U.S. EPA "State of VI Science" Workshop

Vapor Intrusion Protection Cost-Effectiveness Simulation Tool (2.0)

Contaminant Transport & Storage: Interactions Between Natural and Human-Built Environments

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Disclaimer: The views expressed in this presentation are those of the author and do not necessarily represent the views or policies of U.S. EPA.

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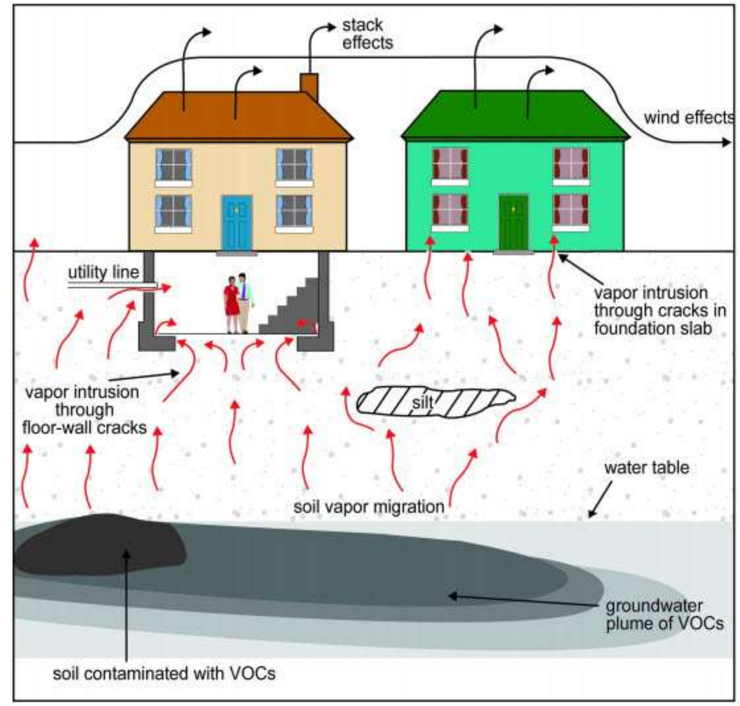
Outline

- Contaminant Sources and Pathways in Natural Environment
- Transport, Storage & Mass Transfer Basics
  - Vadose Zone
  - Groundwater
  - Mass Transfer Processes
- Interactions with Human-Built Environment
- Timescales & Concentration Variability
- Illustrative Results from Three Sites
- Concepts for Soil Vapor Control & Verification
- Key Points



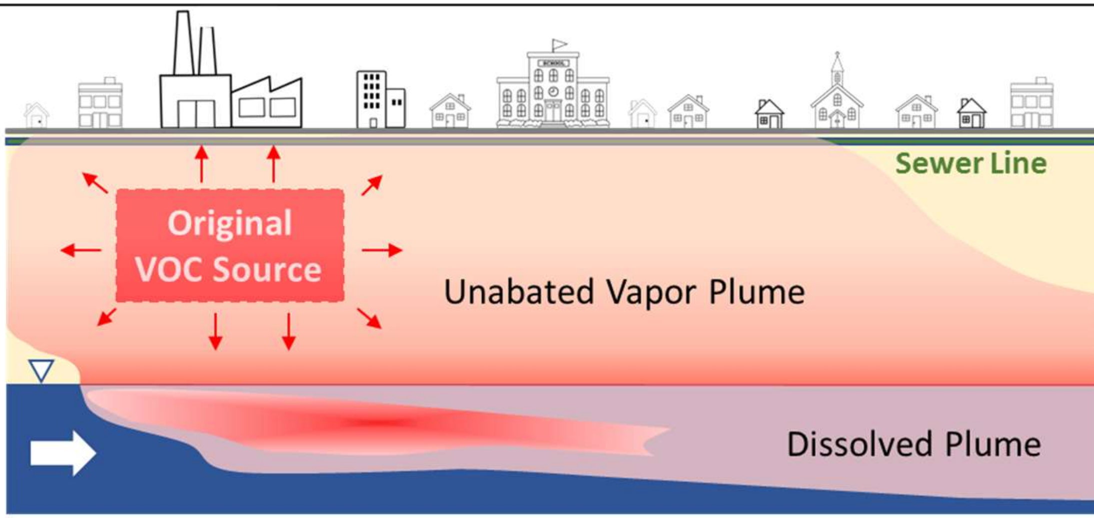
References: USEPA 2012, USEPA 2015

February 2012 EPA 530-R-10-003

Conceptual Model Scenarios for the Vapor Intrusion Pathway

Sources and Pathways in Natural Environment

- Local Vadose Zone
  - Diffusion of vapors in all directions
  - Small flow (advection) with infiltrating water
- Groundwater Plumes
  - Primarily with flowing groundwater (aka, advection) and dispersion
  - Co-mingles with the vapor plume at the capillary fringe

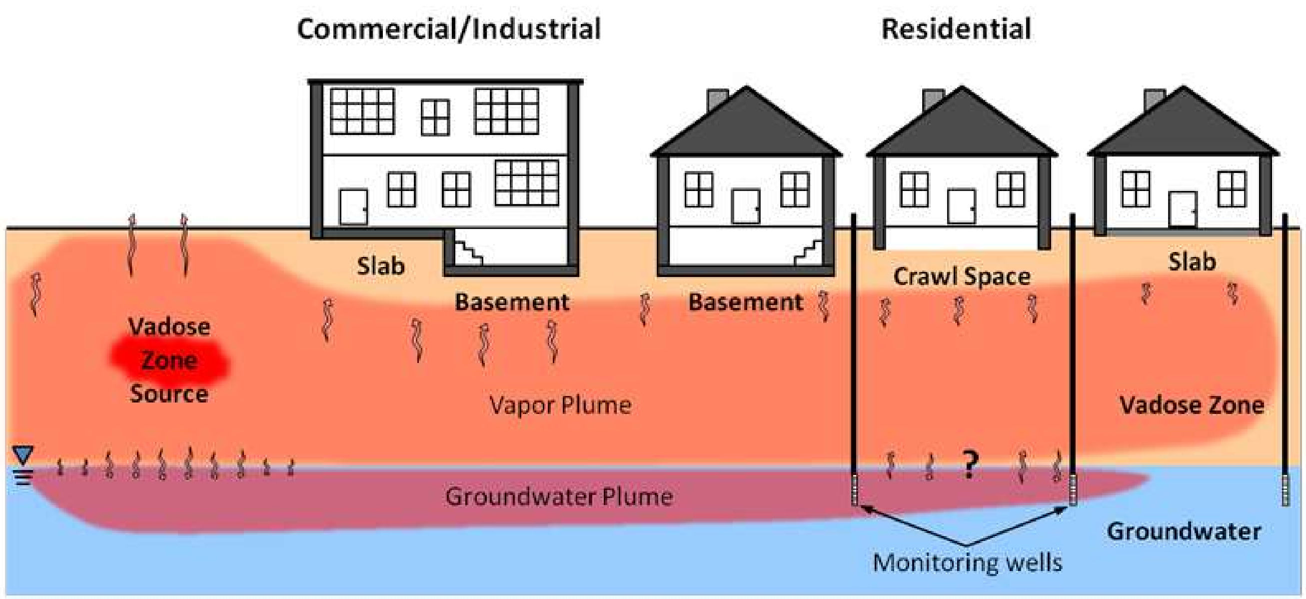


"Original Source" – released contaminant mass produces a persistent vapor plume

Contaminated groundwater migrates further and further downgradient

Sources and Pathways in Natural Environment

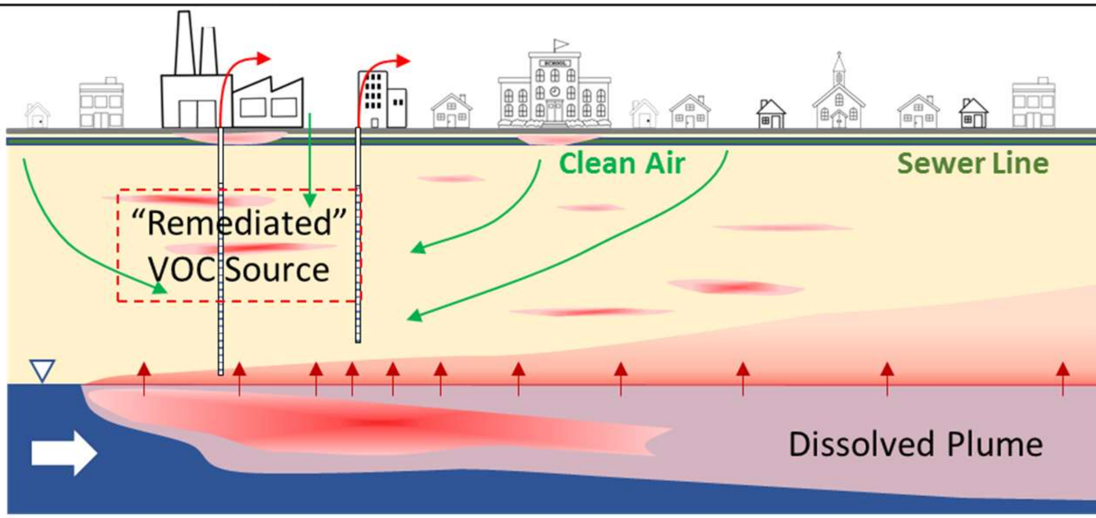
- Contaminant Release confined to Vadose Zone
  - Primarily lateral migration – flux is higher toward the surface
- Groundwater Plumes results from overlying vapors (& some infiltration)



Sources and Pathways in Natural Environment

- Local Vadose Zone
  - Initial cleanup is “complete” but mass remains
- Groundwater Plume
  - Primarily upward vertical migration
  - Vapor plume is fed by volatilization from groundwater

Original source of contaminated vapors is largely reduced but residuals remain scattered over a large volume

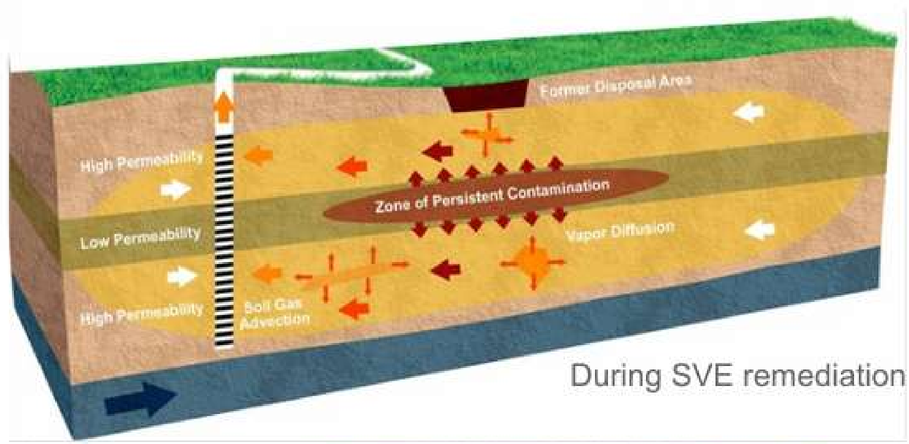


“Original Source” is gone! At least mostly, residuals remain. “Low levels” of VOC are in the soil gas

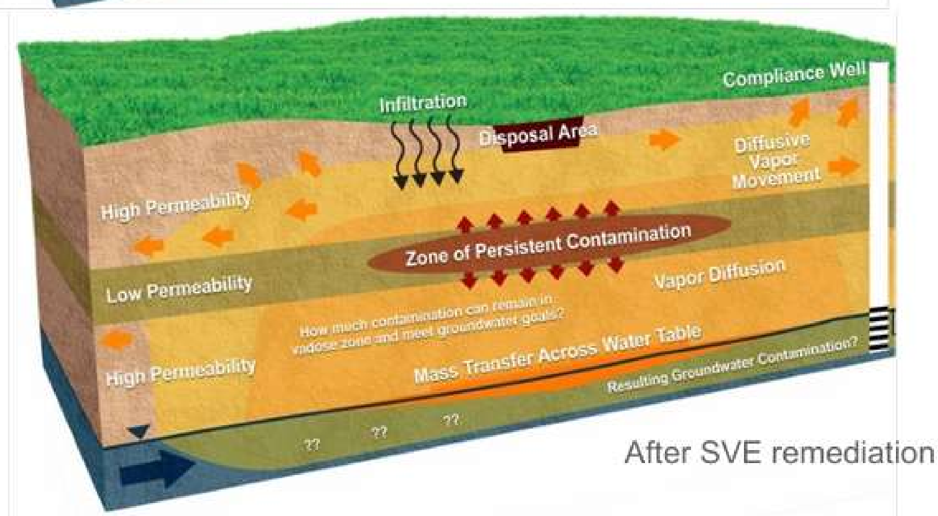
Contaminated groundwater now produces VOC vapors; it’s a **SOURCE**

Sources and Pathways in Natural Environment

- After a contaminant release, vapors are transported from the release point (highest concentrations) toward lower/zero concentrations
- Mass diffuses into all soil types: sands, silts & clays
- During SVE, permeable pathways are swept clean of vapors but mass remains in low permeability lenses (unswept) and diffuses out slowly
- After SVE, **rebound** occurs as vapors diffuse out of low permeability lenses into permeable pathways



