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Vadose zone inverse modeling of pneumatic pumping tests at the Hanford Site: Influence of barometric pressure fluctuations

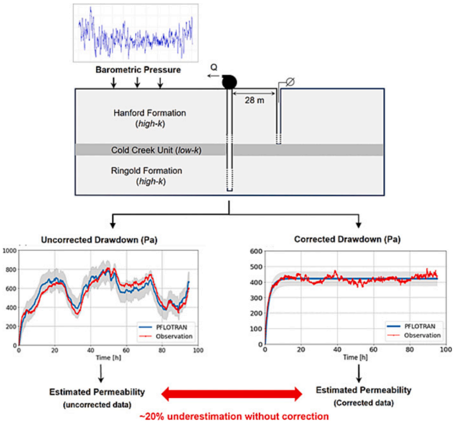
Farzad Moeini [a], Kenneth C. Carroll [b,*], Zhenxue Dai [c,d], Mohamad Reza Soltanian [a,e]

[a] Department of Geosciences, University of Cincinnati, Cincinnati, OH, USA
[b] Plant and Environmental Sciences Department, New Mexico State University, Las Cruces, NM, USA
[c] College of Construction Engineering, Jilin University, Changchun, China
[d] School of Environmental and Municipal Engineering, Qingdao University of Technology, Qingdao, China
[e] Department of Environmental Engineering, University of Cincinnati, Cincinnati, OH, USA

HIGHLIGHTS

- Systematic comparison of barometric pressure effects on air permeability estimation
- Neglecting barometric effects causes ~20 % air permeability underestimation.
- Simple full-domain models outperform complex heterogeneous approaches.
- Practical framework improves pneumatic test interpretation in layered vadose zones.

GRAPHICAL ABSTRACT



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ABSTRACT

Gas flow dynamics in the vadose zone is essential for designing and optimizing environmental remediation technologies such as soil vapor extraction, which depends on air permeability estimates. Barometric pressure has a critical, yet frequently overlooked, influence on subsurface airflow. This study explores barometric pressure impact on pneumatic pumping test parameter estimations applied to the U.S. Department of Energy Hanford Site. Numerical simulations were used to evaluate barometric effects across five model configurations of increasing complexity, ranging from idealized one-dimensional homogeneous domains to two-dimensional models incorporating anisotropy and stratified heterogeneity. Results indicate that neglecting barometric influences can lead to a systematic underestimation of air permeability by ~20 %, with uncorrected estimates ranging from 2.90 to 4.23×10^{-12} m^2 compared to corrected estimates of $3.55–4.97 \times 10^{-12}$ m^2. Among uncorrected scenarios, R^2 values ranged from 0.54 (2D anisotropic half-layer) to 0.87 (1D and 2D full-domain models). For corrected scenarios, R^2 values were more consistent, ranging from 0.71 to 0.82. Sensitivity analysis revealed that the

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[*] Corresponding author.
E-mail address: kccarr@nmsu.edu (K.C. Carroll).

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relative importance of model parameters remained consistent regardless of whether barometric corrections were applied, with permeability (Sobol index ≈ 0.7–1.0) and anisotropy ratio (Sobol index ≈ 0.3) maintaining dominance. While correcting for barometric pressure improves the accuracy of permeability estimates, it does not fundamentally change the hierarchical structure of parameter sensitivities. The results demonstrate that full-domain representation play a more significant role in accurately simulating pneumatic responses than explicit heterogeneity. This study presents a framework for improving pneumatic test interpretation, as an essential step in design and optimization of subsurface remediation strategies.

1. Introduction

Predicting gas flow dynamics in the vadose zone is a complex yet essential task for understanding several natural and engineered systems, particularly in the context of environmental remediation. One prominent application is soil vapor extraction (SVE), a widely implemented technology for removing volatile organic compounds (VOCs) and other gaseous contaminants from the unsaturated zone (USACE, 2002; EPA, 2001*;* Brusseau et al., 2013). In SVE systems, a vacuum is applied to the subsurface to induce airflow through contaminated soils, promoting the volatilization and subsequent extraction of contaminants, thereby mitigating their migration to groundwater or the atmosphere. The effective design of SVE systems relies on accurate estimation of key subsurface properties that govern gas flow in the vadose zone such as soil permeability. These parameters are typically inferred from pneumatic pumping tests, in which gas is withdrawn from an extraction well and pressure responses are measured at surrounding monitoring wells, analogous to hydraulic pumping tests in saturated systems. By interpreting the temporal and spatial patterns of pressure response, researchers can derive effective estimates of subsurface flow properties critical to SVE design. However, modeling gas flow in the vadose zone presents unique challenges relative to groundwater systems, due to factors such as gas compressibility and heightened sensitivity to environmental conditions (Boudouch et al., 2020). These complexities must be carefully accounted for to ensure robust and reliable predictions of gas transport and to optimize the performance of SVE systems.

Fluctuations in atmospheric pressure are a significant external factor that influence subsurface airflow dynamics (Truex et al., 2012; Kuang et al., 2013; Forde et al., 2019; Li et al., 2022; Eklund, 2024). Atmospheric pressure variations create complex interactions with subsurface gas flow through several mechanisms. Declining barometric pressure induces upward gas movement from the vadose zone to the atmosphere, while increasing pressure drives atmospheric gas downward into the subsurface (Forde et al., 2019). These vertical flow components interfere with the predominantly horizontal flow patterns induced by pneumatic pumping, creating measurement artifacts that can mask or amplify the true pneumatic test signal. Thus, understanding these mechanisms is crucial for accurate interpretation of pneumatic test data and reliable estimation of subsurface flow properties (You and Zhan, 2012). These barometric effects have been well-documented in groundwater systems, where they can induce substantial water level fluctuations that, if not properly accounted for, lead to erroneous estimations of hydraulic parameters (Spane, 1999; Butler Jr et al., 2011; Wang and Manga, 2021; Akara et al., 2025). To address this, several barometric correction techniques have been developed and are routinely applied in hydraulic test analyses (Spane, 2002; Toll and Rasmussen, 2007; Kennel and Parker, 2024). Despite this recognition in groundwater applications, the analogous effects on gas flow measurements have received comparatively less attention. You and Zhan (2012) emphasized that barometric fluctuations are often neglected during SVE testing, despite their potential to significantly alter pressure measurements and skew parameter estimations. Their work introduced analytical models capable of simulating the combined influence of barometric pressure variations and active gas extraction on subsurface airflow. Truex et al. (2012) provided quantitative evidence of the influence of barometric pressure fluctuations on parameter estimation in SVE systems using the GASSOLVE program (developed by Falta, 1996 – Clemson University), which implements one-dimensional analytical solutions for gas flow under steady-state and transient conditions. While analytical solutions have been widely employed in SVE applications due to their computational efficiency and ease of implementation (Huang and Goltz, 2017; Feng et al., 2019; McAlary et al., 2020; Stewart, 2022; Ding et al., 2022), these approaches face inherent limitations when applied to complex field conditions, where spatial heterogeneity, multidimensional flow, and dynamic atmospheric influences play a significant role.

