value in the event of a catastrophic spill that affects the Edwards Aquifer. Data on flow and transport of HAZMAT modeled for other kinds of subsurface substrate and other types of aquifers is not readily transferable to karst. Even information developed in a different karst aquifer or in different location in the same aquifer may not be transferrable to another location or aquifer, because flow through karst aquifers is so complex and variable. As a result, we include BMPs, recommended actions, and supporting and cautionary notes on developing and assembling information, such as data on surface and groundwater flows for the Edwards Aquifer, through research that will inform tools (e.g., models) that responders can use during or after emergency events in Bexar County. To help facilitate this, our proposed BMPs also recommend establishing ready access to technical experts and researchers to help support response efforts and gather essential data before, during, and immediately after a HAZMAT spill for use in implementing and improving BMPs. We emphasize anticipating, planning, and preparing for potential events, and supporting actions in response to events by first responders and also by health and safety officials after most—or all—firefighters and first responders have departed from the immediate site of the disaster.

All of this work will be underpinned by existing and new scientific information for karst terrains. Planning for use, developing, and employing many of these BMPs will require support from specialists. Expertise and support to conduct such work is available locally through private firms, not-for-profit research institutes, universities, and government agencies.

VI. BMPs

A. Goal

The goal is to increase the resilience of karst drinking water supplies to natural disaster-related emergency and fire-control activities. Resilience can be increased through the application of science-based solutions presented in this report in the form of BMPs.

B. Summary Listing of BMPs

The following subsections of this report provide a summary listing of BMPs. After the summary listing, several of the BMPs are described in greater detail with expanded supporting information and notes on practical application. Table 1 condenses the listing for quick reference.

1. Pre-Event BMPs

- ➢ Develop location specific models for predicting surface-water flow and aquifer vulnerability at sites suspected as being at risk of contamination by HAZMAT during disaster response fire control or from direct impacts of natural disaster[1]. This should include surface drainage mapping, locations of

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[1] For San Antonio, the EAA has developed a georeferenced database and user interface for many areas of high risk of contamination by HAZMAT during disaster response fire control. This tool provides data displaying reported

containment features, and identification of unprotected drainage features in areas of greatest risk. It should also include an assessment to assist planners in the placement and deployment of 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 (USEPA Emerging Contaminants and Federal Facility Contaminants of Concern). For contaminants of most concern locally, conduct pathway-focused human health risk assessments and incorporate results into response protocols, such as for risk communications, as warranted (Randrianarivelo et al. 2017).
- Develop models to estimate flow characteristics and fate potential of specific HAZMAT that is most likely to enter the aquifer if runoff control measures fail or are not used during firefighting and other disaster responses. While materials in runoff will be incident specific, there are lists of chemicals associated with different industries, facility types, and specific facilities (USEPA Toxics Release Inventory (TRI) Program; USEPA Hazardous Chemical Inventory Reporting).
- Develop plans to preposition and use sensors to sample for contaminates and to track non-toxic dyes[2] during emergency events, with work to include developing 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 risk of contamination, designate potential sampling sites by best use: for sensor locations, for sampling groundwater for dye and contaminants, and for specialized sampling (e.g., air in some wells, caves and even buildings can be tested where highly volatile contaminants are involved in a spill, such as gasoline). For high risk sites, runoff control barriers or sampling/testing materials can be prepositioned[3].
- For sites suspected as being at high risk of contamination, develop site-specific predictive models to estimate transport and fate of site-specific or generalized HAZMAT should it enter the aquifer during firefighting. Use of dye tracing in development and verification of models is recommended for highest risk sites.
- Provide specialized curricula and training to appropriate personnel who can be deployed during emergency response to conduct non-toxic dye tracing, well sampling (i.e., monitoring points for dye/contaminant), and data analysis. Identify and train technical specialists who can be deployed to

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contents and storage locations of HAZMAT, many openings to the karst aquifer (sensitive areas), direction of water flow across the landscape, and embedded recommendations for protective action.

[2] Non-toxic dyes act as surrogates for contaminants when the dyes are injected into aquifer waters at or near a location where runoff carrying HAZMAT is thought to have entered 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 the presence of dye. 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 the presence of contaminants or dyes. Dyes used to track transport and fate of contaminates in karst aquifers are commonly called “tracers“ and the technique is commonly called “dye tracing.”

