Pacific Northwest
NATIONAL LABORATORY

How to Evaluate Soil Vapor Extraction Remedy Performance

Guidance and a Tool from the U.S. Department of Energy

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U.S. DEPARTMENT OF ENERGY
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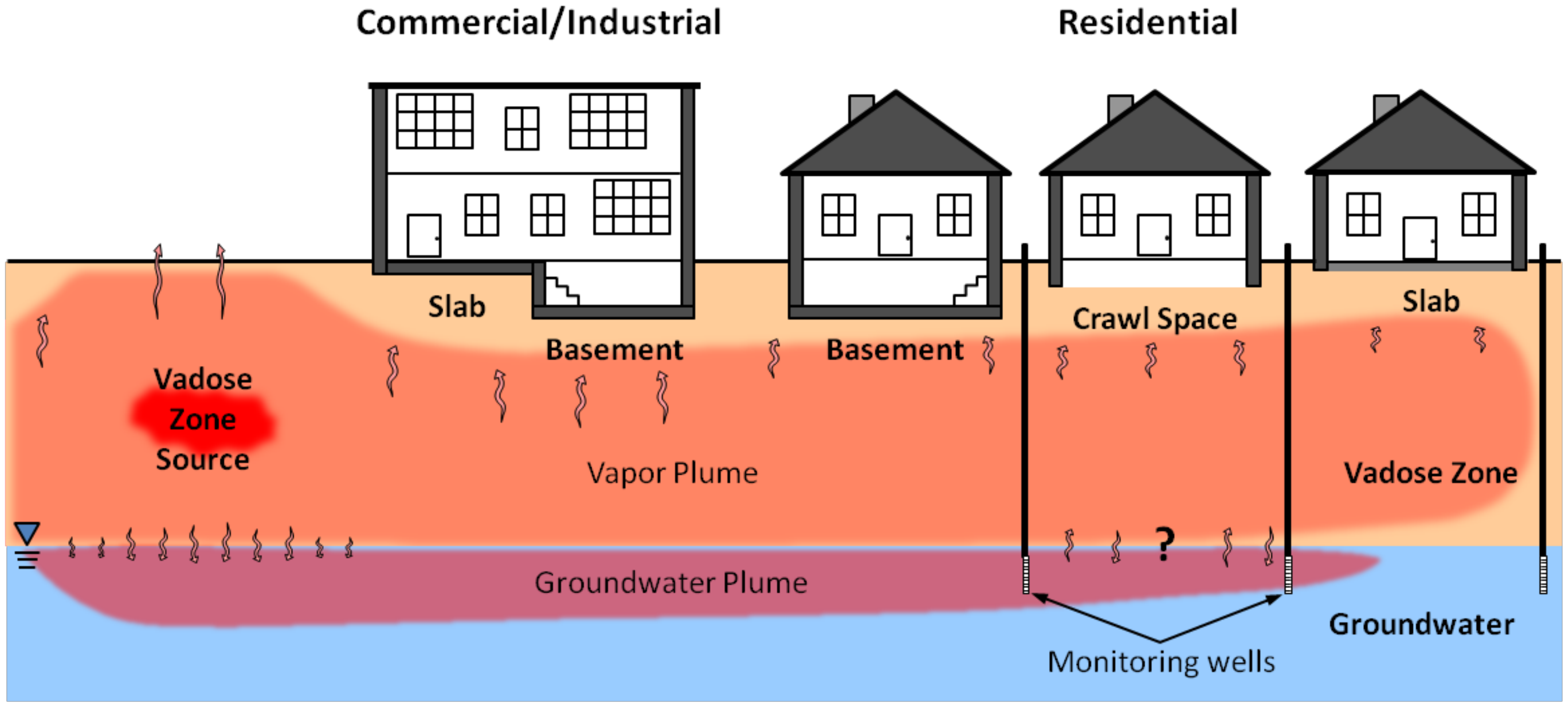
Outline for Today

- Soil vapor extraction (SVE) performance assessment
  - Decisions about vadose zone remediation
  - Structured guidance and decision logic
- Quantifying source impacts
  - SVEET2 tool
  - ESTCP work
- Example applications
- Key takeaways

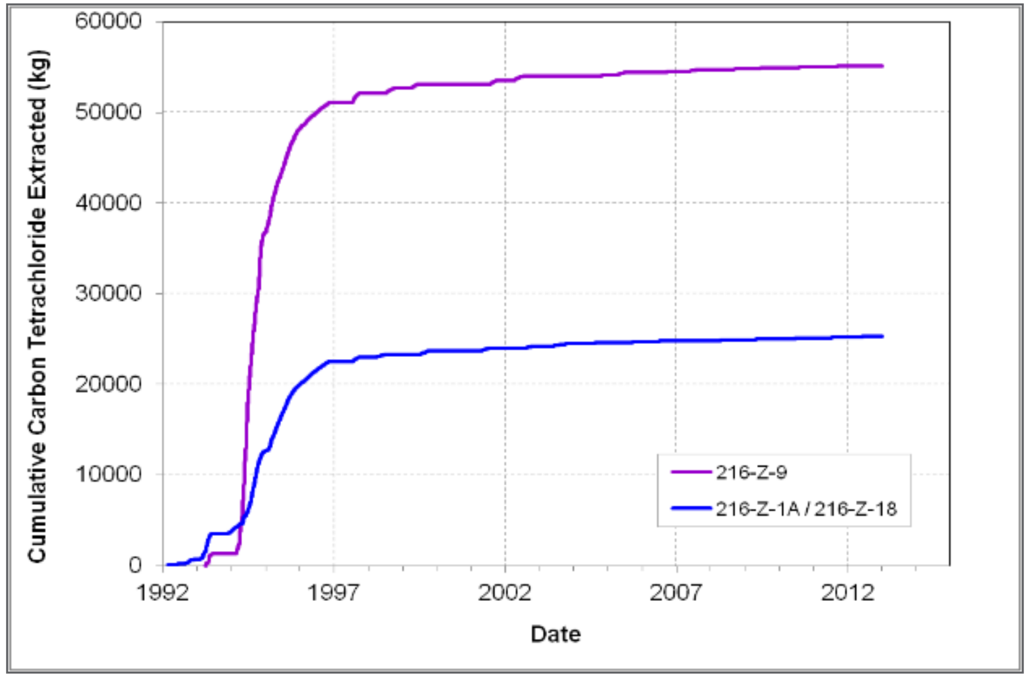


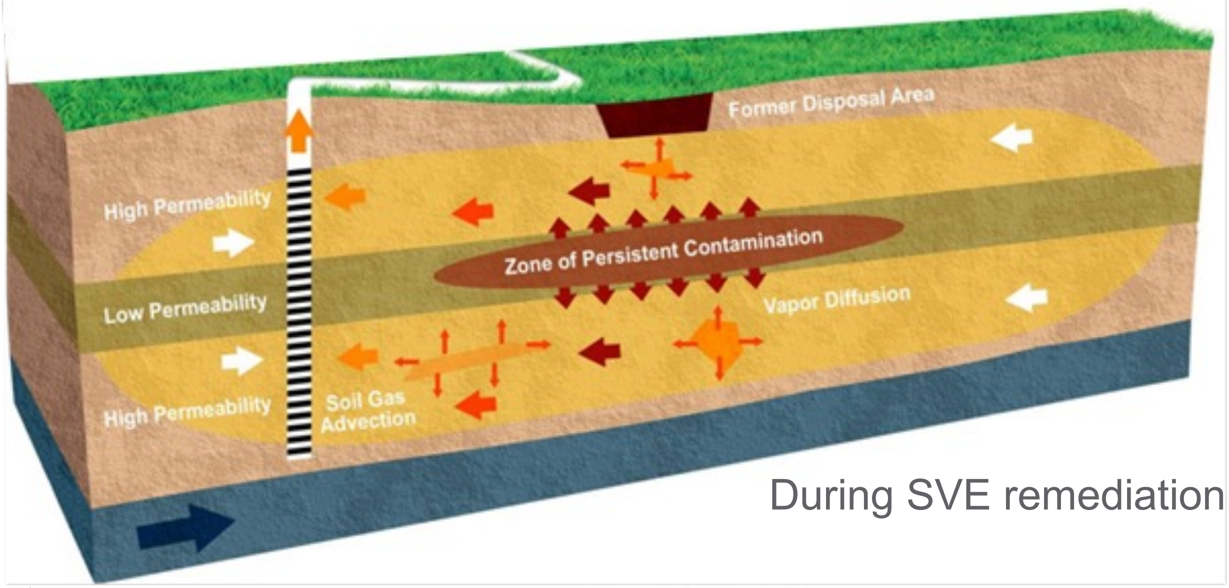
Typical Remediation Questions for Vadose Zone Contamination

- Is SVE needed?
  - Does the vadose zone source pose a risk to groundwater or via vapor intrusion?
- What are the SVE performance goals?
  - For new or currently operating system
  - What mass flux from contaminated zone or soil vapor concentration is acceptable?
- Can SVE be terminated?
  - Will the remaining mass represent a threat to receptors?
- Can alternative technologies address the remaining mass?
  - Cost effectiveness/reasonable duration of active SVE in question

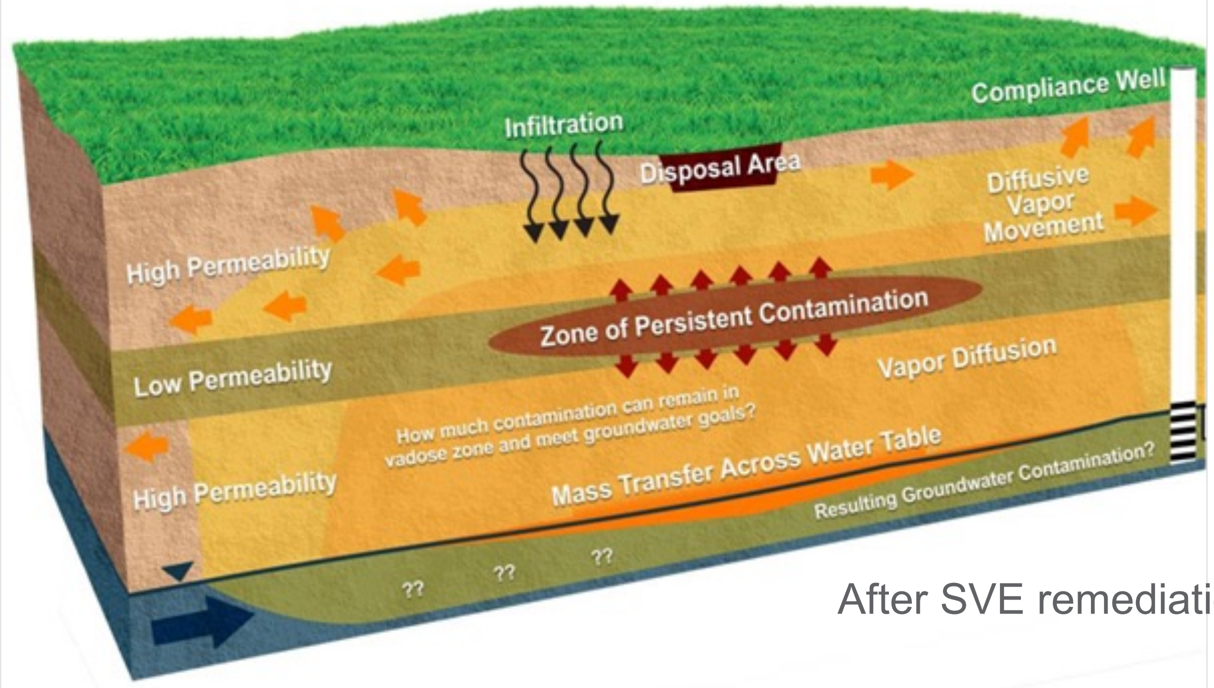
Soil Vapor Extraction (SVE)

- Vacuum extraction of soil gas to remove volatile contaminant vapors
  - Effective, but typically cannot remove all contaminant mass
    - ✓ Diminishing returns





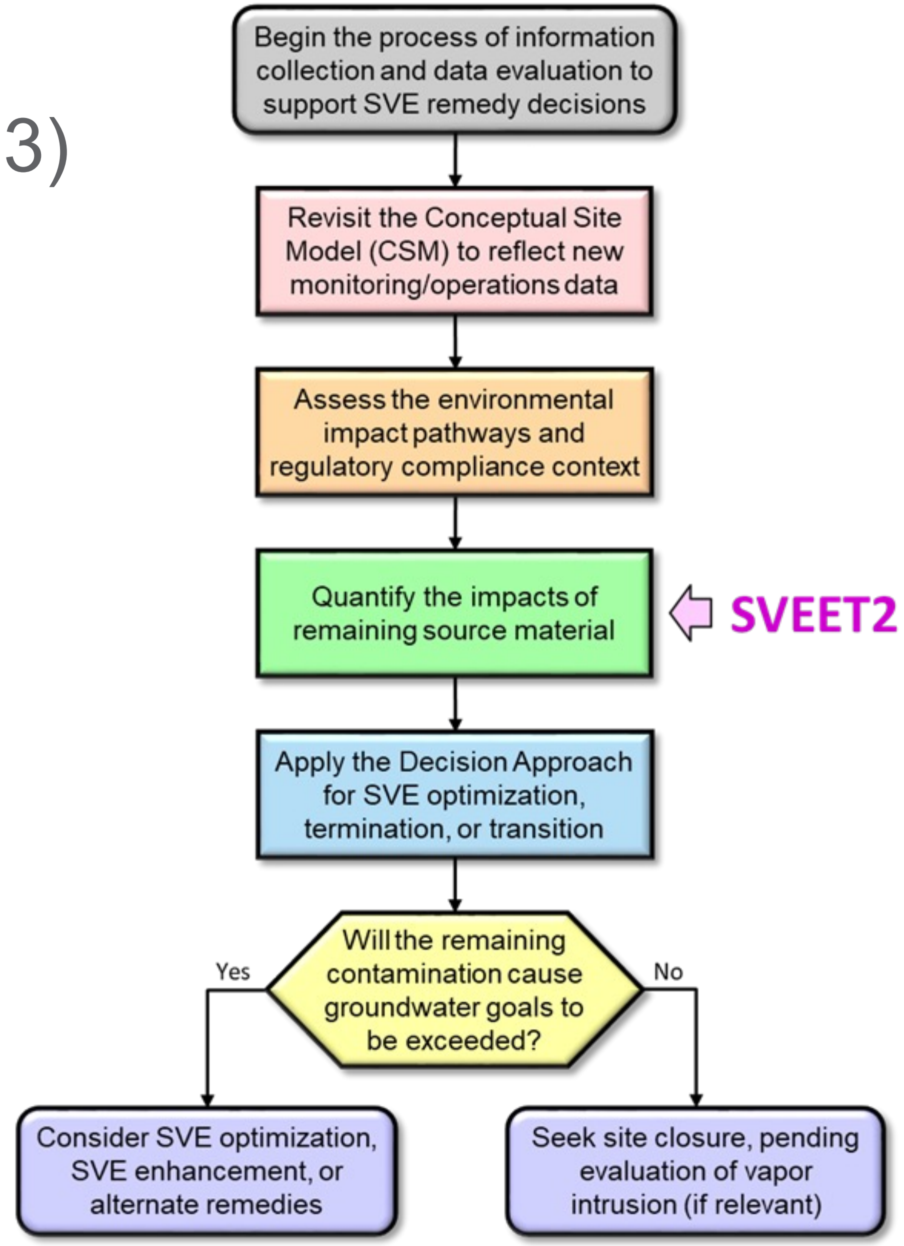
During SVE remediation



After SVE remediation

SVE Performance Assessment

- *Soil Vapor Extraction System Optimization, Transition, and Closure Guidance* (Truex et al., 2013)
- Structured approach
  - Gather/update information
  - Quantify impacts
  - Apply decision logic
- Helps site managers make decisions about vadose zone remediation
  - Continue operations, optimize, terminate, or transition to another remedy
  - Determine remedy goals
- SVEET2 is a companion tool for quantifying the impact of the vadose zone source



Begin the process of information collection and data evaluation to support SVE remedy decisions

Revisit the Conceptual Site Model (CSM) to reflect new monitoring/operations data

Assess the environmental impact pathways and regulatory compliance context

Quantify the impacts of remaining source material

SVEET2

Apply the Decision Approach for SVE optimization, termination, or transition

Will the remaining contamination cause groundwater goals to be exceeded?