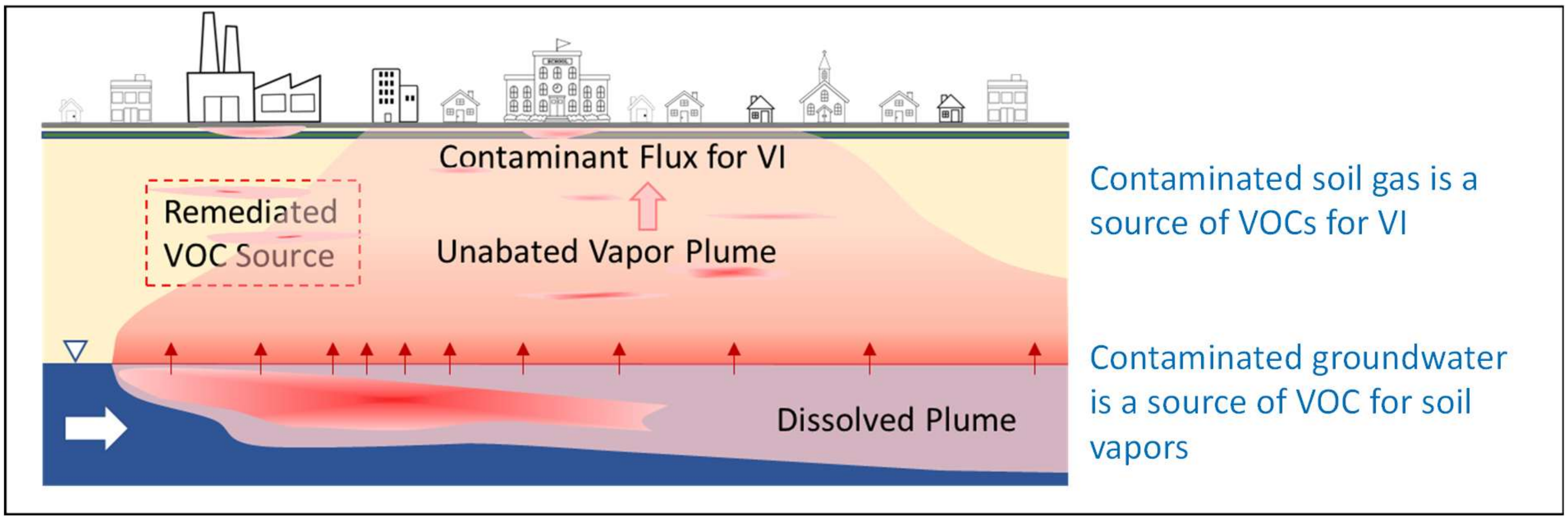
During SVE remediation



After SVE remediation

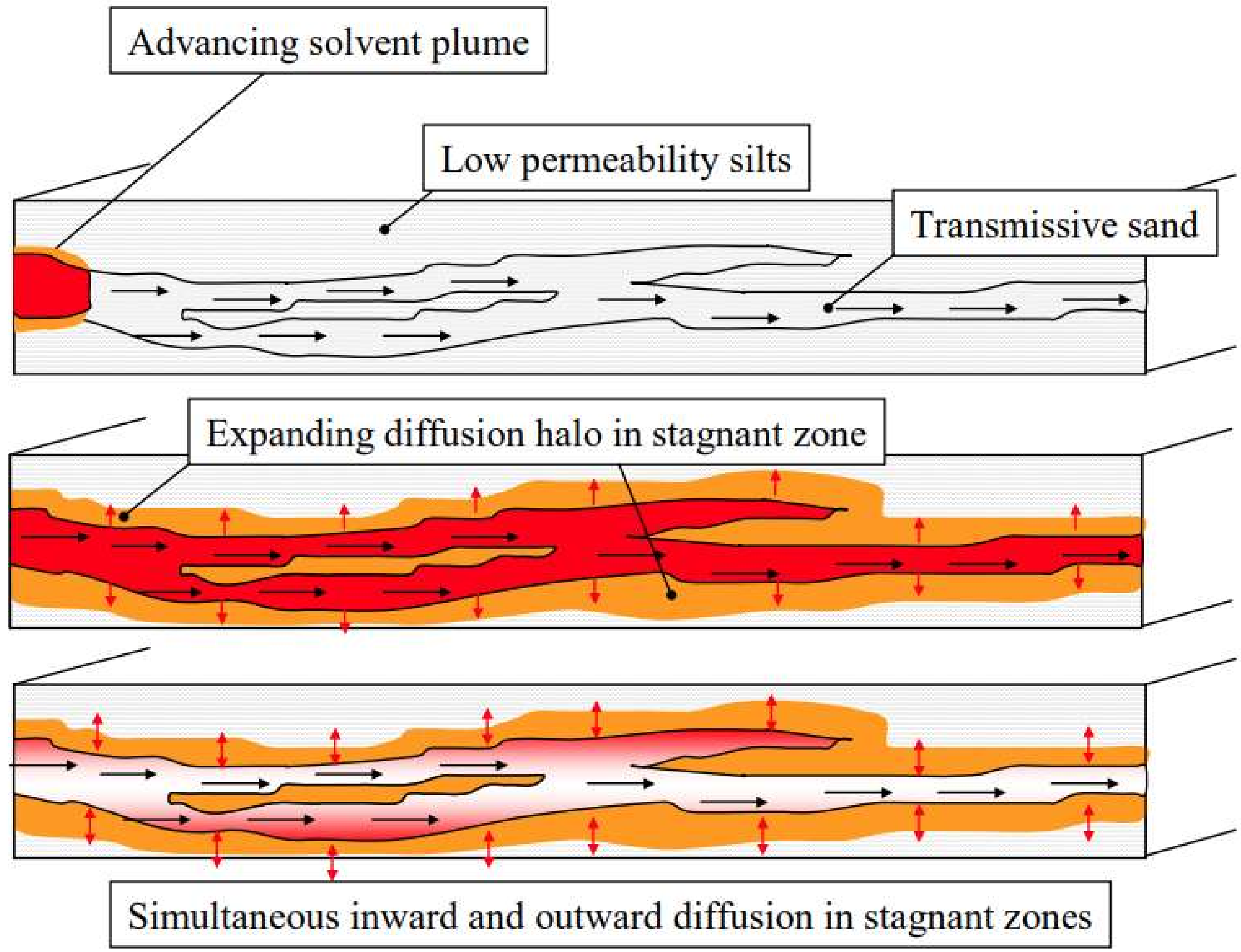
Sources and Pathways in Natural Environment

- Local Vadose Zone
  - Residual mass remains at levels resulting in significant rebound
- Groundwater Plumes
  - Primarily upward vertical vapor migration
  - Vapor plume is fed by volatilization from groundwater



Sources and Pathways in Natural Environment

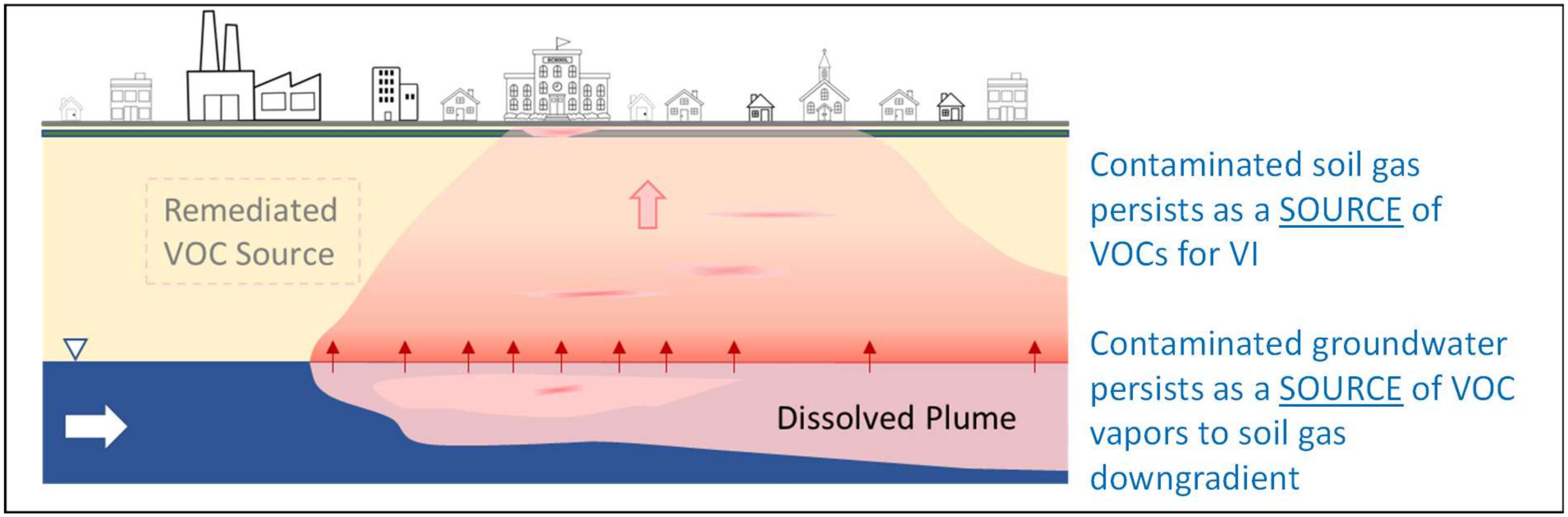
- Equivalent to the release scenario in the vadose zone except contaminant movement is a little more predictable
- Rebound in the groundwater is commonly referred to as **Back Diffusion**



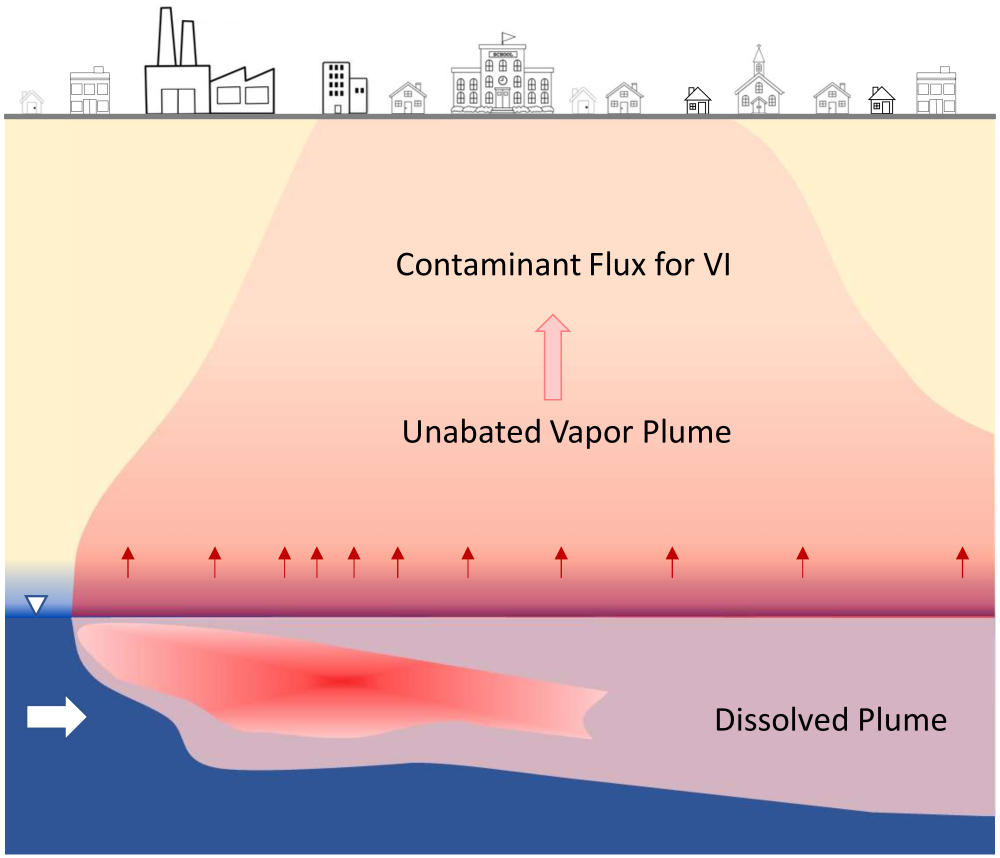
Sources and Pathways in Natural Environment

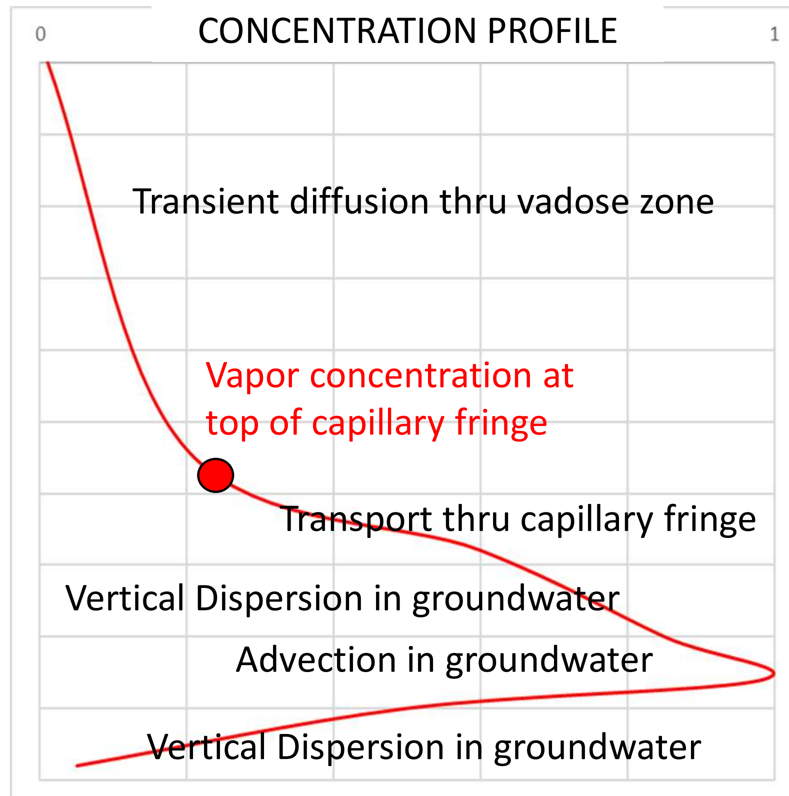
- Evolving Residual Sources
  - Appear after concentration gradient reversal
  - Natural environment (fine-grained sediments, perched water)
  - Built environment (concrete)

Responsible party is “done”, MNA will keep the residuals under control. Or will it?