[3] Various materials can be used for on-site mitigation, including agents that can bond with and help mitigate existing HAZMAT. Spill kits can be assembled and made readily available to address small volume spills. These may not contain sufficient materials to address the potentially large volumes of runoff from extended firefighting. Large quantities of materials can be centrally stored. Storage and maintenance costs may be considered high (e.g., booms, drums of bonding agents, large volumes of absorptive materials, and materials for dyke construction). As an alternative to having local first responders maintain large stores of HAZMAT control materials, it may be possible to pre-plan arrangements with contractors to have such materials available as part of their response programs, including materials for response that may be specific to HAZMAT types stored or frequently transported locally.

support emergency responders by conducting sampling at monitoring points, performing laboratory analysis, monitoring sensor data streams, and assessing HAZMAT transport and fate.

- Conduct modeling of surface or groundwater flows where possible to develop a visualization and predictive tool that can be used on site locally during disaster response to help responders assess on-site safety needs and anticipate contaminant transport and fate to mitigate threats to aquifer water quality.
- Develop a clear communication protocol and contact list to be used in the event a release of HAZMAT is suspected during firefighting. This protocol/list should include all official authorities normally advised of HAZMAT emergencies in the aquifer, such as the Texas Commission on Environmental Quality and EAA, as well as all local authorities, governments, community organizations, and potential volunteer groups that either need to be informed or that can assist in response and community action if needed.
- Develop pre-event public communication plans with a focus on risk and risk communication (FEMA 2021; FEMA National Risk Index Best Practices), 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 protocol for HAZMAT control in karst areas and review of locations of HAZMAT storage, 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[4].
- At least every five 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. BMPs for During Event Response

- If and where possible at an event site identified having high aquifer vulnerability and high risk of contamination by HAZMAT, apply location specific information and models for predicting surface-water flow and aquifer vulnerability[5]. 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. Manage accordingly.

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[4] For example, existing spill prevention, control, and countermeasures planning work may have placed a secondary containment structure, such as a berm, around a tank containing HAZMAT located in the vicinity of openings to the aquifer. Containment structures may collect rain water, so there is often a pipe and valve to allow rain water to drain from the secondary containment. If the valve is left open, the structure won't contain the HAZMAT if spilled. Yet if the valve is permanently left closed, water trapped behind a berm can lead to poorly functioning piping and insect control issues. Periodic inspection of such control structures and resulting current information on its status made available to responders may become important during an emergency event.

[5] Pre-planning may provide location-specific information for the site of an emergency event. While large, easily-seen openings to the aquifer may be present at the site, it is more likely that openings to the subsurface will be small and not easily seen. Even experts often have a difficult time determining the extent of aquifer vulnerability by just looking at the land surface. While karst features are not uniformly distributed across a karst landscape, they are virtually always present to some degree. As a result, 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.

- If appropriate and possible within at least 24 hours of what has the potential to be a significant spill due to the high volume or risk level of contaminants involved, deploy non-toxic dyes to trace contaminant transport and fate. Dye tracing during disaster response can be used to collect real-time data, used in early screening tests to focus sampling for detection of contaminants, used to help verify predictive models and expert assumptions, and used to plan and direct appropriate responses to public health and environmental impacts. Incorporate information as appropriate. 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 fate and transport using a hydraulic-flow model, existing hydrologic studies, expert opinion, and onsite visualization and predictive tools. If relevant, use the results of dye tracing to inform the models or help verify assumptions and predictions from models.
- 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/retention basins, and other measures described in detail for application in Bexar County earlier (ESTI 2021; Rosen and Maxwell 2020; Rosen and Gary 2020; Schindel and Rosen 2021; Schindel et al. 2023). Avoid flushing event runoff that may contain contaminates into a ditch, ravine, dry stream bed, or flowing freshwater stream on the surface in an to attempt to dilute contaminates. Remove or remediate contaminated runoff that remains accessible on the surface as soon as possible.
- As soon as possible after a release of HAZMAT is suspected, report the nature of the release to appropriate authorities and follow the communication protocol established as a pre-event planning BMP. For releases that could affect the Edwards Aquifer in the San Antonio region, authorities include the Texas Commission on Environmental Quality, the EAA, and local emergency responders.
- Inform disaster responders, public health and safety officials, and water providers about the potential fate and transport 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 National Risk Index Best Practices)[6].

3. Post-Event BMPs

- Continue sampling aquifer water at appropriate well sites and openings to the aquifer as long as necessary to complete sampling for contaminants or monitoring of dye tracing points if implemented. Where relevant, continue sampling and analysis of surface-water runoff from the spill site and of surface waters charged by the aquifer. Depending upon local ambient conditions such as presence of vegetation and amounts of recent rainfalls, groundwater velocities may range from feet per day to miles per day. Therefore, it may be advisable to continue sampling at monitoring points for weeks or months.
- Take necessary remedial action as needed based on results from models, water sample collection and testing for contaminants, dye tracing if used, and expert opinion..
- Issue health advisories or other disaster-related communications as appropriate based on data and the communications protocol.