Yes

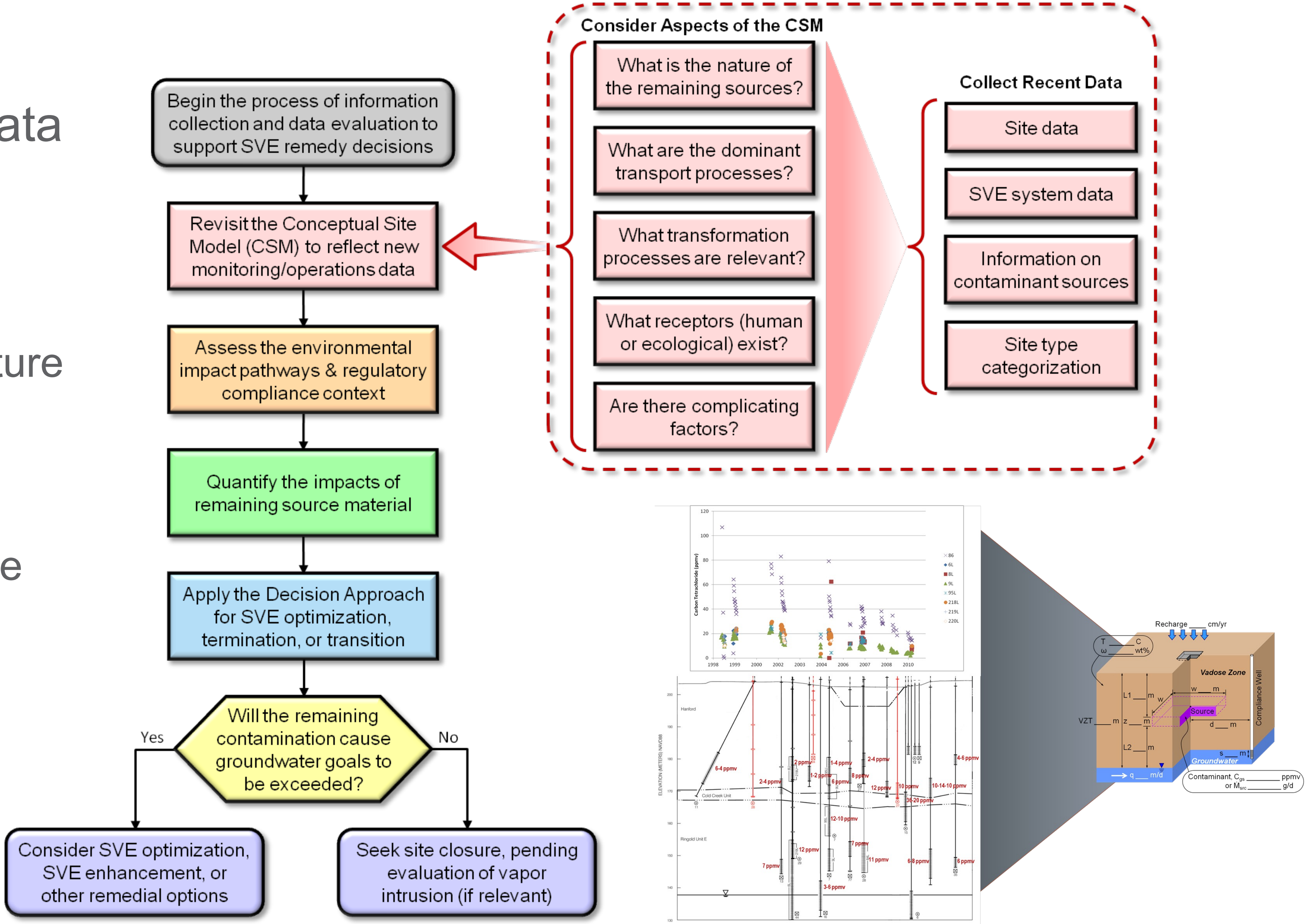
No

Consider SVE optimization, SVE enhancement, or alternate remedies

Seek site closure, pending evaluation of vapor intrusion (if relevant)

Conceptual Site Model (CSM)

- Multiple types of data combine to build a CSM
- Key information:
  - Vadose zone structure and properties
  - Recharge and groundwater flow
  - Contaminant source information
- New site data
- Operations data



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Assess the environmental impact pathways & regulatory compliance context

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Apply the Decision Approach for SVE optimization, termination, or transition

Will the remaining contamination cause groundwater goals to be exceeded?

Yes: Consider SVE optimization, SVE enhancement, or other remedial options

No: Seek site closure, pending evaluation of vapor intrusion (if relevant)

Consider Aspects of the CSM

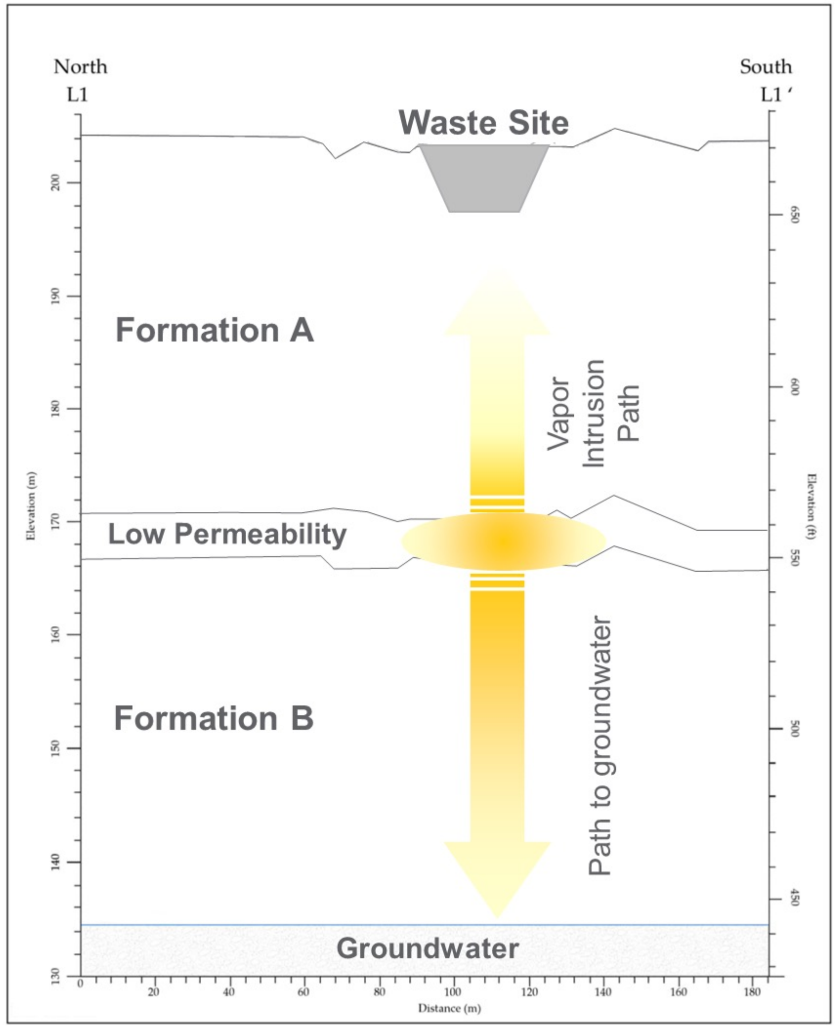
- What is the nature of the remaining sources?
- What are the dominant transport processes?
- What transformation processes are relevant?
- What receptors (human or ecological) exist?
- Are there complicating factors?

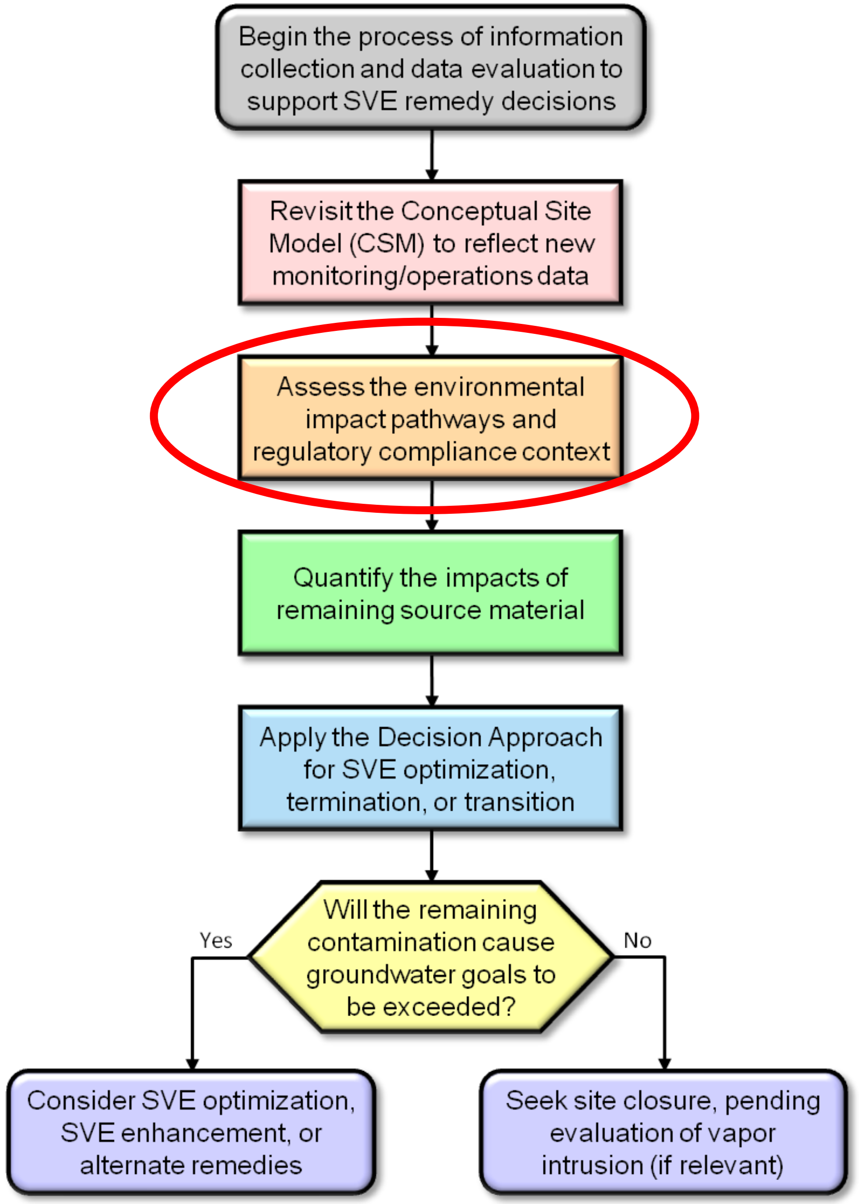
Collect Recent Data

- Site data
- SVE system data
- Information on contaminant sources
- Site type categorization

Environmental Impact and Compliance Context

- Relate remaining source strength to established remediation objectives for exposure pathways
- Exposure Pathways
  - Surface Exposure Pathway
    - ✓ inhalation, direct ingestion, dermal absorption, ingestion of produce
  - Vapor Intrusion Pathway
  - Groundwater Pathway

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Apply the Decision Approach for SVE optimization, termination, or transition

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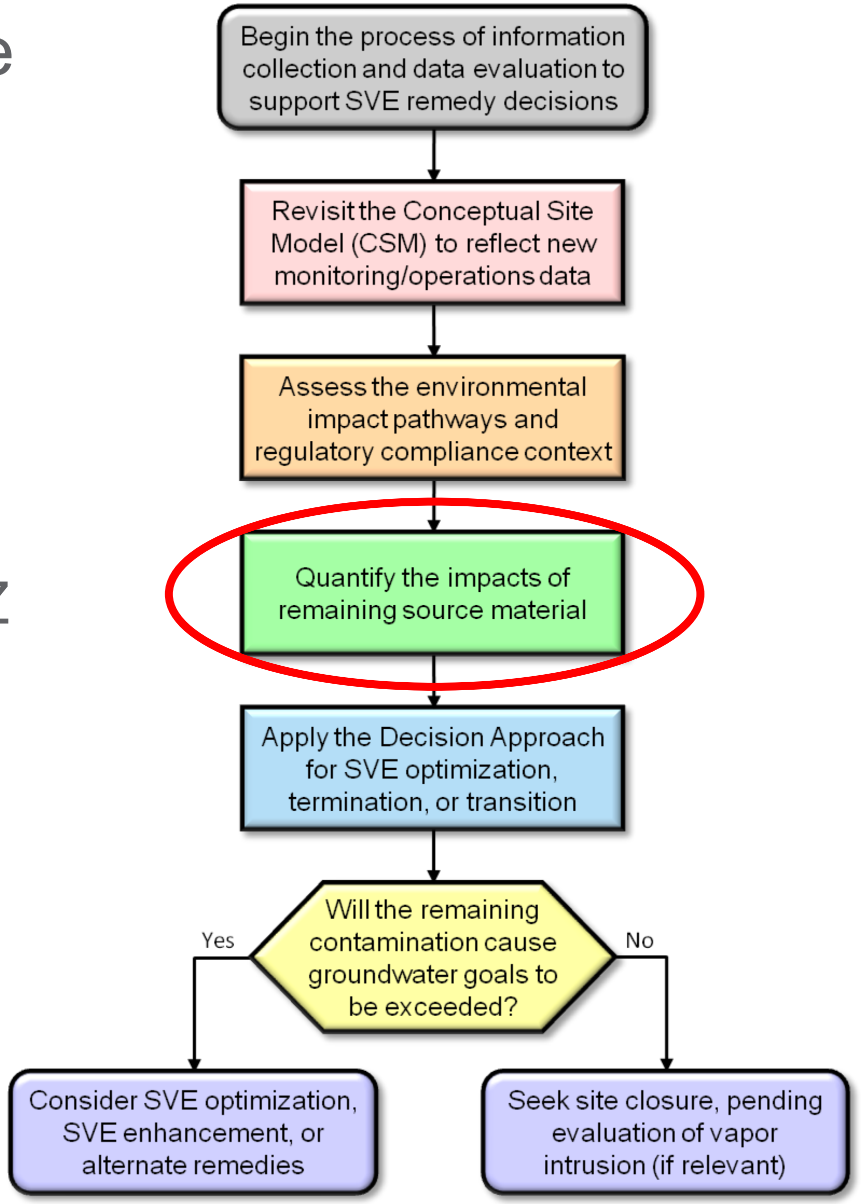
Yes: Consider SVE optimization, SVE enhancement, or alternate remedies

No: Seek site closure, pending evaluation of vapor intrusion (if relevant)

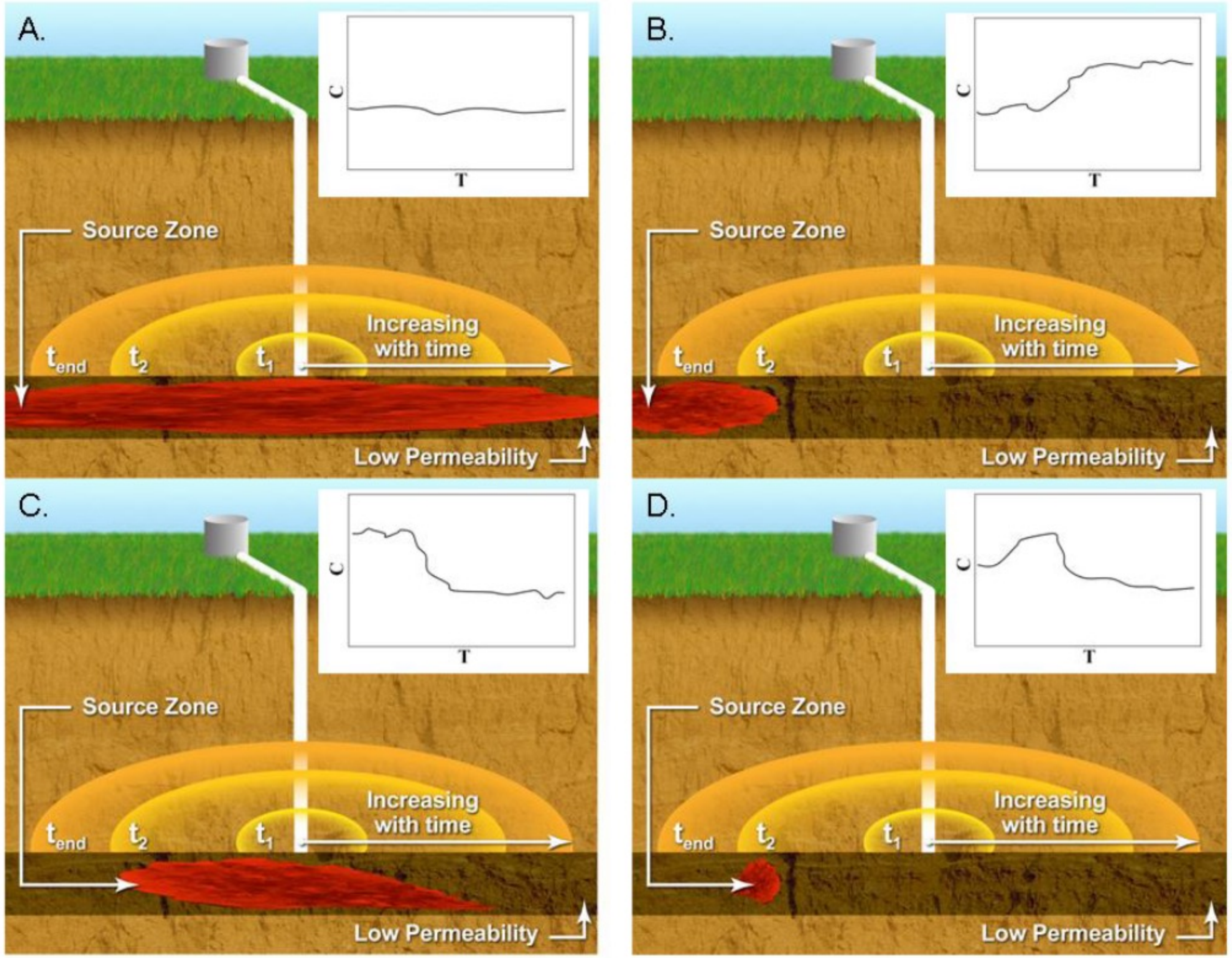
Approach for Quantifying Impact of Remaining Source Material

- Step 1: Quantify the vadose zone (VZ) contaminant source
  - Location
  - Strength (mass discharge or vapor concentration)
- Step 2a: Estimate impact to groundwater (GW)
  - Type I: Low GW concentration, mass transfer from VZ to GW
  - Type II: GW concentration impacts mass transfer from VZ to GW
  - Type III: Primarily GW contamination, mass transfer from GW to VZ
- Step 2b: Estimate impact to vapor intrusion
- Step 3: Estimate impact of source decay/depletion, sorption, and attenuation processes
  - Source depletion: estimate rate of change in mass discharge
  - Sorption: time scale
  - Attenuation processes: time scale, groundwater



