Benzene Contamination of Drinking Water Systems following Wildfires: Remediation research and decision support

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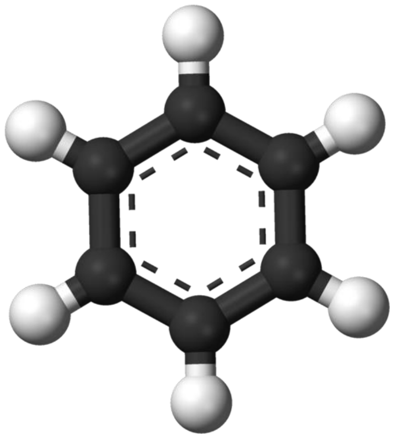
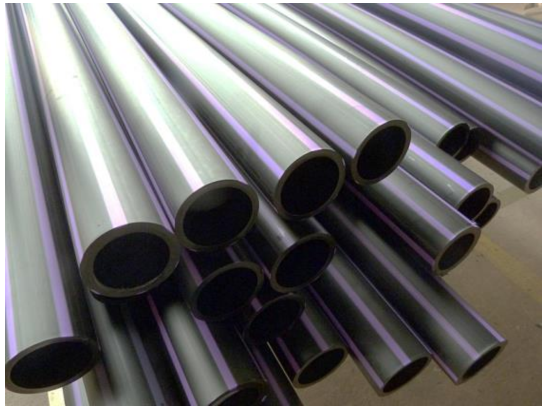
Background

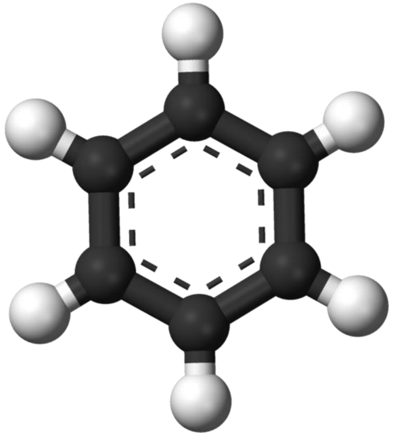
- Benzene is a known human carcinogen.
- Benzene contamination in the wake of wildfires exceeded state and national regulatory limits.
- Some Examples in California:
    - Santa Rosa (2017-2018)
    - Paradise (2018-2019)
    - Riverside Grove (2020)
- Source of Benzene:
    - Benzene can be a combustion product from burning structures.
    - Benzene can be formed in and leach out of pipes heated to high temperatures (Isaacson et al. 2021).
- **Subject of research**: Interactions between benzene and surviving pipes.



Benzene and Polyethylene Pipes

- Polyethylene is permeable to benzene.
  - Benzene can travel all the way through a polyethylene pipe wall.
  - Polyethylene can act as a reservoir for benzene.
- Benzene movement through polymers is slow compared to timescale of some decon processes.
  - Benzene in pipe walls is resistant to decontamination by flushing.
  - Sampling water in a recently flushed pipe may result in a non-detect even if the pipe is contaminated.
- How can we quantify this behavior?



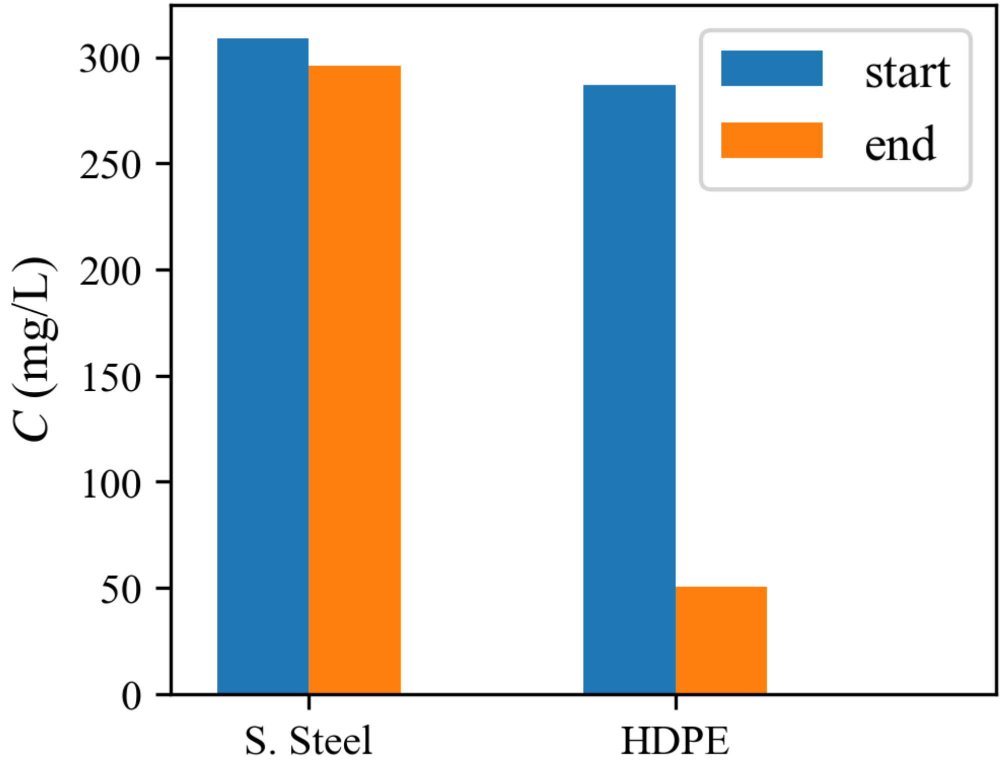


Pipe Segment Experiments

- Polyethylene pipe was contaminated by sealing pipe segments with benzene solution inside for several weeks.
- After contamination, water was changed once per day (except for weekends and holidays), and the benzene concentration in the removed water was measured.