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

- Data from monitoring point sampling, dye tracing, and other information from an event should be used to refine information on fate and transport of HAZMAT in the aquifer. These data may be used by first responders and public health and safety officers, and 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 hydraulic containment, and non-aqueous phase liquids pump-out collection and contaminant removal.

C. Additional Considerations for BMPs to Improve Aquifer Resilience

1. BMPs Involving Surface-Water Flow and Aquifer Vulnerability Modeling

a. Pre-Event: At sites of high risk of aquifer contamination during emergency response, identify and plot locations of aquifer vulnerability and develop models of the surface-water flow regime in those locations (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. Model utility and effectiveness can be enhanced by placement of sensors that can inform the model on a real-time basis in locations of highest risk.

b. During Event Response: Use surface-water modeling during emergency response to (1) predict flow of runoff and make decisions about preventing entry of contaminants into the aquifer, and (2) identify potential entry points of contaminants for instances when preventive measures failed, were not used, or were deemed to be infeasible to implement.

c. Recommended Actions:

- Identify physical sites within the Edwards Aquifer contributing and recharge zones that present a high risk of contamination of the aquifer during firefighting and other emergency response. Examples are a warehouse or a large retail facility that stores HAZMAT. For example, home improvement stores that carry paints, cleaning supplies, and other chemicals, and home and garden centers located near karst features (Rosen and Maxwell 2020). Nitrate used in fertilizers stored in quantity at such locations can be difficult to remediate and can have acute and direct health impacts (Ward et al. 2018).
- Develop a comprehensive ArcGIS project or assemble data layers for application of other geographic information systems (GIS) techniques and applications. Acquire relevant data layers (including data that may be available from past and ongoing work). Principal components will include the following: (1) topography; (2) impervious cover; (3) stormwater containment structures and assigned characteristics; (4) adjoining surface 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 natural 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 can potentially impact the fate and transport of HAZMAT released in runoff.
- Conduct an in-depth assessment of the 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 surface-water 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 surface-water flow.

- Develop and make available a visualization tool using information collected in the course of this work.

d. Supporting and Cautionary Notes:

- Surface-water flow and aquifer vulnerability modeling is recommended to be conducted for specifically defined locations where it assumed that there is a high risk of potential contamination of the aquifer during disaster response, such as (1) locations of HAZMAT storage or transport in close proximity to sensitive karst features, and (2) locations generally at risk of wildfire, flood, flash flood, wind, or other natural disasters where fire control is a likely outcome during disaster response. For urbanized Bexar County much of the work related to this recommendation to locate and characterize locations of high vulnerability to the aquifer has already been conducted or is underway (Schindel and Rosen 2021). Previous work may provide comprehensive data for many locations of high vulnerability in urbanized Bexar County.

- Effective use of models, including any for surface- and groundwater flow or aquifer vulnerability, during an emergency will require that trained technical support and skilled operators be available on-call for immediate deployment. Due to the highly technical nature of deploying models in an emergency and high level of operator skill required, it is recognized that continual readiness training and maintaining availability of trained personnel will be a challenge. Surface-water runoff modeling is a unique skill set requiring expertise to calculate the volume of water created from rainfall, as well as from firefighting activities. This information can be used to estimate the volume of potentially contaminated water that may require treatment, and used to inform responders how much retention area may be needed to contain contaminated water runoff. This is information generally provided by a civil engineer who does flow calculation models for the design of culverts, storm water retention basins, and bridges. This would not ordinarily be a hydrogeologist who deals with groundwater flow, although a single person could have overlapping expertise and experience.

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

a. Pre-Event:

- Develop plans and criteria for deployment to use non-toxic dyes to track contaminant transport and fate in the aquifer, with deployment criteria based on estimated volume and level of risk to public health of the HAZMAT suspected to have entered the aquifer.

- Obtain, store in a readily accessible location, maintain, and prepare to utilize appropriate non-toxic fluorescent dyes during emergency events.

- Identify and provide emergency response training to personnel who can be deployed during emergency response and who have the expertise to conduct dye tracing and analysis. Identify personnel with specialized expertise who can be deployed during emergencies to assist emergency responders in coordination with and support of experts conducting dye tracing work (Quinlan and Ewers 1985; Alexander and Quinlan 1997).