SVE Data – Source Location

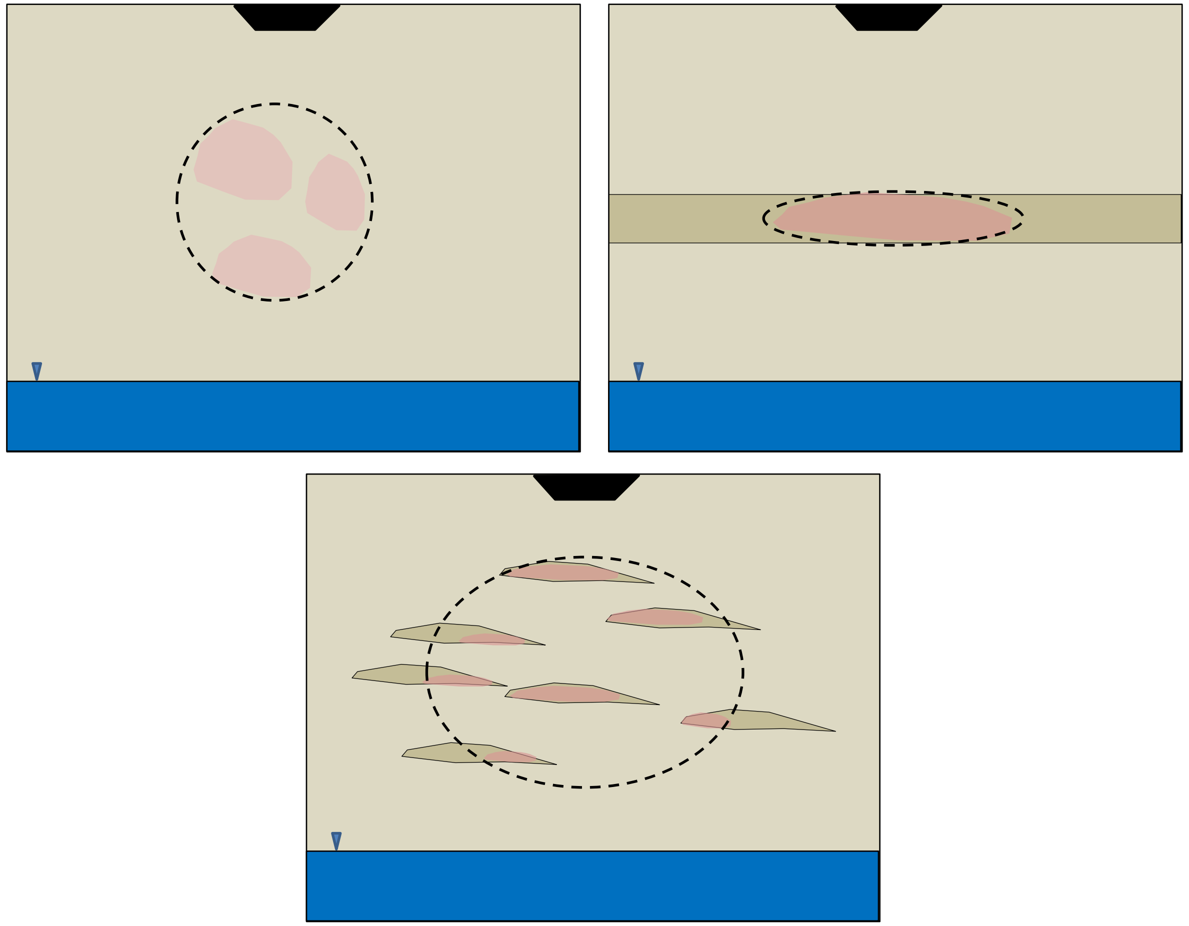
- Mass discharge data to assess source location
- Evaluate data over time to interpret source location
- Use data for multiple distributed wells

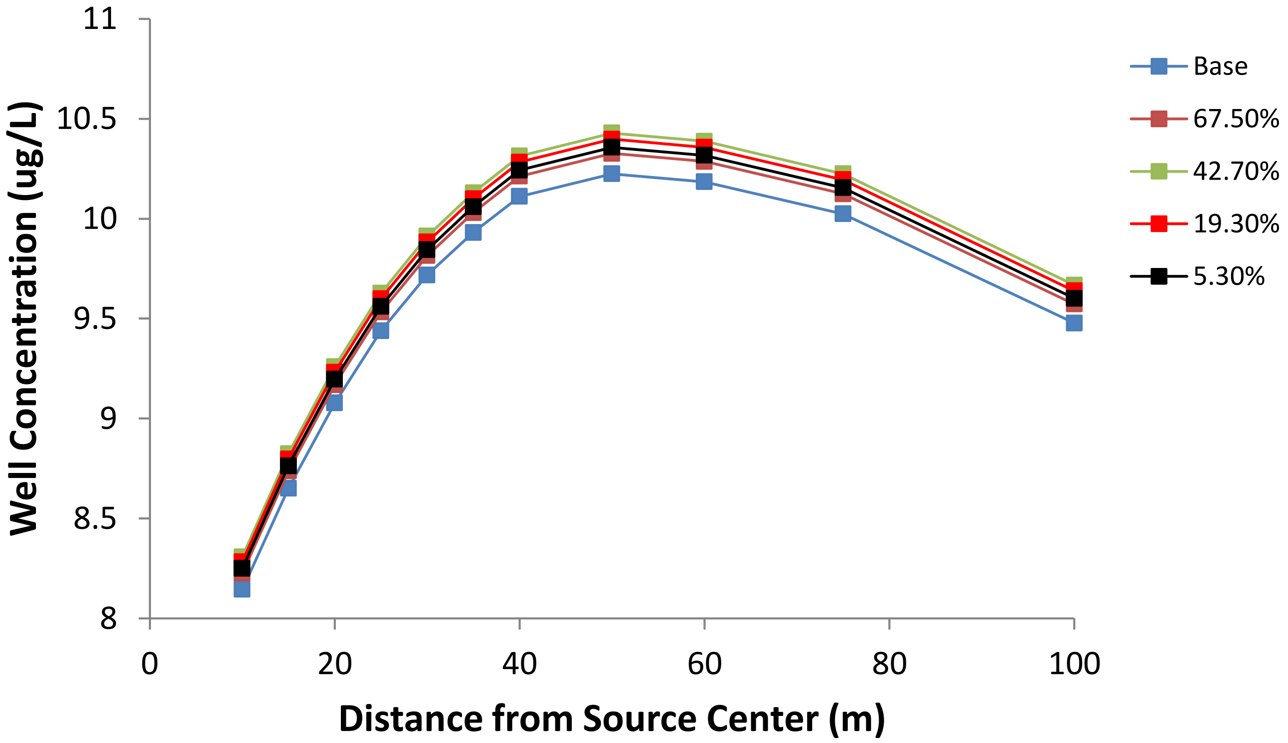


(Carroll et al. 2012, 2013; Truex et al. 2012; Mainhagu et al. 2014; Brusseau 2015)

Source Configuration

- Discrete vadose source zones (versus a uniformly distributed source)
  - Similar patterns of soil gas concentrations
  - Only a small effect on simulated groundwater concentrations

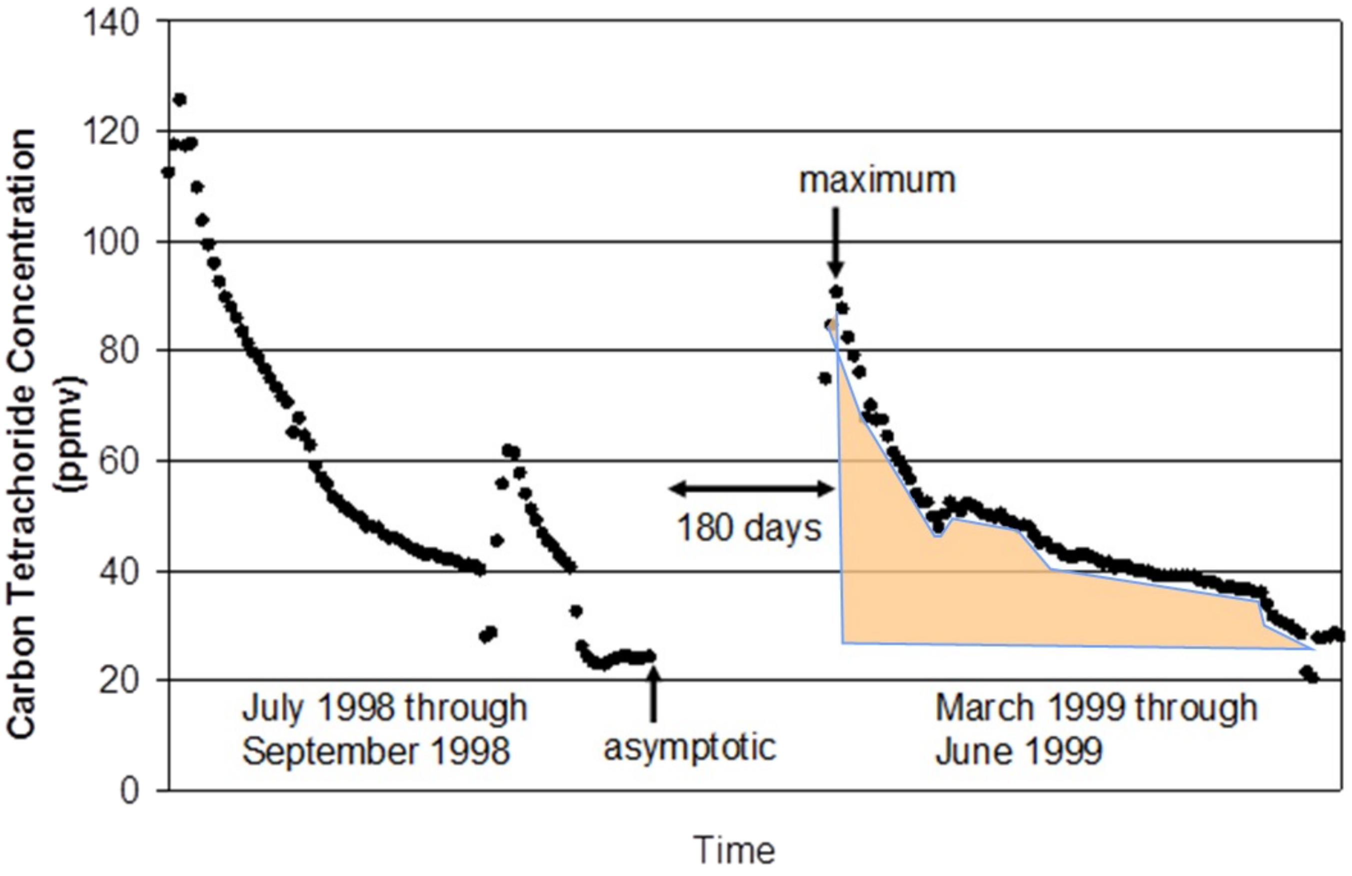




(Truex et al. 2013)

SVE Data – Source Strength

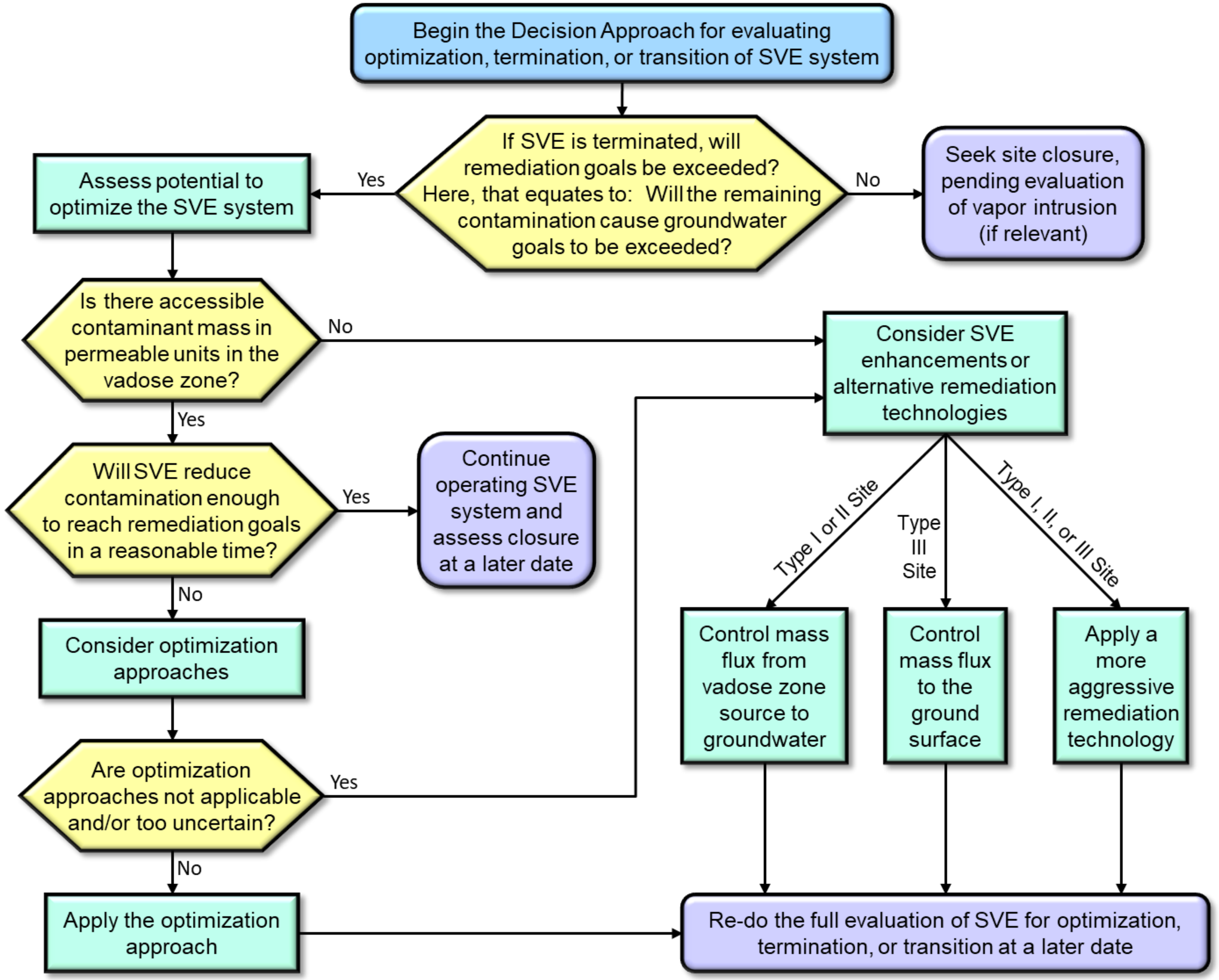
- Data from the SVE system can be used to quantify source strength
  - Contaminant mass discharge
- Rebound analysis
  - Estimate source strength when SVE is halted
  - Can use this information to evaluate whether this source poses a risk



Brusseau et al. 2010; Carroll et al. 2012, 2013; Truex et al. 2012

Soil Vapor Extraction Guidance Decision Logic

- Terminate?
- Continue SVE?
- Optimize SVE system?
- Enhance/Supplement SVE?
    - Targeted areas / hot spots?
- Use alternate treatment technology?
    - Mass flux control or more aggressive technology



Begin the Decision Approach for evaluating optimization, termination, or transition of SVE system

If SVE is terminated, will remediation goals be exceeded? Here, that equates to: Will the remaining contamination cause groundwater goals to be exceeded?

No

Seek site closure, pending evaluation of vapor intrusion (if relevant)

Yes

Assess potential to optimize the SVE system

Is there accessible contaminant mass in permeable units in the vadose zone?

No

Consider SVE enhancements or alternative remediation technologies

Type I or II Site

Control mass flux from vadose zone source to groundwater

Type III Site

Control mass flux to the ground surface

Type I, II, or III Site

Apply a more aggressive remediation technology

Yes

Will SVE reduce contamination enough to reach remediation goals in a reasonable time?

Yes

Continue operating SVE system and assess closure at a later date

No

Consider optimization approaches

Are optimization approaches not applicable and/or too uncertain?

Yes

No

Apply the optimization approach

Re-do the full evaluation of SVE for optimization, termination, or transition at a later date

Possibilities for Optimization and Supplemental Technology

- Optimization or enhancement approaches
  - Focus active extraction in areas with significant mass removal
  - Add/replace extraction wells to get better spatial distribution or screened intervals
  - Add passive/active air injection wells to help air throughput
  - Pulse the extraction system
    - ✓ May achieve the same mass removal with lower operational costs
  - Passive extraction
  - Hydraulic or pneumatic fracturing to increase permeability
- Supplemental or replacement technologies
  - Bioventing
  - Multi-phase extraction
  - In situ air sparging
  - In situ thermal treatment
  - Oil injection