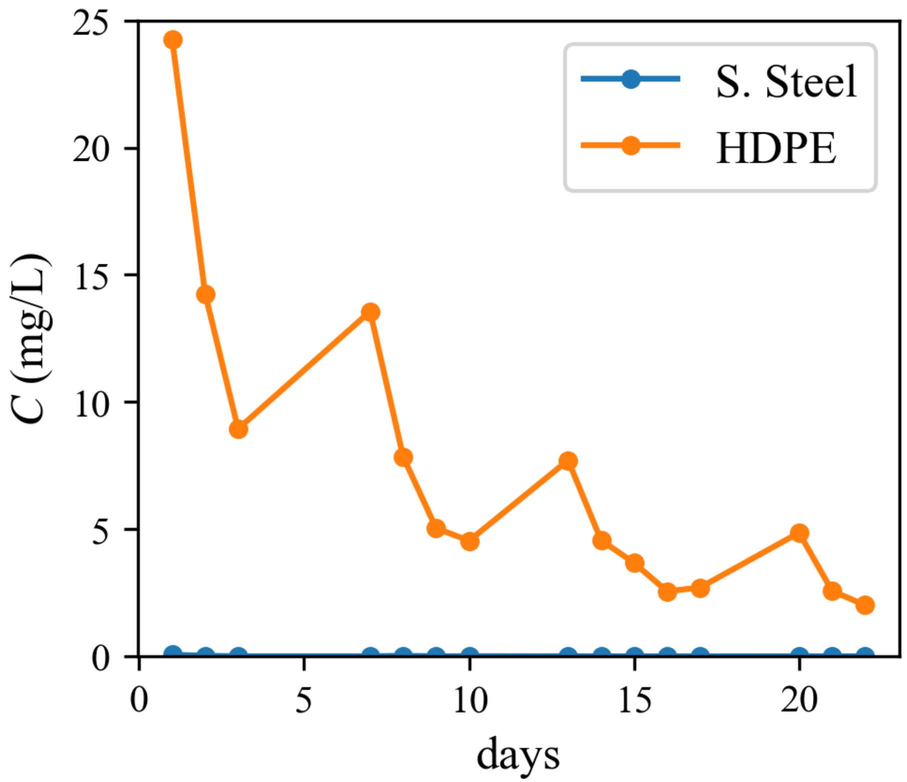
Benzene Uptake

- After 8 weeks, concentration in stainless steel pipe only decreased by 4%.
- Contrast: after only 2 weeks, concentration in HDPE pipe decreased by 82%.



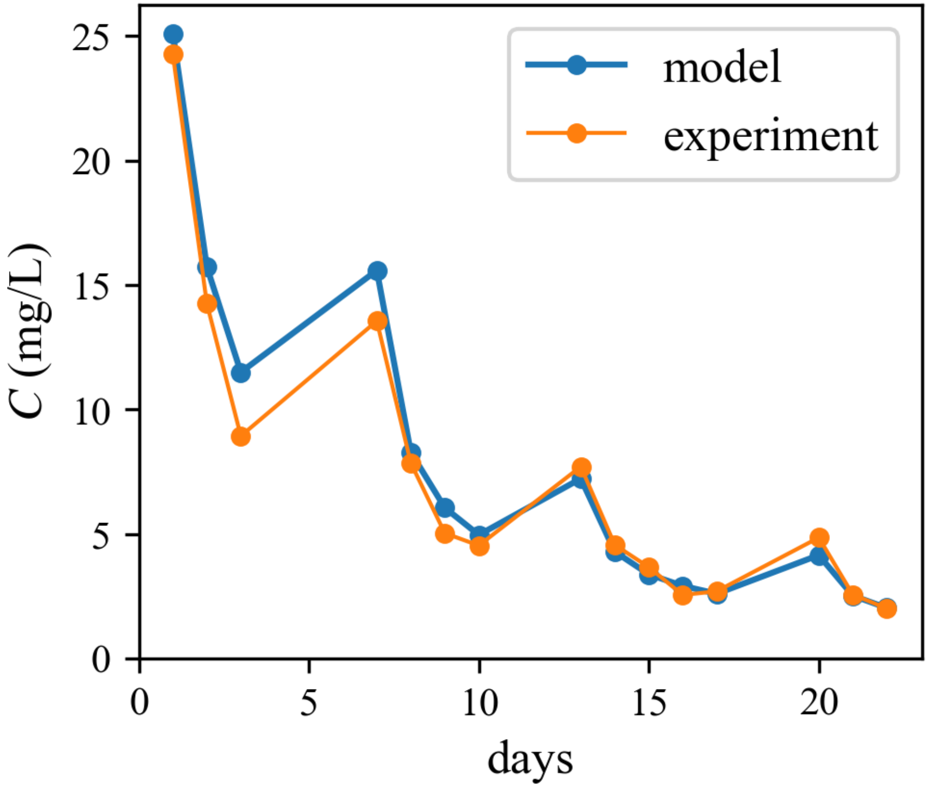
Benzene Desorption

- Stainless steel pipe released very little benzene during stagnation.
- Even after 15 rinses over 22 days, the HDPE pipe still leached benzene to 400x the federal MCL after sitting stagnant for a day.
- Longer stagnation times allowed more benzene to be released.