- Develop an agenda of research using past and new dye tracing data as it becomes available to better describe flows through the aquifer and to provide data for use in conceptual modeling of contaminant transport and fate.

b. During Event Response: Where appropriate, conduct dye tracing work and sample predetermined monitoring points for dye and contaminants.

c. 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.

d. Recommended Actions:

- Dye tracing should be considered for use in the event of significant spills with the potential for catastrophic results due to the high volume or high risk to human health or the environment from the HAZMAT involved. Dye tracing is a highly effective means to collect data on significant HAZMAT spills where there may be potential consequences to public health. Dye tracing is not recommended for small scale or low risk spills.
- In the event of suspected release of contaminates into the aquifer, as soon as possible engage people with appropriate expertise to identify the point of HAZMAT entry, provide insight into the potential amount and concentration of HAZMAT released, ascertain likely transport rate and fate of suspected HAZMAT, and help responders make a judgement on use of dye tracing to collect essential data.
- Use dye tracing as the basis of research in the course of pre-event planning and in the development of science-based action plans that can be used on-site and real-time during disaster response to predict suspected HAZMAT fate and transport through the aquifer and into drinking water supply wells, monitoring wells, and springs.
- 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 laboratory for analyses.
- Non-toxic 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 (e.g., dye recovery sites such as water wells and springs) may be sampled to detect dyes. Dye concentration can be measured by using a synchronous scanning luminescence spectrometer.
- 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.
- 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.
- Data from tracing studies using non-toxic fluorescent dyes, including data from past dye tracing work, should be used to refine any conceptual and analytical predictive modeling of fate and transport of HAZMAT in the aquifer.

e. Recommended Actions Unique to Bexar County in the Transition Zone: Flow paths and transport in the Edwards Aquifer has not been definitively established for the contributing, recharge, or transition zones (Schindel et al. 2005). Accurate science-based information about transport and fate of contaminants in the transition zone is particularly important because that area in Bexar County has been highly urbanized and it is proximal to large water production wells in downtown San Antonio. The Transition Zone is a portion of the aquifer that does not contain outcrops of the Edwards Limestone, and where the aquifer is not fully saturated. Therefore, water may enter or exit the aquifer through fractures, faults, or water wells. Generally, upgradient locations of the Austin Chalk are areas of concern. HAZMAT contamination of the aquifer there could have large-scale consequences for public safety (Schindel et al. 2004). Particular attention needs to be focused on the outcrop area of the Austin Chalk near the north side of downtown San Antonio (e.g., Alamo Heights, San Pedro Park, the University of the Incarnate Word, and Robber Baron Cave as well as the area around the Culebra Salient in western Bexar County).

f. Supporting and Cautionary Notes:

- Dye tracing is a readily available and rapidly deployable tool to use to determine fate and transport of HAZMAT in karst aquifers in real time (Quinlan and Ewers 1985; Alexander and Quinlan 1997; Johnson et al. 2005; 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 karst substrates (Schindel et al. 1996).
- 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. However, dye tracing may be the best available option for use in research and to track 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.
- Previous dye tracing research has revealed that karst aquifers may exhibit a wide range of groundwater velocities and changing flow paths depending upon hydrologic conditions. This variability in flow through karst aquifers is extremely difficult or impossible to predict through numerical modeling (Quinlan and Ewers 1985; Schindel et al. 2001, 2004, 2005; Smith et al. 2005).
- 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.
- Non-toxic dyes used for tracing should be injected into a karst feature within about 500 yards of the suspected location of HAZMAT entry to the aquifer. Additional data may be obtained by injecting two different dyes at the site. One dye should be injected directly into the stream of runoff suspected to be carrying HAZMAT, while the other (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 5000 gallons of water should be used to saturate the surface and subsurface, then inject the dye 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.
- Predictive models of water flow rate and direction in karst aquifers used without some form of corroborating information are often of little use to decision makers where accurate assessments are

needed to protect public health and deliver accurate communications to potentially affected parties (Smith et al. 2005). Water flow and storage characteristics in karst aquifers change constantly. This is driven by aquifer water level changes and inflows throughout the contributing and recharge zones based on how much water enters the aquifer and the location of water entry. Rainfall runoff is highly variable throughout the aquifer's contributing and recharge zones. Water can enter the aquifer in large or small quantities virtually anywhere in these zones. The aquifer is a maze of large to small interconnected pathways. This variability leads to complexity that makes predictive modeling of transport and fate of contaminants an almost impossible task. However, some general trends are known. Over recent years considerable local knowledge of the aquifer has been accumulated as a result of various studies. Use of data from dye tracing can be used to improve the level of confidence in modeling results and help inform use of models on a real-time basis as more empirical data from tracing studies become available or is assembled. Expert opinion can substantiate model results where corroborating data are lacking.