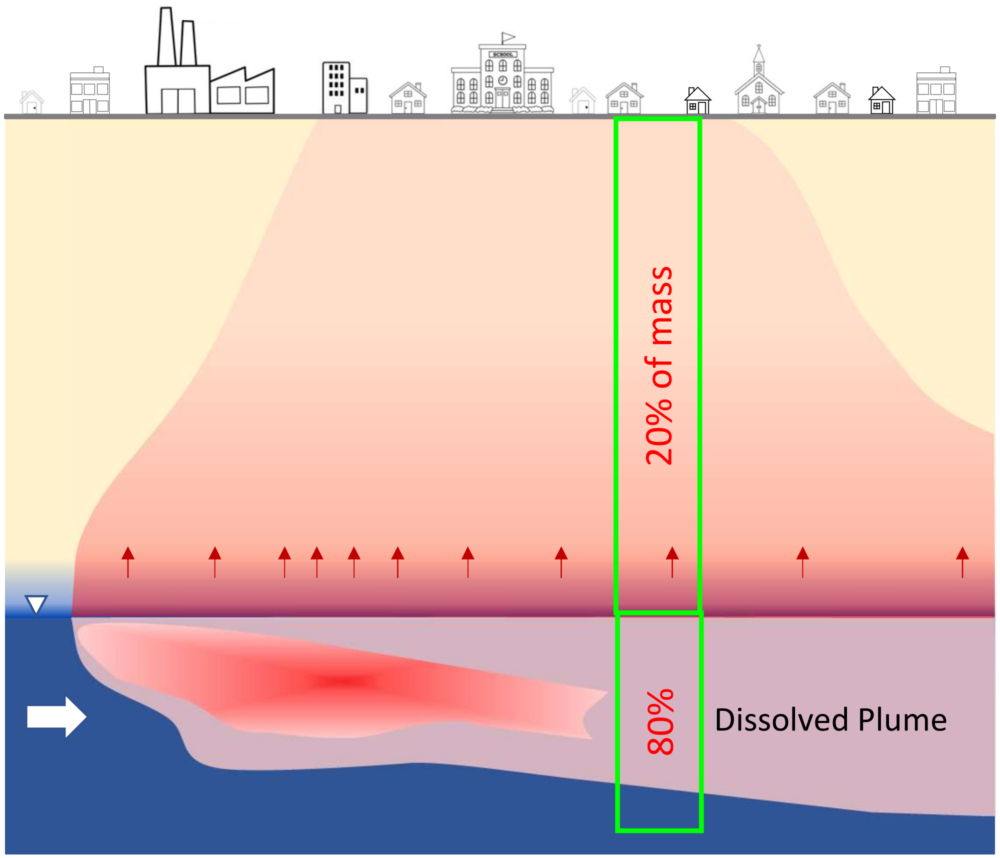


Conceptual Model for Upward Mass Flux from Contaminated Groundwater





Example Calculation of Mass Distribution



Vadose zone

- 30-ft thick
- Linear conc profile (water to surface)
- Deep soil gas ~38 ug/L in vapor

Aquifer

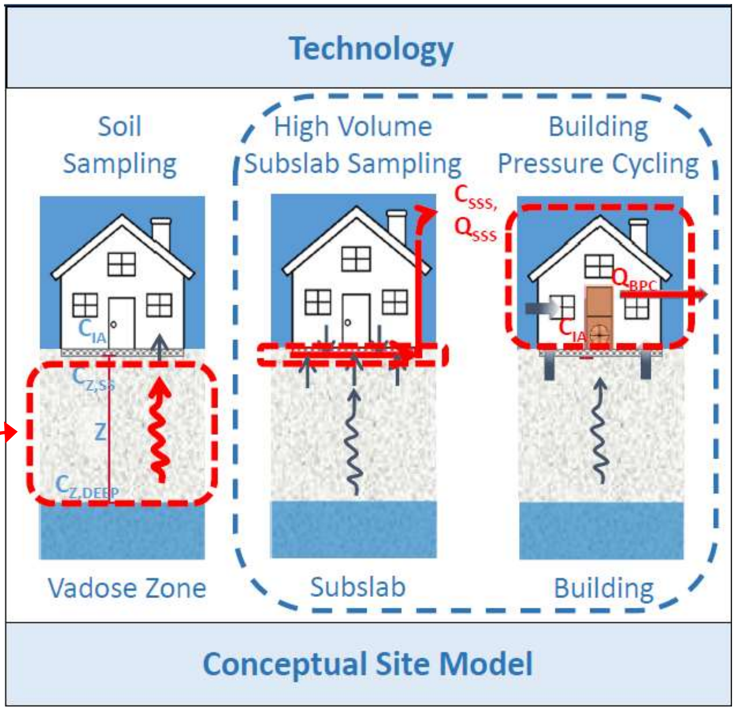
- 10-ft thick
- Uniform concentration 1.0 mg/L

Aquifer only holds about 4 times as much mass as overlying vadose zone

Why not cleanup the GW with SVE?

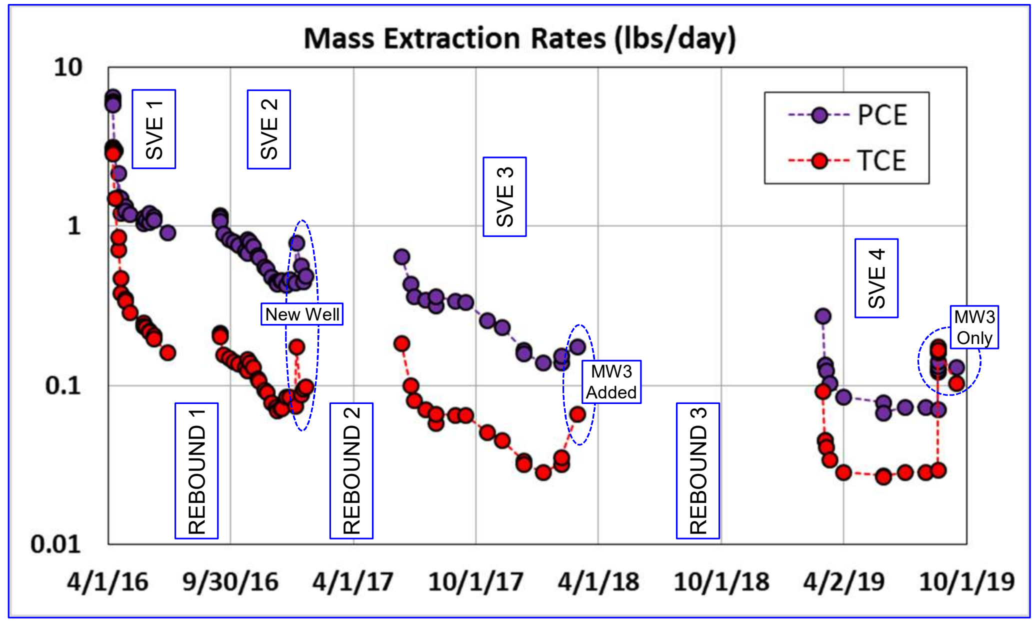
In what phase does most of the mass reside?

Assessing Mass Flux through the Subsurface



Source: ESTCP ER-201503, Geosyntec Consultants

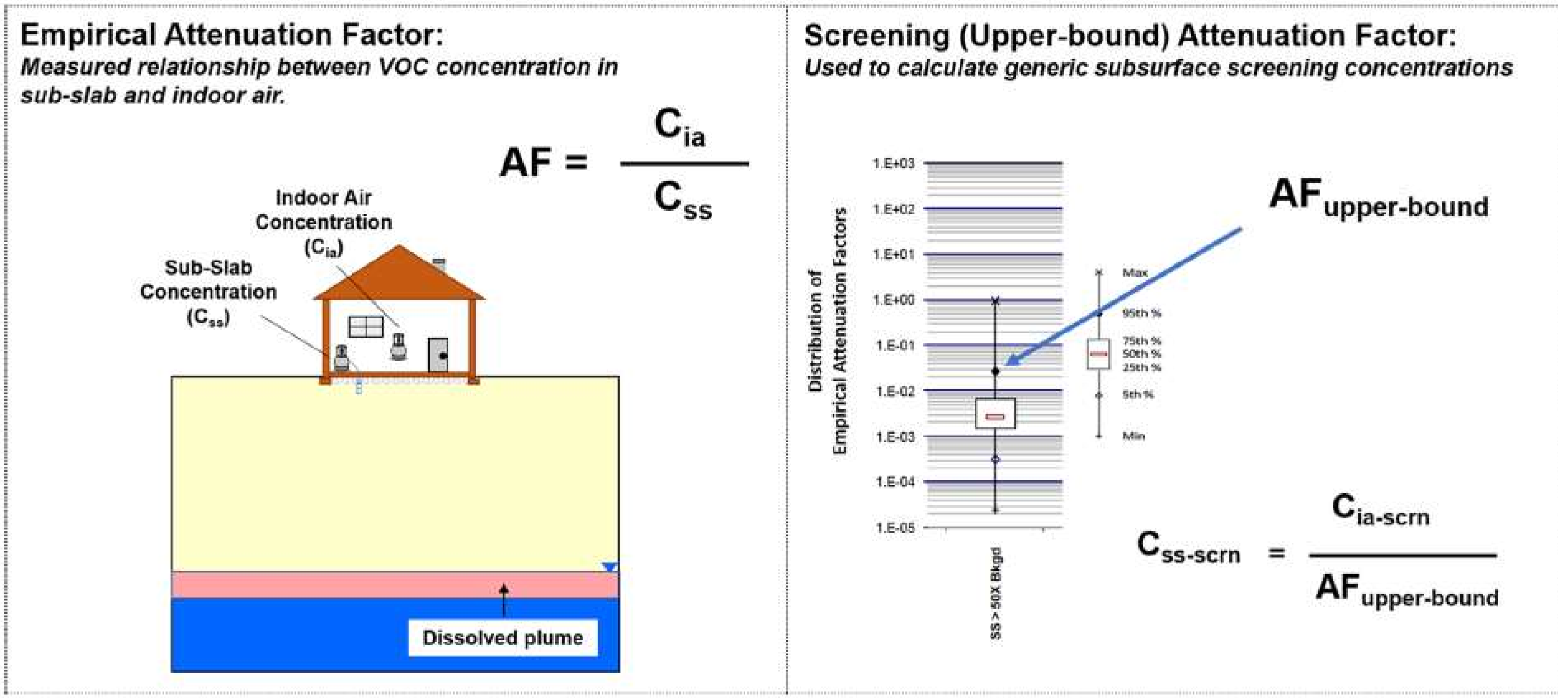
SVE System Performance



Source: Stewart et al, 2018

Diffusive Mass Flux: $\frac{dm}{dt}\left(\frac{1}{Area}\right) = m' = D\frac{dC}{dz} = \frac{D}{L}(C_1\text{-}C_0)$

Are Attenuation Factors equivalent to mass transfer coefficients? No



Ma et al. (2020) Vapor Intrusion Investigations and Decision-Making: A Critical Review. ES&T, 54, 7050–7069

Mass transfer coefficients quantify the rate of mass transfer in a multitude of processes

$$\frac{dm}{dt}\left(\frac{1}{\text{Area}}\right) = m' = \alpha(C_1\text{-}C_0)$$

α = mass transfer coefficient

The rate mass moves across an interfacial area is proportional to the concentration gradient

What are mass transfer coefficients?

- Parameter to quantify the rate mass moves between two locations with differing concentrations (i.e., gradient)
- Generally applied to interfaces between materials
- Assumes concentration gradient is linear (you'll hear it called a first order process)

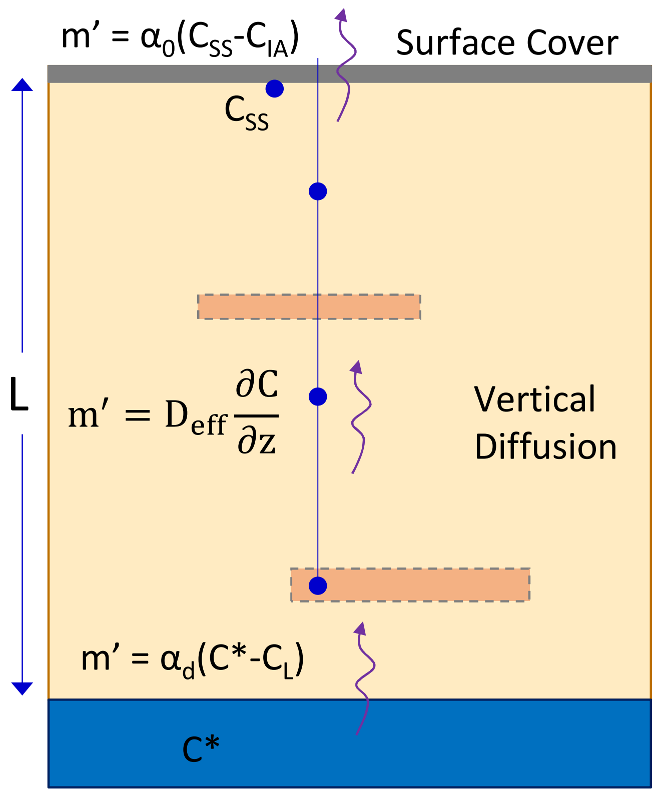
Processes applicable to vapor intrusion studies include:

- Contaminated groundwater & deep soil gas
- Vapors diffusing through a sandy vadose zone with embedded clay lenses
- Vapors in subslab material and indoor air

Diffusive Mass Flux:

$$\frac{dm}{dt}\left(\frac{1}{\text{Area}}\right) = m' = D\frac{dC}{dz} = \frac{D}{L}(C_1\text{-}C_0)$$

Mass transfer coefficients quantify the rate of mass transfer in a multitude of processes



$m' = \alpha_0(C_1-C_0)$

The rate mass moves across an interfacial area is proportional to the concentration gradient

$\boxed{\alpha = \text{mass transfer coefficient}}$

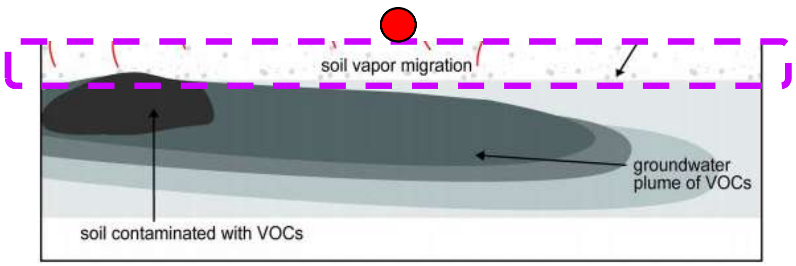
What are mass transfer coefficients?