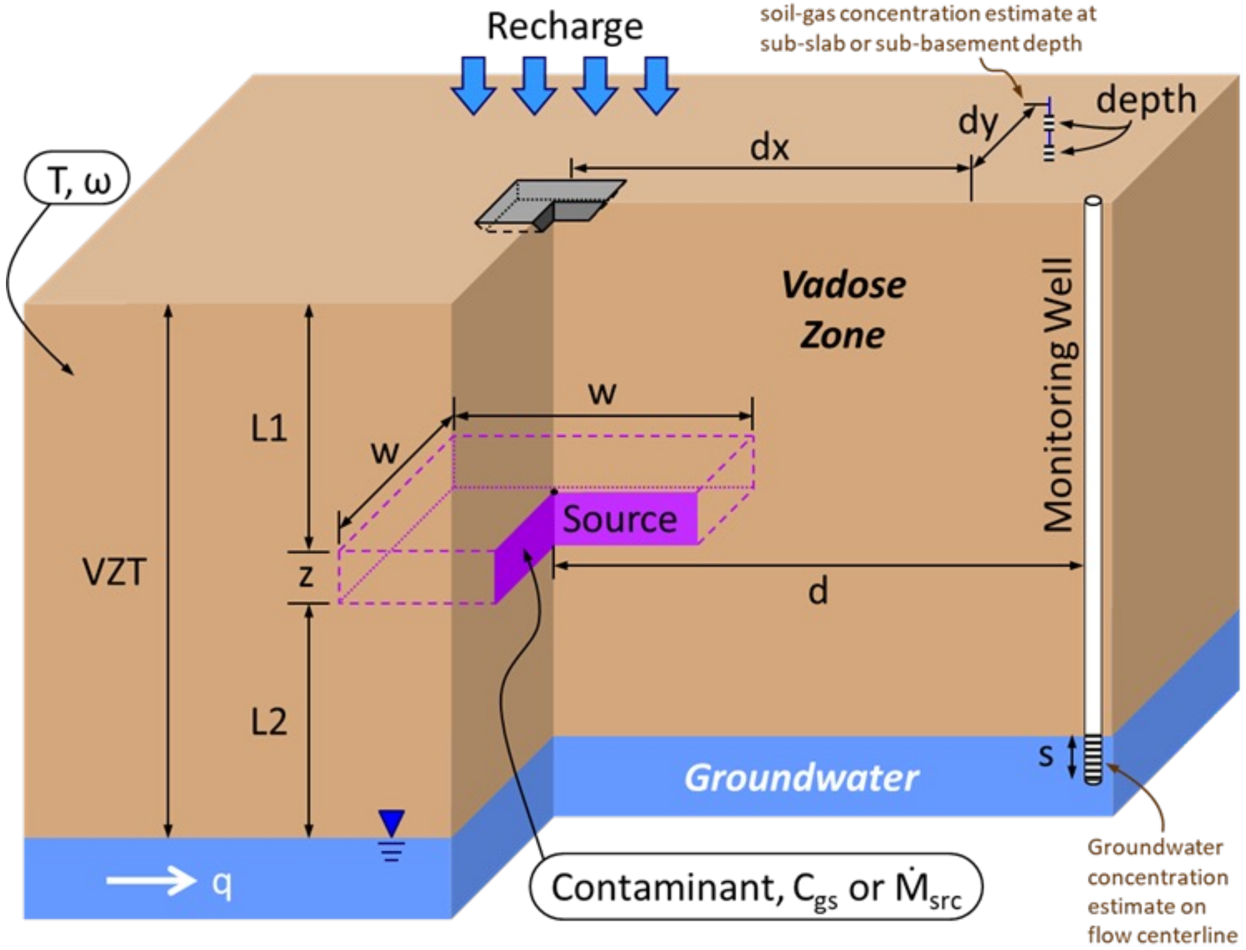
Brief Description of SVEET2

- User-friendly spreadsheet tool
  - Input a small number of parameters to describe site and vadose zone source
  - Estimates contaminant concentrations in groundwater and soil gas
- Soil Vapor Extraction End-state Tool (v. 2) – updated through ESTCP project
  - Objective: provide DoD with a widely applicable tool to support assessment of volatile contaminant remediation in the vadose zone
    - ✓ Enhanced functionality and acceptability for DoD applications in support of remediation decisions
  - Provide basis for potentially significant reductions in DoD's cost to complete
- Rigorous underlying basis
  - 5760 numerical simulations (pre-modeled scenarios)
  - Contaminant transport under natural conditions (vapor-phase diffusion, recharge, & mixing into GW)
- SVEET2 itself is not a numerical model
  - Interpolates between pre-modeled scenarios
  - Scaling for parameters with linear relationship

Generalized Conceptual Framework

- Conceptual framework for describing a site
- Based on prior studies to determine controlling parameters
  - Lower permeability layers have only small effect on long-term vapor transport
  - For vapor-phase dominated transport, contaminant concentrations controlled by limited set of parameters
- Key parameters
  - Sr – residual saturation
  - VZT – vadose zone thickness
  - RSP – relative source position
  - SA – source area (footprint)
  - q – groundwater flow rate

  - Source strength
  - Recharge
  - Partitioning



Numerical Simulations

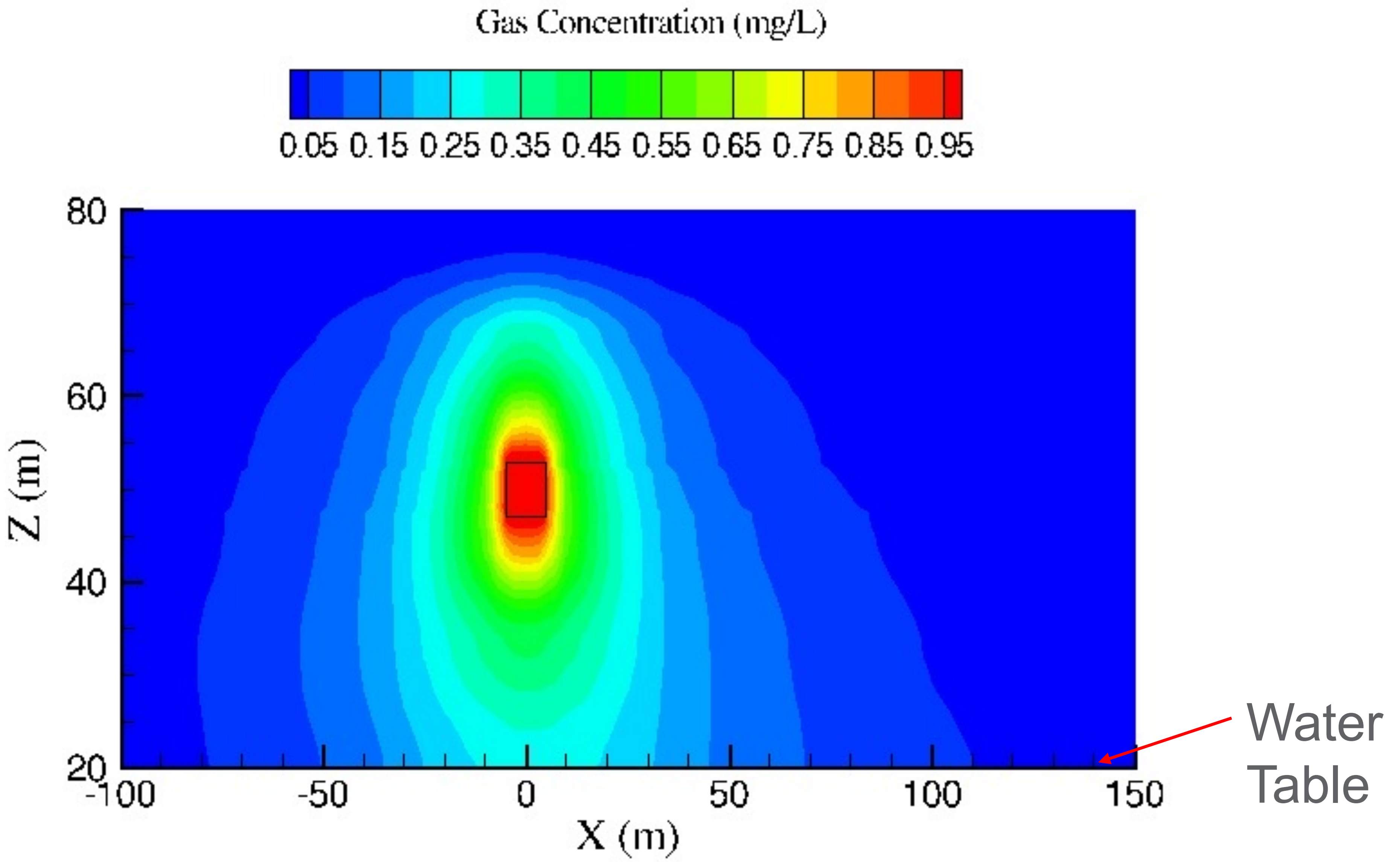
- Used the STOMP (Subsurface Transport Over Multiple Phases) code
  - Fully-implicit, integrated finite difference model (White and Oostrom, 2006)
  - Governing equations: mass-conservation equations for water, volatile organic compounds (VOCs), and air
- 3-D domain: 2000 m long (x), 500 m wide (y), and variable height (depending on the case)
  - Emphasis of grid refinement on the region near the water table, source boundaries, and domain top
- Simulations were conducted for a base case set of parameter values and 5759 other parameter permutations
  - Carbon tetrachloride was selected as the base case VOC
  - Other VOCs are considered through variation of contaminant-specific properties
- SVE process itself was not simulated
- An immobile organic liquid phase was emplaced in the source zone at a saturation of ~2-3%
  - If needed, organic liquid was automatically replenished.
- Transport simulations were conducted for 200 years, although steady-state conditions were often reached within a few years

Numerical Model Assumptions

- Water content is maintained at uniform value throughout the vadose zone
- Mass loading from the vadose zone into the groundwater is maximized by imposing a water saturation in the range of 0.24 to 0.27 in the lowest unsaturated grid block
- Water table is assumed to be effectively horizontal over computational domain
- Gas-phase diffusion and tortuosity in source zone are not affected by organic liquid content in source zone
- Sorption may delay impact to groundwater, but has minimal impact on the overall long-term contaminant distribution for a constant strength source (Carroll et al. 2012)

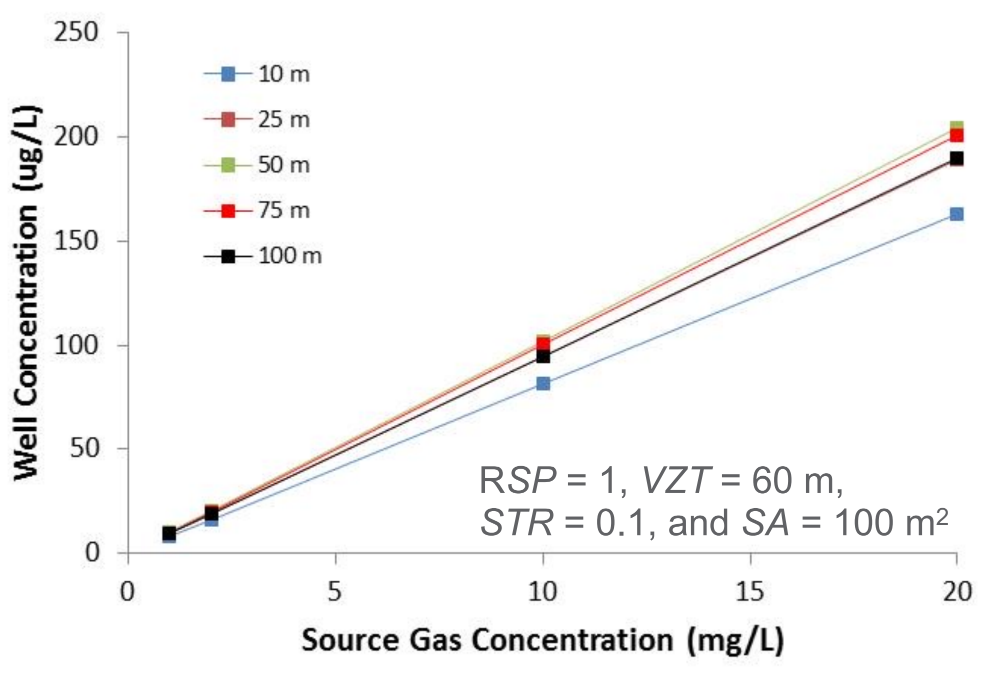
Example Simulation Results

- VOC transport simulated until steady state conditions were obtained
- CT concentration

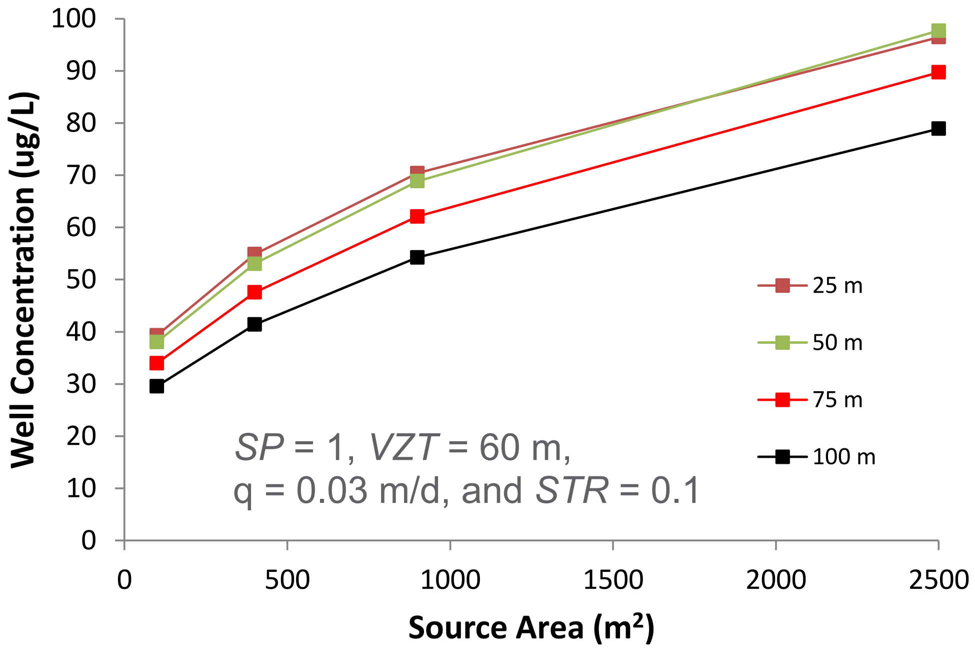


Relationship of Parameters to Groundwater

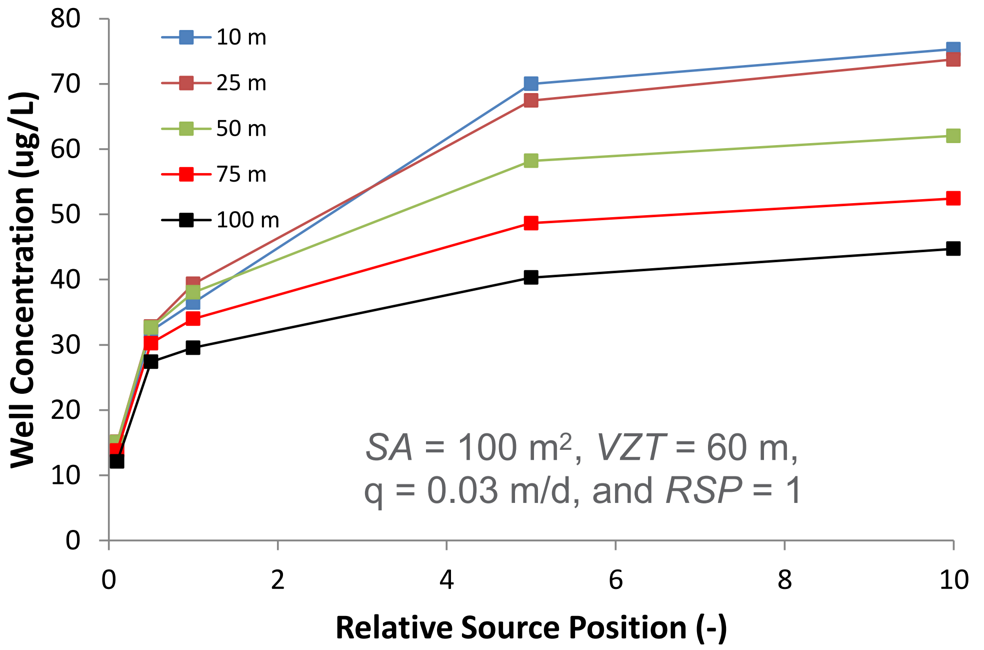
- If vapor diffusion is the dominating vadose zone VOC transport mechanism
  - Mass flux into groundwater controlled by site-specific dimensions, vadose zone properties, and source characteristics
- Relationships are either linear or nonlinear:



RSP = 1, *VZT* = 60 m, *STR* = 0.1, and *SA* = 100 m^2



SP = 1, *VZT* = 60 m, q = 0.03 m/d, and *STR* = 0.1



SA = 100 m^2, *VZT* = 60 m, q = 0.03 m/d, and *RSP* = 1

(Oostrom et al. 2014)

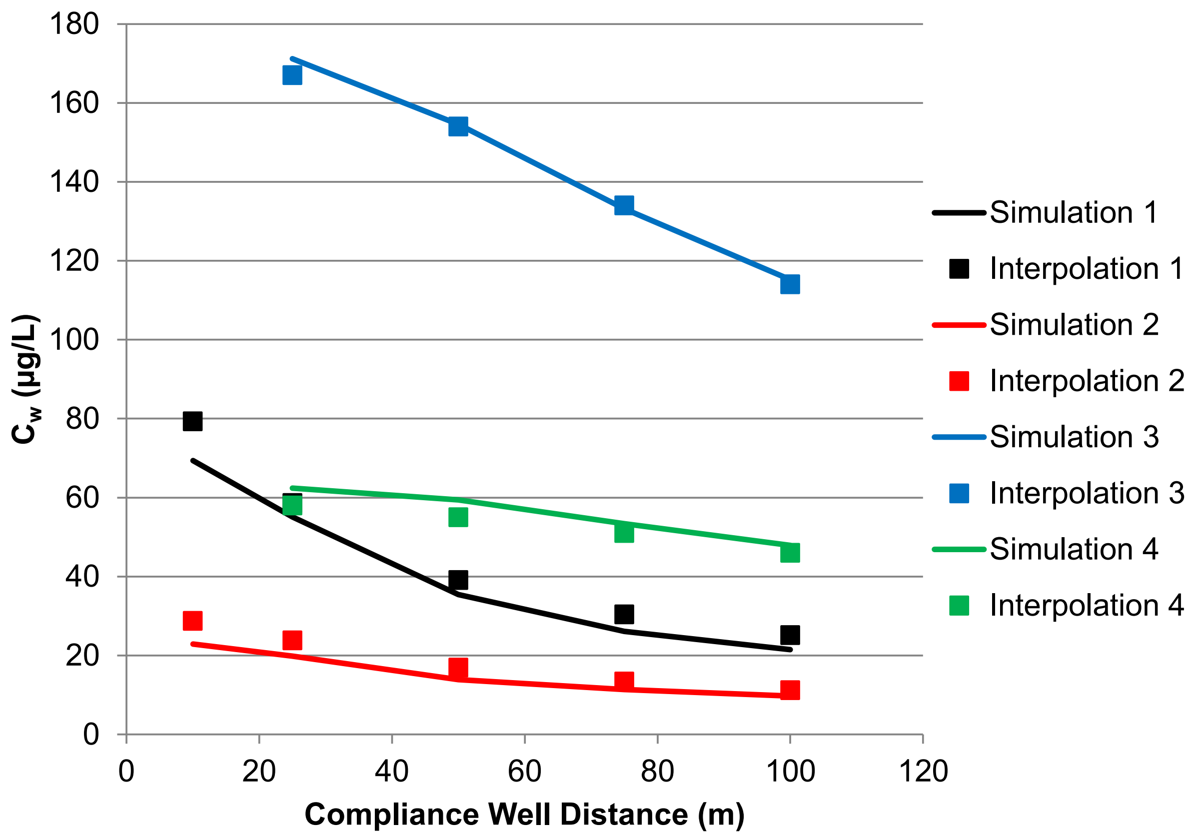
Interpolation & Scaling

- Linear interpolation
  - Start with 64 simulation results, C_{sim}
  - Interpolate between key values for each parameter
  - Final value is the unscaled groundwater concentration, C_{wu}
- Scale C_{wu} to obtain final value, C_w
  - Henry's law constant
  - Recharge
  - Source strength

