The Subsurface Vapour Intrusion Pathway: Recent Developments for Model Prediction and Empirical Site Data

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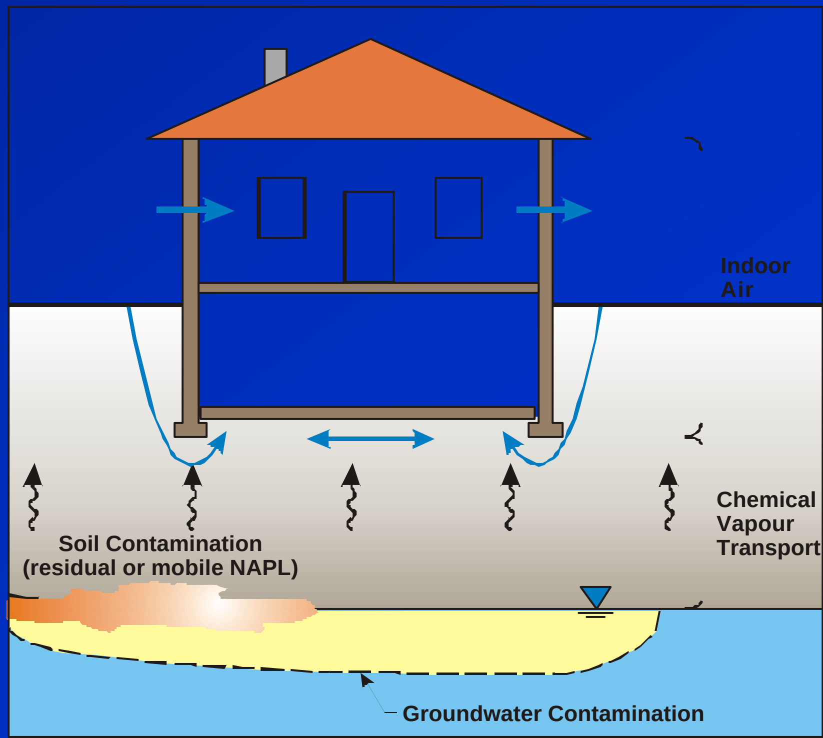


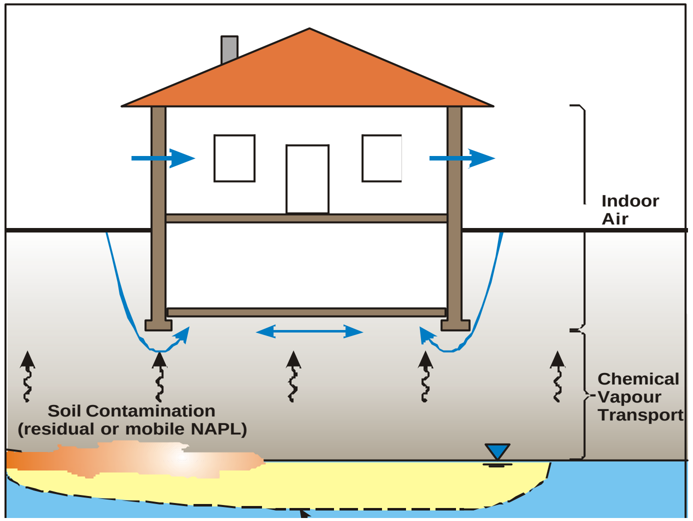
Presentation Outline

- Background Information
- Health Canada Screening Level Risk Assessment Vapour Intrusion Guidance (further to 2003 guidance)
  - Pathway Framework
  - Vapour attenuation factor charts (J&E model)
  - Critical inputs to J&E model (how derived)
  - Validation of model results using empirical data
  - Adjustments to attenuation factors (e.g., biodegradation)
- Conclusions

Background and Key Issues

- Common approach
  - Johnson & Ettinger (J&E) model used to derive regulatory criteria, and for site specific risk assessment
  - Biodegradation and source depletion have in some cases been added to J&E model framework
  - Historically there has been concern over possible conservatism associated with J&E model

Johnson & Ettinger Model



a = air conc. / vapour conc.

- **Mixing in Breathing Zone**
- **Convective Transport into Bldg**
- **Diffusive Transport Soil and Building Foundation**
- **Equilibrium Partitioning Soil/ Groundwater to Soil Vapour**

$$a = \frac{\left[\frac{D_T^{eff} A_B}{Q_B L_T}\right]\exp\left(\frac{Q_{soil} L_{crack}}{D_{crack}^{eff} h A_B}\right)}{\exp\left(\frac{Q_{soil} L_{crack}}{D_{crack}^{eff} h A_B}\right) + \left[\frac{D_T^{eff} A_B}{Q_B L_T}\right] + \left[\frac{D_T^{eff} A_B}{Q_{soil} L_T}\right]\left(\exp\left(\frac{Q_{soil} L_{crack}}{D_{crack}^{eff} h A_B}\right) - 1\right)}$$

Primary Parameters

- D_{eff} = Effective diffusion coefficient
- L_T = Depth to source
- A_B = Building area in contact with soil
- Q_B = Building ventilation rate
- Q_{soil} = Soil gas convection rate
- D_{crack} = Eff. diff. coeff. through cracks
- L_{crack} = Crack thickness
- h = Building crack factor

Secondary Parameters

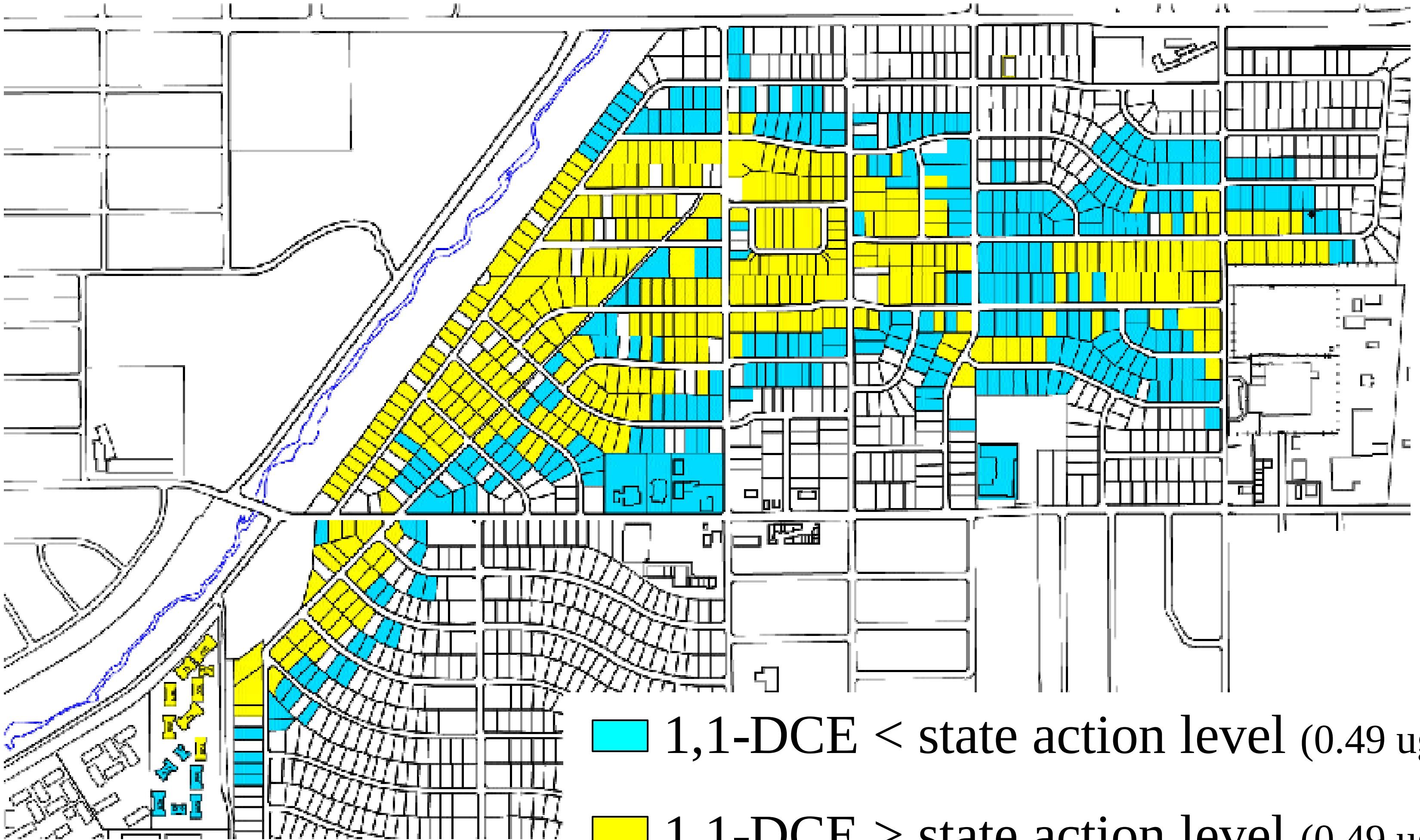
- D_{eff} = fn(H, D_{water}, D_{air}, q_T, q_w) *for each layer*
- L_T = S (L_i)
- Q_{soil} = fn(k, DP, rcrack, zcrack, xcrack)

$$Q_{Soil} = \frac{2p\ ?\ P\ k_v\ X_{crack}}{\mu \ln\left[2\ Z_{crack} / r_{crack}\right]}$$

Background and Key Issues (cont)

- Recent Experience
  - Increasing number of sites where significant vapour intrusion impacts have been documented (the pathway is real!)
  - In a few cases has lead to severe consequences for public reaction, receptor relocation, and/or interim vapor mitigation measures when health risk demonstrated or perceived to be unacceptable
  - Increased regulatory and industry interest in this pathway!

Redfield Site, Denver CO

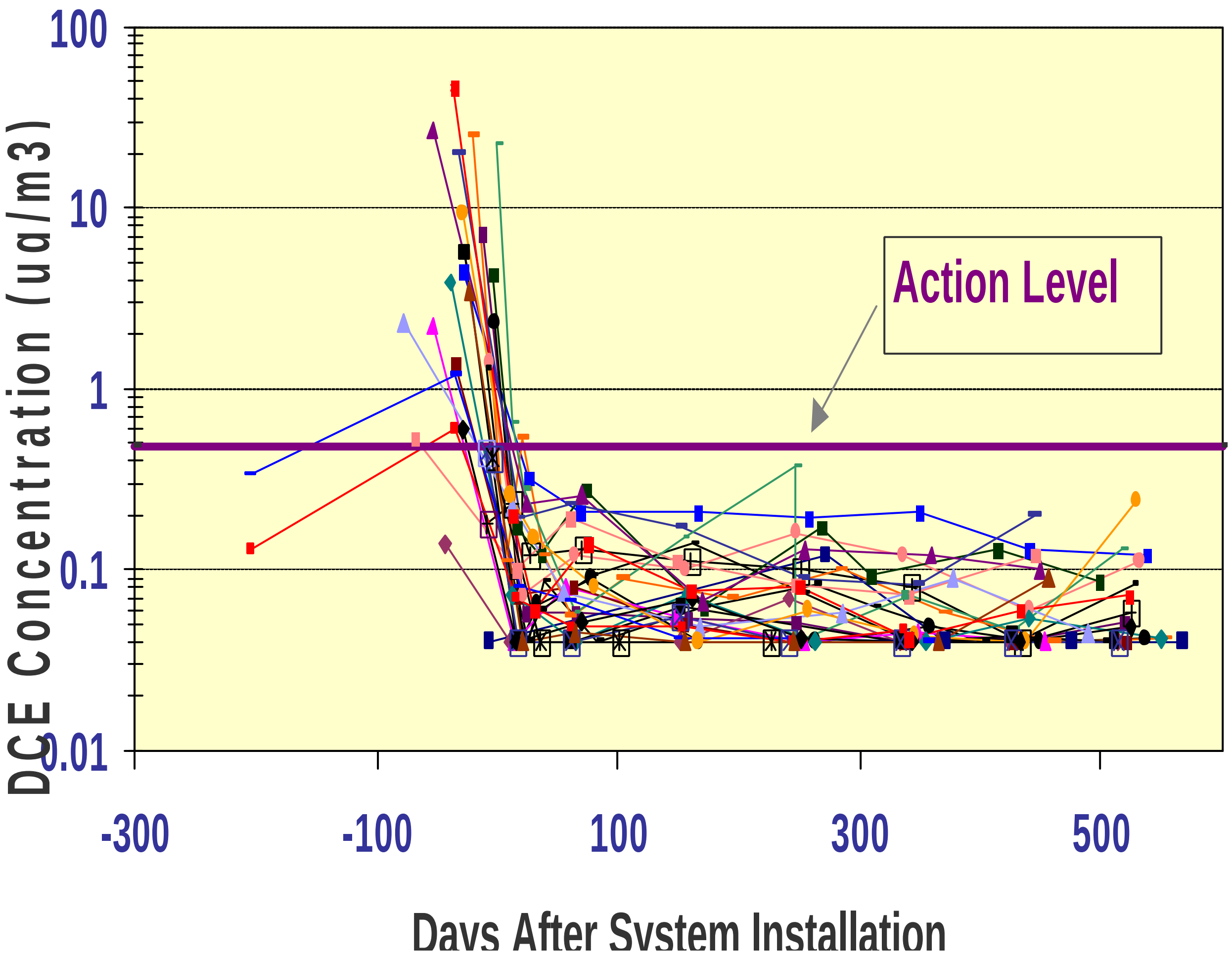


1,1-DCE < state action level (0.49 ug/m3)