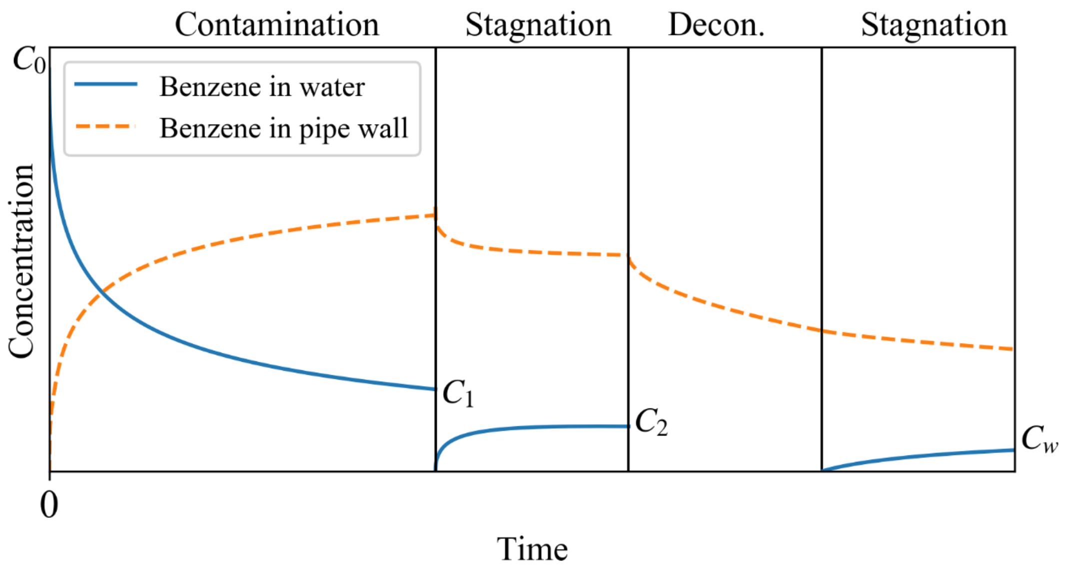
Desorption Modeling

- Feeding HDPE/benzene parameters from Mao et al. (2015) into the diffusion model from Haupert and Magnuson (2019) describes the data reasonably well.
- Experiments with different pipe materials, as well as pipes from wildfire affected sites, are currently underway at EPA's Testing and Evaluation facility.
- There are a lot of HDPE service lines out there, though. We can use the model to make some predictions about their behavior.



Modeling a Service Line Contaminated After a Wildfire

- Contamination: Site abandoned for safety reasons. Benzene concentration at the beginning (C_0) and the end of contamination (C_1) are unlikely to have been measured.
- Stagnation 1: An initial flush clears contaminated water from the system. After some stagnation time, benzene concentration is measured (C_2).
- Decon.: Removal of benzene by decontamination (e.g., with a flushing program).
- Stagnation 2: Sampling after a fixed period of stagnation detects benzene at concentration (C_w)

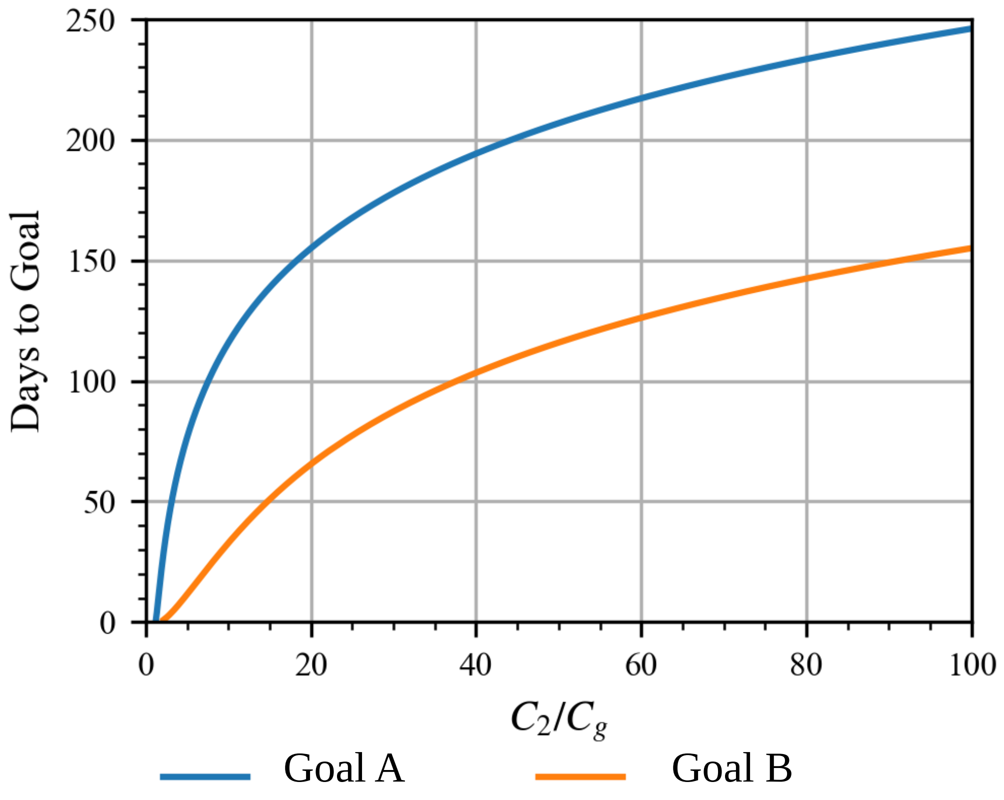


Model Application: Decontamination by Flushing

- We would like to estimate, given a water sampling result, how much flushing would be needed to decontaminate a pipe.
- We will need:
  - A decontamination goal
  - The length of time the pipe was in contact with contaminated water.
  - A water sample result taken from a stagnant pipe shortly after the system returns to operation.
  - The pipe diameters.