C_{sim} Data	*RSP* Interp.	*q* Interp.	*SA* Interp.	*VZT* Interp.	*STR* Interp.	*ω* Interp.
24.19	33.65	20.49	29.45	26.48	27.94	**28.67**
43.12						
5.26	7.33					
9.40						
56.85	63.17	38.41				
69.50						
12.25	13.65					
15.06						
15.23	28.49	17.39	23.50			
41.74						
3.36	6.30					
9.23						
32.35	48.37	29.61				
64.40						
7.21	10.85					
14.49						
32.28	24.67	16.52	28.49	29.40		
17.05						
7.01	8.38					
9.75						
62.74	66.54	40.46				
70.33						
13.52	14.38					
15.23						
26.80	38.92	23.81	30.31			
51.03						
5.98	8.70					
11.42						
46.94	59.98	36.82				
73.01						
10.61	13.65					
16.69						
25.06	35.02	21.58	31.06	26.97	29.39	
44.98						
5.77	8.14					
10.50						
59.06	65.95	40.54				
72.85						
13.39	15.12					
16.85						
14.83	27.93	16.90	22.87			
41.03						
3.06	5.87					
8.67						
31.56	47.54	28.85				
63.51						
6.59	10.16					
13.73						
33.51	40.12	24.73	33.76	31.82		
46.74						
7.73	9.34					
10.95						
65.35	69.60	42.80				
73.84						
14.87	16.00					
17.12						
26.33	38.53	23.42	29.88			
50.74						
5.56	8.30					
11.04						
46.22	59.55	36.34				
72.88						
9.93	13.13					
16.33						

STOMP Results vs. Interpolation

- Comparison of STOMP simulations and interpolations (Oostrom et al. 2014)



Parameter	Test Case 1	Test Case 2	Test Case 3	Test Case 4
ω	3%	3%	7%	7%
STR	0.175	0.175	0.375	0.375
VZT	20	20	45	45
SA	250 m^2	250 m^2	1700 m^2	1700 m^2
q	0.0175 m/d	0.165 m/d	0.0175 m/d	0.165 m/d
RSP	0.55	0.55	5.5	5.5

Effects of Parameter Variation

- GW concentration change with increasing parameter input value for a gas concentration input source type
  - (+ = Increase; – = Decrease)

User Input	GW Concentration Change with Increasing User Input Value
Temperature, T	–
Average Moisture Content, ω	–
Average Recharge, R	+
Vadose Zone Thickness, VZT	–
Depth to Top Source, L1	+
Source Thickness, z	+
Source Width, w	+
GW Darcy Velocity, q	–
Distance to Compliance Well, d	configuration dependent
Well Screen Length, s	–
Source gas concentration, C_{gs}	+

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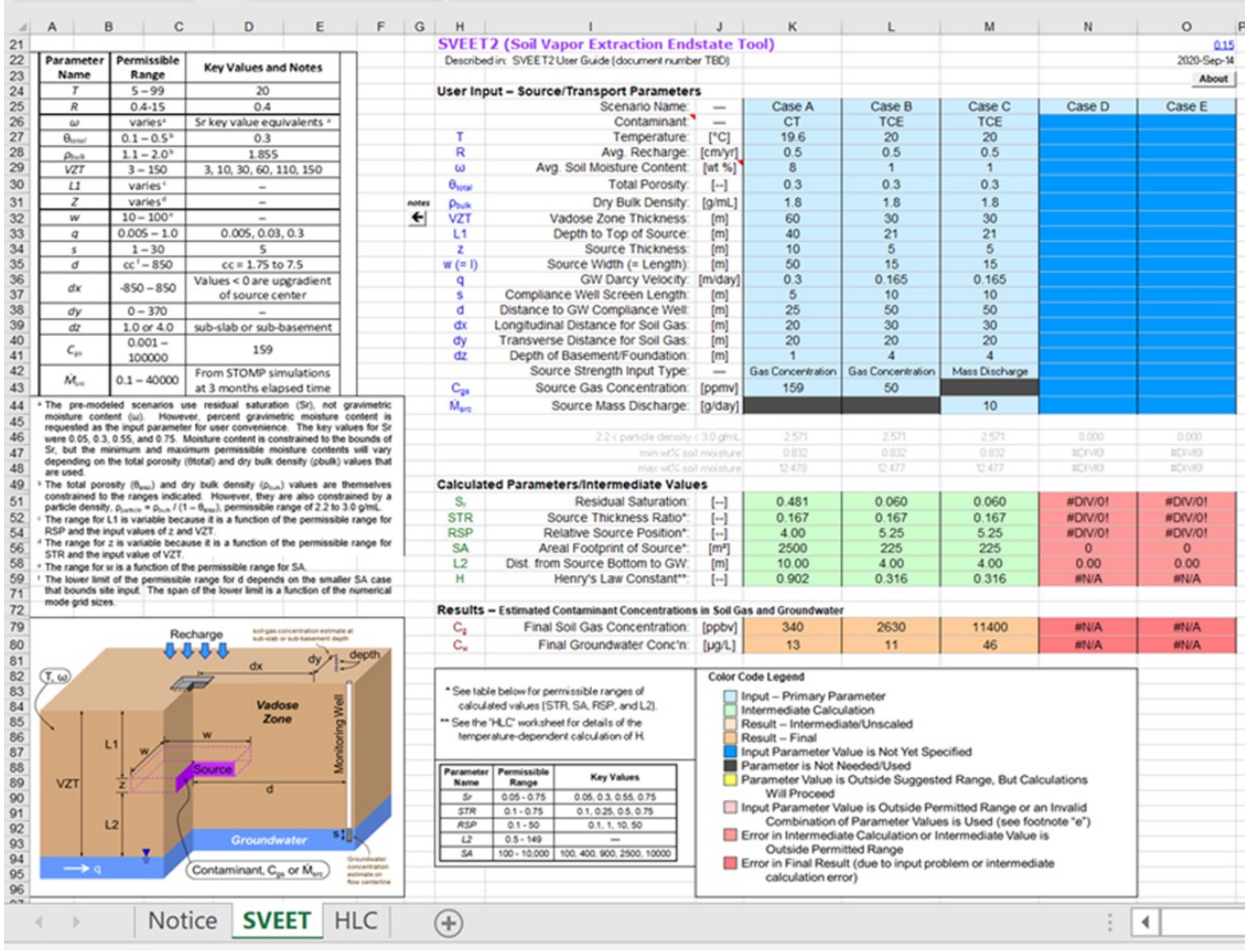
SVEET2 Interface

- Excel spreadsheet (xlsm)
- Up to 5 scenarios
- Errors and warnings flagged by cell color
- No results if inputs are invalid
- Associated worksheet with contaminant data



Parameter Name	Permissible Range	Key Values and Notes
T	5 – 99	20
R	0.4-15	0.4
ω	varies[a]	Sr key value equivalents [a]
θ_{total}	0.1 – 0.5[b]	0.3
ρ_{bulk}	1.1 – 2.0[b]	1.855
VZT	3 – 150	3, 10, 30, 60, 110, 150
L1	varies[c]	–
Z	varies[d]	–
w	10 – 100[e]	–
q	0.005 – 1.0	0.005, 0.03, 0.3
s	1 – 30	5
d	cc[f] – 850	cc = 1.75 to 7.5
dx	-850 – 850	Values < 0 are upgradient of source center
dy	0 – 370	–
dz	1.0 or 4.0	sub-slab or sub-basement
C_{gs}	0.001 – 100000	159
$\dot{M}_{src}$	0.1 – 40000	From STOMP simulations at 3 months elapsed time

[a] The pre-modeled scenarios use residual saturation (Sr), not gravimetric moisture content (ω). However, percent gravimetric moisture content is requested as the input parameter for user convenience. The key values for Sr were 0.05, 0.3, 0.55, and 0.75. Moisture content is constrained to the bounds of Sr, but the minimum and maximum permissible moisture contents will vary depending on the total porosity (θtotal) and dry bulk density (ρbulk) values that are used.

[b] The total porosity (θ_{total}) and dry bulk density (ρ_{bulk}) values are themselves constrained to the ranges indicated. However, they are also constrained by a particle density, $\rho_{particle} = \rho_{bulk} / (1 - \theta_{total})$, permissible range of 2.2 to 3.0 g/mL.

[c] The range for L1 is variable because it is a function of the permissible range for RSP and the input values of z and VZT.

[d] The range for z is variable because it is a function of the permissible range for STR and the input value of VZT.

[e] The range for w is a function of the permissible range for SA.

[f] The lower limit of the permissible range for d depends on the smaller SA case that bounds site input. The span of the lower limit is a function of the numerical mode grid sizes.

SVEET2 (Soil Vapor Extraction Endstate Tool) 0.15

Described in: SVEET2 User Guide (document number TBD) 2020-Sep-14

User Input – Source/Transport Parameters

	Scenario Name:	—	Case A	Case B	Case C	Case D	Case E
	Contaminant:	—	CT	TCE	TCE		
T	Temperature:	[°C]	19.6	20	20		
R	Avg. Recharge:	[cm/yr]	0.5	0.5	0.5		
ω	Avg. Soil Moisture Content:	[wt %]	8	1	1		
θ_{total}	Total Porosity:	[--]	0.3	0.3	0.3		
ρ_{bulk}	Dry Bulk Density:	[g/mL]	1.8	1.8	1.8		
VZT	Vadose Zone Thickness:	[m]	60	30	30		
L1	Depth to Top of Source:	[m]	40	21	21		
z	Source Thickness:	[m]	10	5	5		
w (= l)	Source Width (= Length):	[m]	50	15	15		
q	GW Darcy Velocity:	[m/day]	0.3	0.165	0.165		
s	Compliance Well Screen Length:	[m]	5	10	10		
d	Distance to GW Compliance Well:	[m]	25	50	50		
dx	Longitudinal Distance for Soil Gas:	[m]	20	30	30		
dy	Transverse Distance for Soil Gas:	[m]	20	20	20		
dz	Depth of Basement/Foundation:	[m]	1	4	4		
	Source Strength Input Type:	—	Gas Concentration	Gas Concentration	Mass Discharge		
C_{gs}	Source Gas Concentration:	[ppmv]	159	50			
$\dot{M}_{src}$	Source Mass Discharge:	[g/day]			10		
	2.2 < particle density < 3.0 g/mL		2.571	2.571	2.571	0.000	0.000
	min wt% soil moisture		0.832	0.832	0.832	#DIV/0!	#DIV/0!
	max wt% soil moisture		12.478	12.477	12.477	#DIV/0!	#DIV/0!

Calculated Parameters/Intermediate Values

S_r	Residual Saturation:	[--]	0.481	0.060	0.060	#DIV/0!	#DIV/0!
STR	Source Thickness Ratio*:	[--]	0.167	0.167	0.167	#DIV/0!	#DIV/0!
RSP	Relative Source Position*:	[--]	4.00	5.25	5.25	#DIV/0!	#DIV/0!
SA	Areal Footprint of Source*:	[m²]	2500	225	225	0	0
L2	Dist. from Source Bottom to GW:	[m]	10.00	4.00	4.00	0.00	0.00
H	Henry's Law Constant**:	[--]	0.902	0.316	0.316	#N/A	#N/A

Results – Estimated Contaminant Concentrations in Soil Gas and Groundwater

C_g	Final Soil Gas Concentration:	[ppbv]	340	2630	11400	#N/A	#N/A
C_w	Final Groundwater Conc'n:	[µg/L]	13	11	46	#N/A	#N/A

* See table below for permissible ranges of calculated values (STR, SA, RSP, and L2).

** See the 'HLC' worksheet for details of the temperature-dependent calculation of H.

Parameter Name	Permissible Range	Key Values
Sr	0.05 - 0.75	0.05, 0.3, 0.55, 0.75
STR	0.1 - 0.75	0.1, 0.25, 0.5, 0.75
RSP	0.1 - 50	0.1, 1, 10, 50
L2	0.5 - 149	—
SA	100 - 10,000	100, 400, 900, 2500, 10000

Color Code Legend

🟦	Input – Primary Parameter
🟩	Intermediate Calculation
🟧	Result – Intermediate/Unscaled
🟧	Result – Final
🟦	Input Parameter Value is Not Yet Specified
⬛	Parameter is Not Needed/Used
🟨	Parameter Value is Outside Suggested Range, But Calculations Will Proceed
🟥	Input Parameter Value is Outside Permitted Range or an Invalid Combination of Parameter Values is Used (see footnote "e")
🟥	Error in Intermediate Calculation or Intermediate Value is Outside Permitted Range
🟥	Error in Final Result (due to input problem or intermediate calculation error)

Updates for SVEET2

- Range of updates to improve usability and applicability
  - New contaminants
  - Can do more scenarios at once
  - Flexible groundwater well locations
  - Soil gas output
  - Increased permissible ranges
    - ✓Source strength (concentration or flux)
    - ✓Recharge
    - ✓Sr
    - ✓VZT
    - ✓RSP
    - ✓SA
    - ✓q
  - Can specify porosity and bulk density

SVEET v. 1.-	SVEET2
Contaminants: Chloroform Carbon Tetrachloride Dichloromethane cis-1,2-Dichloroethene Chloromethane trans-1,2-Dichloroethene Chloroethane 1,1,1,2-Tetrachloroethane Vinyl Chloride 1,1,2,2-Tetrachloroethane Tetrachloroethene 1,1,1-Trichloroethane Trichloroethene 1,1,2-Trichloroethane 1,1-Dichloroethene 1,1-Dichloroethane 1,2-Dichloroethane	Added these contaminants: 1, 2-Dichloropropane 1, 3-Dichloropropane 1,2,3-Trichloropropane MIBK MTBE MEK Chlorobenzene BTEX constituents Freons (11, 12, 113) 1,4-Dioxane Note: biodegradation effects are not included in SVEET v. 1.0 or SVEET2.
Input/Output Structure: 3 concurrent scenarios are allowed	Allow 5 concurrent scenarios
GW Monitoring Well Locations for Output: 10, 25, 50, 75 and 100 m downgradient along groundwater flow centerline from source area	Allow any user-specified distance ≤ 850 m, along centerline
Vadose Zone Soil Gas Concentrations for Output: *Not a SVEET output (but available in VIETUS)*	Allow user-specified lateral location (-850 to 850 m in x direction, 0 to 370 m in y direction) and depth of 1 or 4 m (for sub-slab or basement)
Source Gas Concentration: 1 – 2,000 ppmv	0.001 - 100,000 ppmv
Source Mass Flux: 0.1 – 5,000 g/d	0.1 – 40,000 g/d
Recharge: 0.4 – 7.5 cm/yr	0.4 – 15 cm/yr
Bulk Density and Porosity: Fixed at 1.855 g/mL and 30%, respectively.	Allow user-specified bulk density and porosity values
Relative Water Saturation (Moisture Content): 0.05 – 0.55 (1 – 9 wt%)	0.05 – 0.75 Allowable moisture content depends on bulk density and porosity
Vadose Zone Thickness: 10 – 60 m	3 – 150 m
Source Thickness Ratio: 0.1 – 0.5	0.1 – 0.75 0.75 STR is allowed for VZT ≤ 10 m
Relative Source Position: 0.1 – 10	0.1 – 50 50 RSP is allowed for VZT ≥ 30 m
Source Footprint (square): 100 – 2,500 m²	100 – 10,000 m²
Groundwater Darcy Velocity: 0.005 – 0.3 m/d	0.005 – 1.0 m/d

Expanding Permissible Ranges

- Parameters having non-linear impacts
- Expanded from 972 simulations to 5760 simulations
- Significant effort to build and manage the simulations and output

Parameter	Evaluation Points as the Basis for Interpolation					
Residual Moisture Saturation (—)		0.05	0.3	0.55	**0.75**	
Source Thickness Ratio (—)		0.1	0.25	0.5	**0.75**	
Vadose Zone Thickness (m)	**3**	10	30	60	**110**	**150**
Source Area (m^2)		100	400	900	2,500	**10,000**
Groundwater Velocity (m/day)		0.005	0.03	0.3	**1**	
Relative Source Position (—)		0.1	1	10	**50**	

SVEET2 Assumptions and Limitations

- Vapor-phase transport dominates vadose zone contaminant movement
  - But recharge-driven transport is accounted for
- Groundwater is initially uncontaminated
- Contaminant source can be represented as a single source area
- Homogeneous subsurface with uniform properties
- Steady-state / equilibrium site conditions
- Constant strength vadose zone source
  - No source depletion
- Well screen starts at the water table (i.e., the groundwater sample context)
- Does not include:
  - Adsorption
  - Biological reactions/degradation
  - Groundwater concentration estimates off the plume centerline