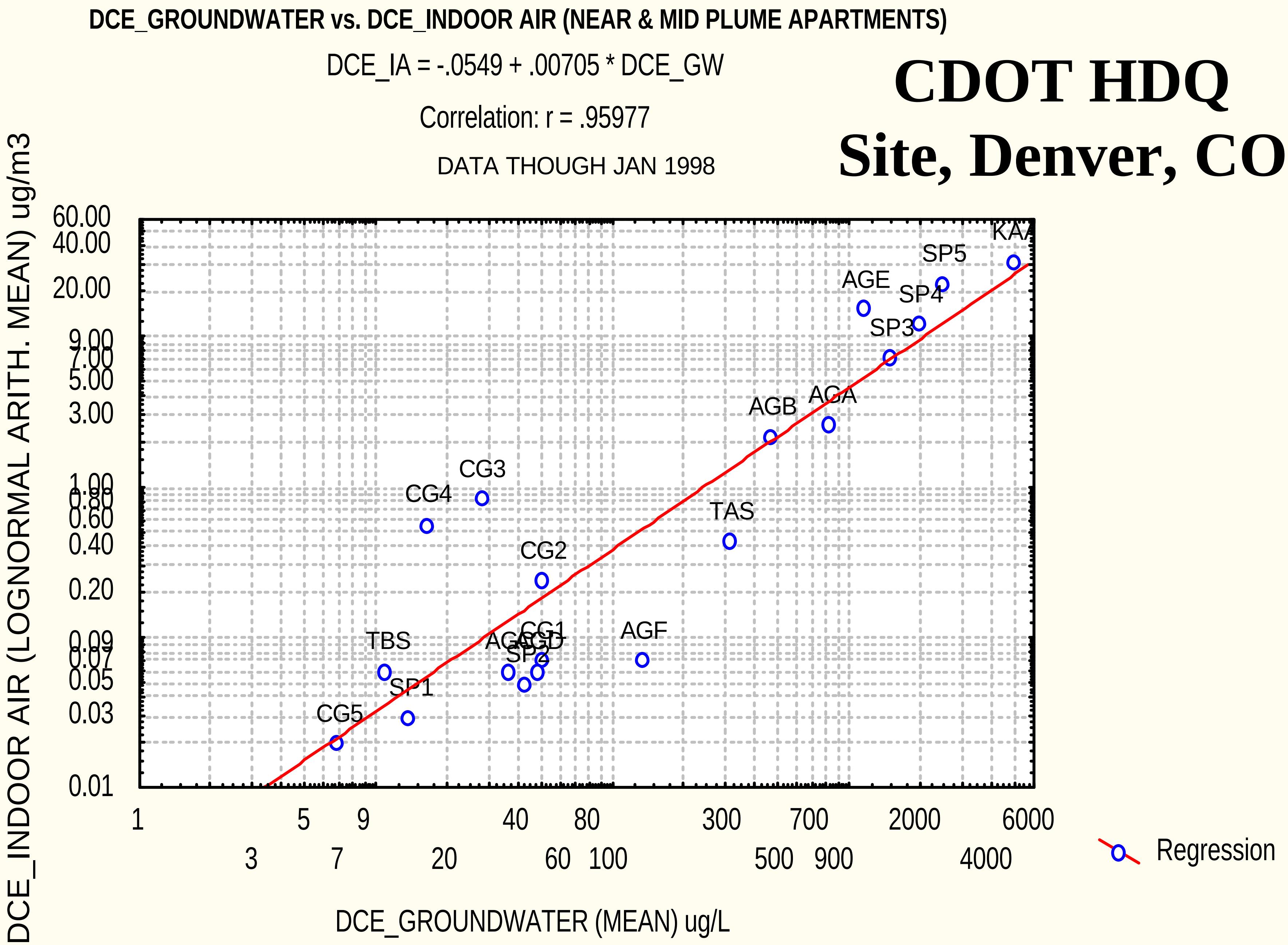
1,1-DCE > state action level (0.49 ug/m3)

1,1-DCE > EPA action level (200 ug/m3)

Redfield Site, Subslab Depressurization Performance



CDOT HDQ Site, Denver, CO

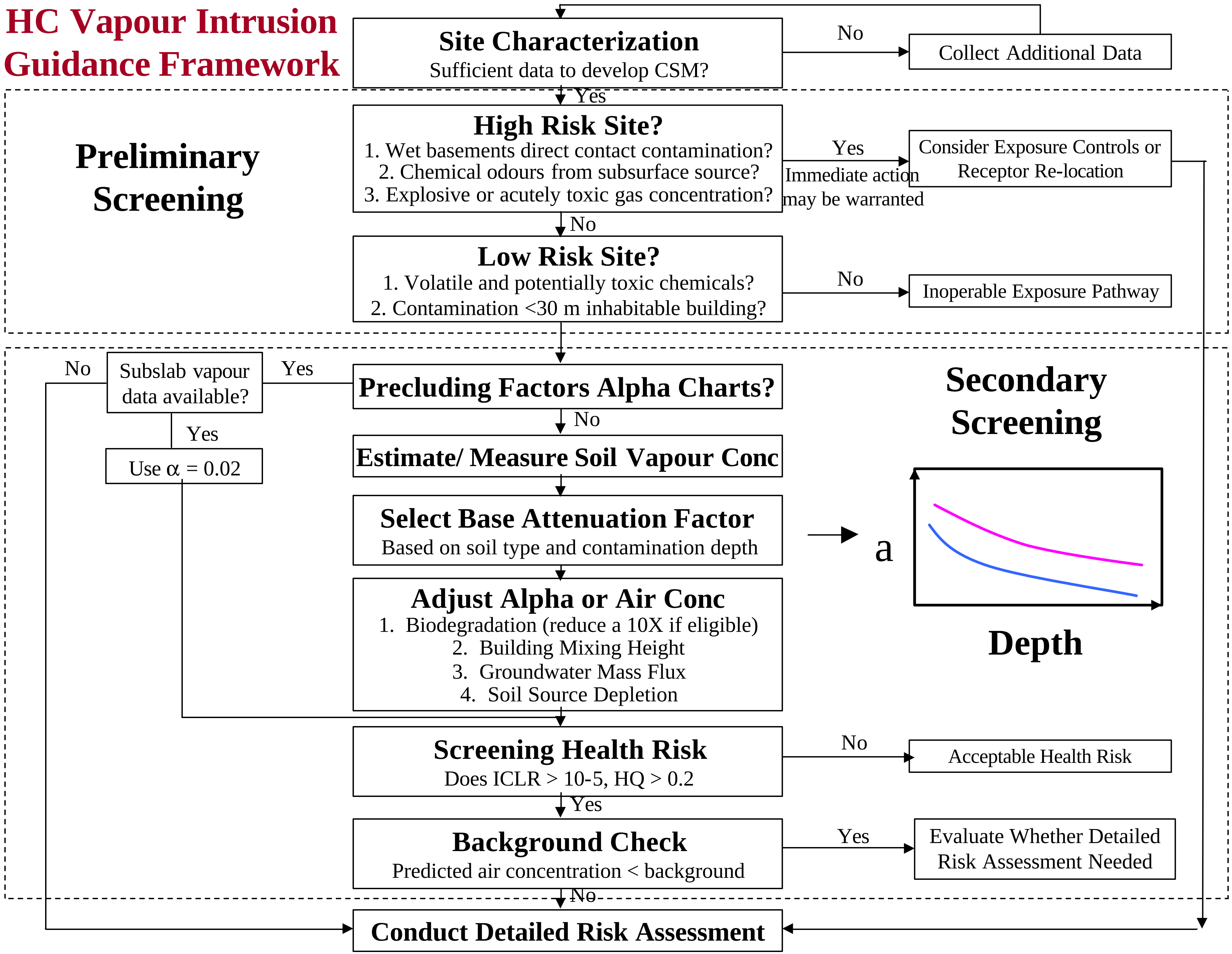


Background and Key Issues (cont)

- Challenges
  - Pathway is complex, variable and difficult to model
  - Model predictions can vary several orders of magnitude
  - Model reliability not well characterized (but improving with recent studies)
  - Generic standards/criteria tend to be overly conservative for most sites
  - Site-specific use of model to derive criteria preferable but requires higher level modeling capabilities and appropriate input parameters

Background and Key Issues (cont)

- Recent Developments
  - Tiered framework for site screening using basic site data & modifying factors for more realistic evaluation of vapour intrusion combined with protocol for site-specific use of models (USEPA, Health Canada, BC SAB)
  - Increased use of empirical data to validate models & develop criteria
  - Use of soil vapour data as opposed to soil data
  - Recognition that in some cases subslab vapour and indoor air testing may be warranted
  - Supporting protocols (e.g, API Soil Gas Protocol)


HC Vapour Intrusion Guidance Framework
Site Characterization
Sufficient data to develop CSM?
No
Collect Additional Data
Yes
Preliminary Screening
High Risk Site?
1. Wet basements direct contact contamination?
2. Chemical odours from subsurface source?
3. Explosive or acutely toxic gas concentration?
Yes
Immediate action may be warranted
Consider Exposure Controls or Receptor Re-location
No
Low Risk Site?
1. Volatile and potentially toxic chemicals?
2. Contamination <30 m inhabitable building?
No
Inoperable Exposure Pathway
No
Subslab vapour data available?
Yes
Yes
Use α = 0.02
Precluding Factors Alpha Charts?
No
Estimate/ Measure Soil Vapour Conc
Select Base Attenuation Factor
Based on soil type and contamination depth
Secondary Screening
a
Depth
Adjust Alpha or Air Conc
1. Biodegradation (reduce a 10X if eligible)
2. Building Mixing Height
3. Groundwater Mass Flux
4. Soil Source Depletion
Screening Health Risk
Does ICLR > 10-5, HQ > 0.2
No
Acceptable Health Risk
Yes
Background Check
Predicted air concentration < background
Yes
Evaluate Whether Detailed Risk Assessment Needed
No
Conduct Detailed Risk Assessment

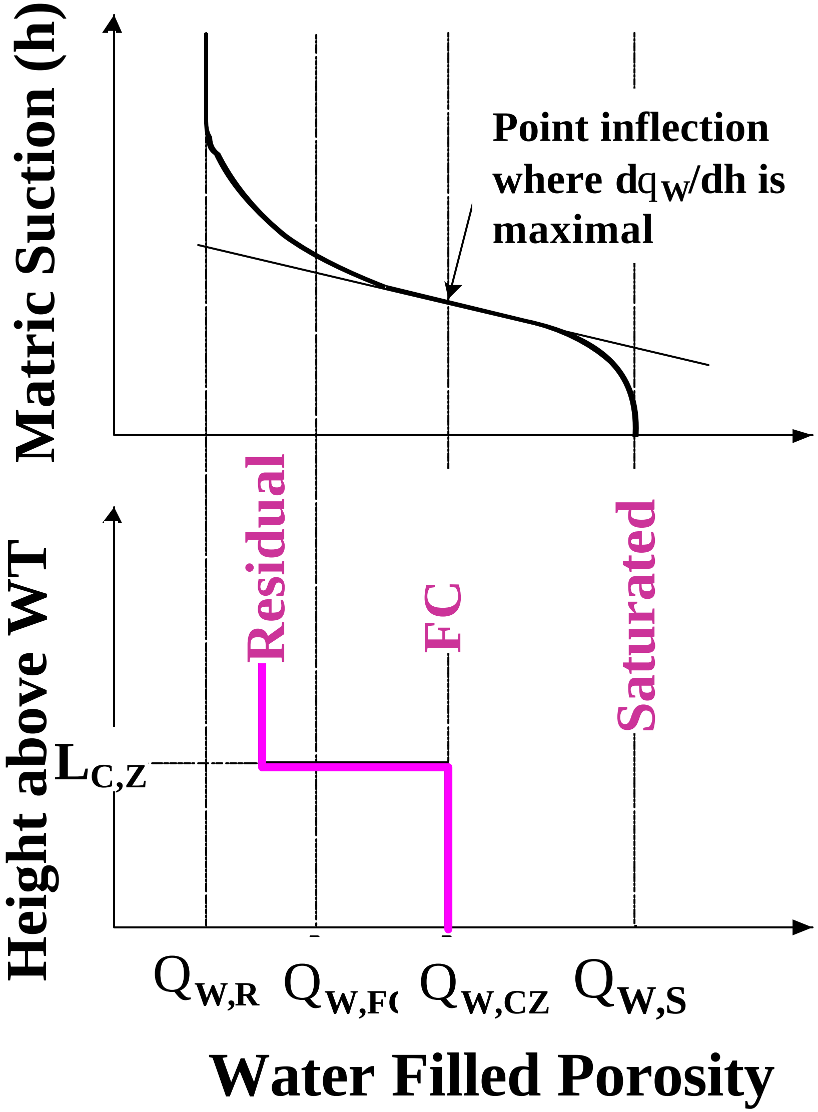
Attenuation Factor Charts

- Derived using J&E model for groundwater-to-indoor air (includes capillary transition zone) and soil vapour-to- indoor air pathways
- Fine- and coarse-grained soil and varying depth to contamination
- Residential (basement) & commercial scenarios (slab-at-grade)
- Factors are for benzene with assumption that properties most chemicals sufficiently similar to benzene
- Model inputs combination typical (average) and conservative values, based on latest science
- Base HC attenuation factors over one order-of-magnitude higher than CCME 2000 CWS-PHC values (why?)