To address the limitations of analytical approaches, numerical modeling has been increasingly utilized in SVE applications to simulate realistic subsurface processes and dynamic interactions that analytical solutions cannot fully represent. For example, Carroll et al. (2012) used numerical modeling to investigate correlations between vapor-phase mass discharge from persistent vadose-zone contaminant sources and resulting groundwater concentrations. Esrael et al. (2017) investigated mass transfer coefficient estimation effects on SVE modeling by testing five existing equations and proposing a reference NAPL saturation model for improved simulations. Qi et al. (2020) developed a numerical model to optimize LNAPL remediation by multi-phase extraction, analyzing pump positioning, soil characteristics, and extraction strategies to improve contaminant removal efficiency. Shi et al. (2020) investigated layered versus unlayered soil vapor extraction for benzene removal using numerical modeling and experimental studies. Ouoba and Bénet (2023) conducted numerical modeling of water transfer in low-moisture soils to identify dominant transport mechanisms between liquid filtration and capillary rise in the hygroscopic domain. Sun et al. (2023) used numerical modeling to simulate thermally-enhanced SVE (T-SVE) and validated the model against field data to optimize T-SVE parameters. In most of these studies, the atmospheric boundary pressure was assumed constant, and the impact of barometric pressure fluctuations was largely unaccounted for. In addition, while numerical models offer the flexibility to incorporate spatial heterogeneity and nonlinear flow processes, their increased complexity raises important questions about trade-offs between model fidelity, computational cost, and interpretability (Dai et al., 2008). Bridging this analytical-numerical divide requires comparative frameworks that can quantify the practical gains from model enhancements and identify when advanced methods are justified based on the nature of the data and the geological setting.

In this study, we investigate the impact of barometric pressure fluctuations on air permeability estimates derived from pneumatic pumping tests conducted at the Hanford Z-9 Trench site. Building on the work of Truex et al. (2012), we employ a series of increasingly sophisticated numerical modeling strategies to systematically quantify the effects of barometric pressure corrections under varying subsurface conditions. Our modeling framework accounts for gas flow driven by both well-based extraction and atmospheric pressure fluctuations. While previous studies have emphasized the importance of incorporating barometric variability into SVE data interpretation (You and Zhan, 2012*;* Truex et al., 2012*;* Kuang et al., 2013*;* Li et al., 2022), our approach extends this by evaluating the influence of such corrections across a structured range of model complexities – from idealized homogeneous domains to geologically more realistic settings with anisotropy and stratified heterogeneity. The novelty of this study lies in several key contributions that advance pneumatic test interpretation. First, we provide the first systematic quantification of how barometric pressure corrections affect parameter estimation across different model complexities, addressing a critical gap since analytical solutions cannot accommodate time-varying atmospheric boundary conditions required for proper barometric correction. Second, we establish a comprehensive framework for evaluating the trade-offs between model complexity and predictive accuracy in pneumatic test analysis, systematically comparing how dimensionality, domain representation, anisotropy, and heterogeneity influence barometric correction effectiveness. Third, we develop a practical methodology for selecting optimal modeling approaches that balance correction accuracy with computational efficiency, moving beyond the traditional assumption that more complex models necessarily provide better parameter estimates. This approach provides essential guidance for practitioners conducting pneumatic tests in complex vadose zone environments where barometric effects significantly influence subsurface characterization. Through comparative analysis of analytical solutions from Truex et al. (2012), numerical simulation results, and field observations, we demonstrate how barometric correction enhances the reliability of parameter estimation, particularly in layered or anisotropic systems. Our findings establish clear quantitative links between model structure, correction methodology, and the uncertainty in permeability estimates, ultimately offering actionable insights to improve vadose zone characterization and support the design of more effective SVE remediation systems.

2. Methods

2.1. Site description and data collection

This study investigates the vadose zone underlying the Hanford Site's Z-9 Trench, situated in the 200-East Area of the Hanford Reservation in south-central Washington State (Fig. 1a). Historically, this location functioned as a liquid waste disposal facility during Cold War nuclear fuel processing operations, leading to extensive subsurface contamination by carbon tetrachloride (CT) (Gee et al., 2007; Gephart, 2010; Peterson et al., 2018). In response to this contamination, the U.S. Department of Energy (DOE) initiated long-term remediation using SVE technology (Rohay, 2008). Throughout the SVE operations, a comprehensive dataset has been collected, including vapor-phase concentrations, gas flow rate, applied vacuum levels, and temperature. These data have been instrumental in evaluating subsurface transport processes and improving remediation strategies (Truex et al., 2009; Oostrom et al., 2010; Brusseau et al., 2010; Truex et al., 2012; Carroll et al., 2012, 2013; Oostrom et al., 2014). Building on the work of Truex et al. (2012), this study utilizes the same historical pneumatic test data collected in September 2011 to estimate air permeability in the vadose zone while explicitly assessing the influence of barometric pressure fluctuations (Fig. 2) on parameter estimation. For this purpose, barometric pressure records from the nearby Hanford Meteorological Station provide a reliable representation of site conditions, as the terrain is relatively flat and the spatial separation from the test location is modest. These regional pressure changes are coherent over kilometer scales, making them suitable for correcting pneumatic test data at this site; however, sites with more complex topography or local meteorology may require onsite barometric monitoring for optimal accuracy.

The subsurface beneath the Z-9 Trench is composed of three primary hydrostratigraphic units (Fig. 1b). The Hanford formation, characterized by interbedded sequences of sand and mud, coarse to medium sand, and sandy gravel deposited during glaciofluvial events, and the Ringold formation, a sedimentary sequence of fluvial-lacustrine clay, silt, sand, and granule to cobble gravel deposited by the ancestral Columbia River, represent relatively high-permeability (*k*) zones. These units are separated by the Cold Creek Unit (CCU), a thin, low-*k* layer consisting of caliche (or calcrete), a calcium-carbonate cemented paleosol, and cohesive, compact, massive to laminated, and stratified fine-grained sand and silt (i.e., sandy mud) that serves as a partial barrier to vertical gas flow. The order-of-magnitude permeability contrast between high-*k* and low-*k* layers reflects documented site conditions and represents realistic geological heterogeneity (Khaleel and Freeman, 1995). This contrast controls vertical flow communication and influences the relative importance of layered structure in pneumatic test responses. The site is instrumented with an extensive network of monitoring wells, many of which are screened at multiple depths across these stratigraphic units, enabling detailed spatial characterization of pneumatic responses throughout the vadose zone. In this study, the upper screen of well 299-W15–8 (hereafter “W#8 U”) was used as the extraction well, while well 299-W15–48 (hereafter “W#48”) served as the observation well. For this configuration, a 95-h pneumatic pumping test was conducted from September 15 to 19, 2011, during which air was extracted at a constant rate of 0.0416 kg/s from W#8 U. Pressure responses were continuously recorded at 15-min intervals at both wells. The monitoring-well pressure monitoring equipment included Dwyer model 616 W-2-LCD differential pressure transmitters with 4–20 mA output (0–6 inH2O range; 0.25 % FSO accuracy) for measuring pressure (vacuum). For post-test ambient monitoring, pressures were measured with Dwyer model 616 W-20B-LCD differential pressure transmitters with 4–20 mA output (−10“ to +10” inH2O range; 0.25 % FSO accuracy). In both cases, the differential pressure transmitters were configured with the high-pressure port vented to the atmosphere and the low-pressure port connected directly to barbed fittings on the well head with ¼” (6.4 mm) diameter Tygon tubing. The transmitters were connected to Supco model L420 data loggers (±0.05 mA accuracy), and data were recorded at intervals between 5 and 20 s depending upon the length of each test. Barometric pressure monitoring was conducted at the site during the single well testing and for several weeks after the shutdown of operations using an Instrumentation Northwest Inc. model PT2X-BV (15 PSIA range; 0.1 % FSO accuracy) barometric sensor with internal data logger capability. This experimental configuration generated a high-resolution pneumatic dataset that underpins the numerical modeling and parameter estimation analyses presented in this study (Truex et al., 2012).