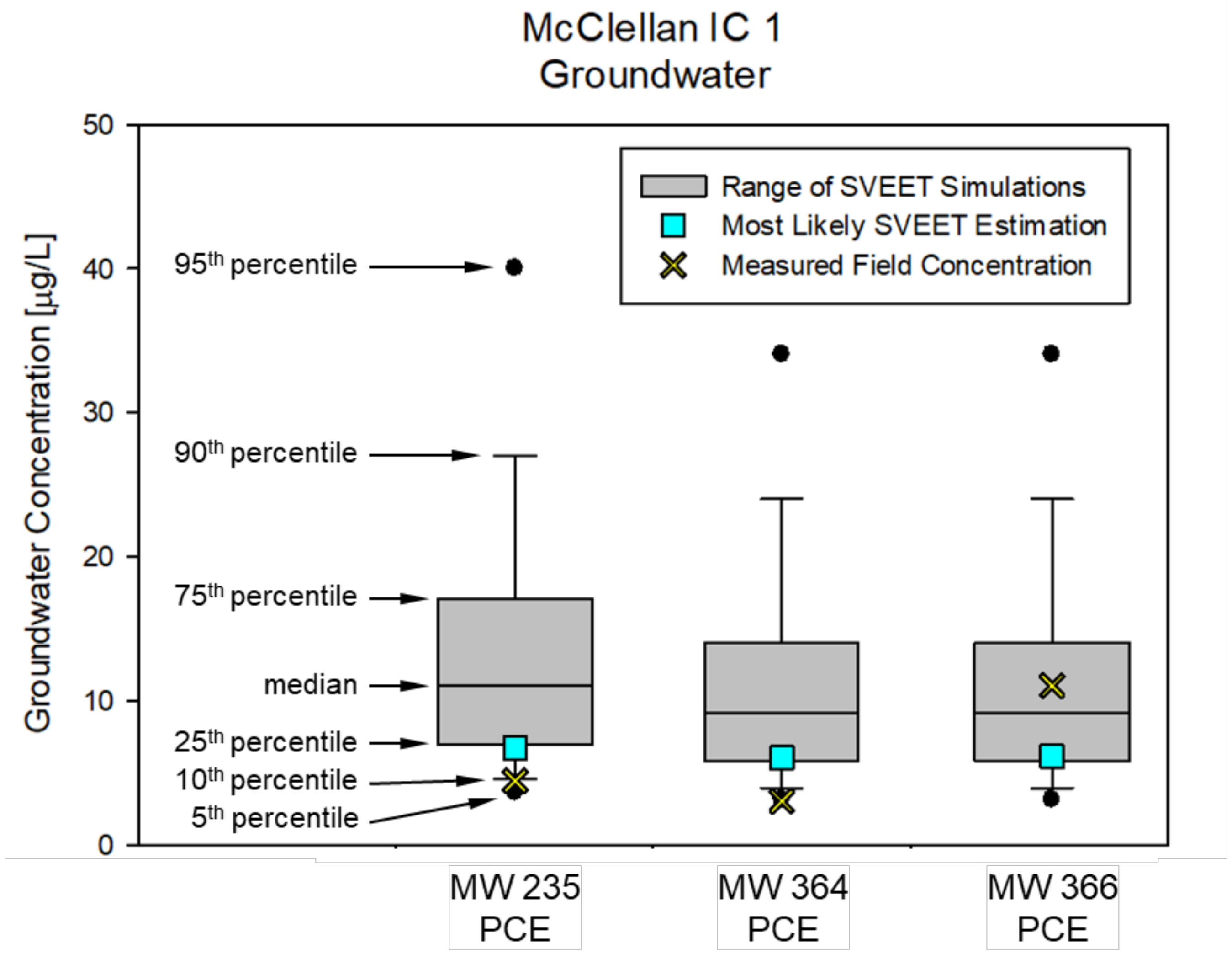
ESTCP Demonstration Elements

- Type 1 – SVEET2 Ground-Truthing (2+ sites)
  - The site must have reached equilibrium conditions
    - ✓ Ideally, demonstrated by long term data
  - Soil gas and/or groundwater data required for comparison to SVEET2 results
  - Performance metric: observed values are within 3 standard deviations of SVEET2 sensitivity results
    - ✓ Monte-Carlo (MC) analysis (n = 2,500) with randomly selected input parameter values in defined min./max. range

- Type 2 – SVEET2 Tool User Testing (2+ sites)
  - Ideally, had SVE operations approaching asymptotic removal and shutdown is being considered
  - Soil gas and/or groundwater data required
  - Qualitative feedback on usability and applicability
  - Performance metric: Applicable to ≥ 80% of sites investigated

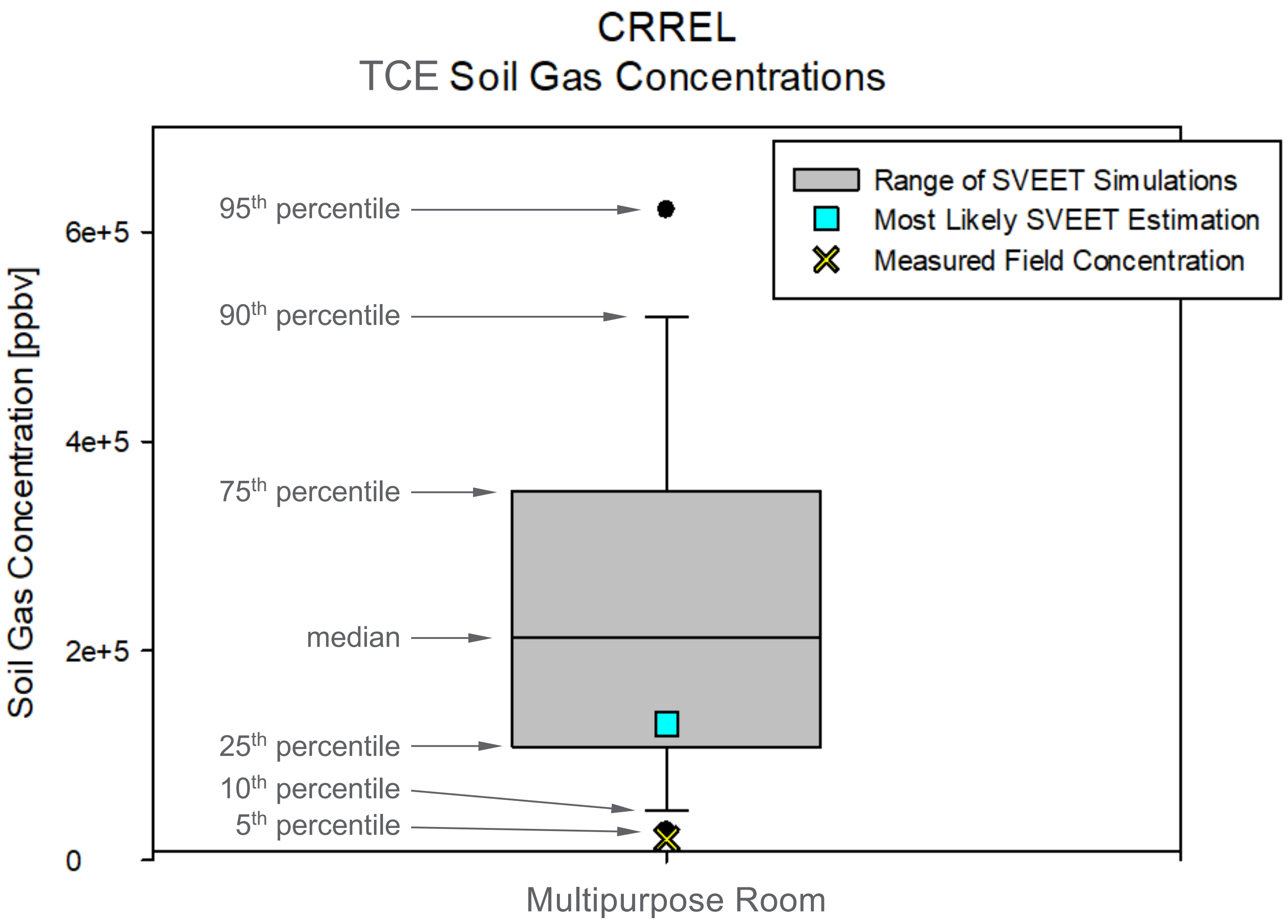
SVEET2 Demo – McClellan IC-1

- Tetrachloroethene (PCE) source impact on groundwater at McClellan AFB IC-1
    - SVE was recently terminated
    - Comparison for three monitoring wells
- SVEET2 estimates met performance objectives, matching observed data within defined metric



SVEET2 Demo – CRREL AOC 2

- Trichloroethene (TCE) source impact on soil gas for CRREL AOC 2 to assess vapor intrusion
- SVEET2 estimate met performance objectives, matching observed data within defined metric



Ground-Truthing Demo Summary

- Overall, SVEET2 provided reasonable concentration estimates
  - Six cases matched observed data, meeting the performance metric
  - Three cases had estimates less than observed data
    - ✓ Estimates for all were within a factor of 2-3 of observed data
  - Four cases had estimates larger than observed data
    - ✓ Conservative with respect to supporting decisions about SVE termination
- Challenging to find a site meeting all SVEET2 assumptions
  - Need to distinguish between ground-truthing and application to support remedial decisions

ESTCP Demo – Usability and Applicability

- Widely applicable: 93% of DoD sites surveyed (n = 14)
  - Issues: recharge (too great) or site size (too small/thin or too large)
- Feedback: SVEET2 was appliable and helpful
  - User friendly and straightforward input requirements
    - ✓ Inputs are readily available from existing site data
- Easy to vary inputs and quickly run multiple scenarios or what-if analyses
  - Rapid assessment results
  - Major benefit vs. traditional approaches (site-specific numerical model)
    - ✓ Less labor effort, less data intensive, and lower cost to obtain estimated impacts
    - ✓ Similar level of professional judgement and assumptions
  - What-if scenarios are helpful when inputs have high degree of uncertainty
    - ✓ One site noted that application provided insight regarding controlling processes
  - Provides useful information for decision making

DoD Site Application for Eight SVE Systems

- SVEET2 used to assess trichloroethene (TCE) sources at each SVE system
  - Recently: operate during warmer weather, shut down in winter
  - Source strength based on soil gas concentrations at end of winter shut down period
  - Source zone geometry challenging to define
  - Multiple cases were used for assessment
- SVEET 2 results compared to:
  - Maximum contaminant level (MCL)
    - ✓ Less than MCL implied termination of SVE would be protective of groundwater
  - Actual groundwater monitoring results
- Outcome based on comparison
  - SVEET2 estimates less than MCL for 5 systems
  - SVEET2 estimates greater than MCL for 3 systems
  - Aligned with actual groundwater monitoring data

Example SVEET2 Results

	Scenario Name:	—	Site #1	Site #5
	Contaminant:	—	TCE	TCE
T	Temperature:	[°C]	14	14
R	Avg. Recharge:	[cm/yr]	1.6	1.6
ω	Avg. Soil Moisture Content:	[wt %]	7	7
θ_{total}	Total Porosity:	[--]	0.34	0.34
ρ_{bulk}	Dry Bulk Density:	[g/mL]	1.75	1.75
VZT	Vadose Zone Thickness:	[m]	110	90
L1	Depth to Top of Source:	[m]	40	37
z	Source Thickness:	[m]	45	15
w (= l)	Source Width (= Length):	[m]	50	15
q	GW Darcy Velocity:	[m/day]	0.052	0.052
s	Compliance Well Screen Length:	[m]	6	6
d	Distance to GW Compliance Well:	[m]	65	100
C_{gs}	Source Gas Concentration:	[ppmv]	8.75	4.3
C_w	Final Groundwater Conc'n:	[µg/L]	20	3.6
C_{meas}	Measured Groundwater Conc'n	[µg/L]	15	1.7

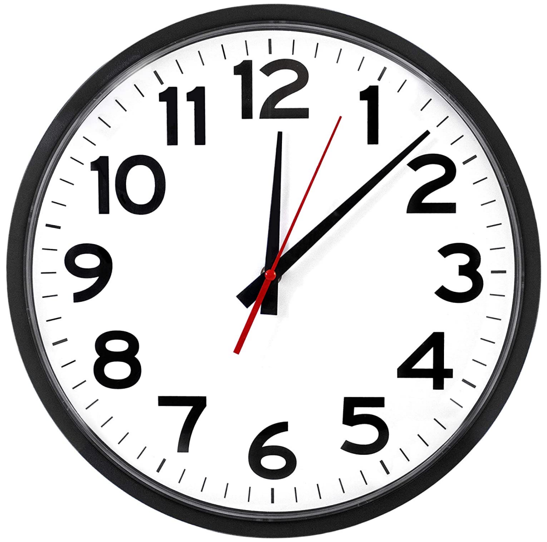
Potential Cost Savings for Example DoD Site

- Five locations: could terminate SVE ("Shutdown")
- Three locations: should continue SVE (“Run”)
- Cost savings estimated from current SVE operational costs
    - Typical of SVE operational costs (NFESC, 2005; EPA, 2007)
    - Cost savings of roughly $663,500 per year
    - 61.5% decrease in annual operational costs
- Two systems are moving forward with the shutdown recommendation

System	Run/Shutdown	Operating Cost ($/y)
1	Run	$ 142,025
2	Shutdown	$ 128,400
3	Run	$ 122,700
4	Shutdown	$ 118,650
5	Shutdown	$ 46,675
6	Shutdown	$ 161,325
7	Run	$ 151,075
8	Shutdown	$ 208,450
Estimated Potential Cost Savings for Shutdown Systems		**$663,500**

DoD Site Application Notes

- Personnel unfamiliar with the SVEET2 software:
  - Expect roughly 16 hours of labor to run site-specific scenarios
    - ✓ Download/install
    - ✓ Learning SVEET2
    - ✓ Gathering site data
    - ✓ Performing data analysis and interpretation
  - Most time will be spent in gathering site data and assessing scenario variations to support remedy decisions
  - Overall, less labor costs than traditional approaches

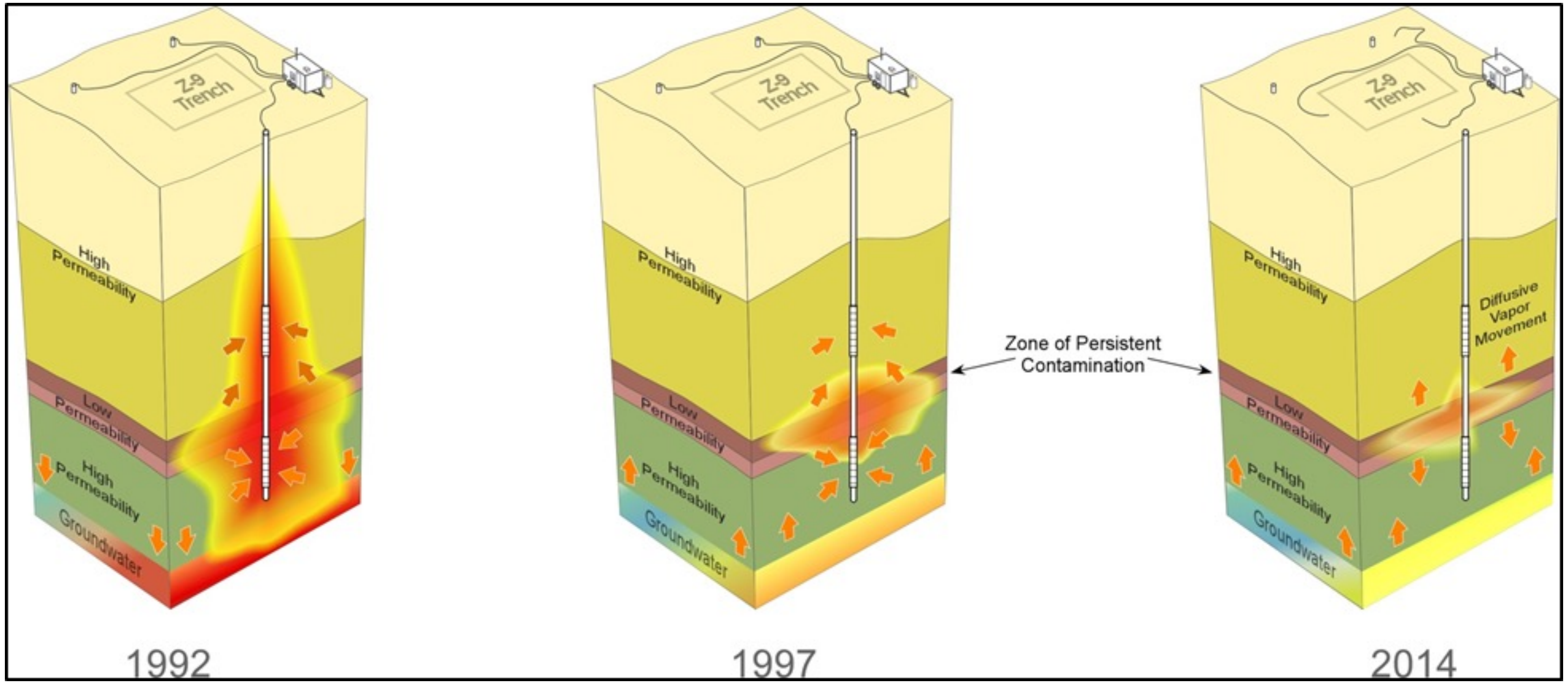


Integrating Calculations into a Remedy Decision

- Two examples
  - DOE Hanford Site – SVE Performance Assesment
  - Private Site – Setting SVE Performance Targets