Critical Input Parameters for J&E Attenuation Factor Charts

- Soil Moisture
- Soil Gas Advection (Q_{soil})
- Building air exchange and mixing height

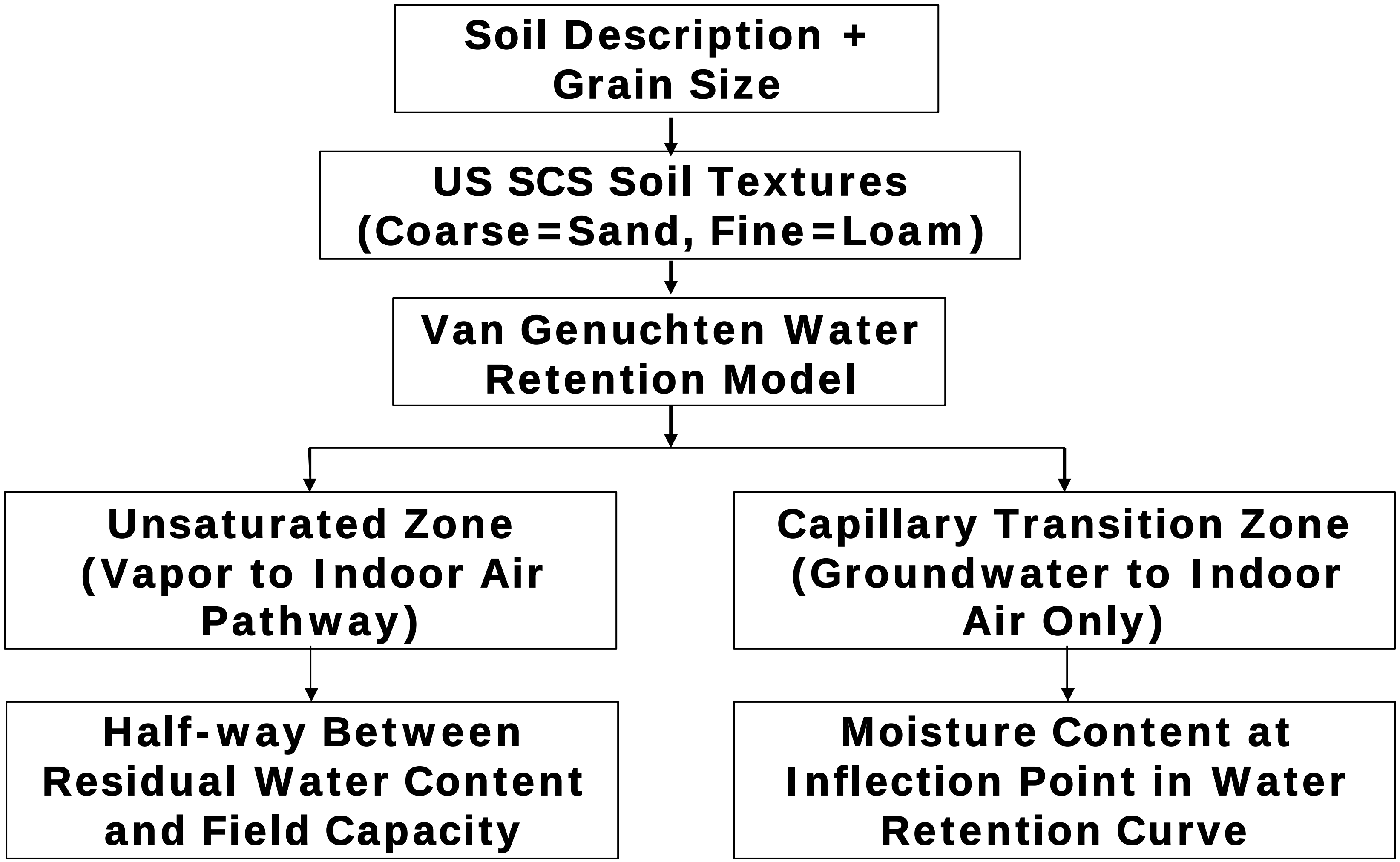
Soil Moisture



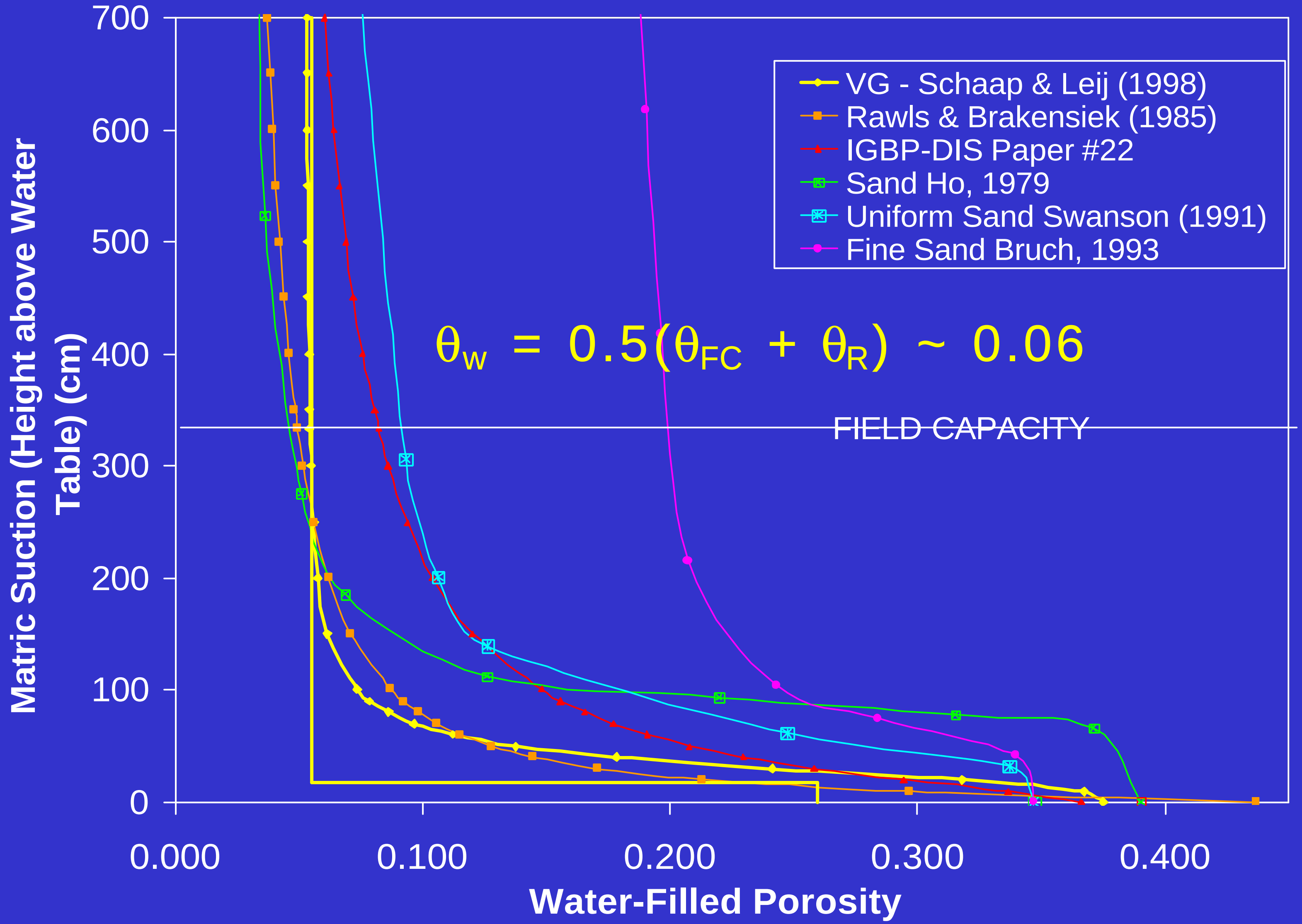
Water Retention Curves (Van Genuchten model) for Sand (Coarse-grained) & Loam (Fine-Grained) - US SCS Classification

Conceptual Simplification

Soil Moisture



Comparison Water Retention Factors Sand



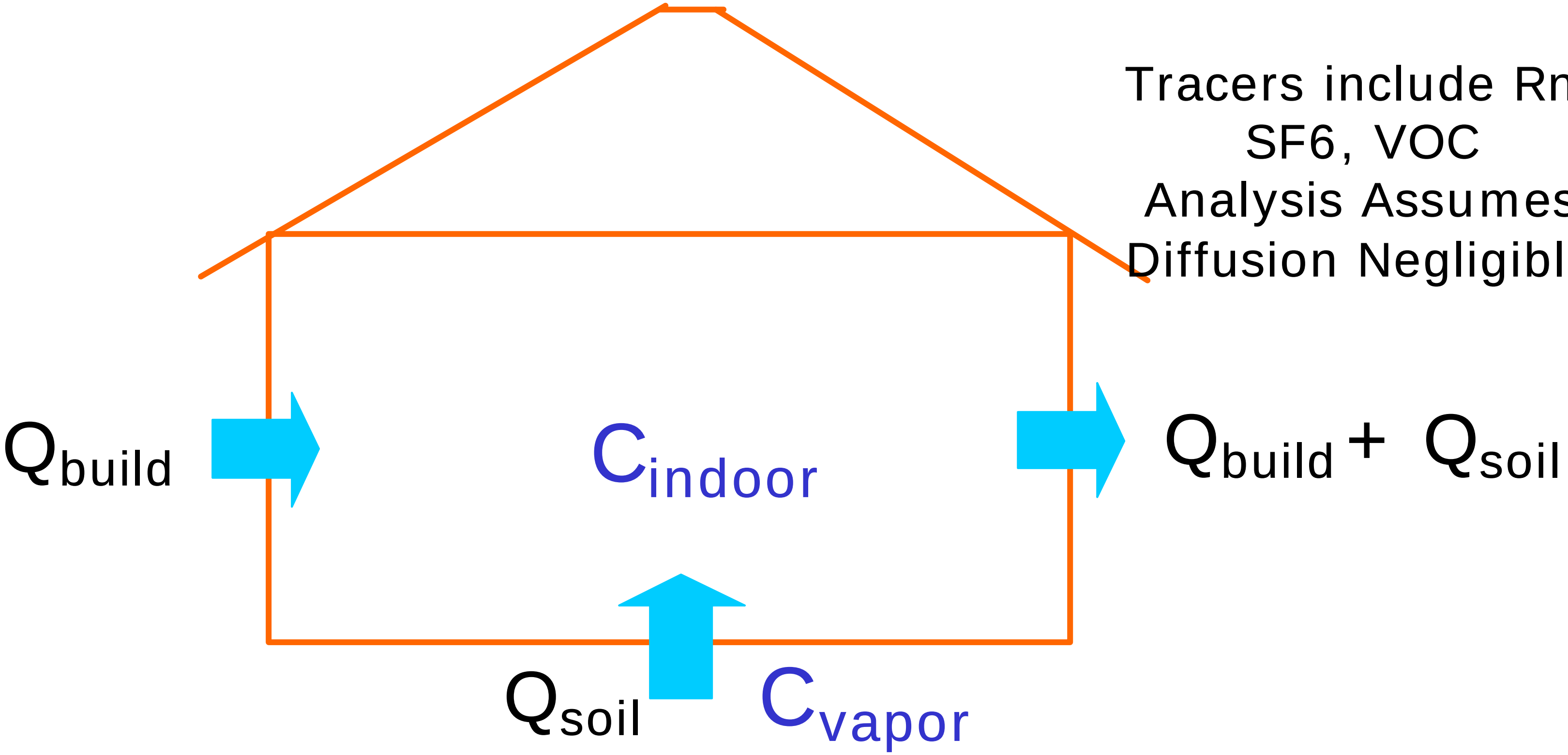
Soil Moisture

- Water retention model for capillary transition zone results in modeled moisture content (MC) that is lower than true MC
- But there is evidence for lateral groundwater flow in capillary fringe (tension saturated zone), also water table fluctuations, therefore upper contamination boundary is above water table
- Analysis involving integration of effective diffusion coefficient suggests effect of:
  - Conservative water retention model and non-contaminated capillary fringe is off-set by …
  - True water retention model and contaminated capillary fringe & true water retention model off-set by (balancing effect)

Soil Gas Advection (Qsoil)

- Function ΔP, soil properties (adjacent to foundation!), foundation properties
- ΔP depends on stack effect (indoor/outdoor temperature difference), wind, fan operation, unbalanced return air ducts, insufficient combustion air, fireplace use
- *Stack effect*: Inside building heated (furnace, sunlight on roof), hot air rises, leaves "top of building", creates ΔP, air enter available openings, which can be doors, windows, subsurface foundation (soil gas!)
- ΔP varies depending on house construction, season and climatic region
- Can estimate Q_{soil} using perimeter crack model (reliability?) or from empirical data (tracer tests)

Q_{soil} Estimated Using Tracer Test



Tracers include Rn, SF6, VOC
Analysis Assumes Diffusion Negligible

$\alpha = C_{indoor}/C_{vapor} \sim Q_{soil}/(Q_{soil}+Q_{build}) \sim Q_{soil}/Q_{build}$

If know Q_{build}, then can estimate Q_{soil}
Keep in mind tracer test α is for source directly below building

HOUSE VAPOR INTRUSION TRACER STUDIES

Study	Building	Soil Type	Tracer	ΔP	Q_{soil}/Q_{build}	Q_{soil} (L/min)	Q_{soil}/Area (L/m^2)	Q_{soil}/Area-ΔP (L/m^2-Pa)
Olson & Corsi (2001)	House w\basement Paulsboro	Sand, some silt	SF_6	3.6 to 6.2	0.003 to 0.01	5.8 to 6.7	0.18 (6.2 Pa)	0.03
Mose & Mush-rush (1999)	Houses Virginia	N/A	Radon	N/A	0.003 to 0.02	N/A	N/A	N/A
Hers (Chatterton) (1998)	Experimental Greenhouse	M. Sand	BTX	10 to 30	0.0003 to 0.0006	2.7 to 4.2	N/A	0.005 to 0.01
Fischer et al. (1996)	Small Commercial Building	F. Sand	SF_6	3	0.0002 to 0.0004	1.4 [1]	0.018	0.006
Garbesi et al. (1993)	Small Experimental Basement	F. Sand	N/A	10	N/A	9.7		0.04
Little et al. (1992)	Houses USA	N/A	Radon	N/A	0.0016 (Avg)	N/A	N/A	N/A
Garbesi & Sextro (1989)	House w\basement	Sandy Loam to Loamy Sand	SF_6	30	~0.001	67 (Best)	N/A	0.01(Best)
Rezvan et al. (1989)	Houses	Gravel	Rn	N/A	0.0079 to 0.045	17 to 96[2]	N/A	N/A

1 Estimated by Fischer et al (1996) from wind-loading (Qbuilding not available)
2 Estimated using assuming values for house volume (366 m3) and AEH (0.35/hr) (Qbuilding not available)
3 Cyclohexane, MTBE, Pentane, 2,2,4-Trimethylpentane