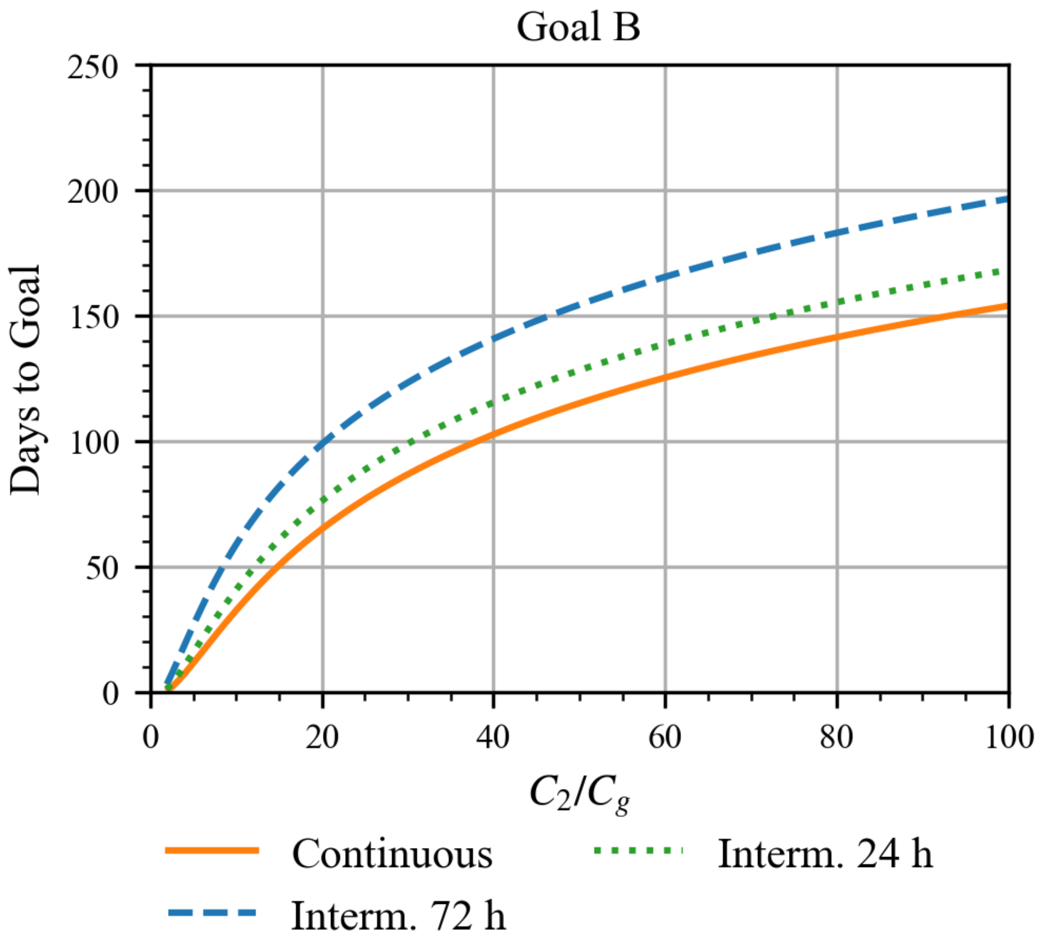
Example: Continuous Flushing

- Example:
  - One-inch HDPE Pipe
  - 12-week contamination period
- Determine goal concentration, C_g, (for example, the CA MCL: 1.0 µg/L)
- Define decon success:
  - Goal A: Deplete benzene in the pipe wall so that concentration in water will never exceed C_g
  - Goal B: Benzene concentration in water remains lower than C_g for a certain stagnation time (e.g., 72-h)
- Compare C_2 (initial measurement) with C_g to estimate decon duration.
- Predictions can inform cost/benefit analysis.



Alternate Example: Intermittent Flushing

- Decontamination by continuous flushing may require more water than is feasible.
- One option to potentially save on cost is to flush intermittently rather than continuously running water.
- Examples:
  - Flushing briefly once every three days.
  - Flushing briefly once every day.
- Uses much less water (about 98% less).
- However, doing so increases overall decon time, depending on C_2/C_g .