- Extensive research on the physical properties of a karst aquifer is required to effectively assess the fate and transport of contaminants. Injecting tracers into the aquifer is the most reliable and effective method to directly determine flow direction, identify potential monitoring points, estimate time of travel during different hydrologic conditions, and estimate the potential concentration of contaminants at monitoring points of concern (Quinlan and Ewers 1985; Schindel et al. 1996).
- Karst hydrogeology experts should be consulted as soon as possible during the course of responding to an event where HAZMAT has been assumed to enter 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 actions may be among many considered by responders, but choosing which – if any – will be aided by expert on-site evaluation:
    - Is use of nontoxic dye the best way to proceed given the nature of the HAZMAT, suspected amounts of HAZMAT at issue, 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 dye remains detectable for the distance's 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, will well water become discolored, and if so, who should be made aware and what should they be told to do if that happens?

3. BMPs Involving Transport and Fate Potential of Specific Hazardous Materials

a. 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 on fate of contaminants likely to enter the aquifer from firefighting actions during disaster response if runoff control measures fail or are not used. If specific conditions at high-risk locations and related aquifer characteristics allow for accurate projections of fate to be developed through modeling, then predictive models of the potential fate of specific HAZMAT should be developed.

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

c. Post-Event: Use information on transport, fate, and testing obtained during or immediately after the event to inform short- and long-term response and mitigation actions; inform communication plans.

d. Recommended Actions:

- Assemble information on transport characteristics of selected legacy contaminants in the aquifer by review of available literature or by studies that describe characteristics of flow through conduit-dominated karst 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 recommendations on transport and fate potential of HAZMAT pertains to contaminants known to be present in locations of high aquifer vulnerability. Descriptions and examples follow:
    - Industrial solvents, generally Volatile Organic Compounds (VOCs), have a very 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 an 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 (LNAPL) which has a lower density than water and will float on the top of groundwater, or as a Dense Non-Aqueous Phase Liquid (DNAPL) which has a higher density than water and will sink in groundwater. These compounds can collect in the aquifer by sorption or by 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 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 fate and transport, 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 a hundreds of thousands of gallons—and can continue for days. Unlike releases on tightly packed sand, organic, and gravel soils and other substrates where pathogens may be filtered or subject to some bacterial decomposition, the high permeability of karst substrate allows material to flow unfiltered and untreated. Large volumes of contaminants, coupled with rapid groundwater velocities, can result in rapid impacts to private and public water supplies. Mass release of pathogens into a water supply during disaster response could lead to exceeding MCLs, and acute and rapid public health concerns (Mahler 2000; Schindel 2018; White 2018). Chlorination systems for public water supplies may be insufficient to neutralize sanitary waste loads from a large release.
- As groundwater modeling capabilities improve for karst aquifers, it may become possible to develop reliable models for contaminant fate and transport in karst for some locations in the aquifer with

varying degrees of reliability. However, this will require collecting large amounts of data and testing (Quinlan and Ewers 1985; Schindel et al. 2003, 2004, 2005, 2023; Smith et al. 2005).

e. Supporting and Cautionary Notes:

- Cores removed from karst substrates for testing transport and fate of contaminates can be highly variable from one location to the next, often making them of little use and providing misleading data. Unlike cores used for testing flows from sand or gravel aquifers which have relatively uniform porosity and flow characteristics, cores from karst are drawn from a substrate composed of very large to very small openings oriented in all directions and dispersed across large to small distances. Karst aquifer cores are generally not suitable to establish aquifer porosity and permeability for application on a local or regional basis. Permeability of karst aquifers 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, and analysis of results difficult and subject to high variability. Due to the highly variable porosity and flow characteristics of karst aquifers, flow and transport models can yield a wide range of estimates with large errors (Smith et al. 2005). This variability can make reliance on the results counterproductive to good decision making. There is no current technology that can map the interior spaces of a karst aquifer remotely to provide flow and transport models with sufficient information to yield highly reliable results.