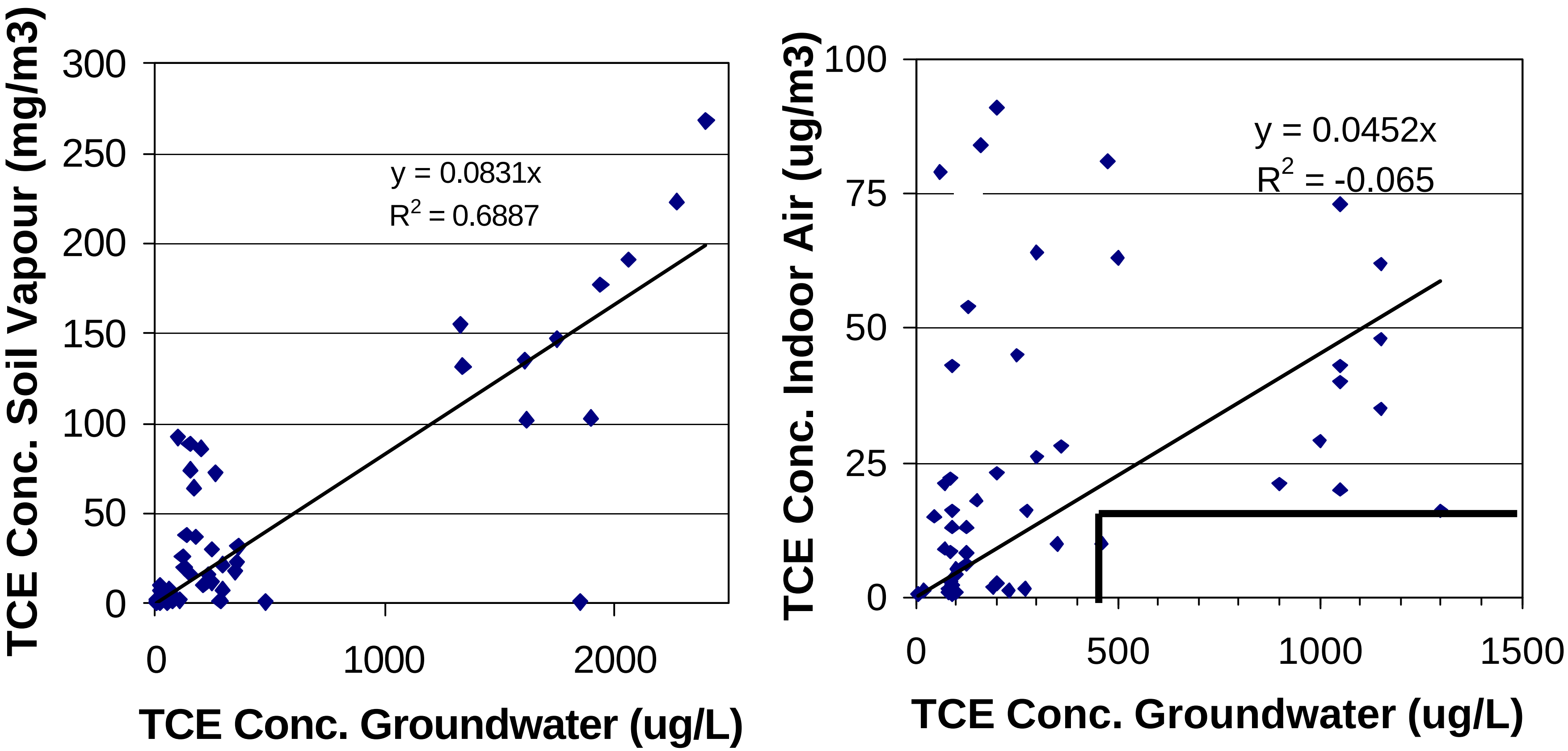
Soil Gas Advection (Qsoil)

- Sites with coarse-grained soils
- Q_{soil}/Q_{build}: 0.0002 to 0.02
- Q_{soil}: 1 to 50 L/min (upper range is uncertain)
- Q_{soil}/Area-ΔP: 0.005 to 0.04 L/m^2-Pa
- Health Canada Guidance
  - Q_{soil} = 5 L/min
  - Q_{soil}/Q_{build} = 0.003

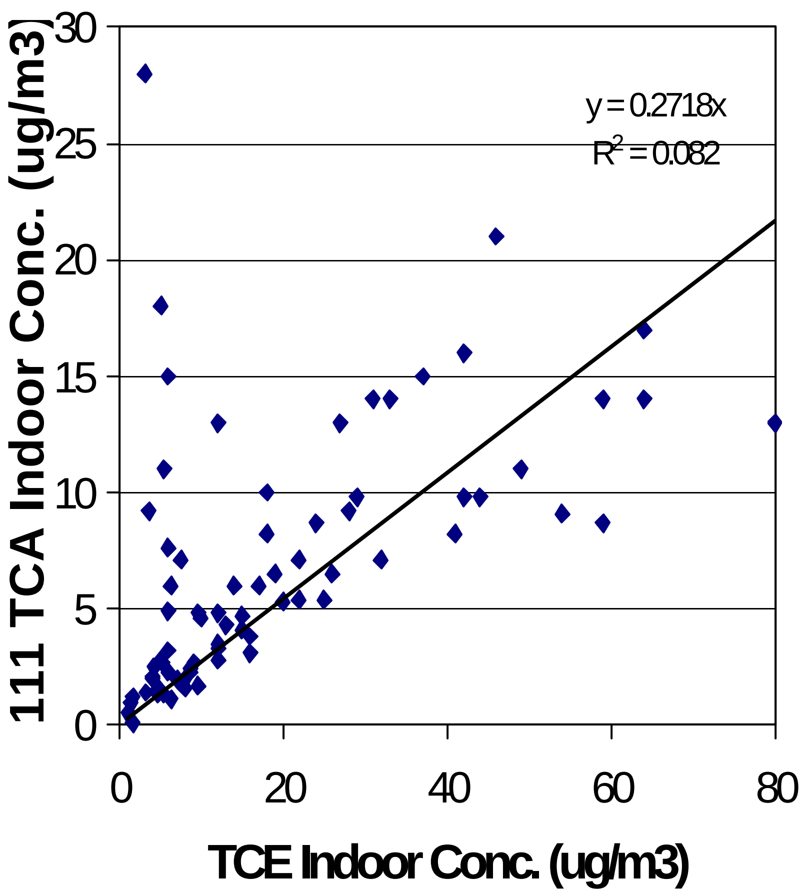
Model Validation Empirical Data

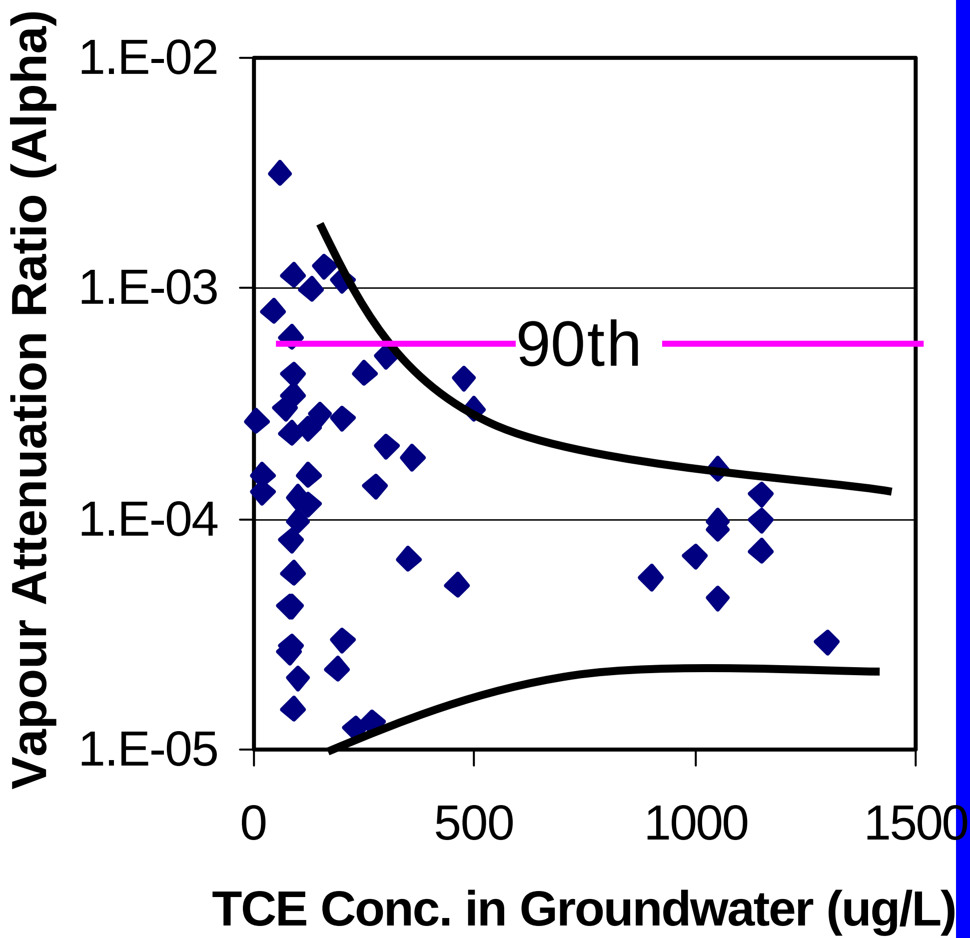
- Empirical evaluation of vapour attenuation factors was important part of guidance development process
- Empirical alpha = measured indoor concentration / interpolated groundwater or soil vapour concentration below house
- Empirical database 36 sites (research, USEPA, projects) … data quantity & quality vary; several sources of uncertainty
- Prior to use, data was carefully evaluated and screened to remove less reliable data:
  - Evaluate data trends and correlations (“vapour pathway analysis”)
  - Evaluate effect of background VOCs
  - Remove low concentration data
- Use 90th percentile or maximum empirical alpha’s for each site since goal is to be protective most sites

Example Pathway Analysis

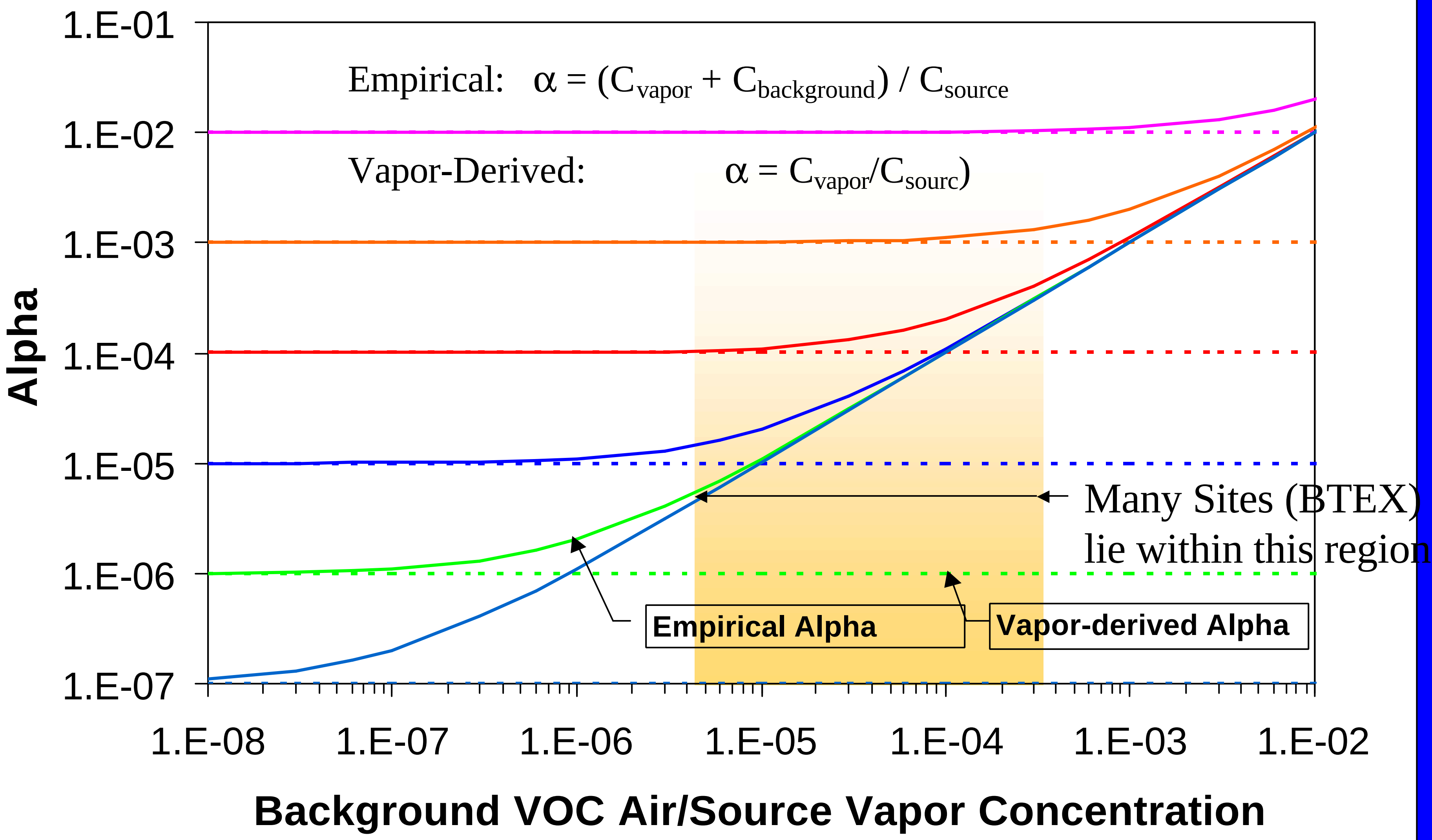


Example Pathway Analysis (cont.)