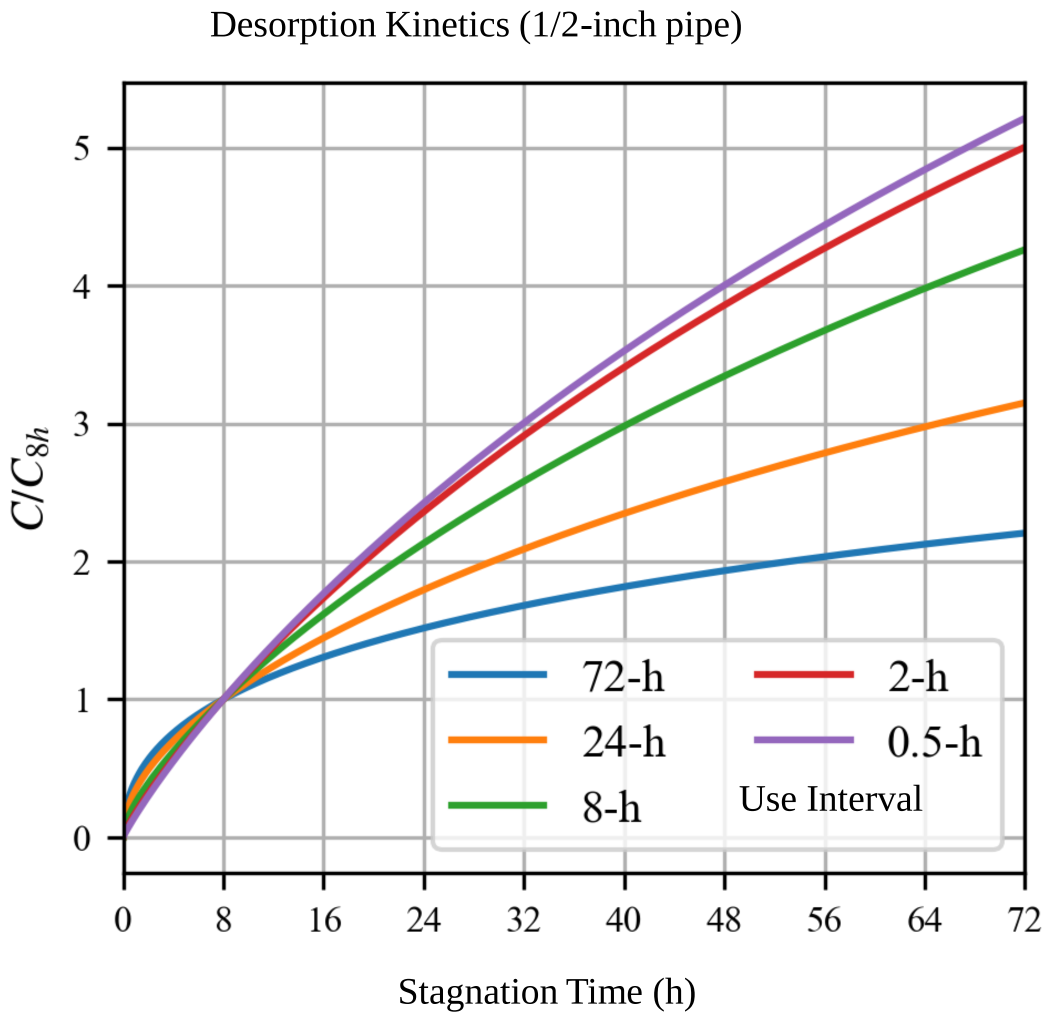


Model Application: Understanding Sampling Results

- Sampling is used to assess contamination extent and decontamination success.
- Problems:
    - Direct measurement of concentration in pipe wall is difficult.
    - 72-h stagnation is a difficult requirement for sampling occupied areas. Going without water for three days at a time is a huge inconvenience.
- Is it possible to relate stagnation at a more convenient time to hypothetical stagnation concentration at longer time?

Model Application: Understanding Sampling Results

- Given a concentration at 8-h stagnation (C_{8h}), what is the expected concentration at longer times?
- Depends on water use interval.
- Example: 3 months of contamination and 6 months of use.
- Using water every half hour is roughly equivalent to running water continuously.
- Frequent water use reduces concentration at shorter stagnation times due to removal of benzene near the inner surface.



Ongoing Research

- So far, Mao et al. (2015) has been the single source of diffusion and partition parameters.
- However model parameters for benzene may vary based on:
  - Material
  - Manufacturer
  - Pipe age
  - Fire related impacts
- Assessment of these variables is the subject of ongoing research at the EPA T&E facility, in collaboration with EPA Region 9.
- Pipe samples from affected sites were collected and shipped to EPA by the California Water Control Boards.

Other Important Notes

- PVC Pipes
  - PVC is expected to be resistant to benzene up to about 1000 mg/L (Mao et al 2009).
  - However, effects of heat damage on this behavior are unknown.
  - Diffusion of chemicals in rigid PVC is different from diffusion in polyethylene and not currently supported by the model.
- Temperature, leaks, and other sources of benzene decay have been neglected.
- How to model benzene uptake and release from melted plastic present in other pipes is still unclear.
- Relating concentration in individual pipes (such as service lines) to expected concentrations at building fixtures where exposure occurs is difficult.

Service line with melted plastic pooled inside.