- Parameter to quantify the rate mass moves between two locations with differing concentrations (i.e., gradient)
- Generally applied to interfaces between materials (e.g., water & air, sand & clay, NAPL & water, pore water & soil solid surfaces)
- Assumes the concentration gradient is linear (you'll hear it called a first order process)

Diffusive Mass Flux: $\boxed{\frac{dm}{dt}\left(\frac{1}{Area}\right) = m' = D\frac{dC}{dz} = \frac{D}{L}(C_1\text{-}C_0)}$

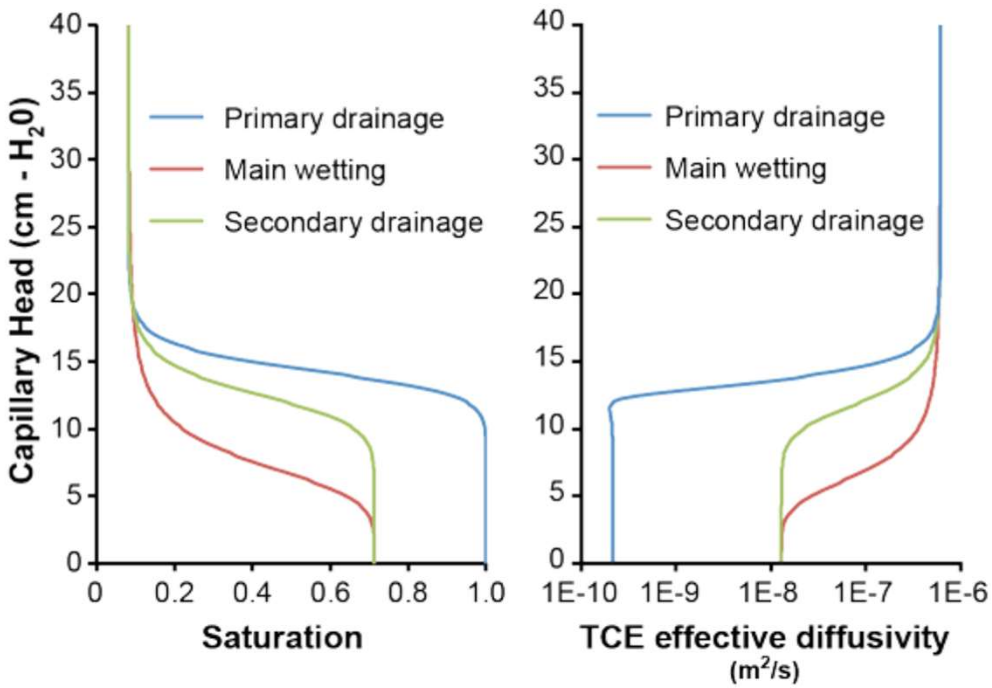
Capillary Fringe Mass Transfer

- Magnitude is proportional to the underlying, bulk groundwater concentration
- Governed by the resistance of upward migration from bulk to capillary fringe
- Resistance is complex function of water saturation profile influenced by water table fluctuations and to lesser extent infiltration of precipitation
- HENCE, this concentration varies temporally but around an approximate mean that decays slowly over time (proportional to bulk GW Conc decay)



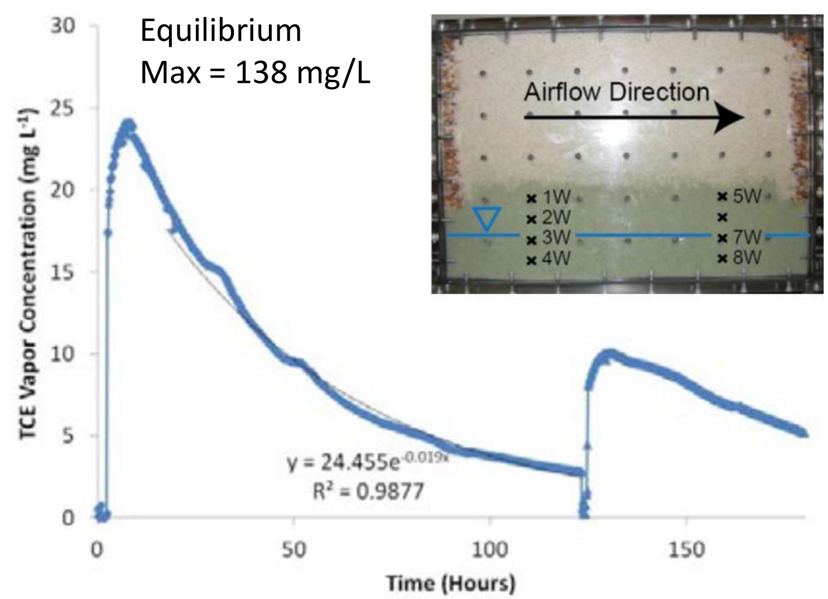
Mass Transfer across the Capillary Fringe

Theoretical saturation and effective diffusivity curves for 20/30 sand



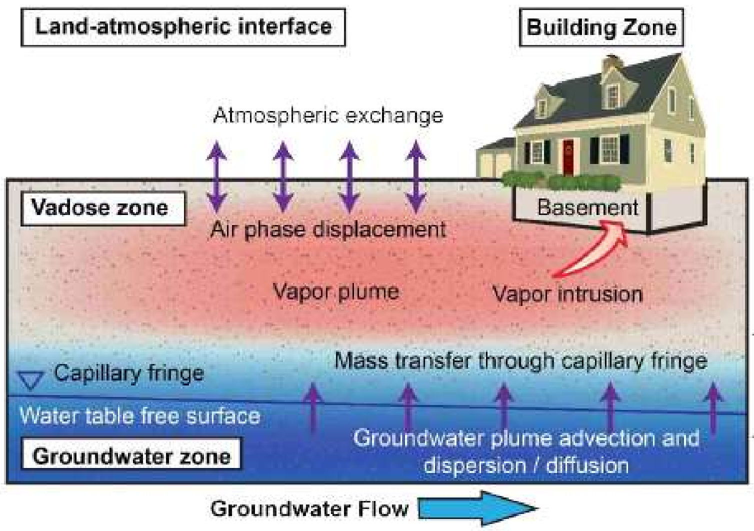
Source: SERDP ER-1687 Final Report, 2014

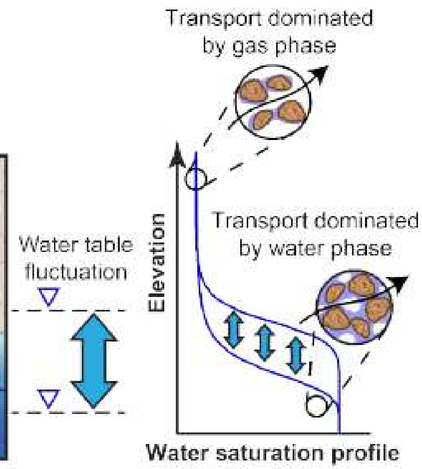
Experimental mass transfer across capillary fringe in coarse sand

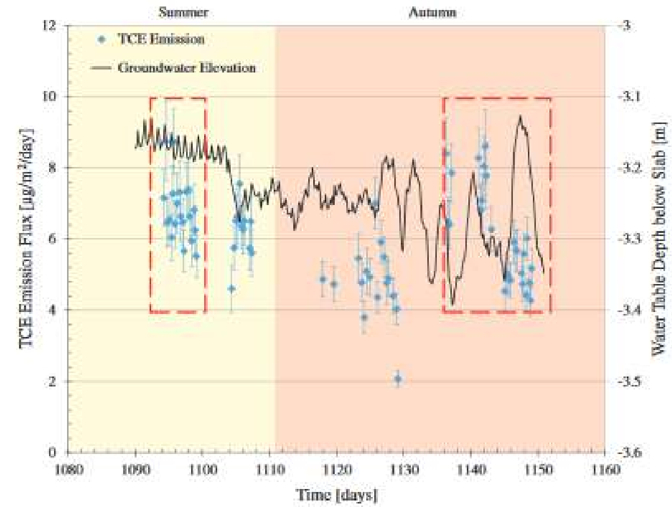


Finer sands yield decreasing transfer rates

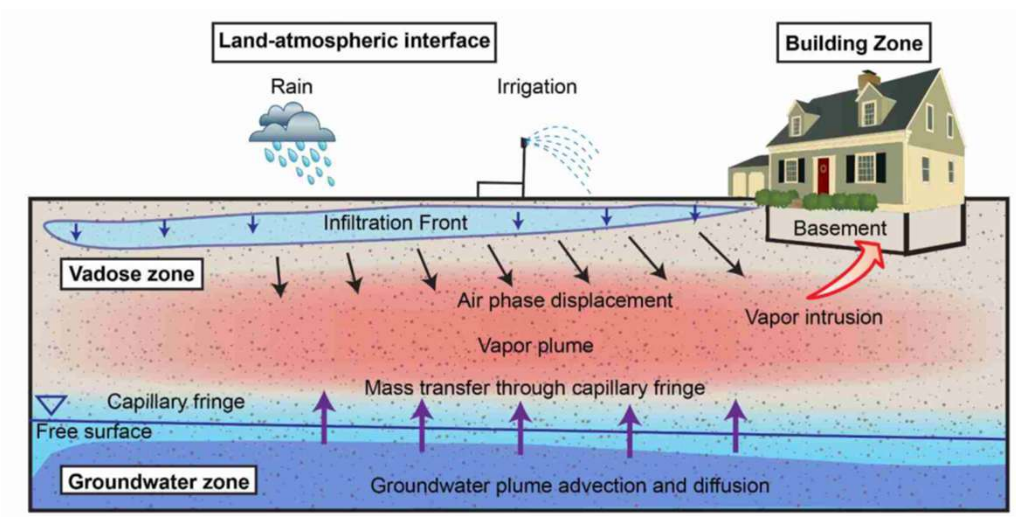
Fluctuation tends to ENHANCE the mass flux

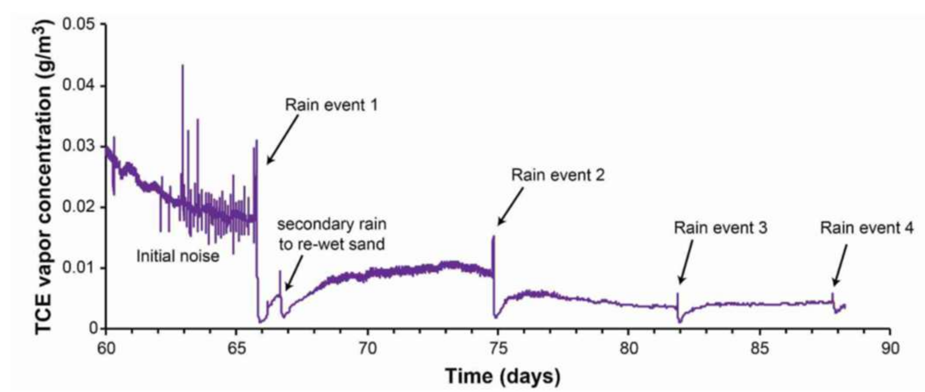






Precipitation tends to SUPPRESS the mass flux

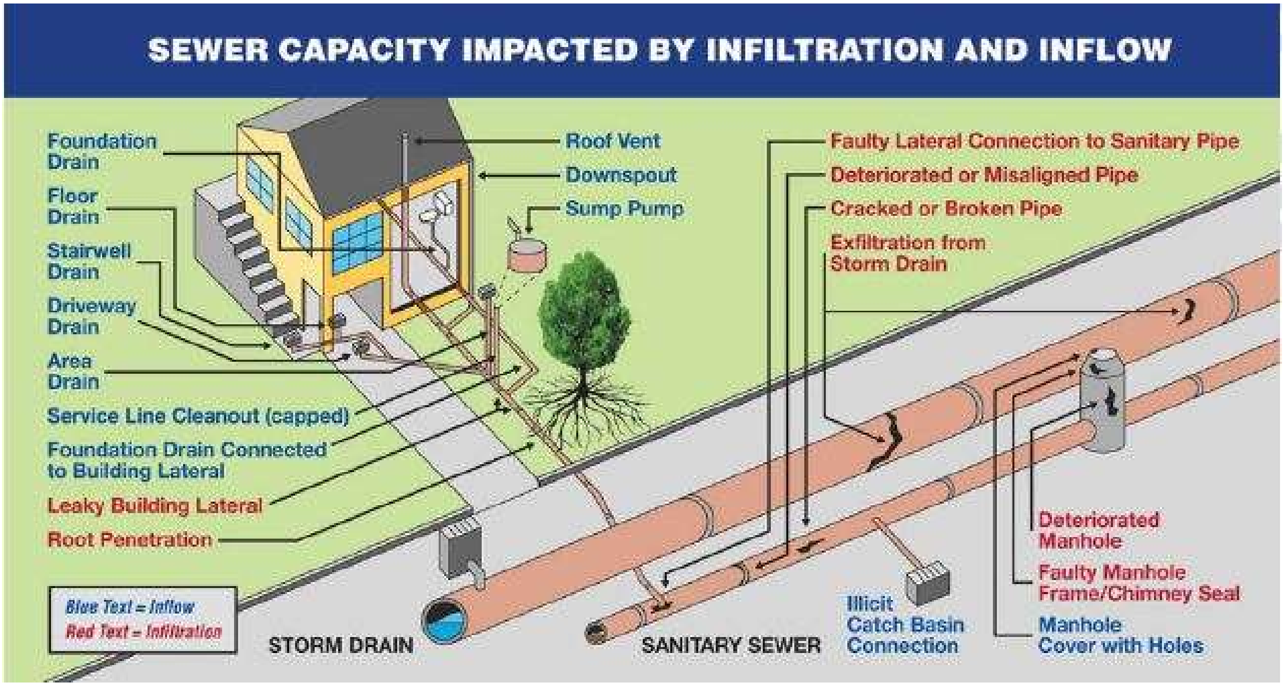




Interactions with Human-Built Environment

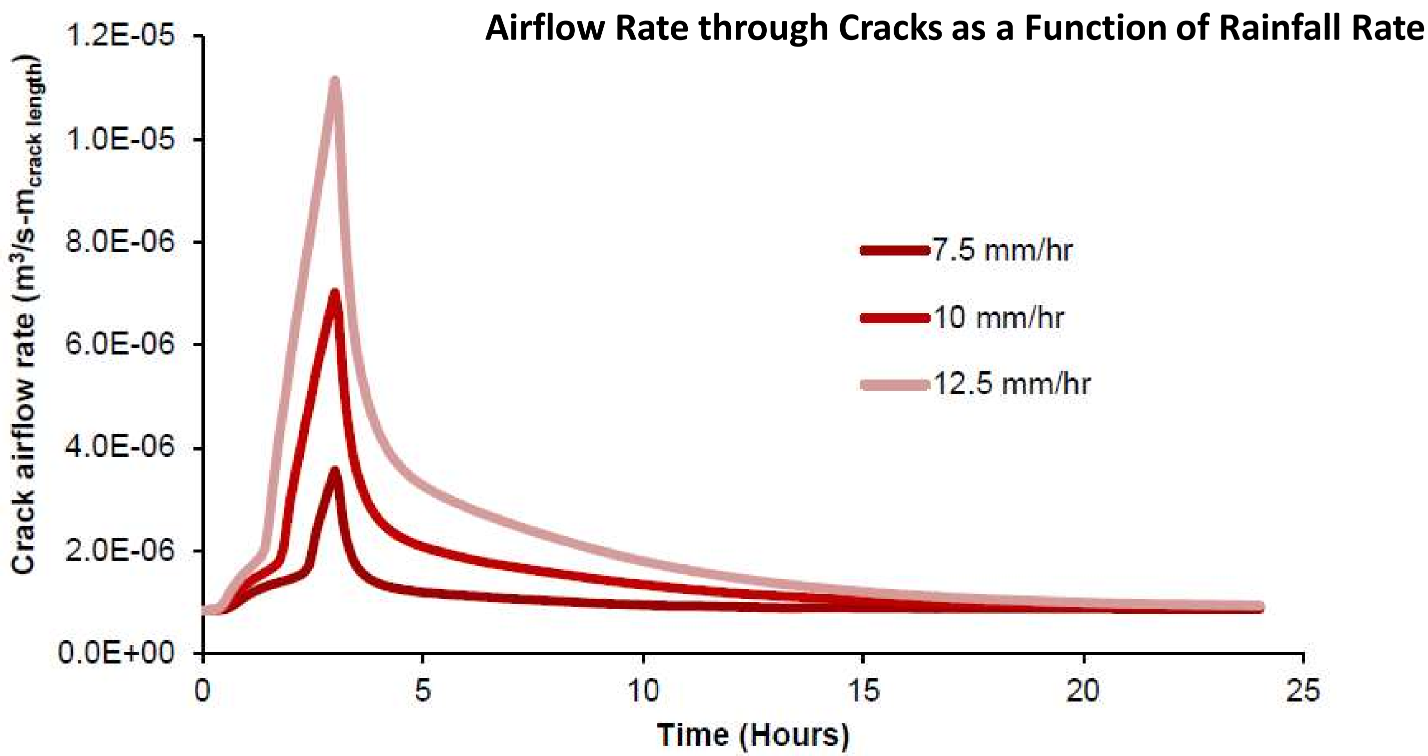
Interaction with the Human Built environment