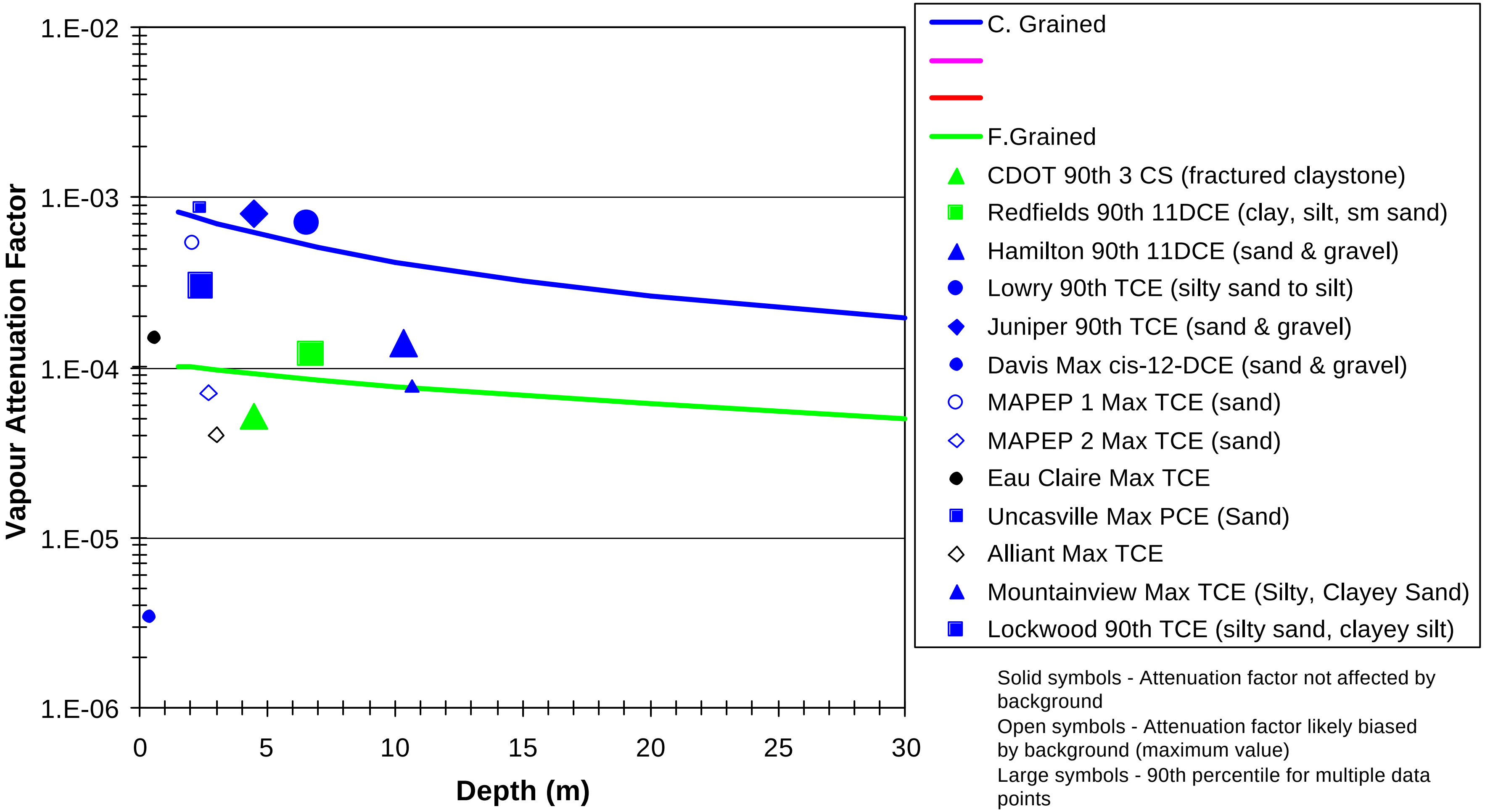


Influence Background VOC Concentration on Attenuation Factor



Groundwater-to-Indoor Air

Chlorinated Solvents - Residential (HC Study)

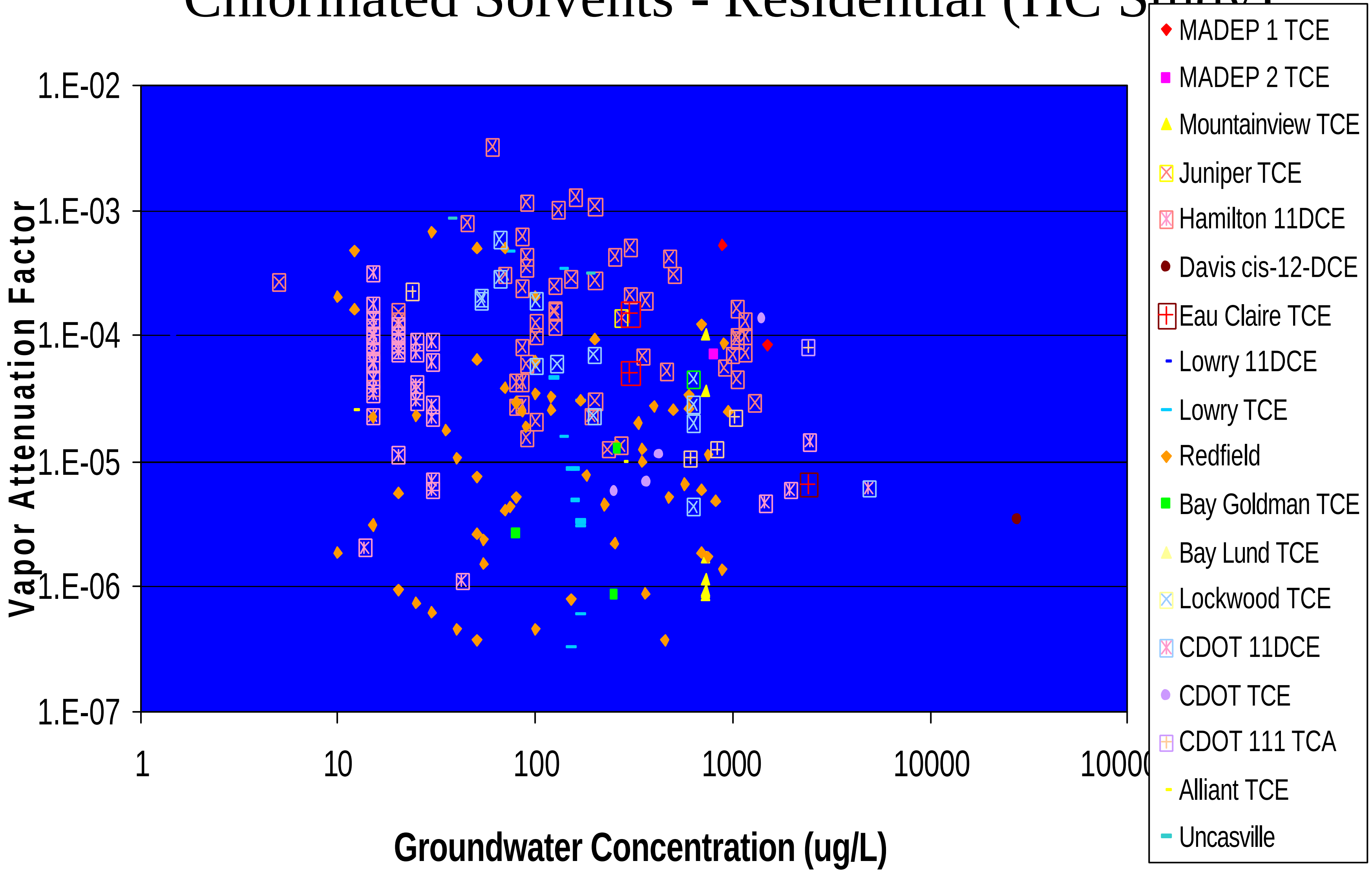


Solid symbols - Attenuation factor not affected by background
Open symbols - Attenuation factor likely biased by background (maximum value)
Large symbols - 90th percentile for multiple data points
Small symbols - Maximum value small data set

Soil vapour concentrations predicted using Henry's Law Constant

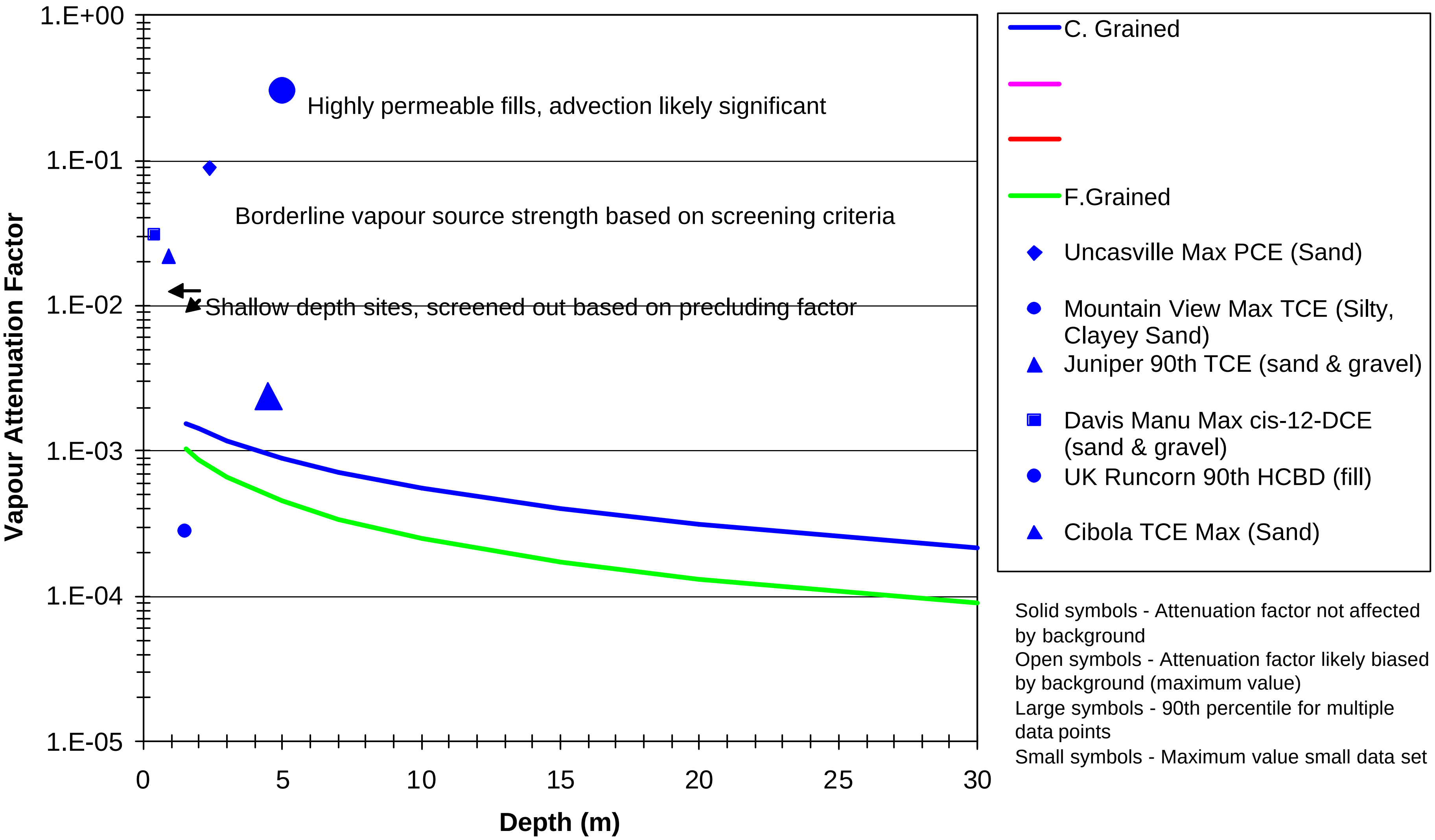
Groundwater-to-Indoor Air

Chlorinated Solvents - Residential (HC Study)



Soil Vapour-to-Indoor Air

Chlorinated Solvents - Residential (HC Study)