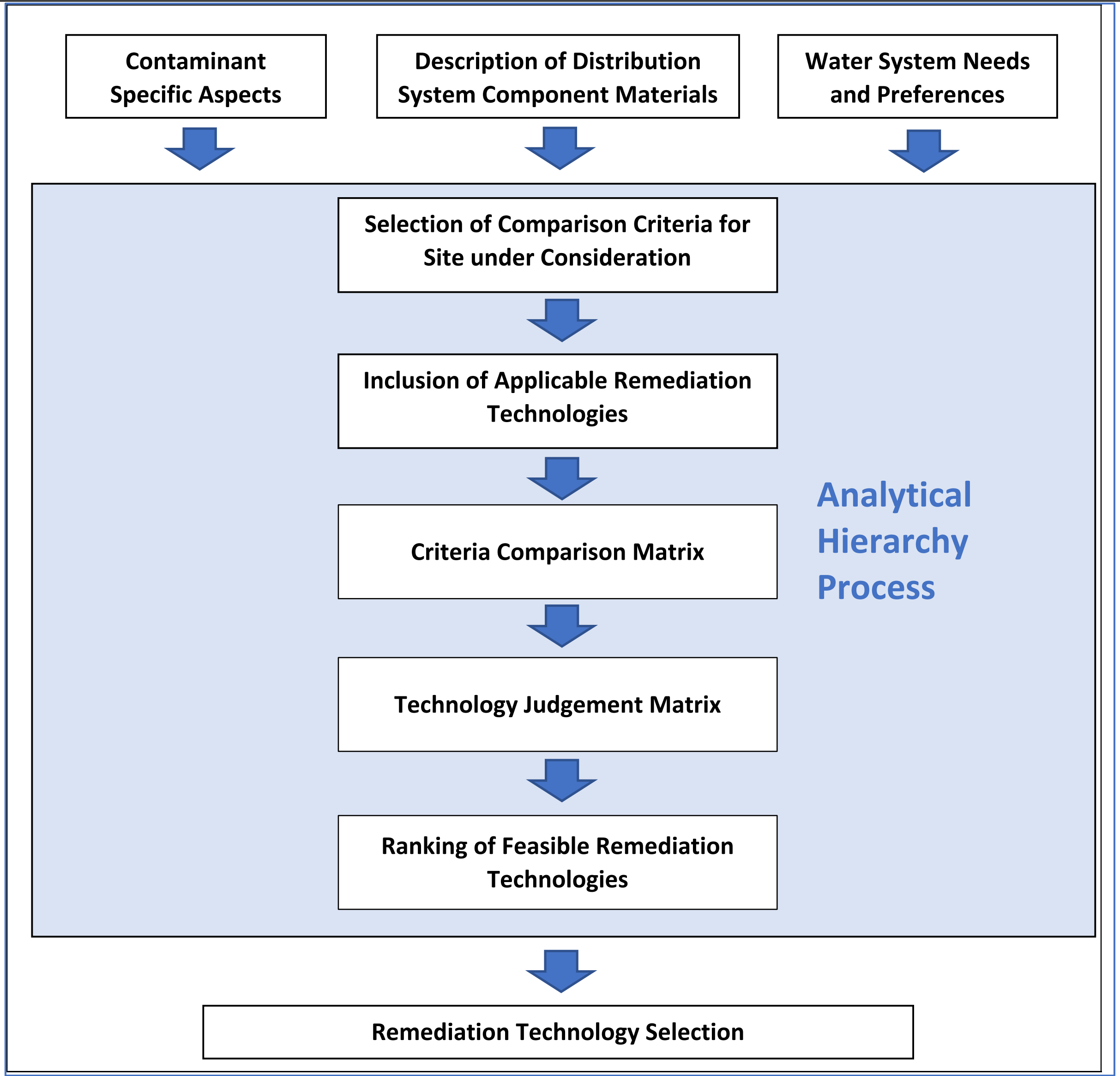
Water-APT

A decision support tool for distribution system remediation

- Why are decision support tools useful? As an example:
  - City of Santa Rosa, California, USA documented their 2018 response to wildfire-induced benzene contamination affecting 13 homes https://www.srcity.org/2801/Water-Quality-Advisory
  - To completely restore water quality, their process, which appears ad hoc (created for the particular purpose), took about 8 months. Not unsurprising because specialized tools are not available.
- Selecting remediation options involves balancing many criteria (sometimes >10) specific to the utility and the contaminant.
- Water-APT leverages the Analytical Hierarchy Process (AHP), a pragmatic and widely accepted method for multi-criteria decision making in several fields with 105,000 hits in Google Scholar.