- Realities are amplified near the interface (increased instances and transients in realities)
- Preferential pathways
- Building Materials, particularly concrete slabs
- These are the reasons to keep vapors away from this interface
- Sun Devil Manor introduction

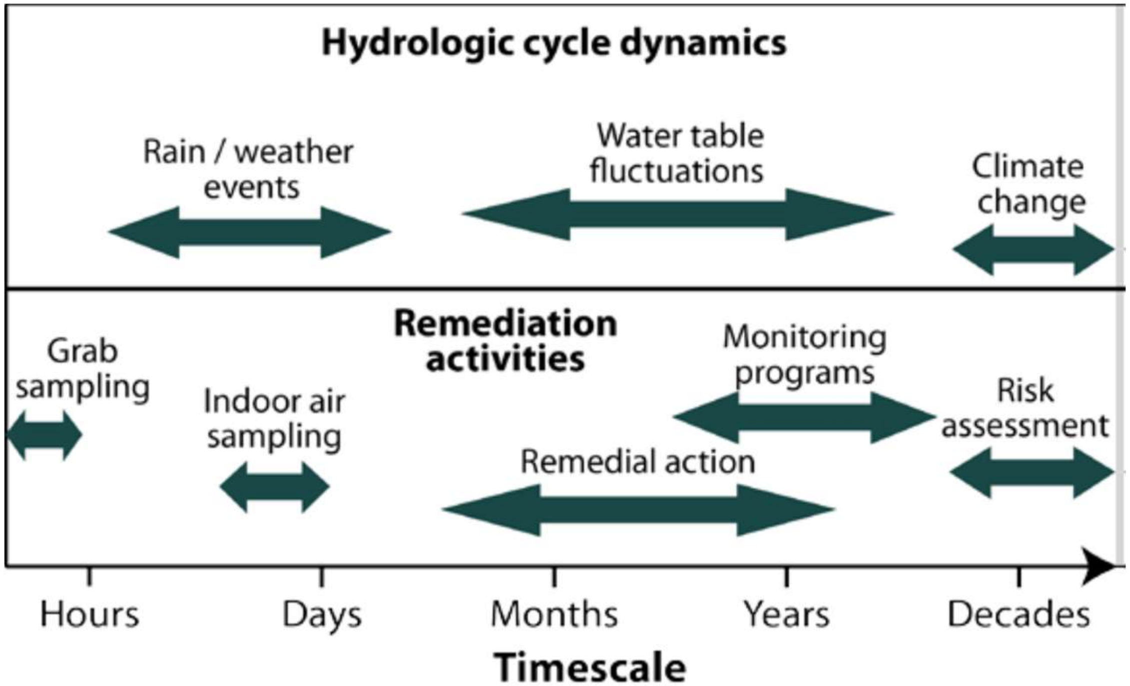


Henry likes to call this the “ZONE OF CHAOS”

Timescales for Transport Processes



Timescales for Transport Processes



Henry's Conceptual Sampling for 1 Bldg. w/ similar 'Coverage'

Media/ Event for Observed Variation	Est. Range of Variation over (3yrs) at one Location	Est. Mid-Point of Variation over Time	Sampling Freq. for similar 'coverage'	Attenuation Mid-Point In OoM	Cum. Total OoM Observed Variation/ Uncertainty
Dissolved in GW	1-3x ?	3x ?	**4** / Yr	0.3	0.3
Partitionig into Deep Soil Gas	1 – 10 x ?	3x ?		0.3	1.0
Shallow Soil Gas < HBE	20x ?	10x ?	__ / Yr	1.0	2.0
Entering the **Human Built Environment**					
In Conduits	10-1000x ?	100x ?	__ / Yr	2.0	4.0 ?
In Buildings	100-1000x ?	100x ?	365 days/ Yr	2.0	6.0 ?? (See 3 >DL)
End of VI pathway is the **most difficult** to represent by samples – (***if* Not Continuous**)					

Changes are slow

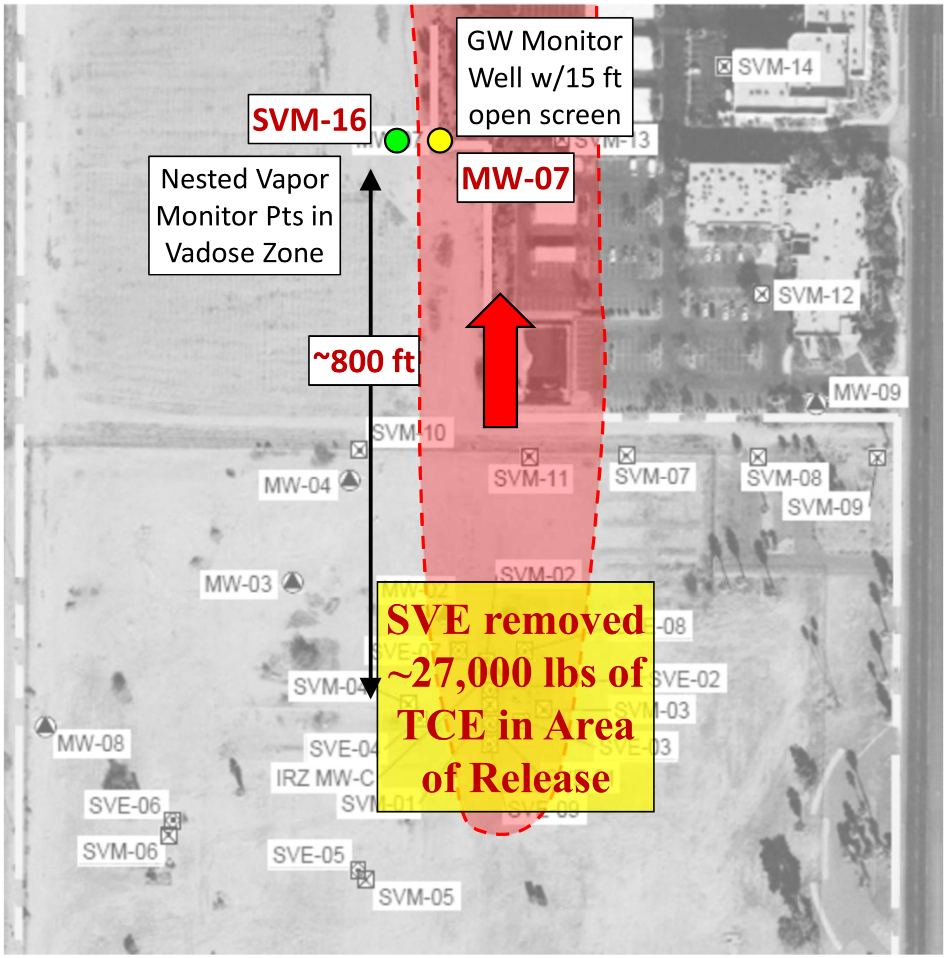
Changes are slow or episodic with low amplitude

Changes are cyclical and episodic with a moderate amplitude

Idk, what do you think?

Changes are cyclical and episodic with a large amplitude

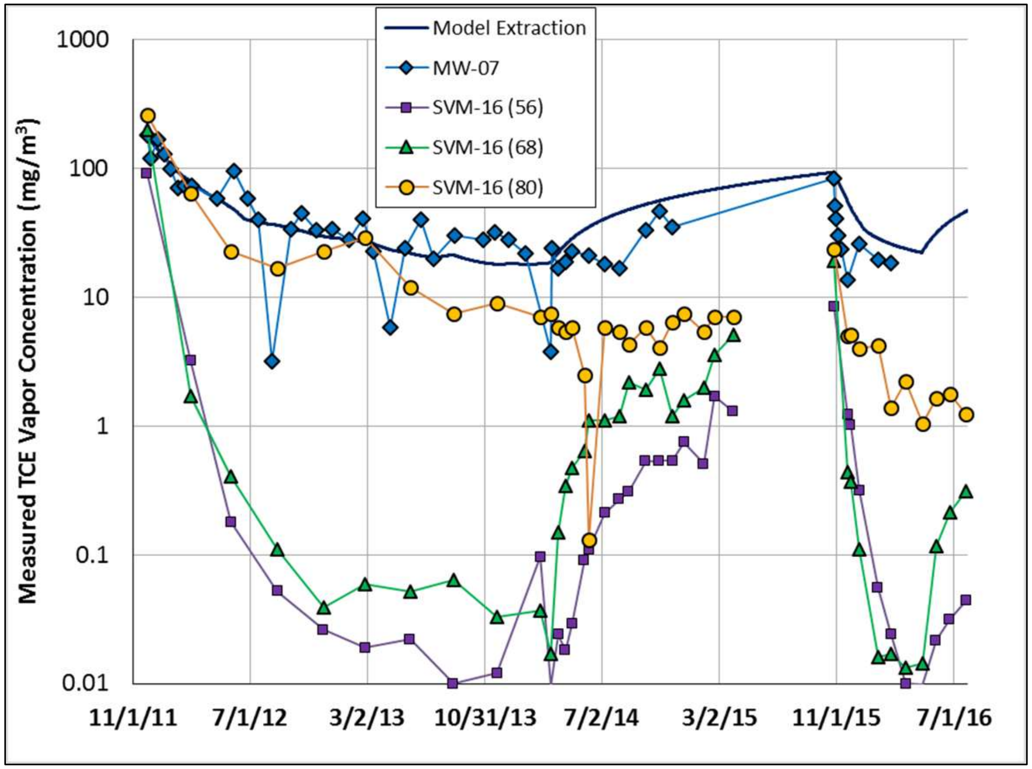
Case Study in Arizona



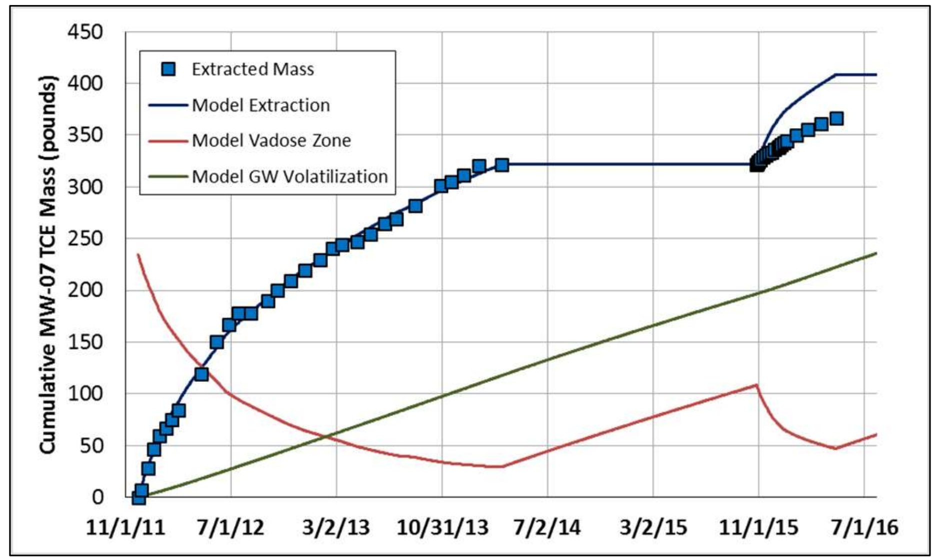
Site Conditions & Remedial History

- 2 decades of SVE removed ~27,000 lbs of TCE from Area of Release
- SVE added to MW-07 removed ~360 lbs
- MW-07 is ~800 feet downgradient
- Water table at ~97 ft bgs
- Clay unit from 45 to 50 ft bgs provides a partial vertical barrier
- Concerns for VI into overlying office buildings

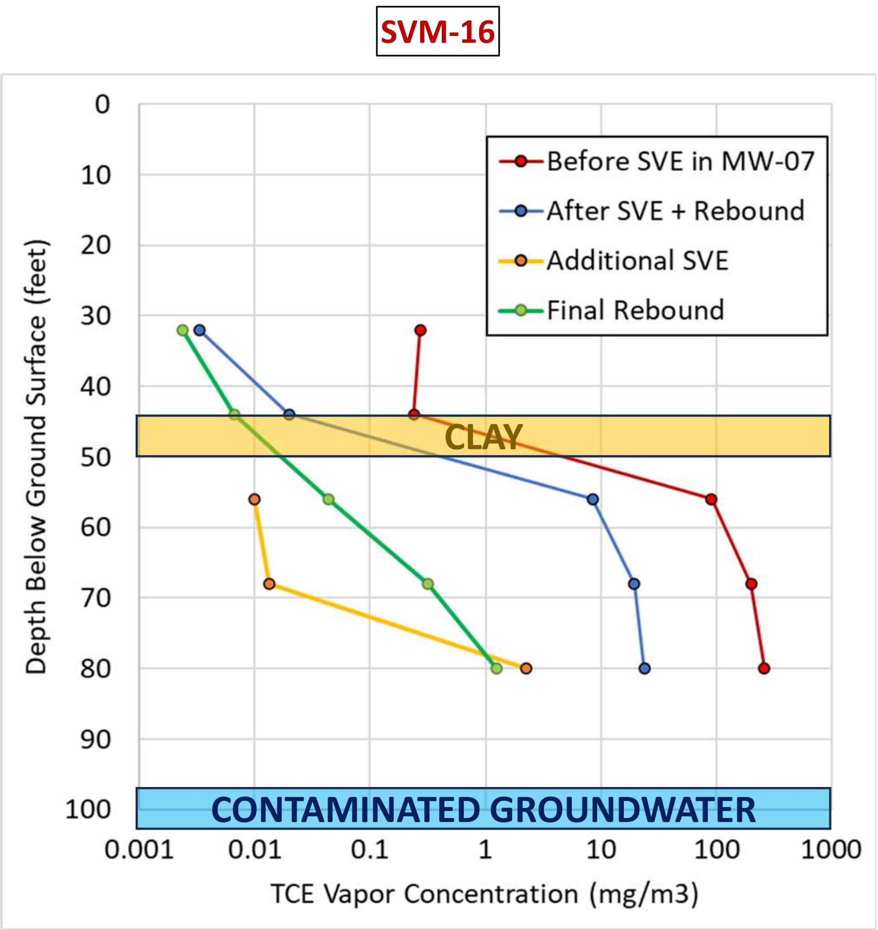
Case Study in Arizona



- SVE can reach far laterally and vertically to reduce vadose zone vapor concs
- SVE contributes to GW cleanup