2.2. Modeling approach

The simulation domain, as depicted schematically in Fig. 3, represents the layered vadose zone structure, consisting of the high-*k* Hanford formation (upper 35 m), the low-*k* CCU (5 m), and the high-*k* Ringold formation (25 m). For modeling purposes, we designated the Hanford and Ringold formations collectively as Layer 1 (high-*k* layer) with identical hydraulic properties, while the CCU was designated as Layer 2 (low-*k* layer), with parameter subscripts corresponding to these layer designations throughout our analysis. To minimize boundary effects, the domain extends 300 m horizontally, with extraction well W#8 U positioned at the center and monitoring well W#48 located 28 m away. To investigate the influence of barometric pressure fluctuations on air permeability estimation, we developed a series of increasingly complex numerical models using PFLOTRAN, a massively parallel subsurface flow and reactive transport code (Hammond et al., 2014). Five distinct simulation scenarios were designed to systematically assess how model complexity influences parameter estimation by evaluating the effects of dimensionality, domain extent, anisotropy, and layered heterogeneity on barometric correction effectiveness. We developed the following set of model cases:

a) Case 1D-HOM-ISO-HL: 1D homogeneous isotropic model, upper high-*k* layer only.
b) Case 1D-HOM-ISO-Full: 1D homogeneous isotropic model, full domain.
c) Case 2D-HOM-ANI-HL: 2D homogeneous anisotropic model, upper high-*k* layer only.
d) Case 2D-HOM-ANI-Full: 2D homogeneous anisotropic model, full domain.
e) Case 2D-HET-ANI-Full: 2D heterogeneous anisotropic model, full domain with distinct high-*k* and low-*k* layers.

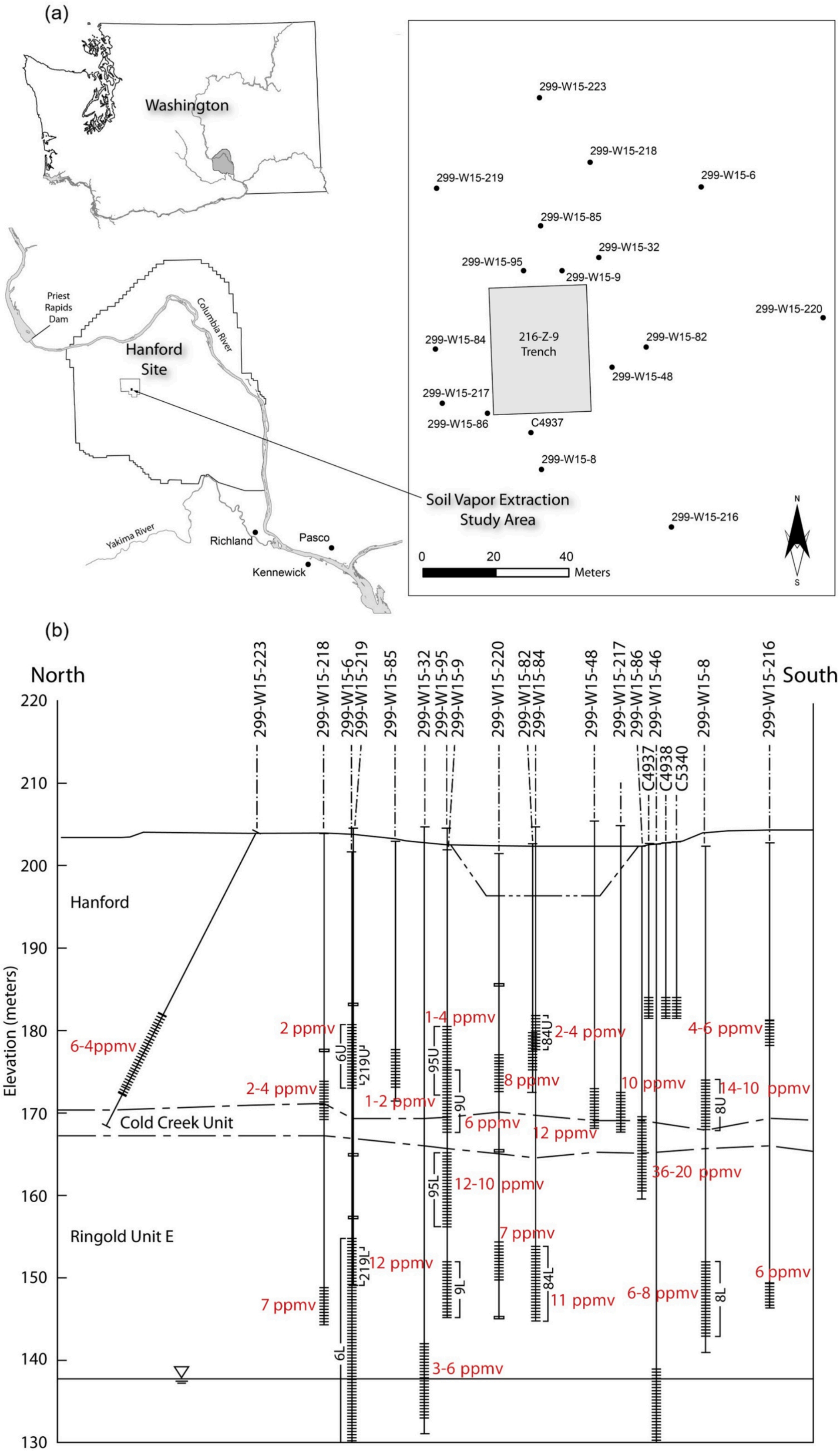

Fig. 1. Site study area map and cross section adapted from Truex et al. (2012). (a) Location of the Hanford Site in Washington State (left) and the Z-9 Trench study area showing monitoring well network (right). (b) North-south cross-section depicting the vadose zone stratigraphy with Hanford formation, Cold Creek Unit, and Ringold layers. Vertical lines represent well locations with screen intervals shown.