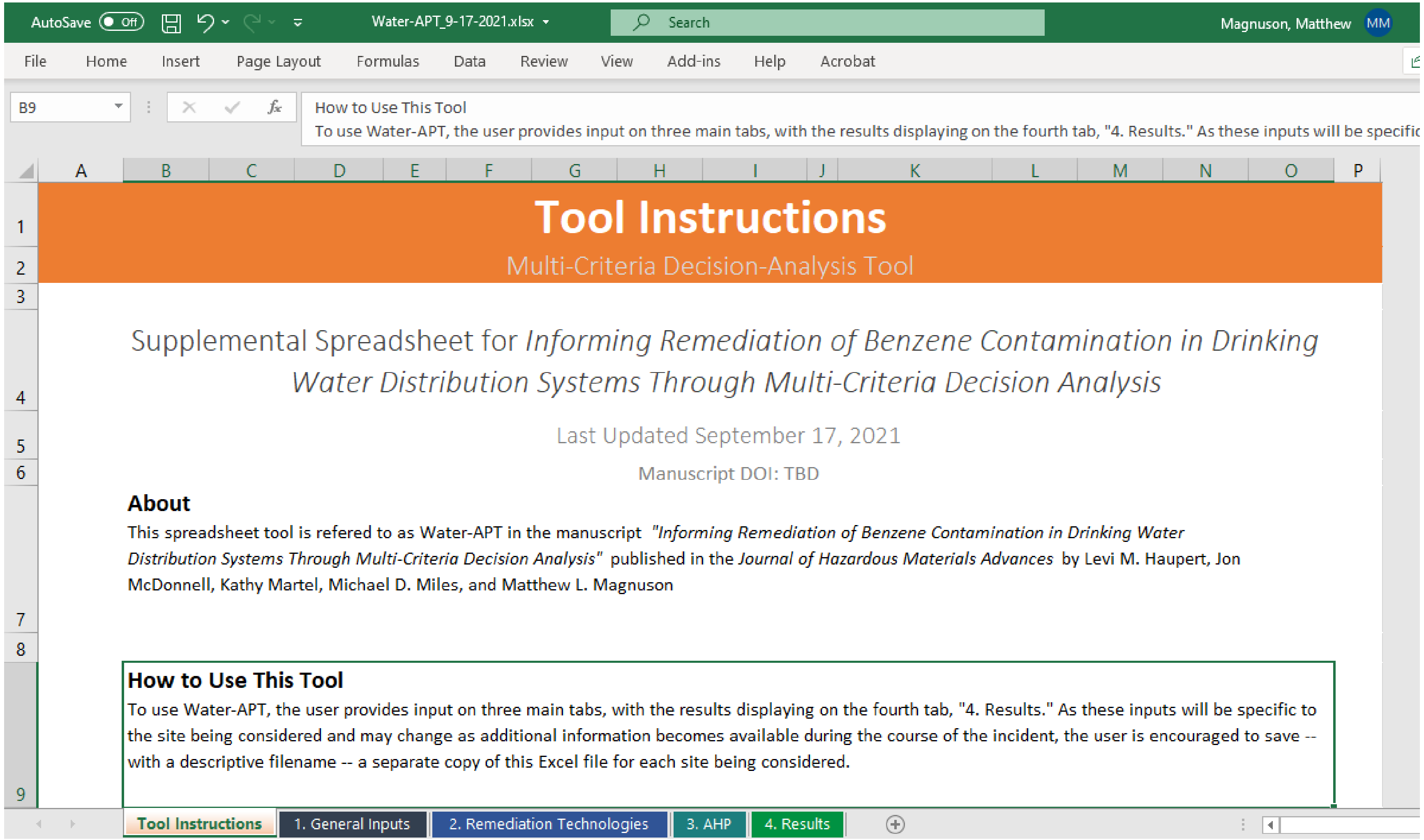
Water-APT

- Developed in consultation with an expert group.
- MS Excel and formula-based, utilizing visual cues and menus to guide the user.
- Structured, transparent, scientific, and explainable.
- Ease of use allows application at dozens of affected sites within water system.
- Rapidly adaptable as incident evolves.
- Output is a ranking of remediation technologies based on system-specific considerations and user's selected performance criteria.
- If used in pre-planning mode, data needs might be anticipated. In response mode, can help users focus on a minimal set of needed data.



Water-APT Walkthrough

Main Tabs
1. General Inputs
2. Remediation Technologies
3. AHP
4. Results



General inputs Tab

- Pipe or component material found at impacted site
- Criteria important for remediation to be compared in AHP calculations

Criteria

Aesthetic Issues with Finished Water
Customer Acceptance
Energy Efficiency
Environmental Impact
Human Health Impact
Impact on Infrastructure
Life Cycle Cost
Long-term Effectiveness
Operator or Worker Safety
Public Safety
Regulatory Impacts and Considerations
Timeframe
Waste Management Considerations
Water Efficiency

Remediation Technologies Tab

- Contains all 10 remediation technologies applicable to benzene or any contaminant.
- Includes benzene specific info.
- Defaults to top 5 technologies, but allows user to select ones applicable to the site.

Remediation Technologies

Component Replacement
Continuous Flushing
Intermittent Flushing
Flushing with an Additive
POU/POE devices
Unidirectional Flushing
Shock Hyperchlorination
Heated Flushing
Pigging
Relining
User-Defined, Novel Technology

AHP Tab

- Users fill out matrices using instructions and language provided.
- It becomes difficult to make consistent comparisons as the number of criteria increases.
- If desired, Water-APT can calculate the closest self-consistent matrix to the user’s input.

		Criteria Comparison Matrix							
	Customer Acceptance	Human Health Impact	Waste Management Considerations						
Customer Acceptance	1	Pick	Pick	Pick	Pick	Pick	Pick	Pick	Pick
Human Health Impact		1	Pick	Pick	Pick	Pick	Pick	Pick	Pick
Waste Management Considerations			1	Pick	Pick	Pick	Pick	Pick	Pick
				1	Pick	Pick	Pick	Pick	Pick
					1	Pick	Pick	Pick	Pick
						1	Pick	Pick	Pick
							1	Pick	Pick
								1	Pick
									1

Then there's math

$$\log(X) = \frac{1}{2n}\sum_{i=1}^{n-1}\frac{\mathrm{trace}\big(\log(A)^T\,\phi(\boldsymbol{y}_i)\big)}{\|\boldsymbol{y}_i\|^2}\phi(\boldsymbol{y}_i)$$

$$B_{i,j} = \frac{A_{i,j}}{\sum_i A_{i,j}}$$

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{n}A_{i,j}\frac{w_j}{w_i}$$

$$[\phi(\boldsymbol{y})]_{j,k} = y_j - y_k$$

$$w_i = \frac{1}{n}\sum_{j=1}^{n}B_{i,j}$$

$$CR = \frac{CI}{RI}$$

$$Y_2 = \begin{pmatrix}1\\-1\end{pmatrix}, Y_3 = \begin{pmatrix}1 & 1\\-1 & 1\\0 & -2\end{pmatrix}, Y_4 = \begin{pmatrix}1 & 1 & 1\\-1 & 1 & 1\\0 & -2 & 1\\0 & 0 & -3\end{pmatrix}, \ldots$$