VII. Outcomes

- Use of BMPs will provide for science-based due diligence to protect the quality of water in the Edwards Aquifer.
- The resilience of karst water supplies to withstand disaster will be increased through the development and use of surface water and aquifer flow and vulnerability models, on-site visualization tools, HAZMAT fate and transport simulations, dye tracing, and aquifer water sampling during events.
- First responders, public health and safety officials, and community leaders in the San Antonio region will gain access to new information, tools, and curricula that can be used for updating emergency response planning and training standards for (1) pre-disaster event planning, (2) use during events, and (3) post-event actions and mitigation planning. Project research and new information for applied use, curricula, and tools will be applicable for increasing resilience of the Edwards Aquifer.
- First responders, public health and safety officials, and community leaders will gain an increased understanding of the threat to drinking water supplies that can result from firefighting near karst openings to the aquifer.
- First responders, public health and safety officials, and community leaders will learn standards, BMPs, and how to use tools to increase the resilience of karst aquifer drinking water supplies during response to disasters.
- First responders, public health and safety officials, and community leaders will have use or access to new science-based standards for training and response, tools (e.g., surface-water flow model), technologies (e.g., dye tracing for significant events), and information for communicating to the public that will help to prevent, limit, and mitigate contamination of karst aquifer drinking water supplies in the course of emergency fire control.
- First responders, public health and safety officials, and community leaders will have use or access to new and timely information that will improve science-based communication to the public about events that could affect water quality in the aquifer.

VIII. Future Steps

A. Extend Training and BMPs

Review by the EAA of the report included a valid observation that it would have been beneficial to extend training to a wider range of first responders. The original objective of the EAA and TAMUSA when proposing the project was directed to training firefighters. Our funding agreement through Prop 1 named urbanized Bexar County as the location of work. This focused our tasks, but it's now obvious that this also limited our coverage. We did not address best practices for the full range of responders, health and safety officials, and community leaders, organizations, and members of the community that play a role or have interest in HAZMAT emergency response and protection of aquifer water quality. While much of our work and many BMPs are applicable generally to emergency response efforts in karst, we neither developed training, tools, or BMP's specific to others involved in emergency response and aquifer protection, nor did we have the expertise to do so. The EAA's recommendation during review of our report is well considered. We recommend that extension of this work to a wider range of responders be considered in further efforts by the City and County to enhance aquifer protection activities.

B. BMPs Provide Response to Increasing Threat of Wildfire

The recharge zone is the aquifer's zone of greatest vulnerability to HAZMAT contamination. That zone also coincides in some locations with the "wildlands urban interface" (WUI), which is the site of highest risk of wildfire in Texas according to Texas A&M Forest Service (Figure 2).

The SAFD describes the northern reaches of San Antonio as among the most at risk 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. The SAFD chief equated fuel loads and topography in the WUI to the wildfire threat faced by many communities in California (Gibbons 2018). The proximity of the WUI to sensitive features exacerbates the threat to the aquifer during fire response to wildfire. Rapid population growth into the WUI and an increasing frequency of elevated fire weather conditions in Texas represent major concerns moving forward (Texas A&M Forest Service 2023). The results of our work are directly applicable to emergency response to wildfire. Training and implementation of BMPs should extend to wildlands firefighters and HAZMAT teams that respond to fires in areas of the WUI that overlap or drain into aquifer sensitive areas.

C. Implementing BMPs Demonstrates a High Level of Due Diligence to Protect the Edwards Aquifer

The Edwards Aquifer was the first aquifer in the nation to be designated by the Environmental Protection Agency in 1975 under Section 1424(e) of the Safe Drinking Water Act of 1974, as a sole source aquifer. This 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. Since that time, the San Antonio Water System has done a highly commendable job diversifying local water supplies, but the Edwards Aquifer still supplies about 60% of the total supply (San Antonio Water System 2023). Protecting the quality and use of this water is critical to the well-being of citizens, the local economy, industries, and the environment.

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 U.S. (Laredo) and the rest of the country. Significant quantities and many different kinds of hazardous materials are stored in or transported through the city and region. Hazardous materials releases at some level are inevitable given the scale of development and nature of activities over the Edwards aquifer's contributing and recharge zones.