Hanford Site Conceptual Model

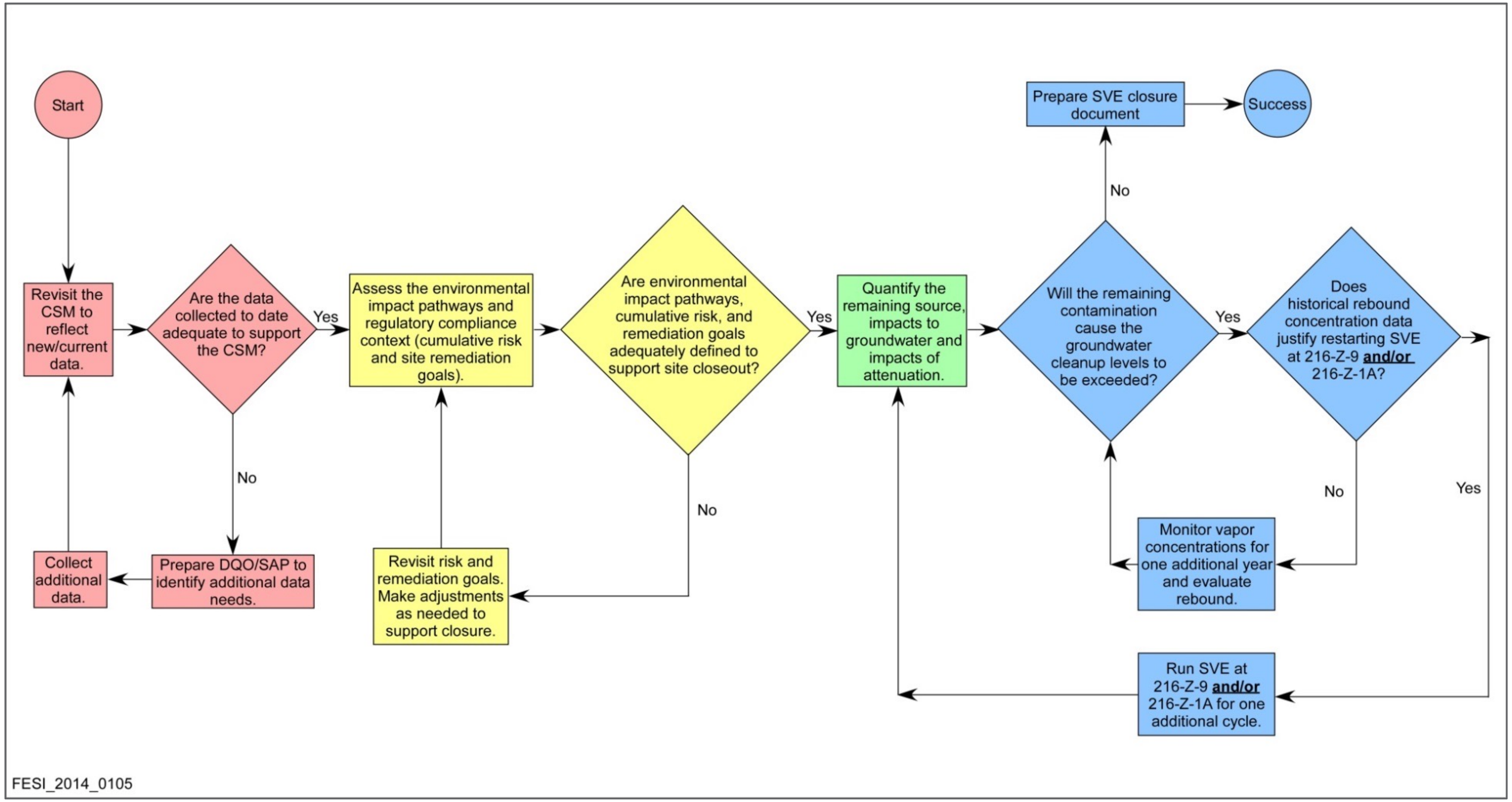
- Carbon tetrachloride (CT) disposal to cribs/trenches
  - Waste from historical plutonium separations activities
- SVE initiated in 1992
- Evolving CSM
  - Diminishing returns from SVE
  - Residual CT in lower permeability zone



(DOE 2014, 2016)

Hanford Site Approach

- Based on SVE performance assessment guidance
- Included some site-specific adaptations to decision logic
- Provided an approach for presentation to and concurrence by regulators



Start

Revisit the CSM to reflect new/current data.

Are the data collected to date adequate to support the CSM?

Yes

No

Prepare DQO/SAP to identify additional data needs.

Collect additional data.

Assess the environmental impact pathways and regulatory compliance context (cumulative risk and site remediation goals).

Are environmental impact pathways, cumulative risk, and remediation goals adequately defined to support site closeout?

Yes

No

Revisit risk and remediation goals. Make adjustments as needed to support closure.

Quantify the remaining source, impacts to groundwater and impacts of attenuation.

Will the remaining contamination cause the groundwater cleanup levels to be exceeded?

Yes

No

Prepare SVE closure document

Success

Does historical rebound concentration data justify restarting SVE at 216-Z-9 **and/or** 216-Z-1A?

No

Yes

Monitor vapor concentrations for one additional year and evaluate rebound.

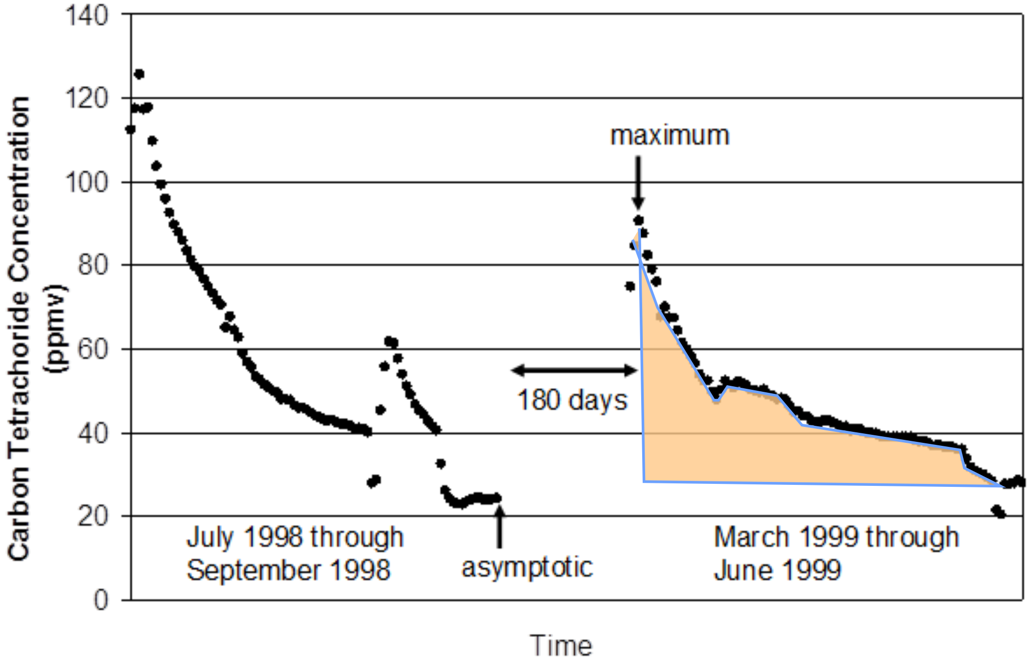
Run SVE at 216-Z-9 **and/or** 216-Z-1A for one additional cycle.

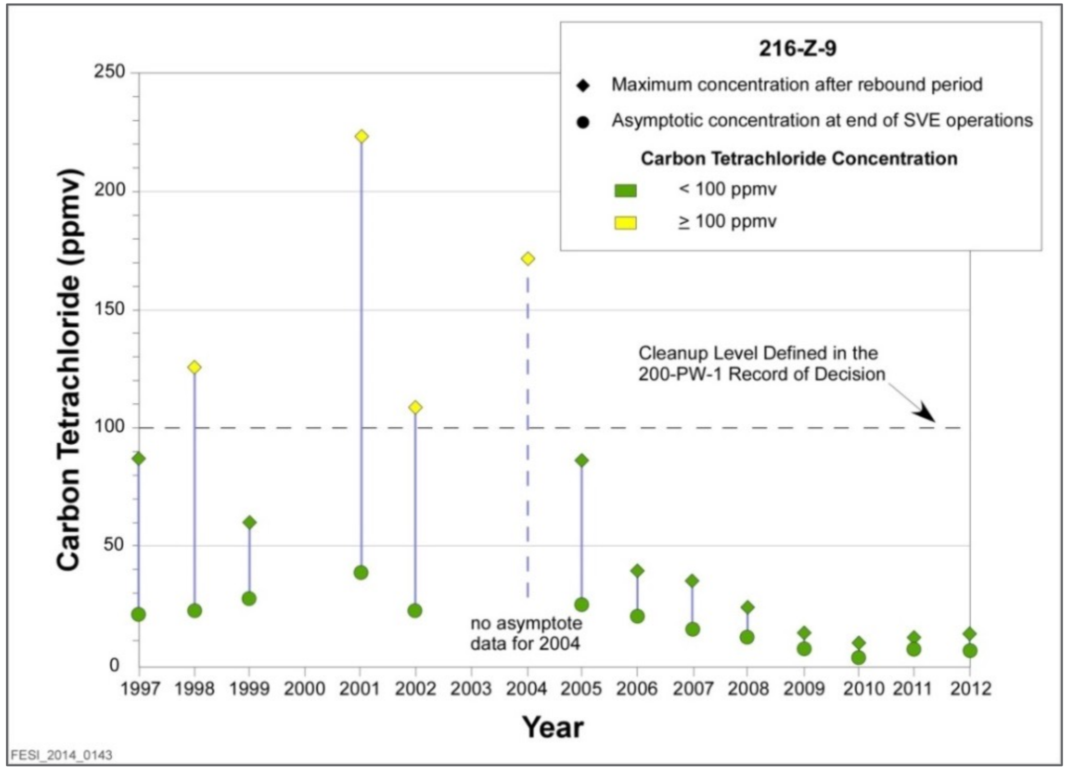
FESI_2014_0105

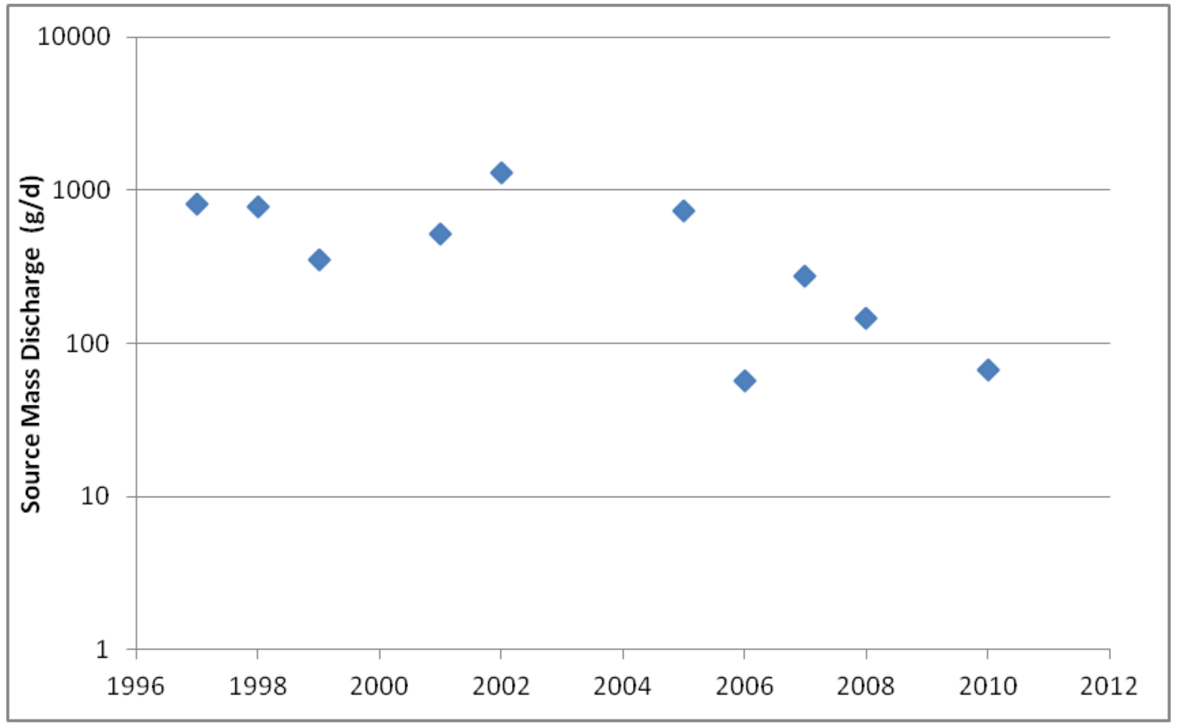
(DOE 2014, 2016)

Source Strength

- Data from cyclic operation and soil gas informed the source strength
  - Concentrations used in SVEET
  - Mass discharge important for long-term evaluation



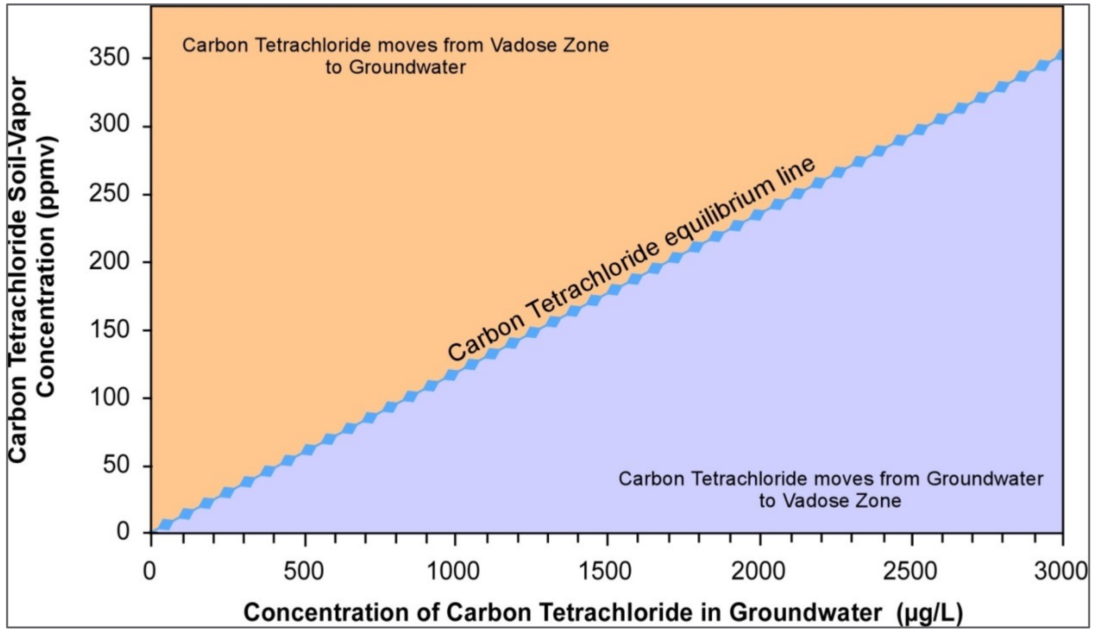


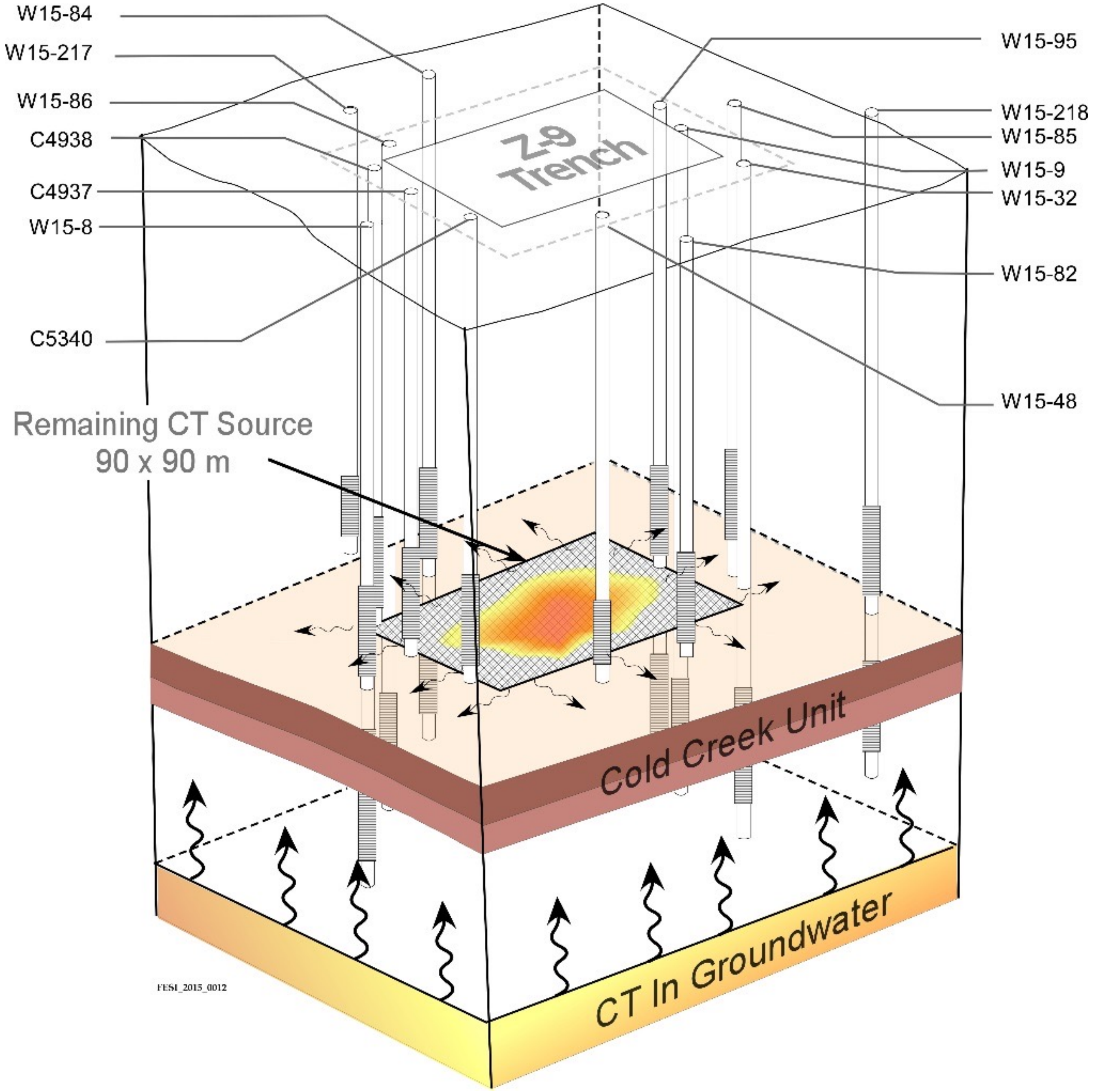


(DOE 2014, 2016)

Hanford Site

- CSM at the time of the evaluation
  - Low soil gas concentrations
  - Only remaining source of CT is contained within the CCU
  - Existing groundwater contamination





(DOE 2014, 2016)