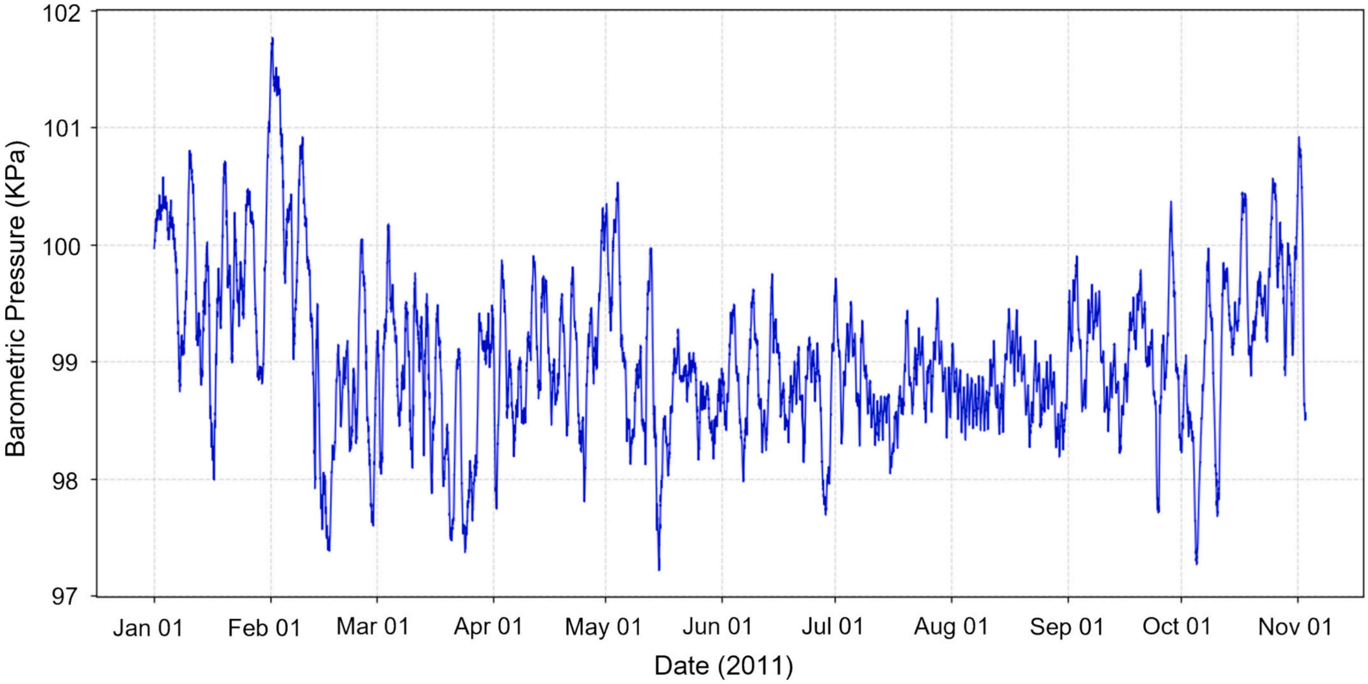

Fig. 2. Barometric pressure measurements recorded at the Hanford Meteorological Station from January through October 2011 (Truex et al., 2012).

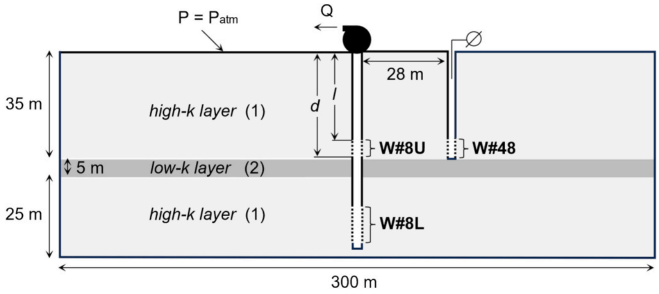

Fig. 3. Schematic representation of the full simulation domain showing the layered vadose zone structure with high-*k* (Hanford/Ringold) formations as Layer 1 and low-*k* (CCU) unit as Layer 2, corresponding to the parameter subscripts in Table 1. The pneumatic test configuration uses well #8 U as the pumping well in this study and well #48 as the monitoring well.

The progression from 1D homogeneous to more realistic 2D layered representations allows isolation of individual modeling factors while maintaining computational tractability. 2D axisymmetric models adequately capture the radial flow patterns characteristic of pneumatic tests and represent the primary geological layering at the site, making them appropriate for comprehensive sensitivity analysis without the computational burden of full 3D representations. For the 1D models (Cases a and b), a one-dimensional domain with 100 grid cells was used, whereas the 2D models (Cases c, d, and e) employed a two-dimensional domain with 60 × 70 grid cells. The "HL" cases considered only the upper 35 m (Hanford layer). The "Full" cases incorporated the entire 65 m vadose zone profile, including the CCU and Ringold formation. To accurately represent field conditions in our 2D simulations, the extraction well W#8 U and monitoring well W#48 were modeled with their actual screen lengths and elevations as shown in Fig. 1b, ensuring that these geometric details were properly captured within the layered vadose zone structure.

For the gas flow simulations, PFLOTRAN solves the general two-phase (liquid water-gas) flow equations based on mass conservation principles. Secondary processes such as biological activity were not considered due to the short timescales of pneumatic tests relative to such processes and site conditions at Hanford that limit their significance. The governing equation for gas flow can be expressed as:

$$\frac{\partial}{\partial t}\phi\left(S_l\rho_l x_i^l + S_g\rho_g x_i^g\right) + \nabla.\left(q_l\rho_l x_i^l + q_g\rho_g x_i^g - \phi S_l D_l\rho_l\nabla x_i^l - \phi S_g D_g\rho_g\nabla x_i^g\right) = Q_i \tag{1}$$

where ϕ is porosity, S is saturation, ρ is density (kg/m^3), x is the mole fraction, q is Darcy velocity (m/s), D is the diffusion coefficient (m^2/s), Q is the source/sink term (kmol/m^3·s), and subscripts l and g represent liquid and gas phases, respectively. The Darcy velocity for the phase β (liquid or gas) is calculated as:

$$q_\beta = -\frac{kk_\beta^r}{\mu_\beta}\nabla\left(p_\beta - \gamma_\beta gz\right), (\beta = l, g) \tag{2}$$

where k is the intrinsic permeability (m^2), k^r is the relative permeability, μ is the viscosity (Pa.s), p is the pressure (Pa), γ is the specific weight (N/m^3), and z is the elevation (m). The relationships for relative permeability and capillary pressure are described using van Genuchten (1980) relation:

$$S_e = \left(1 + (\alpha P_c)^n\right)^{-m} \tag{3}$$

where P_c is the capillary pressure (Pa), α is the inverse of the air entry pressure (Pa^{-1}), n and $m = 1 - 1/n$ are curve fitting parameters, and S_e is the effective saturation defined by:

$$S_e = \frac{S - S_r}{S_0 - S_r} \tag{4}$$

where S_r is the residual saturation, and S_0 is the maximum saturation. Relative permeability is calculated using the Mualem (1976) model based on the van Genuchten parameters:

$$k^r = \sqrt{S_e}\left\{1 - \left(1 - (S_e)^{1/m}\right)^m\right\}^2 \tag{5}$$

The measured pressure data exhibited significant fluctuations that closely correlated with barometric pressure variations, emphasizing the pronounced effect of atmospheric conditions on pneumatic test interpretations. To isolate the pneumatic test signal from barometric effects, we applied Multiple Regression in Excel (MRCX v. 1.1) (Mackley et al., 2010), which implements the multiple regression convolution/deconvolution approach originally developed by Rasmussen and Crawford (1997) for barometric correction. This methodology has been successfully applied in several subsurface studies, including the analytical study by Truex et al. (2012) at the same Hanford Site location, and we used the same approach for comparison and validation of our numerical modeling results. The regression analysis quantified the effect of barometric pressure fluctuation on the monitoring well W#48, and then the barometric effects were removed by de-trending the raw pressure data measured at W#48. This process yielded two distinct datasets for model calibration: uncorrected drawdown data and barometrically corrected data (i.e., with barometric trends removed). For each model scenario, calibration was performed using both uncorrected and barometrically corrected drawdown data. The calibration process employed the PSUADE framework (Tong, 2005), utilizing the Bound Optimization by Quadratic Approximation (BOBYQA) algorithm (Powell, 2009) to minimize the residual sum of errors (RSE) between simulated and observed pressure responses. BOBYQA was selected for its robustness to numerical noise in the objective function and efficiency in handling bound-constrained problems typical of subsurface parameter estimation. While potentially slower than gradient-based methods, BOBYQA avoids derivative calculation requirements and provides reliable convergence for pneumatic test calibration problems.

We defined all boundary conditions in our simulation domain as follows: the upper boundary at the land surface was defined by atmospheric pressure, while lateral and lower boundaries were set as no-flow conditions. For the uncorrected drawdown model simulations, we used the actual time-varying barometric pressure as the transient land surface boundary condition to explicitly include the effect of barometric pressure changes on gas flow. In contrast, for the barometrically-corrected drawdown model, we applied a constant average atmospheric pressure at the land surface boundary, similar to the approach used in GASSOLVE (Falta, 1996). This distinction in boundary conditions between the two modeling approaches is essential for proper interpretation of the results. For initial conditions, we assumed hydrostatic equilibrium with atmospheric pressure prior to the start of the extraction test. While non-hydrostatic initial conditions could potentially influence results, the 95-h test duration allows equilibration from most initial pressure disturbances, and our barometric correction methodology focuses on pressure changes rather than absolute values, minimizing sensitivity to initial condition variations. The extraction well was represented as a specified mass flux boundary condition, with the injection rate set to the field-measured value.

To identify the most influential parameters affecting model predictions and to quantify the impact of barometric pressure corrections on parameter sensitivity, we performed a comprehensive sensitivity analysis using the Sobol method (Sobol, 1993) in PSUADE. This variance-based approach decomposes the total output variance into fractions attributable to individual parameters and their interactions, providing a robust framework for assessing parameter importance under varying modeling conditions. We generated multiple sampling sets for each parameter listed in Table 1 using Latin Hypercube Sampling within specified ranges to efficiently explore the parameter space. PFLOTRAN simulations were then performed for each parameter set to generate pressure responses for both uncorrected and barometrically corrected datasets. First-order Sobol indices were computed to quantify the direct contribution of each parameter to output variance. These indices were compared across both datasets to assess how barometric pressure corrections influence parameter sensitivity rankings. Table 1 presents the uncertain parameters and their sampling ranges, while Table 2 lists fixed parameter values, selected based on representative vadose zone properties at the Hanford site (Khaleel and Freeman, 1995; Pruess et al., 2002).

3. Results

3.1. Sensitivity analysis

The sensitivity analysis was conducted separately for the two model configurations: homogeneous (Case (a)) and heterogeneous (Case (e)), in order to assess how model complexity impacts parameter importance. For the homogeneous isotropic model, six parameters were evaluated: $\boldsymbol{\phi}$, $\boldsymbol{k}$, initial gas saturation ($\boldsymbol{S_{gi}}$) and van Genuchten fitting parameters ($\boldsymbol{\alpha}$, $\boldsymbol{m}$, $\boldsymbol{S_{gr}}$). For the heterogeneous anisotropic model twelve parameters were analyzed, including two sets of the same parameters for both the high-k (Hanford/Ringold) and low-k (CCU) layers, as well as anisotropy ratios for each layer ($\boldsymbol{k_{h1}/k_{v1}}$, $\boldsymbol{k_{h2}/k_{v2}}$). The ranges for all parameters are provided in Table 1.

Fig. 4 presents the first-order Sobol indices for both uncorrected (purple) and corrected (green) drawdown data. The left panel displays sensitivities for homogeneous model parameters, while the right panel shows sensitivities for the heterogeneous model parameters. The results reveal that permeability (k) is the most sensitive parameter in the homogeneous isotropic models for both uncorrected and corrected datasets, with Sobol indices approaching 1.0. This suggests that nearly all the variance in model outputs is driven by variations in permeability, with minimal influence from other parameters. In the heterogeneous anisotropic model, a more distributed sensitivity pattern emerges. The permeability of the high-k layers (k_1) dominates the sensitivity (Sobol index $\approx$ 0.7) for both uncorrected and corrected datasets, followed by the anisotropy ratio of the high-k layers ($\boldsymbol{k_{h1}/k_{v1}}$, Sobol index $\approx$ 0.3). Interestingly, the sensitivity patterns remain largely unchanged between uncorrected and corrected datasets, indicating that barometric pressure fluctuations do not substantially alter the relative importance of parameters in the model. Based on these findings, we prioritized

Table 2
Fixed parameters for subsurface airflow simulations.

Parameter	Value
μ_a (Pa.s): air viscosity	1.80E-05
M_a (g/mol): air molecular weight	28.96
ρ_s (kg/m^3): rock density	2.80E+03
κ_{dry} (W/K.m): thermal conductivity of dry rock	0.50
κ_{wet} (W/K.m): thermal conductivity of wet rock	2.00
c (J/kg.K): rock specific heat capacity	800
l (m): top elevation of the well screen	28.35
d (m): bottom elevation of the well screen	34.44
r_w (m): pumping well radius	7.60E-03
b (m): vadose zone thickness	32.61

Table 1
Parameter ranges for sensitivity analysis of subsurface airflow modeling across two geological layers. Parameter ranges are based on site-specific studies at Hanford (Khaleel and Freeman, **1995**; Pruess et al., **2002**) and validated against broader literature for similar geological formations to ensure representativeness of natural variability.