Solid symbols - Attenuation factor not affected by background
Open symbols - Attenuation factor likely biased by background (maximum value)
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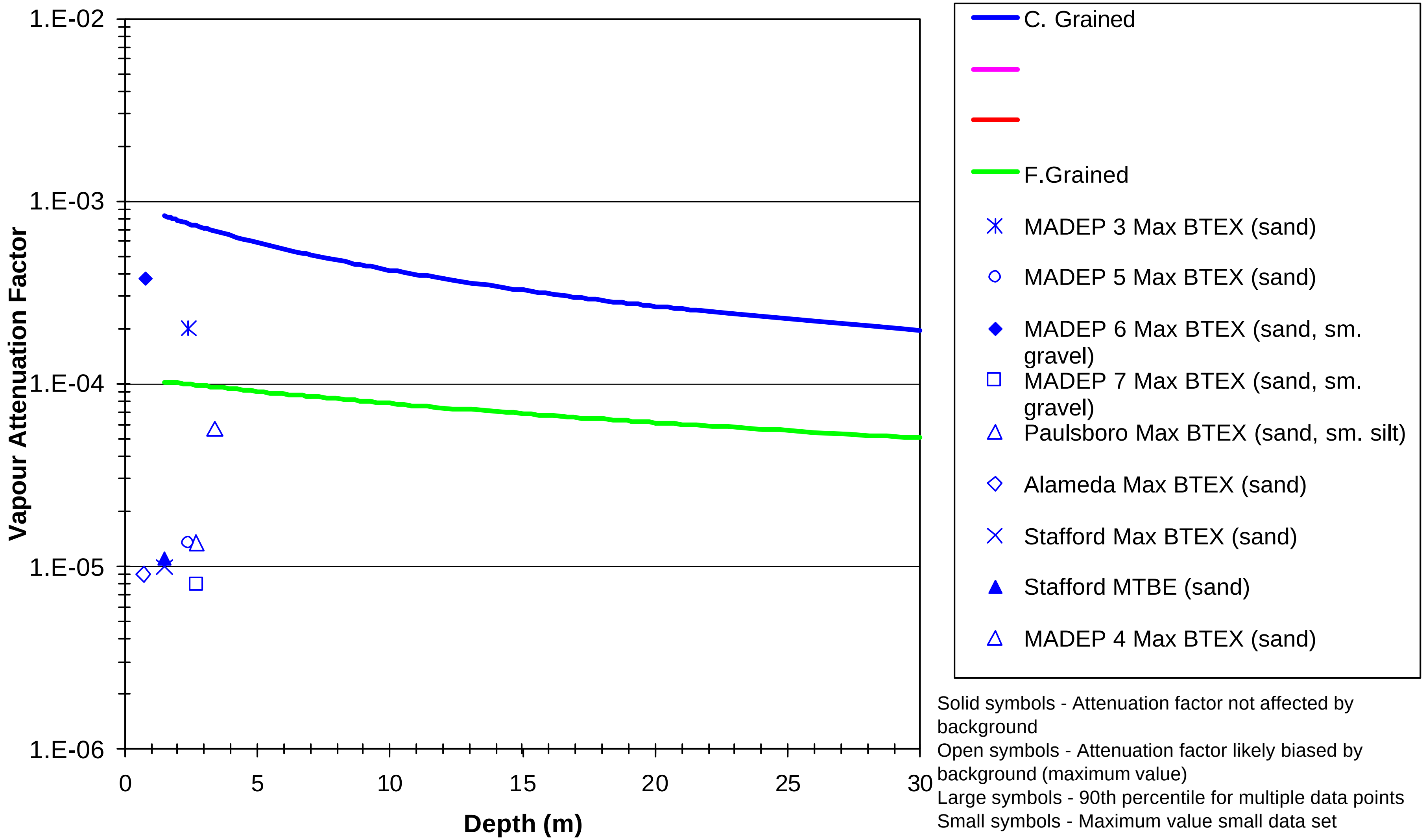
Groundwater -to-Indoor Air

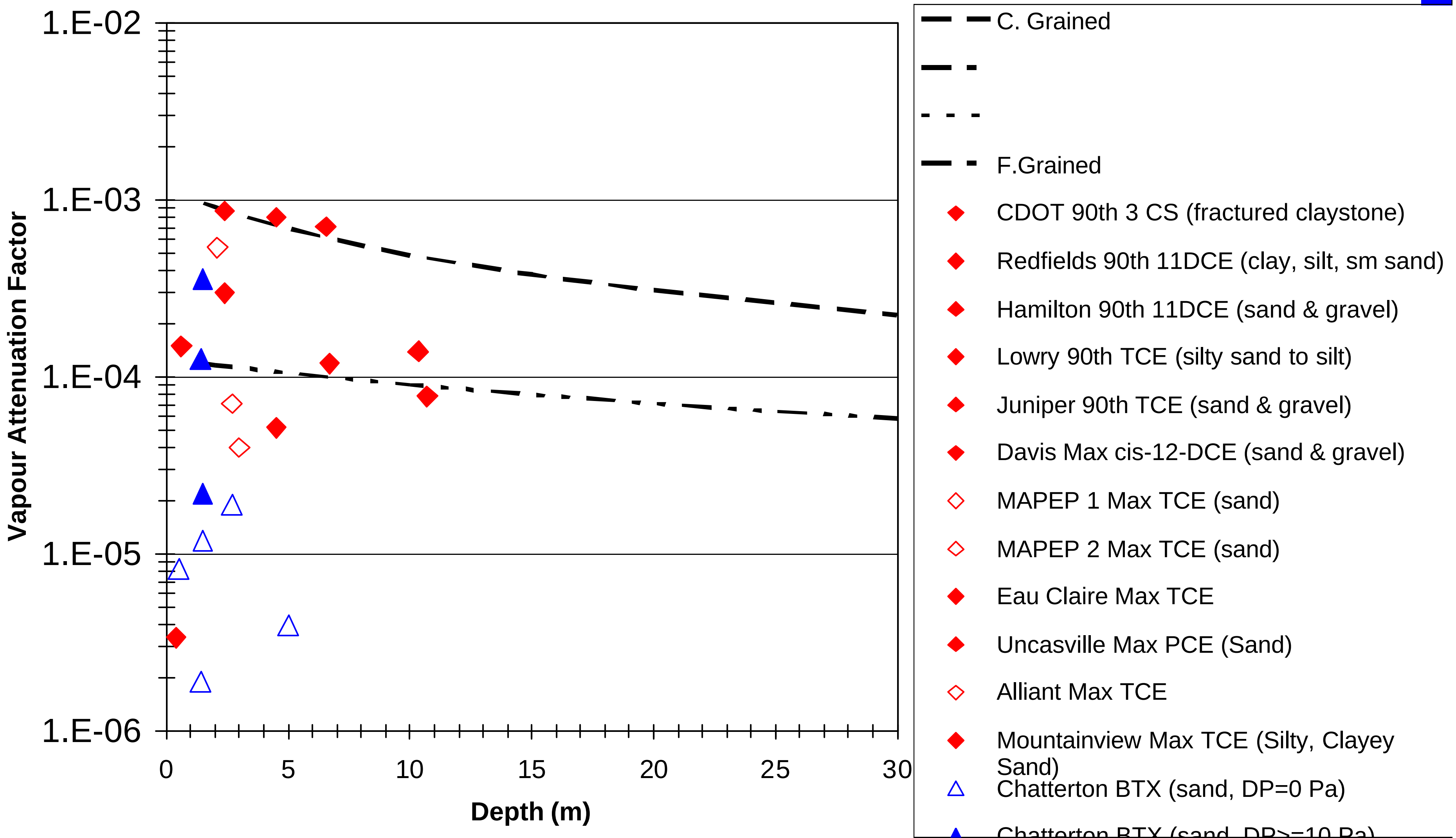
Petroleum Hydrocarbons - Residential (HC Study)



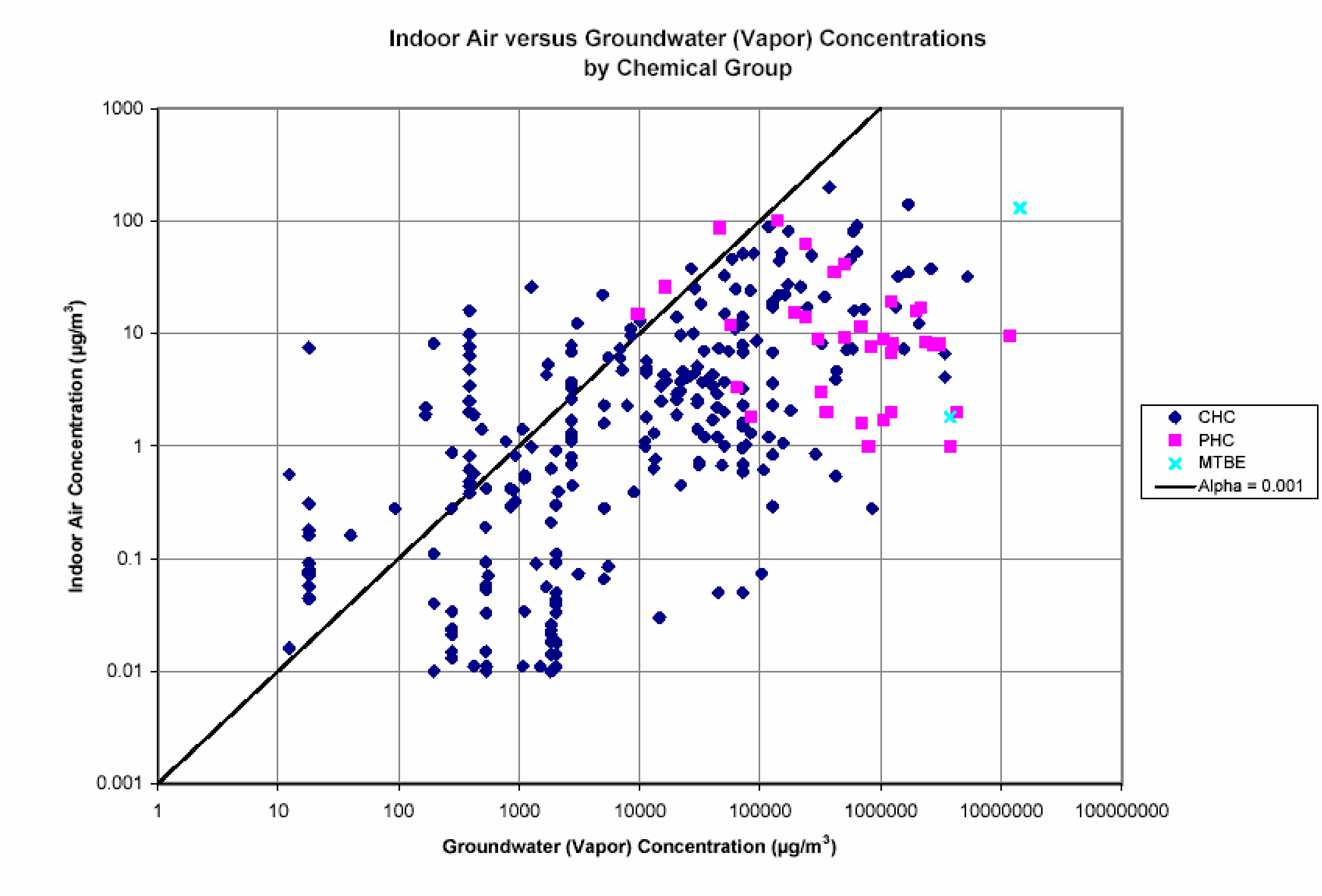
Solid symbols - Attenuation factor not affected by background
Open symbols - Attenuation factor likely biased by background (maximum value)
Large symbols - 90th percentile for multiple data points
Small symbols - Maximum value small data set

Groundwater -to-Indoor Air

All Data - Residential (HC Study)



USEPA IAVI Database



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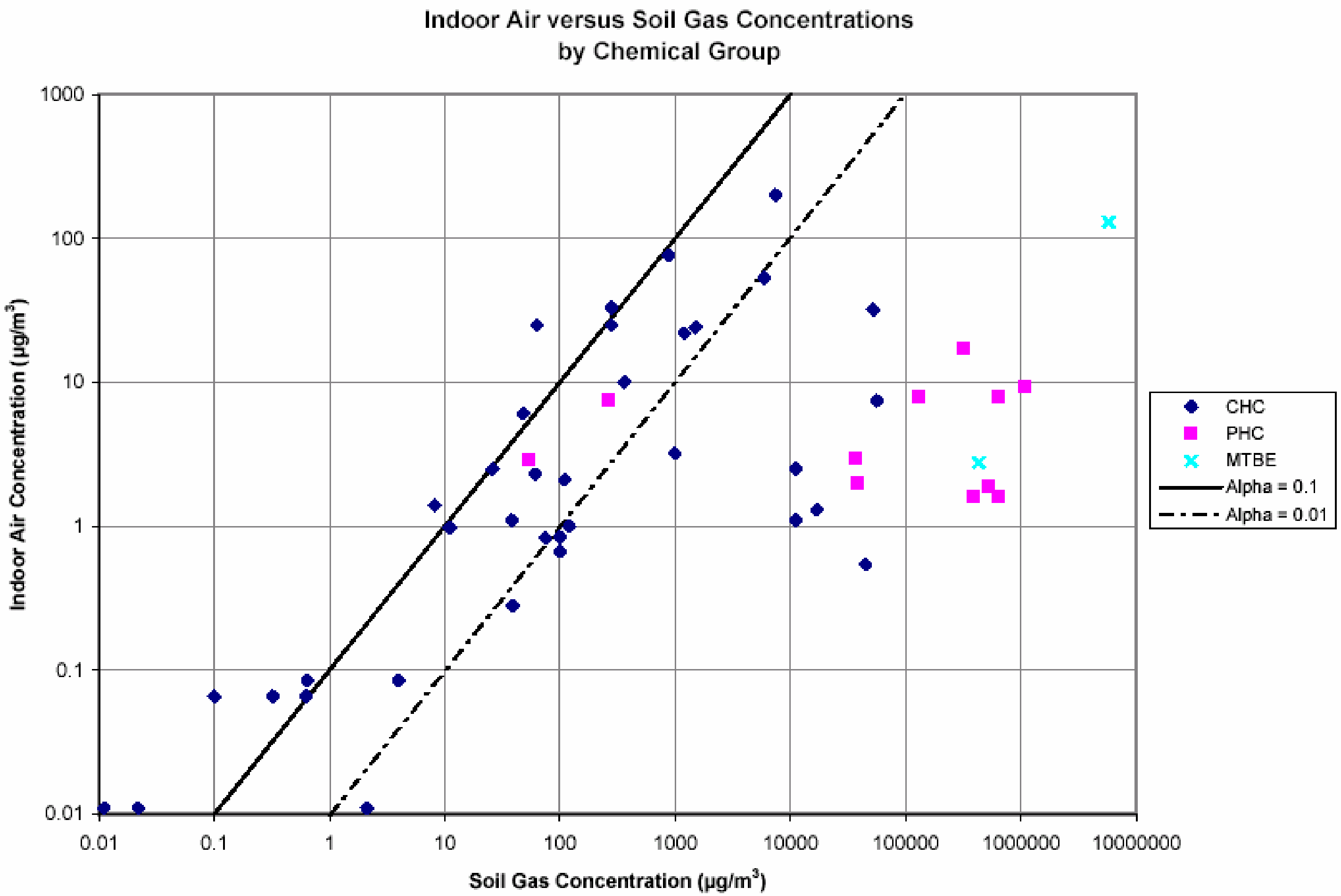