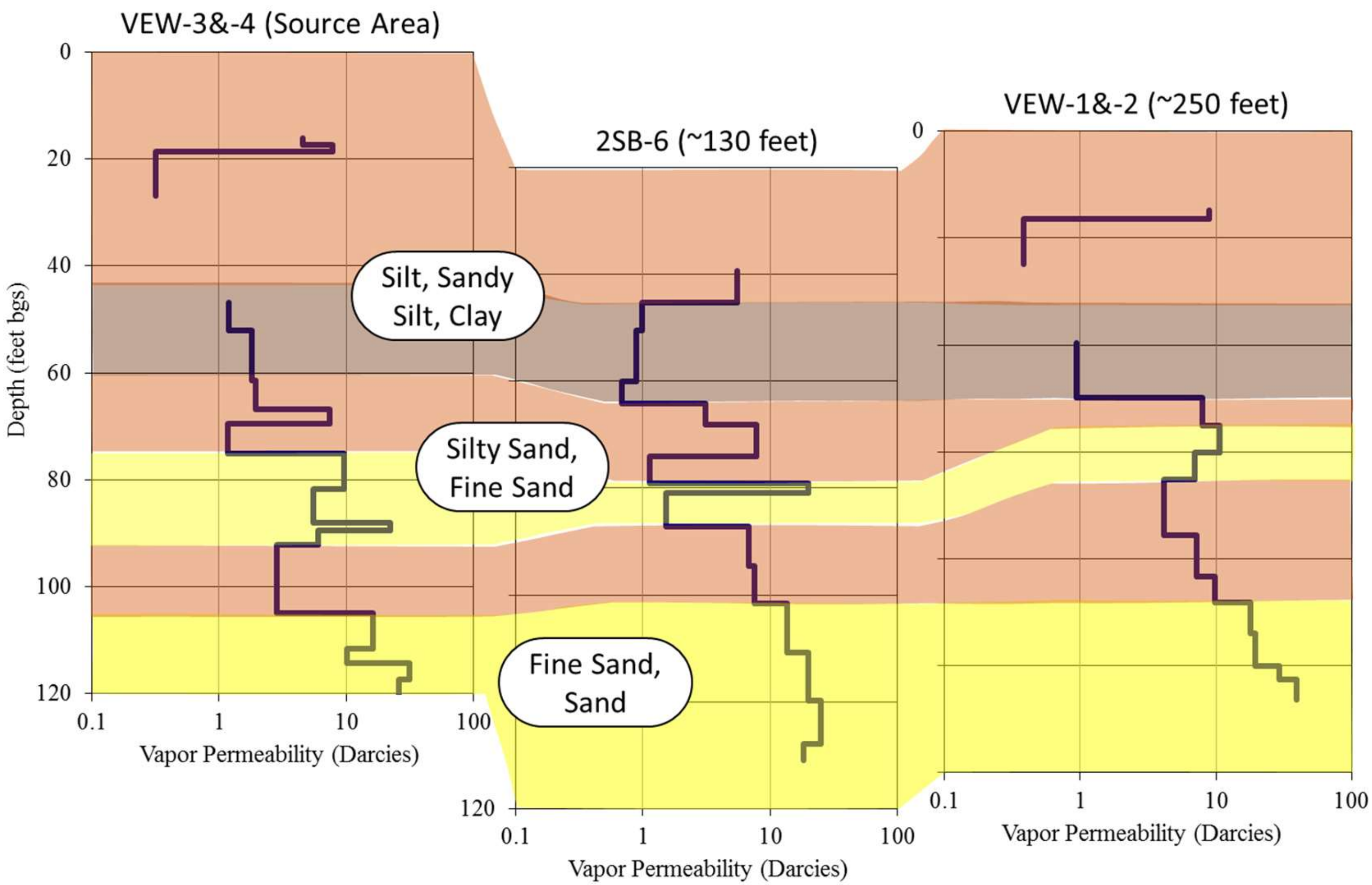


Case Study in Arizona

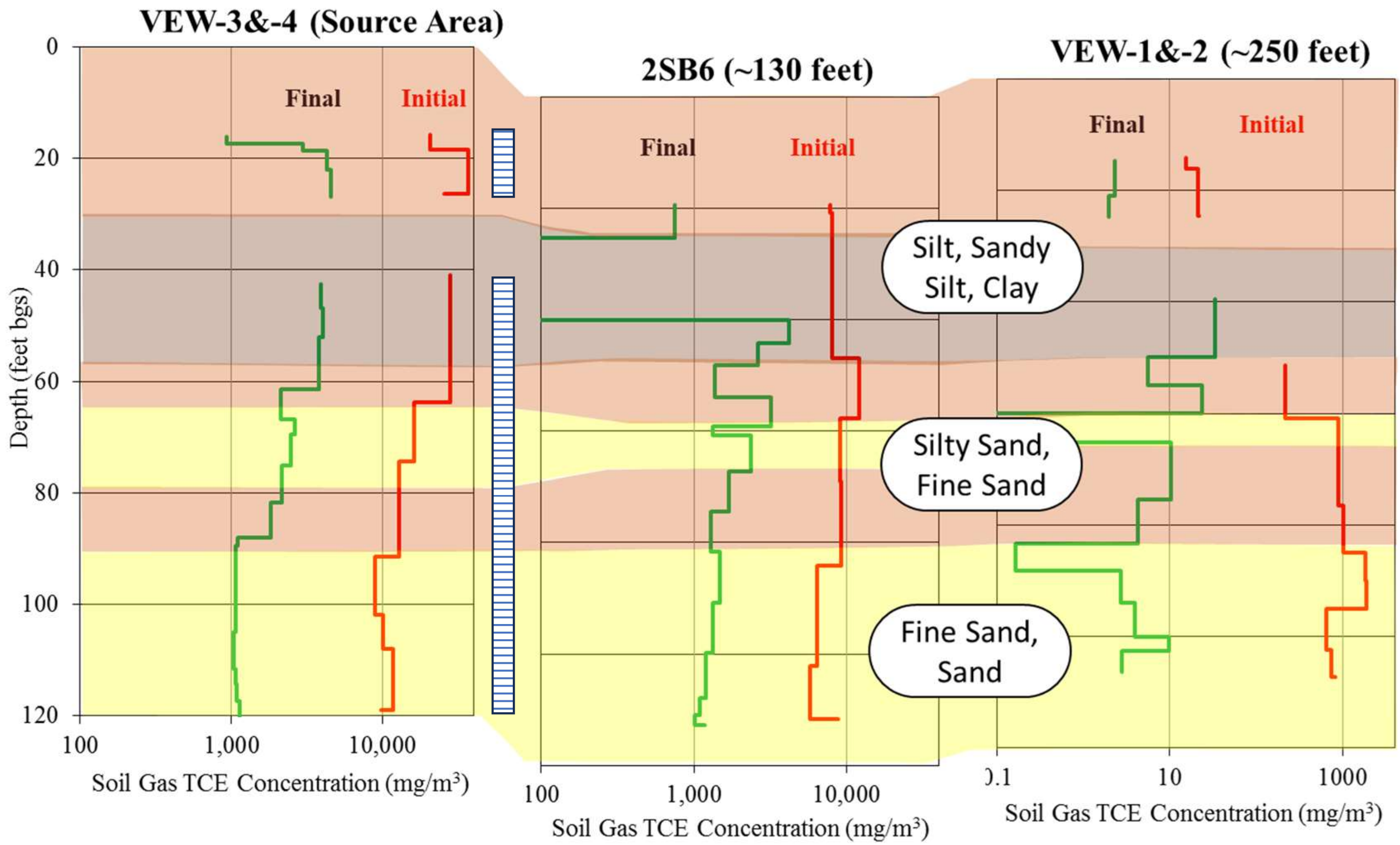


- Clay layer provides a barrier to vapor intrusion
- Groundwater ~1,200 ppb
- Equilibrium Vapor ~460 ppb
- SVE above downgradient plume permanently reduced upward flux

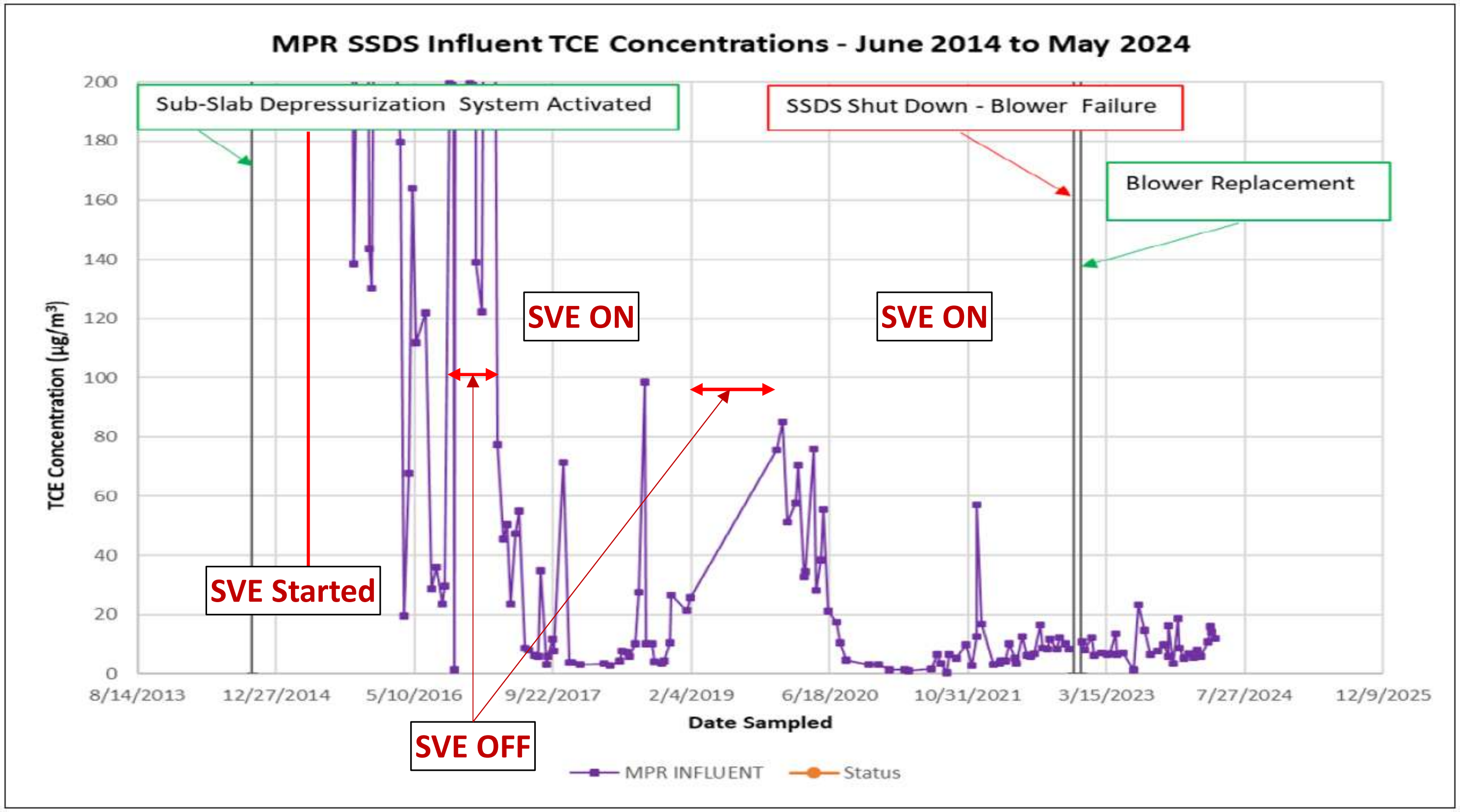
Case Study in New Hampshire



Case Study in New Hampshire



Case Study in New Hampshire



Case Study in Southern California

- Dense urban setting with mixed commercial /manufacturing/ homes
- Site was a metal plating shop using solvents (PCE)
- Prior SVE (1990's) and excavation remedies; VI indicated nearby

Suspected Surface Release Points

Suspected Groundwater Source Mass (Plume)

SS/IA Sampling

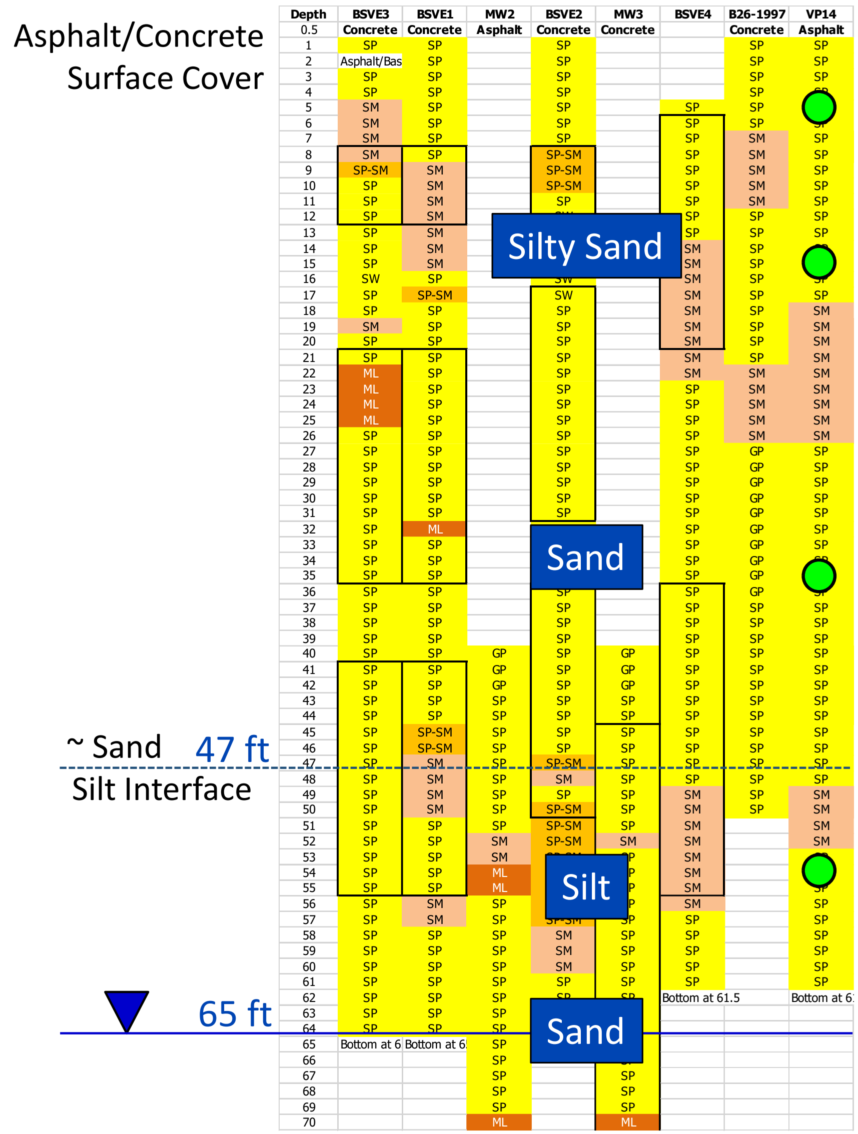
SVE Well

Subsurface Points

Case Study in Southern California

- Asphalt/Concrete Surface Cover
- 4 "model" soil layers
- Water table dropped from 45 to 65 ft bgs after release in '60's – '80's