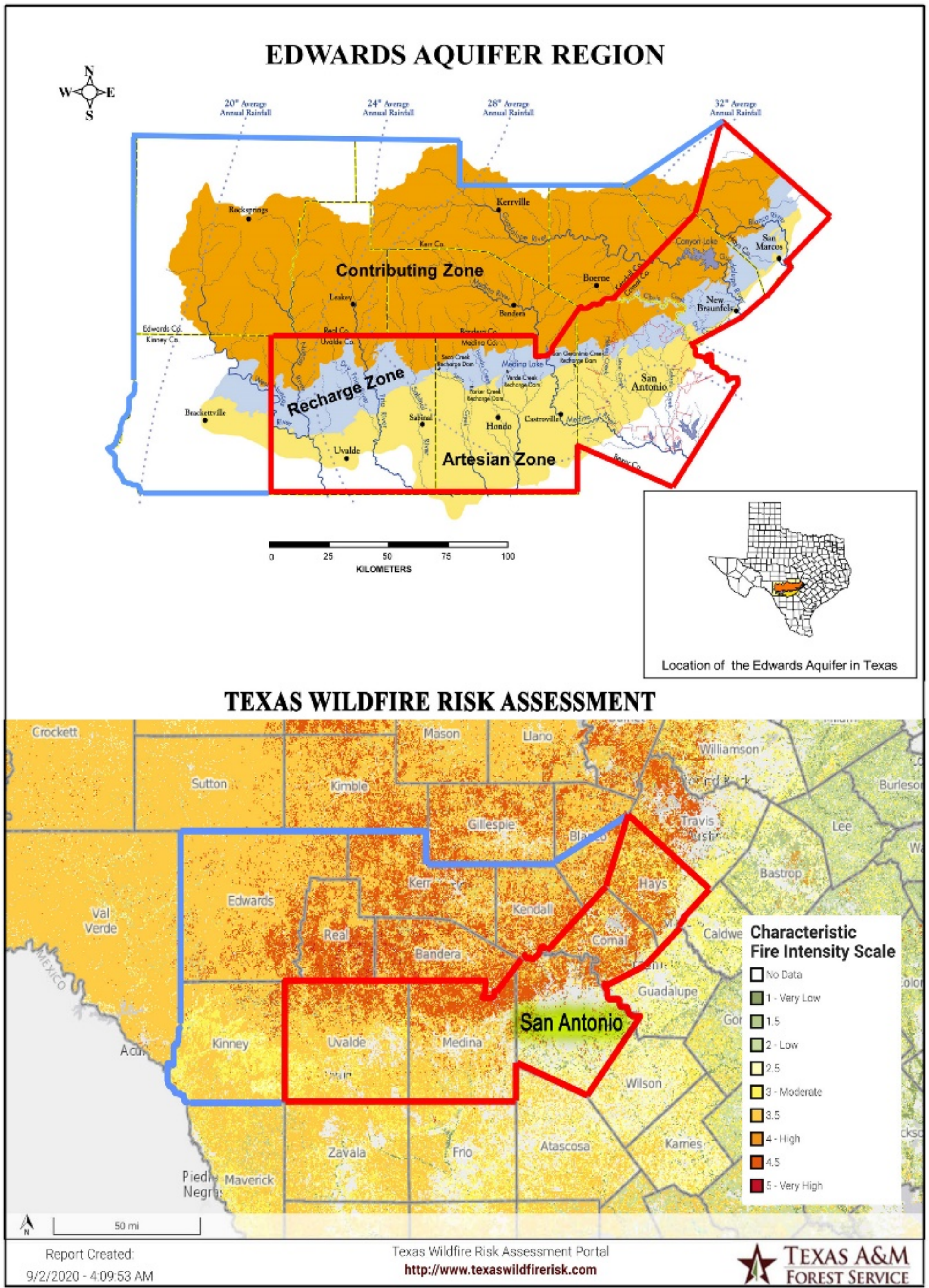

Figure 2. Above: The Edwards aquifer region showing locations of the contributing, recharge, and artesian zones (credit: Edwards Aquifer Authority (Schindel and Rosen 2021). Below: The vulnerable recharge zone coincides with the line of greatest threat of wildfire along the wildland-urban interface running between San Antonio and Austin (credit: Texas A&M Forest Service. Texas Wildfire Risk Assessment Portal, http://www.texaswildfirerisk.com).

It is critical that first responders be supplied with training and tools that will help protect the aquifer, and—even more important—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 involve future spending to assemble existing and acquire new data for optimal application of BMPs, but the spending to prepare for potential catastrophe will be far less than the costs to recover from a catastrophic HAZMAT event in the aquifer.

Spending and effort on preparation and acquisition of data for BMPs 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 entry of HAZMAT to the aquifer—and using BMPs to mitigate impacts if it does—demonstrates a high level of due diligence by the City and County to protect essential water supplies.

IX. Conclusions

Work recommended in this report will place focus on developing measures to be taken and data to be collected that will help increase the resilience of the Edwards Aquifer to fire-control runoff during disaster response. These measures include (1) new predictive models, (2) new basic data on fate of specific contaminants that present a high risk to public safety and are likely to be flushed into the aquifer during a disaster or disaster response, (3) new planning opportunities, (4) new simulations of HAZMAT transport and fate in a karst aquifer, (5) measured use of dye tracing, and (6) new data on which to base timely public communications.