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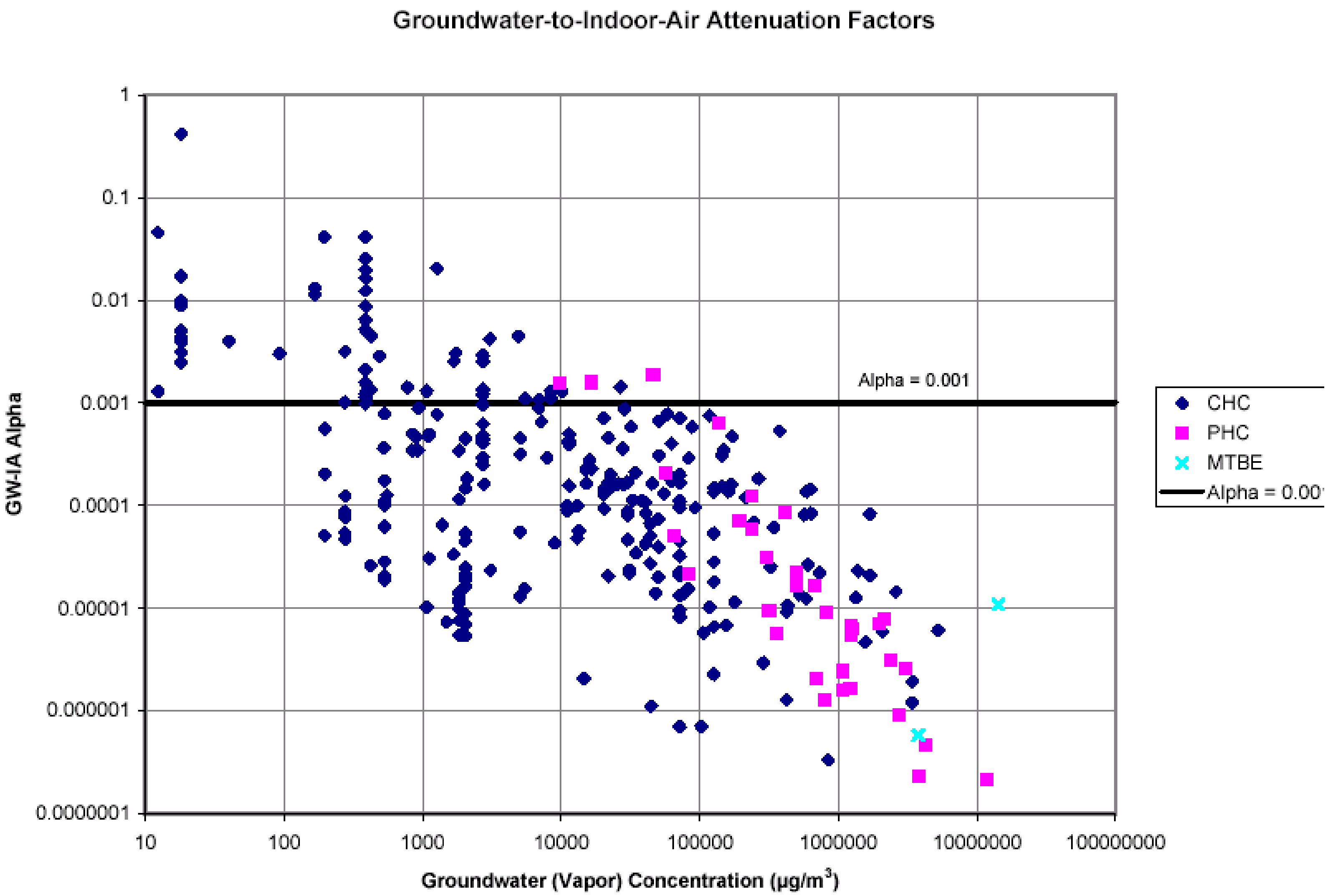
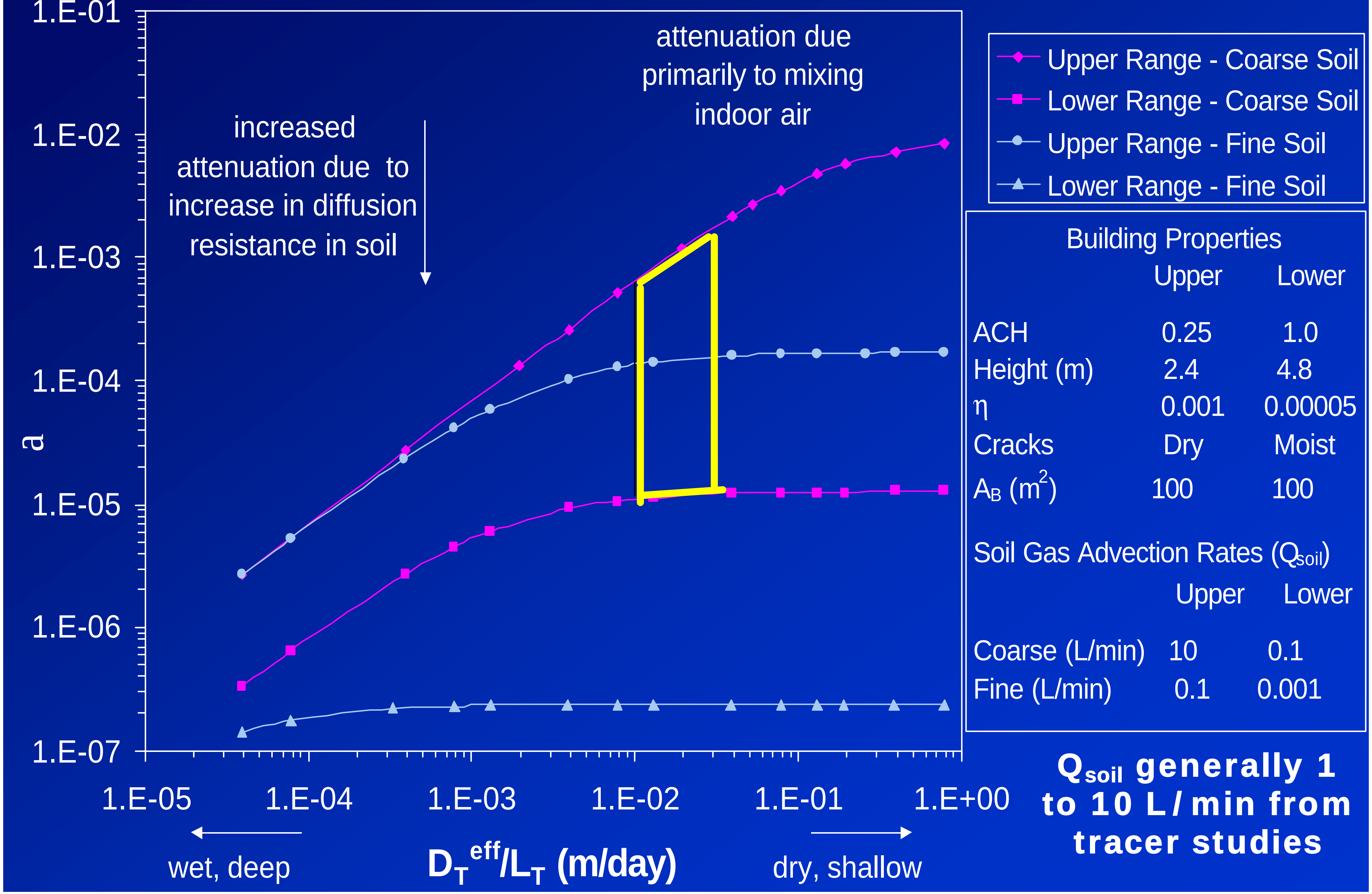


Validation J&E Model



Building Properties

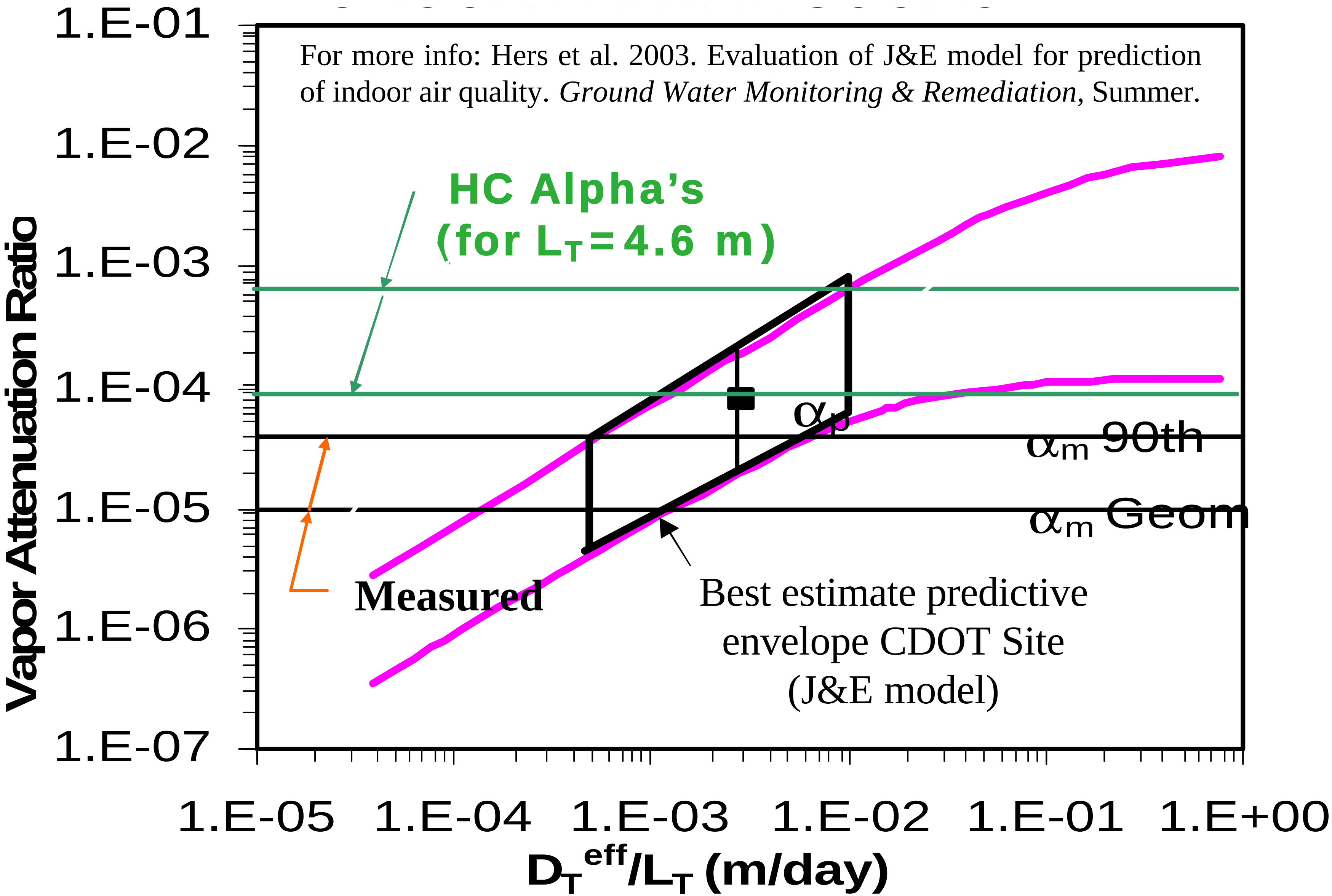
	Upper	Lower
ACH	0.25	1.0
Height (m)	2.4	4.8
η	0.001	0.00005
Cracks	Dry	Moist
A_B (m^2)	100	100

Soil Gas Advection Rates (Q_{soil})

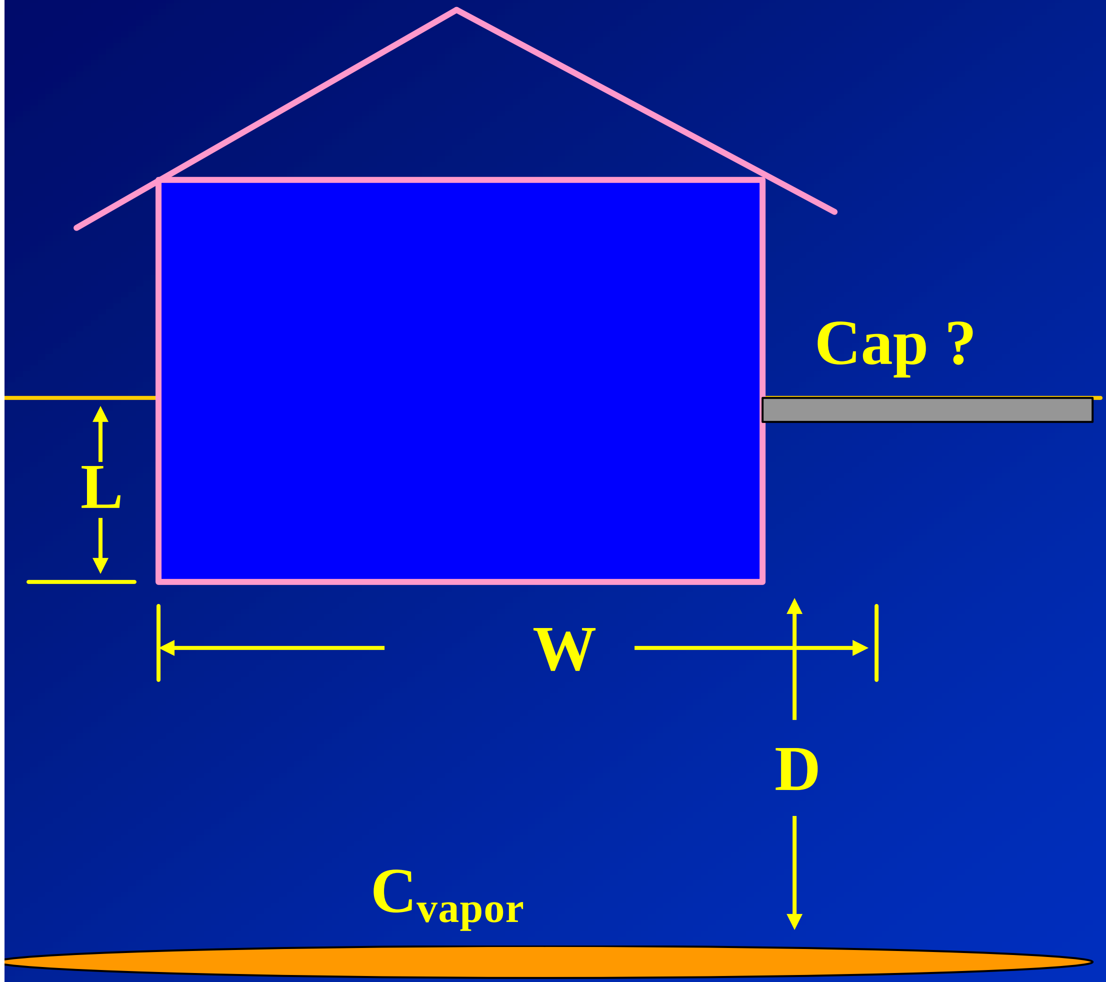
	Upper	Lower
Coarse (L/min)	10	0.1
Fine (L/min)	0.1	0.001