$$CI = \frac{\lambda_{max} - n}{n-1}$$

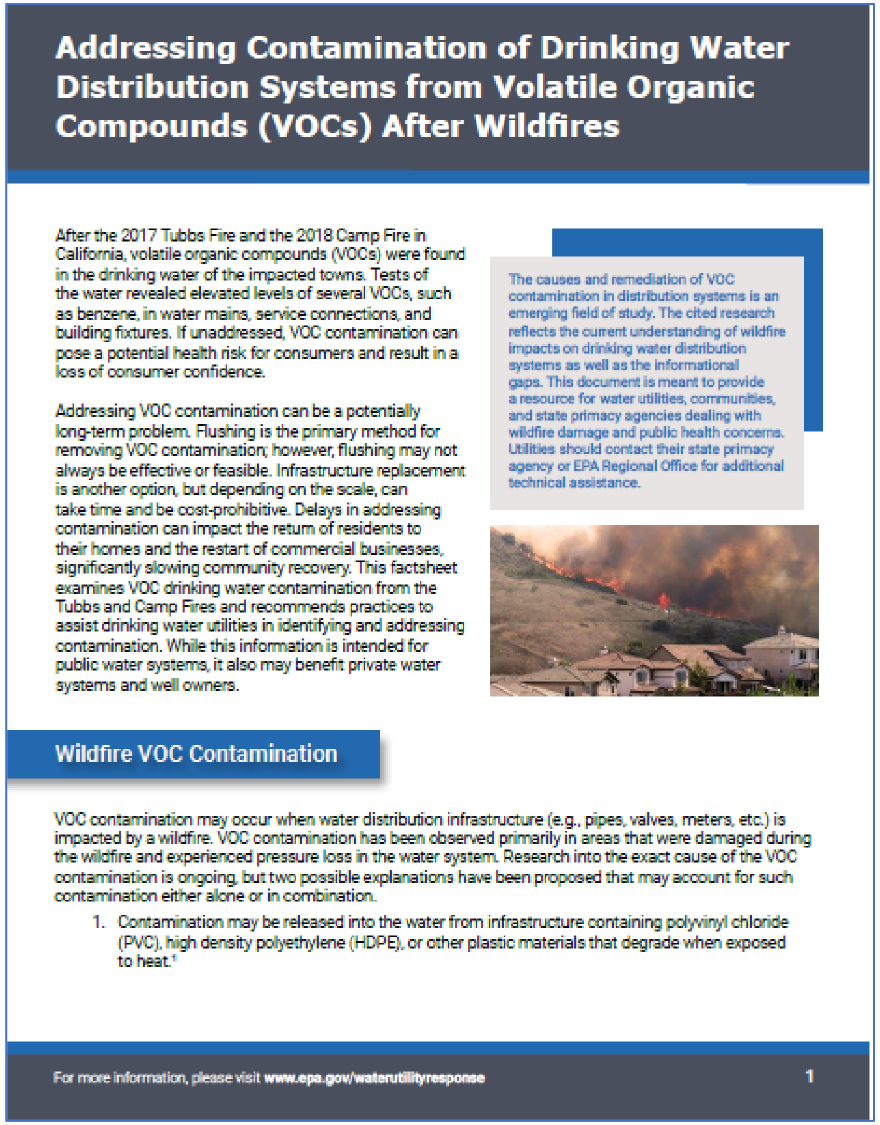
Results Tab

- Rank-ordered remediation technologies
- This example is for a particular site.

Remediation Option	Ranking Algorithm Score	Most Effective Remediation Option
Component Replacement	3.43	
Continuous Flushing	2.87	
Intermittent Flushing	3.76	
Flushing with an Additive	2.71	
POU/POE Device	**4.57**	**POU/POE Device is determined to be the most optimal technology based on the AHP analysis.**

Additional Resources

- For more information about contamination of drinking water systems after wildfires, including a factsheet describing current recommended practices for addressing contamination of drinking water distribution systems from volatile organic compounds after wildfires, visit: https://www.epa.gov/waterutilityresponse/build-wildfire-resilience



Addressing Contamination of Drinking Water Distribution Systems from Volatile Organic Compounds (VOCs) After Wildfires

After the 2017 Tubbs Fire and the 2018 Camp Fire in California, volatile organic compounds (VOCs) were found in the drinking water of the impacted towns. Tests of the water revealed elevated levels of several VOCs, such as benzene, in water mains, service connections, and building fixtures. If unaddressed, VOC contamination can pose a potential health risk for consumers and result in a loss of consumer confidence.

Addressing VOC contamination can be a potentially long-term problem. Flushing is the primary method for removing VOC contamination; however, flushing may not always be effective or feasible. Infrastructure replacement is another option, but depending on the scale, can take time and be cost-prohibitive. Delays in addressing contamination can impact the return of residents to their homes and the restart of commercial businesses, significantly slowing community recovery. This factsheet examines VOC drinking water contamination from the Tubbs and Camp Fires and recommends practices to assist drinking water utilities in identifying and addressing contamination. While this information is intended for public water systems, it also may benefit private water systems and well owners.

The causes and remediation of VOC contamination in distribution systems is an emerging field of study. The cited research reflects the current understanding of wildfire impacts on drinking water distribution systems as well as the informational gaps. This document is meant to provide a resource for water utilities, communities, and state primacy agencies dealing with wildfire damage and public health concerns. Utilities should contact their state primacy agency or EPA Regional Office for additional technical assistance.

Wildfire VOC Contamination

VOC contamination may occur when water distribution infrastructure (e.g., pipes, valves, meters, etc.) is impacted by a wildfire. VOC contamination has been observed primarily in areas that were damaged during the wildfire and experienced pressure loss in the water system. Research into the exact cause of the VOC contamination is ongoing, but two possible explanations have been proposed that may account for such contamination either alone or in combination.

1. Contamination may be released into the water from infrastructure containing polyvinyl chloride (PVC), high density polyethylene (HDPE), or other plastic materials that degrade when exposed to heat.[1]

For more information, please visit **www.epa.gov/waterutilityresponse** 1

Diffusion in plastic pipes can impact sampling and decontamination strategies. Decision support tools for remediation can be balance multiple criteria.

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References

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- Mao, Feng, Say Kee Ong, and James A. Gaunt. "Modeling benzene permeation through drinking water high density polyethylene (HDPE) pipes." *Journal of Water and Health* 13, no. 3 (2015): 758-772.

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- Benzene molecule: Public Domain
- HDPE pipes: https://commons.wikimedia.org/wiki/File:Polyethylene_Pipe_lengths.jpg
- Damaged pipe, service line sampling: Provided by the California Division of Drinking Water
- Fire hydrant being flushed: Daniel Case 2012. Creative Commons Attribution Share Alike 3.0 License: https://creativecommons.org/licenses/by-sa/3.0/deed.en