Geology (pneumogeology?) governs VOC transport in the subsurface

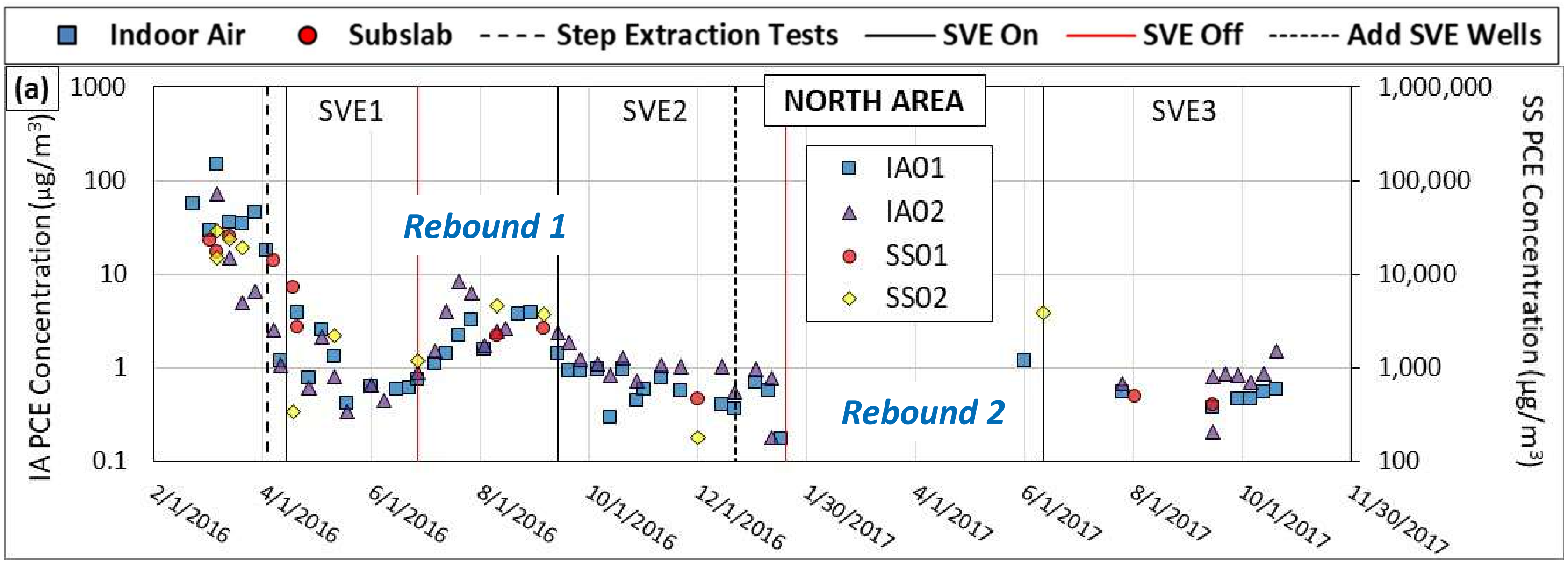


Case Study in Southern California

Results from monitoring wide-area effectiveness

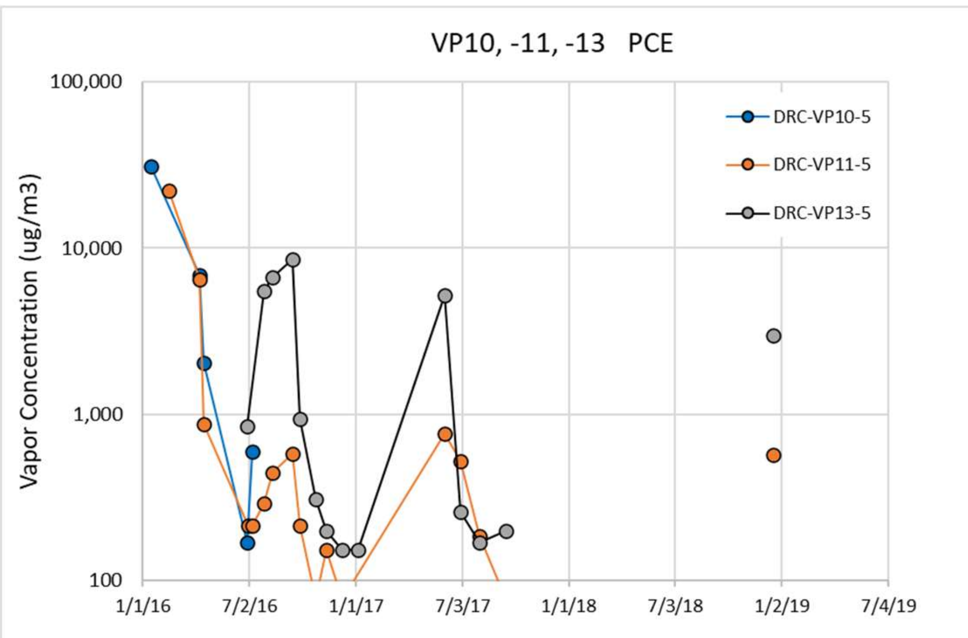
"***Field Study of Soil Vapor Extraction for Reducing Off-Site Vapor Intrusion***", Groundwater Monitoring & Remediation, Jan 2020, https://doi.org/10.1111/gwmr.12359

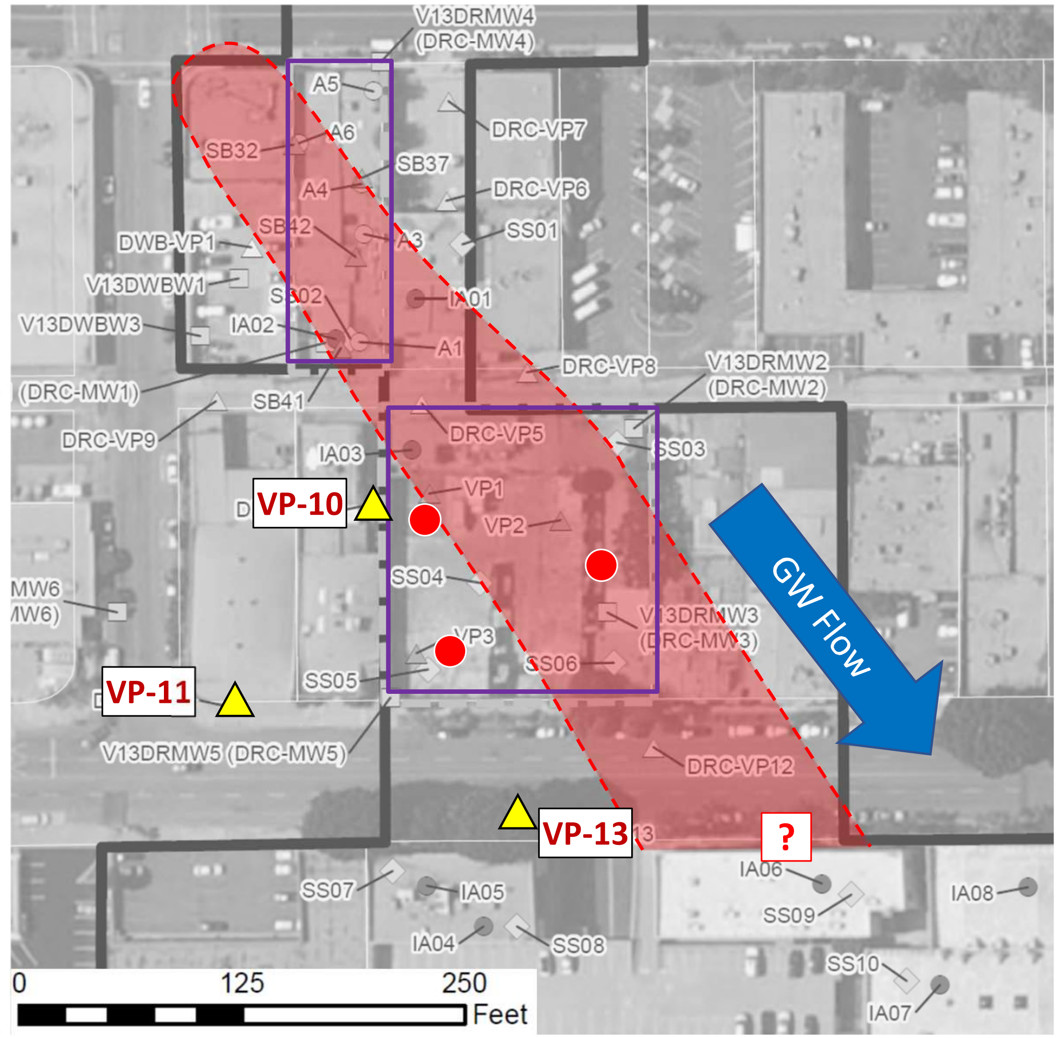
SVE reduces IA and SS concs at buildings 100-200 ft away