Q_{soil} generally 1 to 10 L / min from tracer studies

CDOT HDQ Site, Colorado

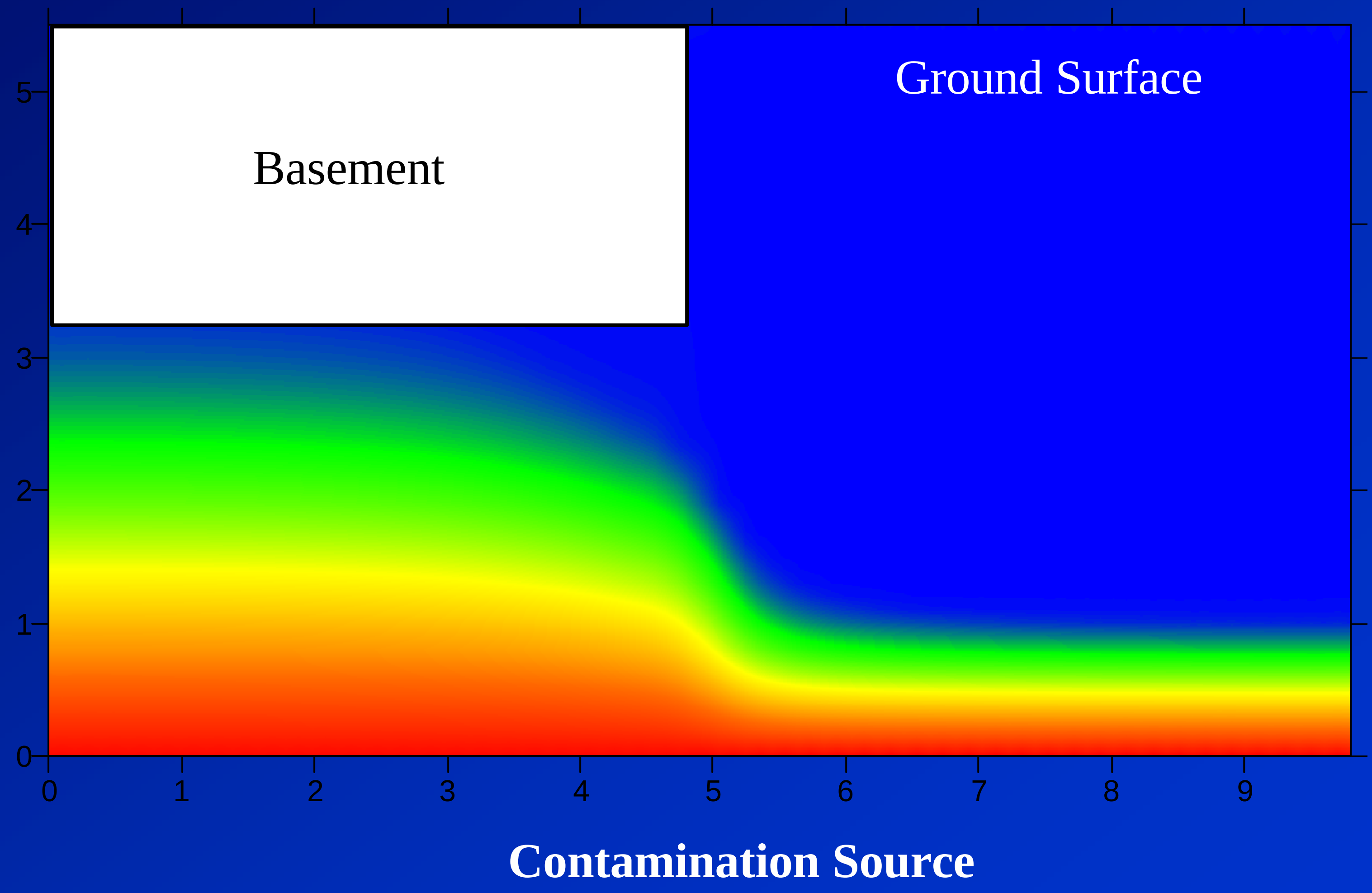


Biodegradation Adjustment (BTEX)

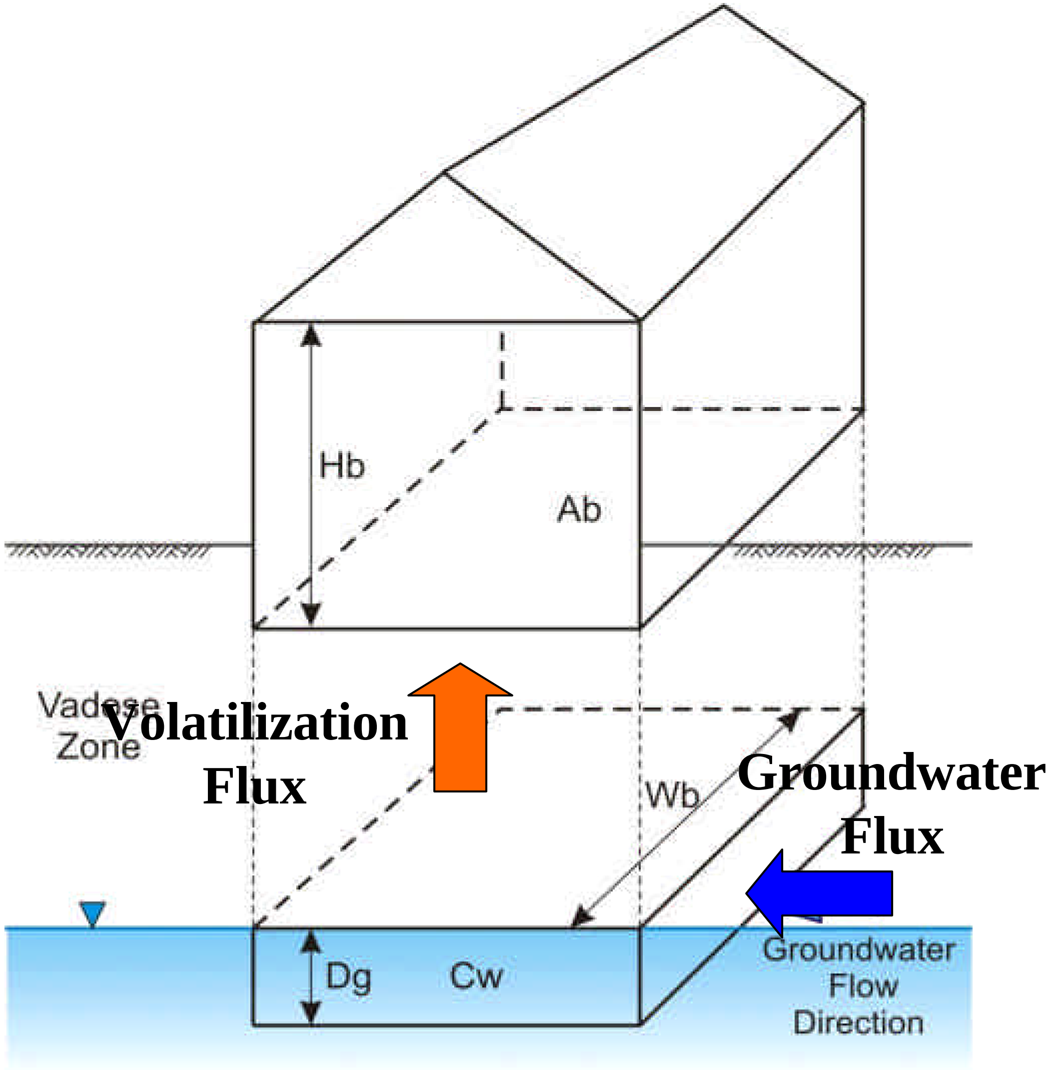


- Key biodegradation potential is O_2 transport below building
- Biodegradation potential affected by D,L,W, C_{vapor}, soil properties, capping effect
- Modeling study was con-ducted to evaluate above parameters for gasoline LNAPL source
- Guidance Criteria: D > 4 m, no significant capping effect

Numerical Model Benzene Vapour Concentrations O2-Limited Biodegradation



Groundwater Mass Flux Adjustment (Conceptual Model)

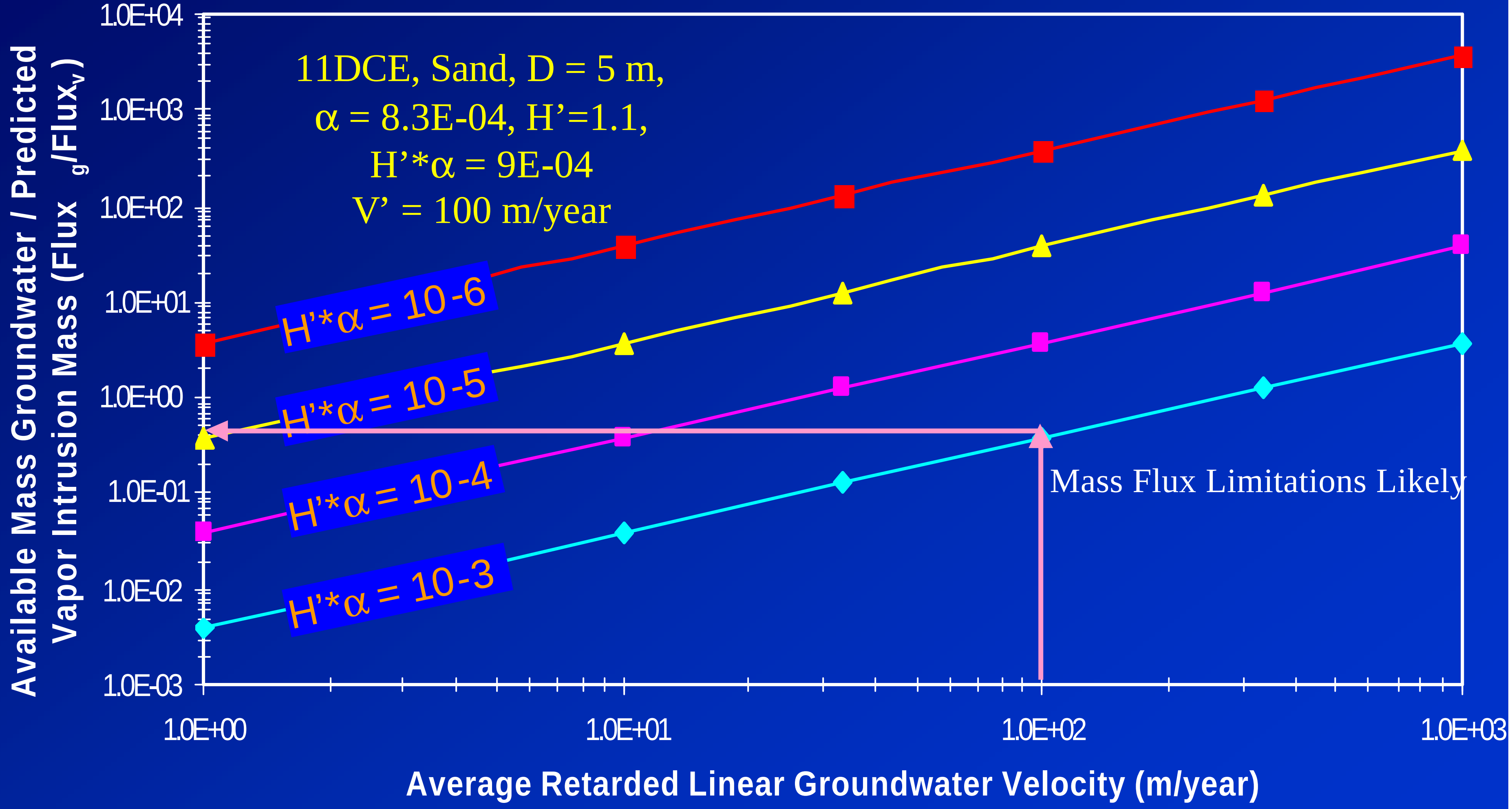


If Volatilization Mass Flux (based on assumed alpha) > Available Groundwater Mass Flux, then Adjust Air Concentration (Alpha)

Relevant for more volatile chemicals (vinyl chloride, 11 DCE) dimensionless Henry's Law Constants > 1

Groundwater Mass Flux Check

(Analytical Model)



Conclusions

- Sound framework for vapour pathway essential
- Health Canada alpha charts incorporate updated inputs based on recent science (different than CCME)
- Empirical validation models important part of process
- Wide variation in empirical alpha, for chlorinated solvents α ranged between ~ 10^{-3} to less than 10^{-6}, for petroleum hydrocarbons α ranged between ~ 10^{-4} and less than 10^{-6}
- 90^{th}/Max measured alpha's for chlorinated solvent sites similar to or less than HC alpha's suggesting HC alpha's are reasonably protective, 90^{th}/Max alpha's for petroleum sites about one order-of-magnitude less
- Adjustments for biodegradation, building height and mass flux important part of guidance