The new BMPs and tools, combined with BMPs recommended previously (Schindel & Rosen, 2021), provide a comprehensive 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 in the event HAZMAT is believed to have reached the aquifer and is headed to public water wells, and; (3) help public health officials mitigate risks based on science and data. to plan for and direct efforts to protect karst aquifer water quality from HAZMAT inadvertently carried in fire control runoff.

X. Acknowledgements

This work was funded by the City of San Antonio through the voter-approved Proposition 1 Edwards Aquifer Protection Venue Project. The project is a partnership effort involving Texas A&M University-San Antonio, Edwards Aquifer Authority, San Antonio Fire Department, Texas A&M Engineering Extension Service's Fire and Emergency Services Training Institute, and Texas Parks and Wildlife Department. This report was authored and edited by Rudolph Rosen (retired Director and Visiting Professor, Institute for Water Resources Science and Technology, Texas A&M University-San Antonio), with contributions and technical reviews by Geary Schindel (Karst Works, Inc, San Antonio) and Ronald Green, and with additional review (2021 and 2023) by Walter Den, George Veni, Mark Black, Edwards Aquifer Authority (various reviewers), San Antonio River Authority (various reviewers), Albert Ogden, Ben Schwartz, Dorothy Vesper, Eiginio Rodriguez, Jason Polk, Mohsen Aghashahi, Shray Saxena, and William Vandertulip.

XI. Tables

Table 1. BMP listing for quick reference.
Pre-Event BMPs
Develop location specific models for predicting surface-water flow and aquifer vulnerability.
Determine the short- and long-term risk potential in the aquifer for contaminants.
Develop models to estimate flow characteristics and fate potential of high risk HAZMAT.
Develop plans to preposition and use sensors and non-toxic dyes.
At sites of high risk of contamination develop site-specific predictive models of HAZMAT transport and fate.
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 five years.
BMPs for During Event Response for Deployment where Possible and when Appropriate
Employ location specific information and models for predicting surface-water flow and aquifer vulnerability.
Deploy non-toxic dyes.
Estimate contaminant fate and transport.
Employ on-site surface mitigation techniques and tools.
Report the nature of HAZMAT release to appropriate authorities.
Inform disaster responders, public health and safety officials, and water providers about the potential fate and transport Hazmat released.
Post-Event BMPs
Continue sampling aquifer water 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 fate and transport of HAZMAT.
Develop an action plan for employing active remediation techniques at high-risk and at-risk sites in the aftermath of a HAZMAT runoff event.

XII. Acronyms

Acronym	Descriptive name
BMP	best management practice
DNAPL	dense non-aqueous phase liquid
EAA	Edwards Aquifer Authority
ESTI	Emergency Services Training Institute
FEMA	United States Department of Homeland Security Federal Emergency Management
FFPs	firefighting products
GIS	geographic information system
HAZMAT	hazardous material
LNAPL	light non-aqueous phase liquid
MCL	maximum contaminant level allowed in drinking water
NFPA	National Fire Protection Association
PFAS	per- and polyfluoroalkyl substances
RM	released material
RQ	reportable quantity
SAFD	San Antonio Fire Department
USEPA	United States Environmental Protection Agency
VOC	volatile organic compound
WUI	wildlands urban interface

XIII. Definition of Terms

The following section is drawn from and adapted from Schindel and Rosen (2021).

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 natural void in the subsurface rock large enough for a person to enter.
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.
Drainage way	A rill, runnel, rivulet, gully, ditch, creek, brook, stream, river or any other surface 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 region 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.
Emerging contaminant	A substance having a perceived, potential, or demonstrated threat to human health or the environment, or is considered a threat but for which there is a lack of current health standards.
Fate and transport	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	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.
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 to enter the subsurface.
Legacy contaminant	A contaminant composed partially or solely of a substance once used in the U.S. 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 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 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.
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.
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.
Sensitive karst feature	An area of high vulnerability to the aquifer where materials may directly enter into the subsurface in karst landscapes and move into aquifer waters. These features include sinkholes, caves, cracks, fractures, faults, holes, and wells 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 the safe management of waste in Texas.
Transition zone of the Edwards Aquifer	The area between the recharge zone and the artesian zone where the water table does not rise above the elevation of the Edwards Limestone.

XIV. References

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Funding is provided by the City of San Antonio under Proposition 1 Edwards Aquifer Protection Projects within Urbanized Areas of Bexar County’s Recharge and Contributing Zones Program.

Funded project title: Edwards Aquifer Water Quality Protection from Catastrophic and Low- to Mid-Level Effects of Discharged of Hazardous and Polluting Materials from Contaminated Water Runoff during Emergency Response.