Case Study in Southern California

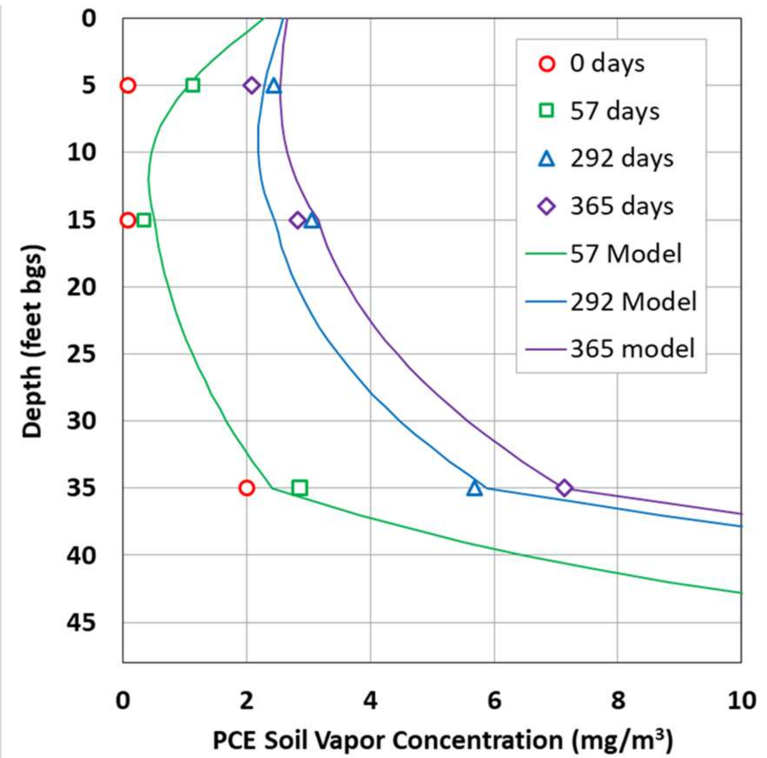
Evaluation of SVE Influence
at 5 ft bgs

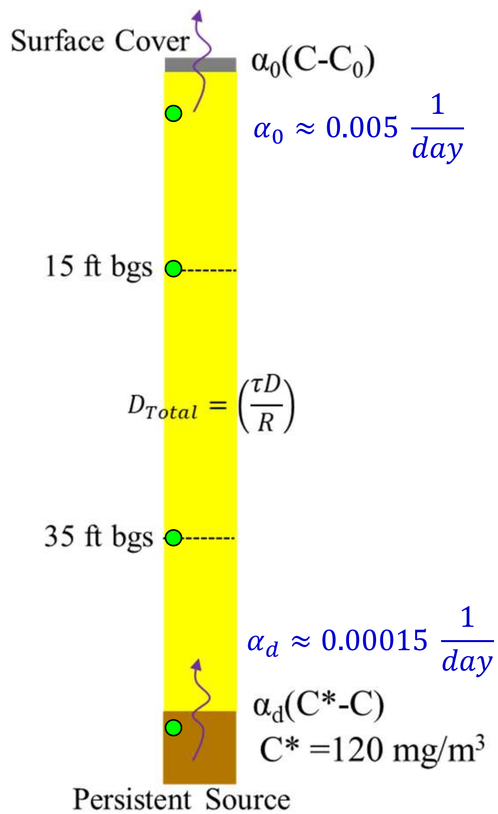


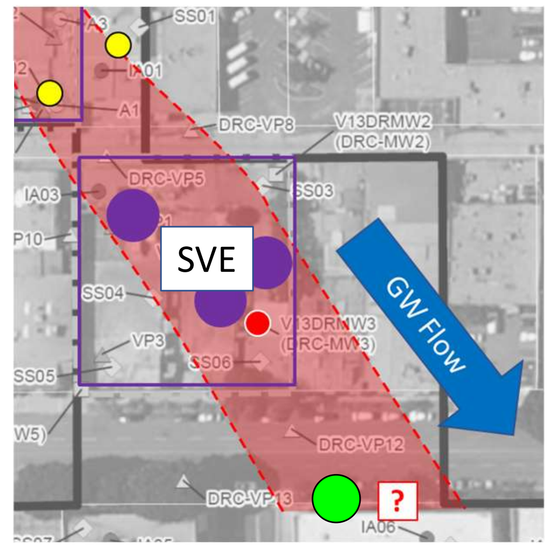


Case Study in Southern California

Evaluation of 1-year of Rebound



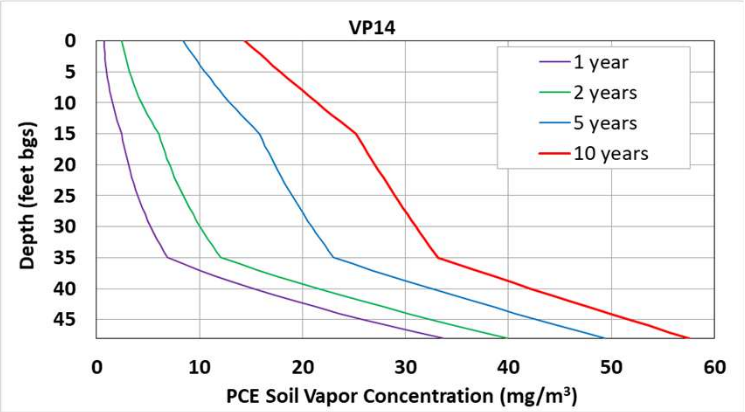


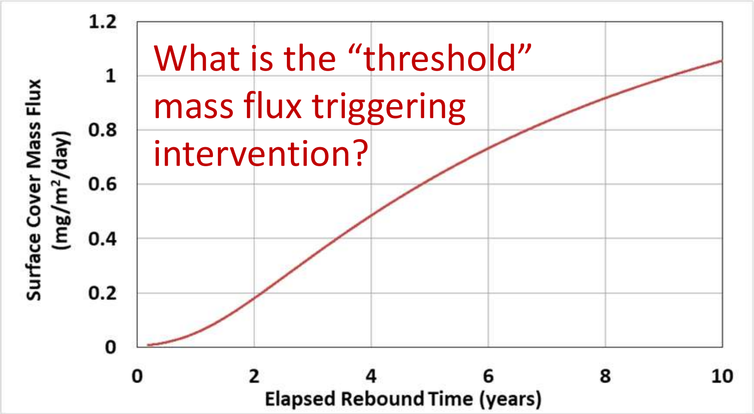


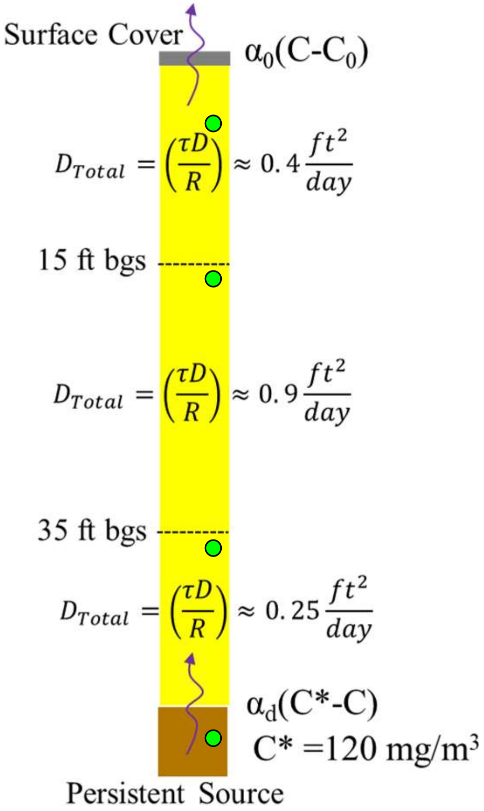
Rebound transients provide reliable data for assessing vapor diffusion coefficients

Case Study in Southern California

Evaluation of Continuous SVE vs Cycling



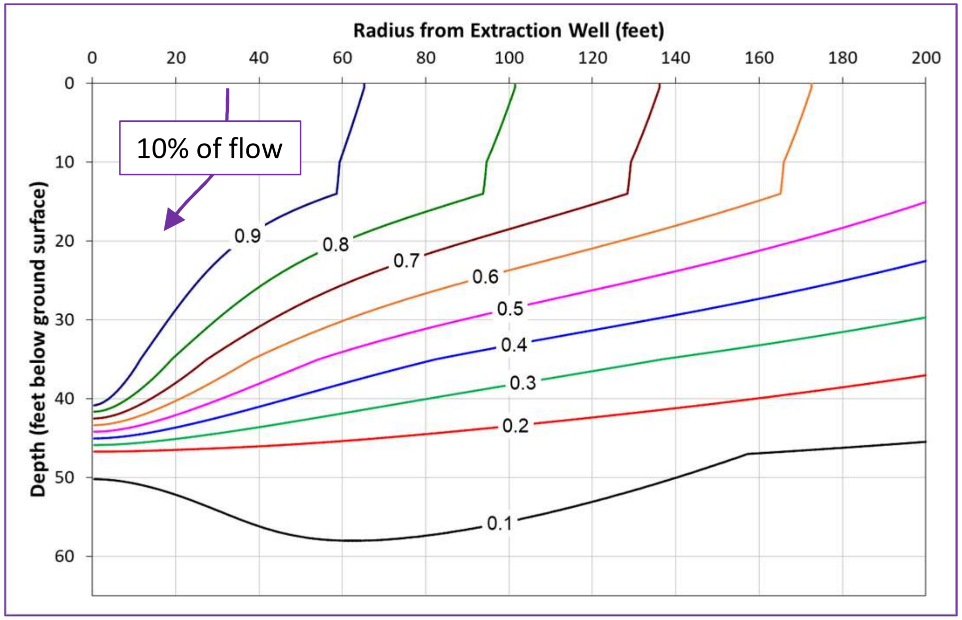




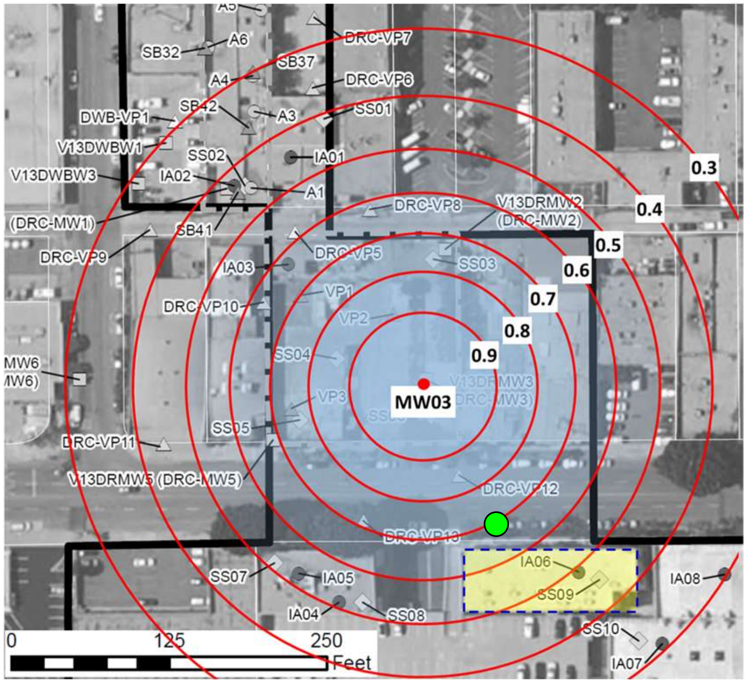
Calibrated transport parameters are reliable predictors; assumed parameters are not.

Case Study in Southern California

Evaluation of Full-Scale SVE vs Soil Gas Containment



Groundwater monitoring well re-purposed for soil vapor control



“***Analytical Solutions for Steady-State Gas Flow in Layered Soils with Field Applications***”, Groundwater Monitoring & Remediation, January 2022, https://doi.org/10.1111/gwmr.12496

Design and Operational Concepts for Soil Vapor Control & Verification: SVE

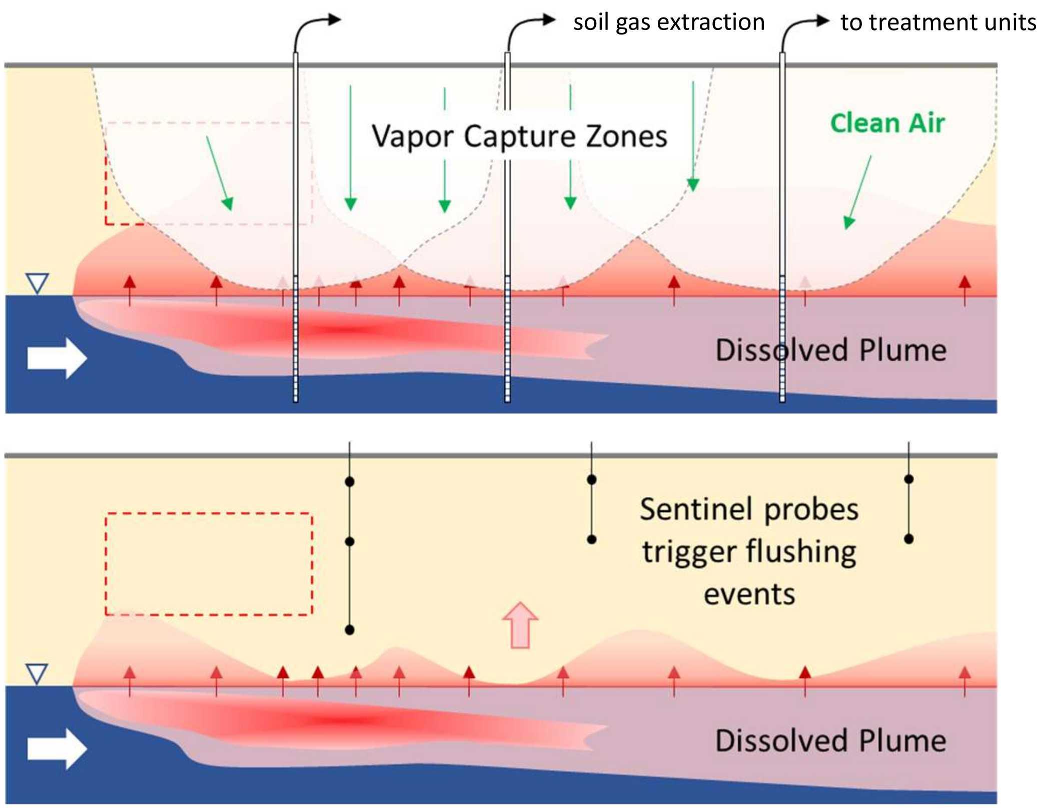
[Vapor Sweep Rate] > [Vertical Mass Transport Rate] = [No opportunity for VI]

Operation is analogous to exchange rates in buildings

Design Issues:

- How far does SVE reach laterally?
- What flow rate and duration provide adequate flush?
- How frequently does the zone require flushing?
- What are appropriate “sentinel” depths and concentrations?

Design and Operational Concepts for Soil Vapor Control & Verification: SVE



Flushing several soil gas pore volumes suppresses the vapor plume, TEMPORARILY

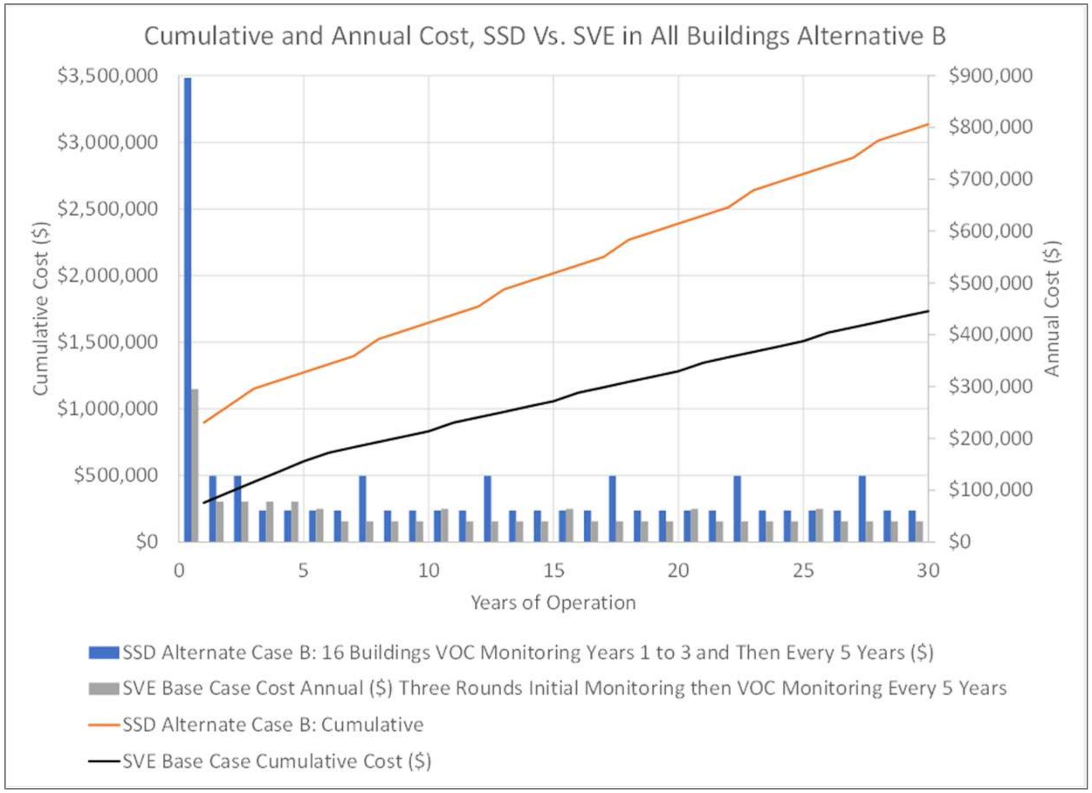
Periodic monitoring of sentinel probes until a threshold concentration is detected; triggers flushing event

Economic Analysis for Soil Vapor Control

Assess cost effectiveness

"***Cost Comparison of Soil Vapor Extraction and Subslab Depressurization for Vapor Intrusion Mitigation***", GWM&R, Spring 2022
https://doi.org/10.1111/gwmr.12510

Cost comparison of individual 16 SSD systems vs cycling an SVE system (see Chris' bullets)



Design and Operational Concepts for Soil Vapor Control & Verification: Barriers

[(Barrier Attenuation)(Source Conc)] < [VISL] = [No opportunity for VI]*

Design Issues for barriers placed in the natural environment:

- How distant should the barrier be placed from pathways?
- Can the barrier's continuity be verified?
- What is the expected lifespan of the barrier?
- What are appropriate methods of verification?

Key Points

- Concentrations in the natural environment are demonstrably more consistent than the built environment
- Migration pathways in the natural environment are more easily controlled than pathways into buildings
- Soil vapor control & verification is best done distant from receptors (e.g., *community vs individual bldgs, reliable*)
- Subsurface samples can predict future; allow readily recognizable, verifiable, achievable goals
- Contaminated soil gas should be treated analogously to contaminated groundwater
- SVE, where applicable, is highly developed and well understood