Parameter	ϕ_1	k_1 (m^2)	k_{h1}/k_{v1}	α_1 (Pa^{-1})	m_1	S_{gr1}	S_{gi}
Range	(0.10, 0.40)	(2.00E-12, 7.00E-12)	(0.50, 1.00)	(1.00E-05, 1.00E-03)	(0.30, 0.70)	(0.01, 0.30)	(0.85, 0.99)
Parameter	ϕ_2	k_2 (m^2)	k_{h2}/k_{v2}	α_2 (Pa^{-1})	m_2	S_{gr2}	S_{gi}
Range	(0.10, 0.40)	(1.00E-14, 1.00E-12)	(0.10, 1.00)	(1.00E-05, 1.00E-03)	(0.30, 0.70)	(0.01, 0.30)	(0.85, 0.99)

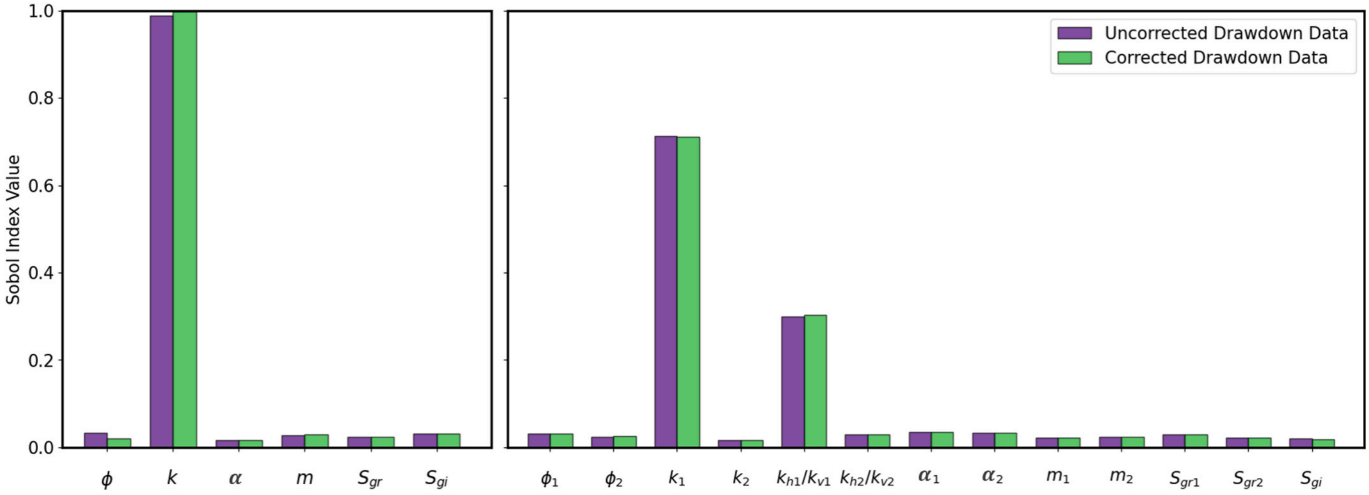

Fig. 4. First-order Sobol indices for uncorrected (purple) and corrected (green) drawdown data. Left panel: sensitivities for homogeneous model parameters. Right panel: sensitivities for heterogeneous model parameters across high-*k* and low-*k* layers.

permeability and anisotropy ratio for calibration. Although the sensitivity analysis suggests minimal influence from parameters of the low-k layer in Case (e), we still included them in the calibration process to reflect the layered heterogeneity observed in the field.

3.2. Calibration results

Fig. 5 presents the comparison between observed and simulated vacuum pressure responses based on uncorrected data. The time-series plots (left panels) depict the temporal evolution of pressure responses, while cross-plots (right panels) provide a quantitative evaluation of model performance via R^2 values. The shaded regions in the time-series plots represent uncertainty ranges corresponding to two standard deviations (2σ) of the prediction error. Using uncorrected data, the 1D homogeneous isotropic model with a half-layer domain (Case 1D-HOM-ISO-HL; Fig. 5a) showed moderate agreement with observed pressures ($R^2 = 0.7016$) but displayed systematic deviations during periods of strong barometric fluctuations. Expanding the domain to include the full subsurface profile in Case 1D-HOM-ISO-Full (Fig. 5b) significantly improved model performance ($R^2 = 0.8745$), indicating that deeper layers – despite being treated homogeneously – substantially contribute to the overall system response. Interestingly, the introduction of anisotropy in Case 2D-HOM-ANI-HL (Fig. 5c) reduced the model's fit ($R^2 = 0.5398$) relative to the isotropic configurations, suggesting that including anisotropy without proper domain representation may amplify model uncertainty. In contrast, when full domain representation was combined with anisotropy in Case 2D-HOM-ANI-Full (Fig. 5d), the model achieved the highest performance among the uncorrected scenarios ($R^2 = 0.8724$). The heterogeneous model (Case 2D-HET-ANI-Full; Fig. 5e) exhibited intermediate performance ($R^2 = 0.7611$), implying that while explicit heterogeneity adds realism, it may also introduce parametric uncertainty that does not proportionally enhance model fidelity under uncorrected conditions. The uncorrected pressure measurements in Fig. 5 clearly demonstrate how barometric pressure fluctuations create high-frequency oscillations that obscure the underlying pneumatic drawdown signal. These barometric-induced artifacts are particularly evident during periods of rapid atmospheric pressure change, where responses deviate significantly from expected smooth drawdown curves. The temporal correlation between atmospheric pressure variations and measurement noise leads to the systematic parameter estimation errors observed in our analysis.

Fig. 6 presents model calibration results using barometrically corrected drawdown data. The corrected dataset exhibited markedly reduced fluctuations and smoother drawdown curves, which eliminated much of the noise observed in the uncorrected measurements. This enhanced signal clarity allows for more reliable interpretation of subsurface flow behavior. Among the scenarios using barometrically corrected data, Case 1D-HOM-ISO-Full (Fig. 6b, $R^2 = 0.8088$) and Case 2D-HOM-ANI-Full (Fig. 6d, $R^2 = 0.8221$) yielded the best fits, with the latter performing slightly better. These results suggest that, even when using barometrically corrected input data, accounting for full-domain representation and anisotropy can improve model fidelity in simulating pressure responses, with full-domain inclusion generally exerting a more noticeable influence. The time-series plots in Fig. 6 demonstrate that models calibrated to barometrically corrected data effectively capture the underlying drawdown pattern without the high-frequency oscillations present in the uncorrected data (Fig. 5). Cross-plots comparing observed versus simulated pressures for the barometrically corrected cases display more tightly clustered data around the 1:1 line, indicating stronger systematic agreement between models and observations. Importantly, RSE values decreased by approximately two orders of magnitude when using barometrically corrected data compared to uncorrected data (Table 3), highlighting a substantial improvement in model-data consistency despite the slightly lower R^2 values in some corrected cases relative to their uncorrected counterparts. The dramatic RSE reduction with modest R^2 changes reflects removal of high-frequency barometric noise while preserving the underlying pneumatic signal structure. R^2 serves to compare relative performance among modeling scenarios within each dataset, while RSE improvement is the more relevant metric for assessing correction effectiveness as it indicates reduced systematic error.