Estimated Impact to Groundwater

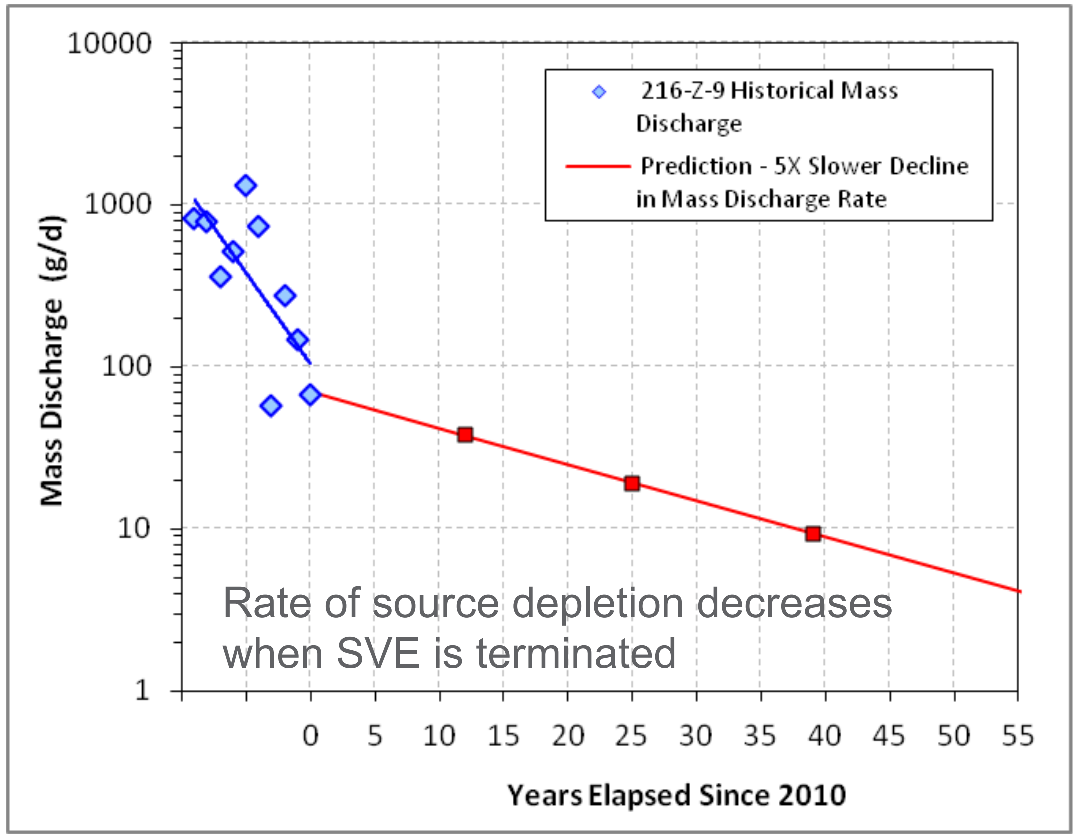
- SVEET was used to calculate soil vapor impacts to groundwater
  - Assumes underlying aquifer is clean and no CT sources in the groundwater
  - Assumes that vadose zone source remains constant over time
- Estimated groundwater impact for source based on current vadose zone CT concentrations
  - Impacts are consistent with 216-Z-9 Trench treatability test estimates (PNNL-21326)

Waste Site:	**216-Z-9**	**216-Z-1A**	**216-Z-18**
Source gas concentration (ppmv)	24.7	13.9	9.65
Estimated groundwater concentration (µg/L)	27	17	12

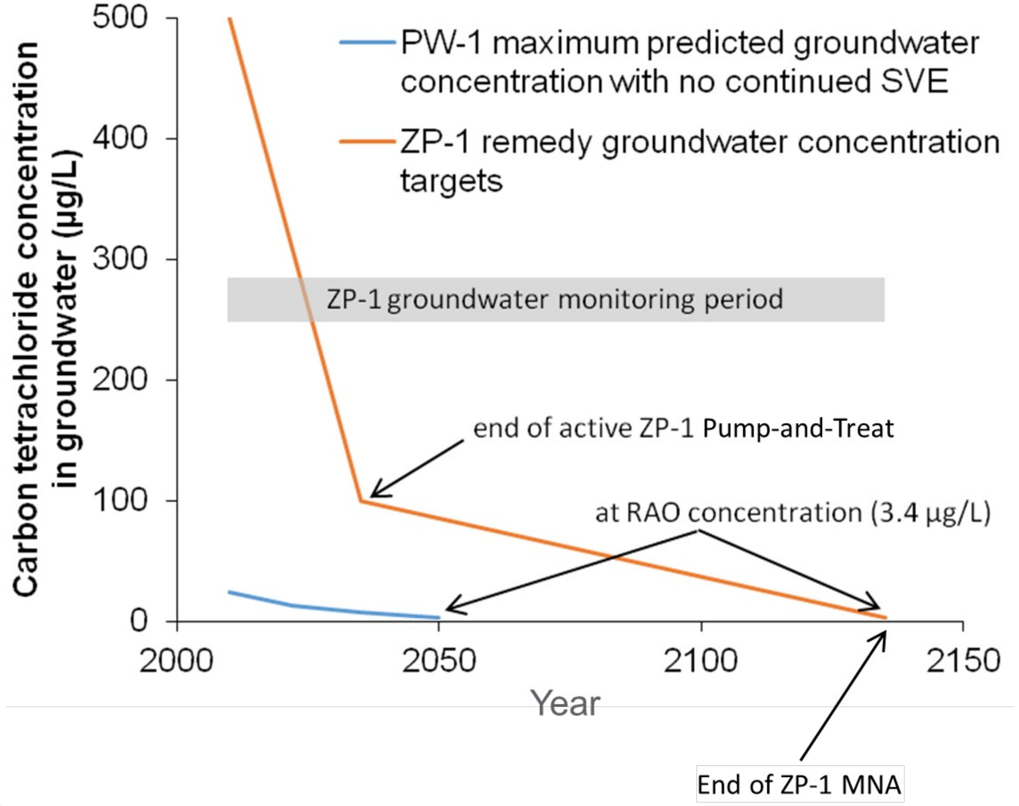
ppmv = parts per million by volume

Impact In Context and Over Time

- Context: groundwater pump-and-treat (P&T) + monitored natural attenuation (MNA)
  - 3.4 µg/L CT goal
- Calculated the estimated impact over time with source depletion
- By 2050, remaining vadose zone CT will NOT cause groundwater concentration above 3.4 µg/L
- However, existing groundwater CT levels are not expected to drop below 3.4 µg/L until year 2135



Rate of source depletion decreases when SVE is terminated



ZP-1 groundwater monitoring period

end of active ZP-1 Pump-and-Treat

at RAO concentration (3.4 µg/L)

End of ZP-1 MNA

(DOE 2014, 2016)

Application of SVEET for Setting Goals

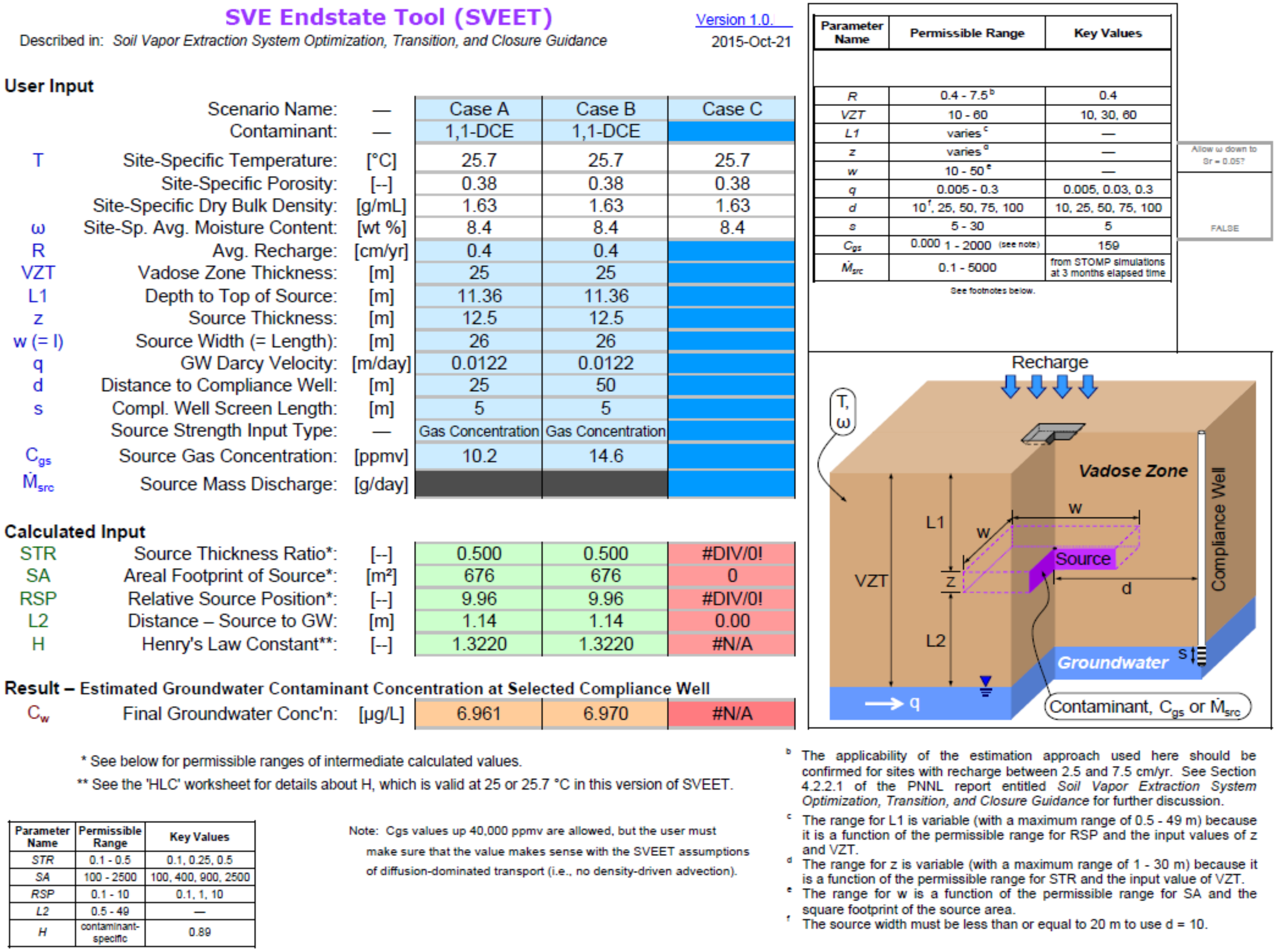
- Superfund site in the Southwest US
  - Liquid disposal in pits in 1979-80 timeframe
  - 80-ft vadose zone: Sands/gravel over silt and silty sand, buried basalt flow within silty zone
  - Remedy: Cap, P&T, SVE
  - Installed SVE system in early 1990s
    - ✓ Operated for several years with thermal oxidizer
    - ✓ Restarted in 2006 with pressure condensation treatment
  - Cumulative SVE mass removal over 200,000 lbs, mass removal still >1000 lb/quarter
  - Recent shift to carbon treatment for SVE offgas

Application of SVEET for Setting Goals

- SVE goals reset several times
    - Initial goals based on SESOIL modeling
    - Revised goals in 2009 based on leaching and State soil screening levels
    - Didn’t account for vapor transfer to water table
    - Vapor concentrations in soil gas close to 2009 goals, but still large mass recovery
- Project team decided to revisit goals in 2015 using SVEET
    - Adjustments made to SVEET for site specific factors (e.g., contaminants)
    - Collaborative effort between regulatory agencies and responsible parties
    - SVEET tool was instrumental in resolving this difficult issue

Application of SVEET for Setting Goals

- Example
  - 1,1-dichloroethane
  - MCL = 6 µg/L
- Essentially back-calculating the source strength to achieve MCL goal



SVE Endstate Tool (SVEET) Version 1.0 2015-Oct-21

Described in: *Soil Vapor Extraction System Optimization, Transition, and Closure Guidance*

User Input

			Case A	Case B	Case C
	Scenario Name:	—	Case A	Case B	Case C
	Contaminant:	—	1,1-DCE	1,1-DCE	
T	Site-Specific Temperature:	[°C]	25.7	25.7	25.7
	Site-Specific Porosity:	[--]	0.38	0.38	0.38
	Site-Specific Dry Bulk Density:	[g/mL]	1.63	1.63	1.63
ω	Site-Sp. Avg. Moisture Content:	[wt %]	8.4	8.4	8.4
R	Avg. Recharge:	[cm/yr]	0.4	0.4	
VZT	Vadose Zone Thickness:	[m]	25	25	
L1	Depth to Top of Source:	[m]	11.36	11.36	
z	Source Thickness:	[m]	12.5	12.5	
w (= l)	Source Width (= Length):	[m]	26	26	
q	GW Darcy Velocity:	[m/day]	0.0122	0.0122	
d	Distance to Compliance Well:	[m]	25	50	
s	Compl. Well Screen Length:	[m]	5	5	
	Source Strength Input Type:	—	Gas Concentration	Gas Concentration	
C_{gs}	Source Gas Concentration:	[ppmv]	10.2	14.6	
$\dot{M}_{src}$	Source Mass Discharge:	[g/day]			

Calculated Input

			Case A	Case B	Case C
STR	Source Thickness Ratio*:	[--]	0.500	0.500	#DIV/0!
SA	Areal Footprint of Source*:	[m²]	676	676	0
RSP	Relative Source Position*:	[--]	9.96	9.96	#DIV/0!
L2	Distance – Source to GW:	[m]	1.14	1.14	0.00
H	Henry's Law Constant**:	[--]	1.3220	1.3220	#N/A

Result – Estimated Groundwater Contaminant Concentration at Selected Compliance Well

			Case A	Case B	Case C
C_w	Final Groundwater Conc'n:	[µg/L]	6.961	6.970	#N/A

* See below for permissible ranges of intermediate calculated values.

** See the 'HLC' worksheet for details about H, which is valid at 25 or 25.7 °C in this version of SVEET.

Parameter Name	Permissible Range	Key Values
STR	0.1 - 0.5	0.1, 0.25, 0.5
SA	100 - 2500	100, 400, 900, 2500
RSP	0.1 - 10	0.1, 1, 10
L2	0.5 - 49	—
H	contaminant-specific	0.89

Note: Cgs values up 40,000 ppmv are allowed, but the user must make sure that the value makes sense with the SVEET assumptions of diffusion-dominated transport (i.e., no density-driven advection).

Parameter Name	Permissible Range	Key Values
R	0.4 - 7.5[b]	0.4
VZT	10 - 60	10, 30, 60
L1	varies[c]	—
z	varies[d]	—
w	10 - 50[e]	—
q	0.005 - 0.3	0.005, 0.03, 0.3
d	10[f], 25, 50, 75, 100	10, 25, 50, 75, 100
s	5 - 30	5
C_{gs}	0.000 1 - 2000 (see note)	159
$\dot{M}_{src}$	0.1 - 5000	from STOMP simulations at 3 months elapsed time

See footnotes below.

Allow ω down to Sr = 0.05?

FALSE

[b] The applicability of the estimation approach used here should be confirmed for sites with recharge between 2.5 and 7.5 cm/yr. See Section 4.2.2.1 of the PNNL report entitled *Soil Vapor Extraction System Optimization, Transition, and Closure Guidance* for further discussion.

[c] The range for L1 is variable (with a maximum range of 0.5 - 49 m) because it is a function of the permissible range for RSP and the input values of z and VZT.

[d] The range for z is variable (with a maximum range of 1 - 30 m) because it is a function of the permissible range for STR and the input value of VZT.

[e] The range for w is a function of the permissible range for SA and the square footprint of the source area.

[f] The source width must be less than or equal to 20 m to use d = 10.

Application of SVEET for Setting Goals

- Soil Vapor Performance Standards report
  - Described calculation process and selected performance targets
- Explanation of Significant Difference
  - Used to incorporate remedy adjustments and updated soil vapor performance targets
- Performance Monitoring Plan
  - Defined how site data will be used to evaluate vadose zone source strength for comparison to the identified soil vapor performance targets

Conclusions Regarding SVEET2

- SVEET2 is easy to use, makes use of readily available data
  - Gives spreadsheet-fast estimates of vadose zone source impacts on groundwater and soil gas concentrations
- SVEET2 provides reasonable concentration estimates
  - Estimates are generally conservative with respect to decision making
    - ✓ Favors higher concentration estimates
    - ✓ Appropriate for predictive applications in support of decision making
- SVEET2 provides a defensible estimate of contaminant transport as a basis for supporting remedy decisions
  - Endpoint analysis
  - Remedial performance goals
  - Assess potential vapor intrusion concerns

Broad Perspective Key Takeaways

- PNNL guidance offers useful structured approach for SVE performance assessment
- Need to update CSM and regulatory context
- Quantify impacts of remaining contamination
  - SVEET2
- Use the results and the site context to walk through decision logic to determine an appropriate outcome
  - Outcomes may include SVE termination, but may point at optimization or a need to consider a supplemental or replacement technology
- Can be applied and communicated with regulators to facilitate decision making

Key References

- Project web page (with reports, the SVEET2 software, and a link to the ESTCP project)
  - https://www.pnnl.gov/projects/remediation-performance-assessment/soil-vapor-extraction

- Truex, M.J., D.J. Becker, M.A. Simon, M. Oostrom, A.K. Rice, and C.D. Johnson. 2013. *Soil Vapor Extraction System Optimization, Transition, and Closure Guidance*. PNNL-21843, Pacific Northwest National Laboratory, Richland, WA.
- Oostrom, M., M.J. Truex, A.K. Rice, C.D. Johnson, K.C. Carroll, D.J. Becker, and M.A. Simon. 2014. "Estimating the Impact of Vadose Zone Sources on Groundwater to Support Performance Assessment of Soil Vapor Extraction." *Ground Water Monitoring and Remediation*. 34(2):71-84. https://doi.org/10.1111/gwmr.12050
- Johnson, C.D., K.A. Muller, M.J. Truex, G. Tartakovsky, D.J. Becker, C.M. Harms, and J. Popovic. 2022. "A Rapid Decision Support Tool for Estimating Impacts of a Vadose Zone Volatile Organic Compound Source on Groundwater and Soil Gas." *Groundwater Monitoring & Remediation*, 42(1):81-87. http://doi.org/10.1111/gwmr.12468

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https://www.pnnl.gov/projects/remediation-performance-assessment/soil-vapor-extraction

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