The estimated permeability values (Table 3) exhibit systematic differences between analyses using uncorrected and barometrically corrected data. For the uncorrected case, the estimated k_1 values ranged from 2.90×10^{-12} to 4.23×10^{-12} m^2, with a mean of 3.56×10^{-12} m^2. In contrast, the corrected dataset produced consistently higher estimates, ranging from 3.55×10^{-12} to 4.97×10^{-12} m^2, with an average of 4.26×10^{-12} m^2. This represents an average increase of approximately 20 %, indicating that neglecting barometric effects leads to systematic underestimation of permeability values. Notably, the permeability estimate from our Case 1D-HOM-ISO-HL using uncorrected data (2.90×10^{-12} m^2) aligns closely with the value reported by Truex et al. (2012) using the GASSOLVE analytical solution (2.71×10^{-12} m^2), supporting the validity of our modeling framework. The uniformly elevated permeability values obtained from corrected data across all scenarios reinforce the critical role of barometric correction in producing reliable parameter estimates during pneumatic testing.

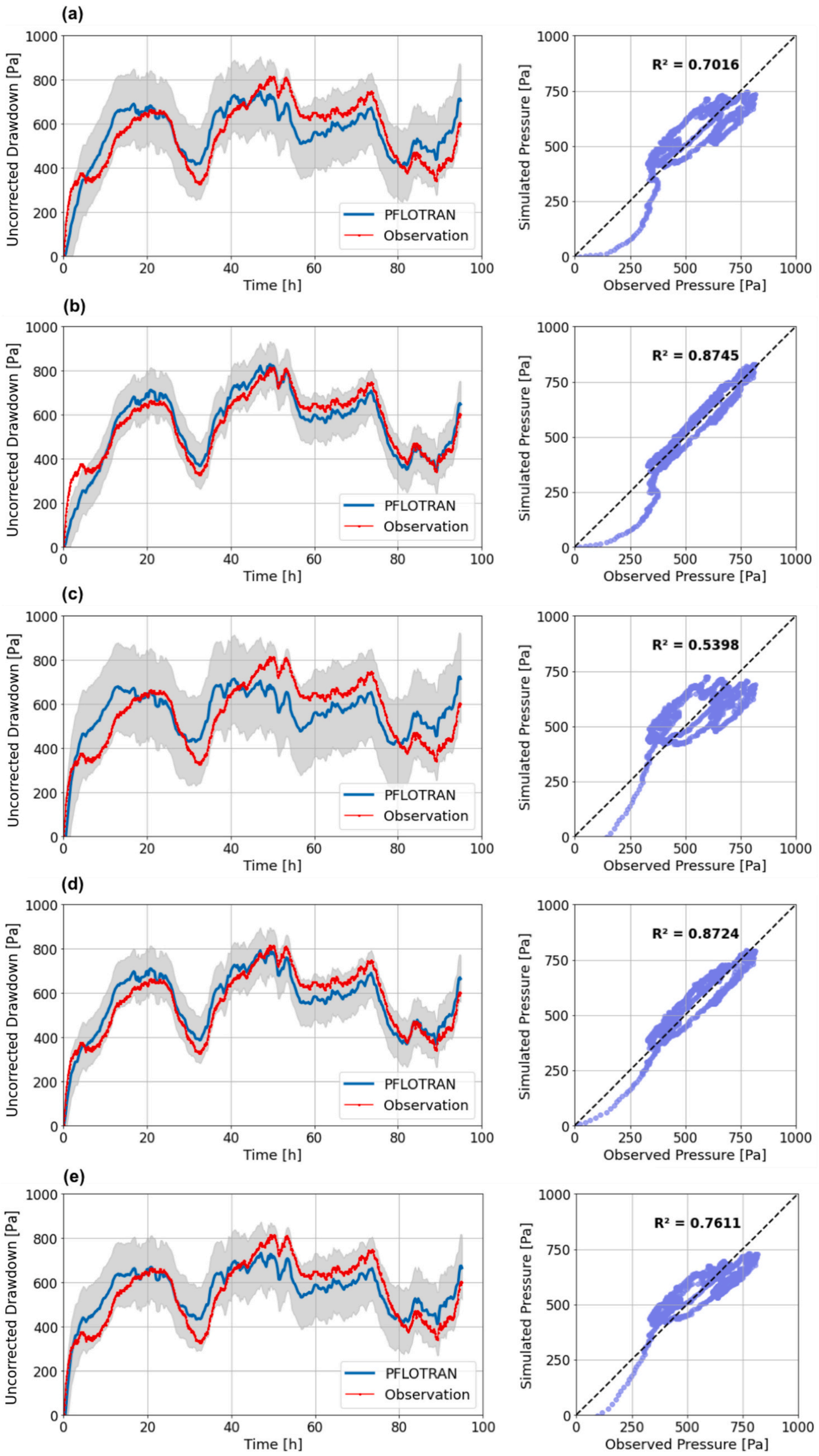

Fig. 5. Comparison of observed and simulated vacuum pressure responses for five modeling scenarios: (a) Case 1D-HOM-ISO-HL, (b) Case 1D-HOM-ISO-Full, (c) Case 2D-HOM-ANI-HL, (d) Case 2D-HOM-ANI-Full, and (e) Case 2D-HET-ANI-Full. Left panels show time series data; right panels display cross-plots with corresponding R^2 values.

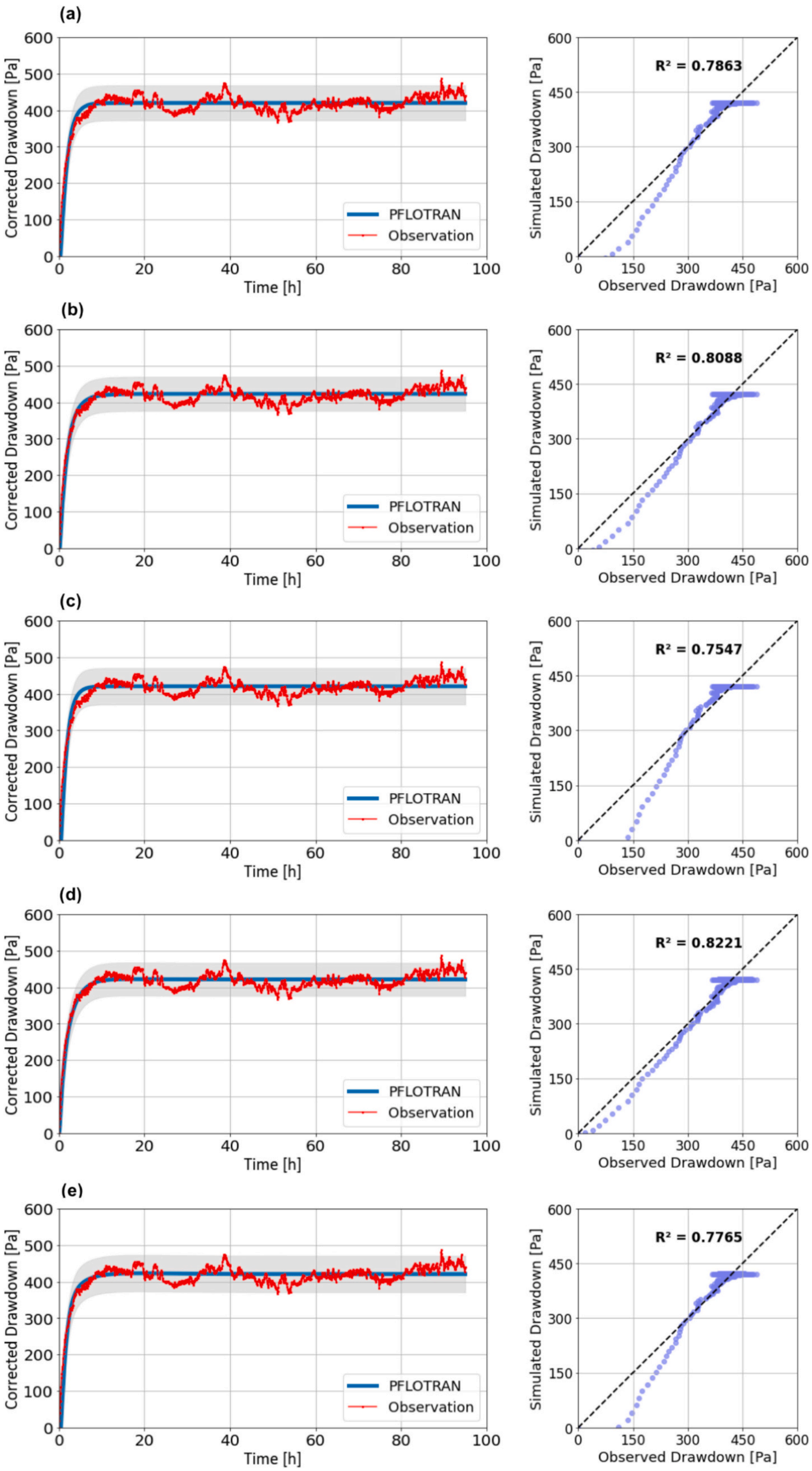

Fig. 6. Comparison of observed and simulated corrected drawdown for five modeling scenarios: (a) Case 1D-HOM-ISO-HL, (b) Case 1D-HOM-ISO-Full, (c) Case 2D-HOM-ANI-HL, (d) Case 2D-HOM-ANI-Full, and (e) Case 2D-HET-ANI-Full. Left panels show time series data; right panels display cross-plots with corresponding R^2 values.

Table 3

Estimated air permeability parameters and RSE for different modeling scenarios using uncorrected and corrected drawdown data.

Uncorrected drawdown data						
Parameter	GASSOLVE Truex et al., 2012	Case (a): 1D-HOM-ISO-HL	Case (b): 1D-HOM-ISO-Full	Case (c): 2D-HOM-ANI-HL	Case (d): 2D-HOM-ANI-Full	Case (e): 2D-HET-ANI-Full
k_1 (m^2)	2.71E-12	2.90E-12	4.23E-12	4.23E-12	4.09E-12	3.90E-12
k_{h1}/k_{v1}	1.00	1.00	1.00	0.95	0.95	0.95
k_2 (m^2)	–	–	–	–	–	3.90E-13
k_{h2}/k_{v2}	–	–	–	–	–	0.95
RSE	**1.91E+07**	**7.37E+06**	**3.10E+06**	**1.12E+07**	**3.15E+06**	**5.90E+06**
R^2	**0.22**	**0.70**	**0.87**	**0.54**	**0.87**	**0.76**
Corrected drawdown data						
k_1 (m^2)	3.79E-12	3.55E-12	4.74E-12	4.97E-12	4.64E-12	4.39E-12
k_{h1}/k_{v1}	1.00	1.00	1.00	0.95	0.95	0.97
k_2 (m^2)	–	–	–	–	–	4.91E-13
k_{h2}/k_{v2}	–	–	–	–	–	0.65
RSE	**4.46E+05**	**4.82E+05**	**4.31E+05**	**5.56E+05**	**4.07E+05**	**5.04E+05**
R^2	**0.80**	**0.79**	**0.81**	**0.75**	**0.82**	**0.78**

3.3. *Discussion*

The systematic differences in estimated permeability between analyses using uncorrected and corrected data provide clear quantitative evidence of the influence of barometric pressure fluctuations on parameter estimation. The consistent underestimation of permeability when using uncorrected data occurs because barometric pressure fluctuations introduce both constructive and destructive interference with the pneumatic test signal. During periods of declining barometric pressure, the resulting vacuum effect compounds with the extraction-induced vacuum, amplifying the apparent response. In contrast, when barometric pressure increases, the induced test signal is partially obscured. The 32-m vadose zone thickness at our site is relatively thick compared to many contaminated sites. Since significant barometric effects were observed even in this thick vadose zone, thinner vadose zones common at other sites would likely experience stronger atmospheric coupling, making barometric correction even more critical for accurate parameter estimation. Additionally, it's important to note that barometric pressure causes primarily vertical gas flow, while the pumping well induces predominantly horizontal gas flow. This dimensional difference in flow patterns further explains why our 1D models, which primarily account for horizontal flow components, show different results compared to the 2D models that can capture both flow dimensions. The significant improvement in model performance following barometric correction highlights the importance of addressing these fluctuations for accurate subsurface characterization. By removing the confounding barometric effects, the corrected data better represents the true subsurface response to pneumatic testing, leading to more reliable parameter estimates. The systematic ~20 % underestimation of air permeability when barometric effects are ignored has significant consequences for SVE system design. Underestimated permeability can lead to installation of 20–30 % more extraction wells than necessary, oversized vacuum systems with higher capital and operating costs, and extended remediation timeframes (Cao et al., 2021; Lutes et al., 2022). These overconservative designs result in substantial unnecessary expenses and increased energy consumption throughout the operational period, highlighting the economic importance of accurate barometric correction in pneumatic test interpretation.

Our results reveal a non-linear relationship between model complexity and predictive performance. The progression from simple 1D homogeneous models to complex 2D heterogeneous representations led to several key insights. Extending the domain to include all layers consistently improved model performance, regardless of dimensionality or anisotropy. Full-domain models account for complete pressure communication pathways, including the influence of the low-permeability CCU layer, whereas half-layer models truncate the flow domain and omit important boundary effects. This explains why 1D full-domain models outperform 2D half-layer representations, indicating that domain completeness can outweigh dimensionality and anisotropy. Incorporating anisotropy proved beneficial only when combined with full domain representation, as demonstrated by Case 2D-HOM-ANI-Full achieving the highest R^2 values for both uncorrected and corrected data. This suggests that while anisotropy provides some benefit when combined with full domain representation, its influence is less pronounced than initially anticipated and should be considered alongside computational complexity and parameter uncertainty. Interestingly, explicitly modeling heterogeneity in Case 2D-HET-ANI-Full did not improve model performance despite the added parameterization. The superior performance of Case 2D-HOM-ANI-Full compared to the explicitly heterogeneous model likely reflects the nature of pneumatic pumping tests, which measure bulk or effective properties over the test domain rather than fine-scale heterogeneities (Yeh et al., 2015). Furthermore, the dimensional difference between barometric-induced vertical flow and pumping-induced horizontal flow influences permeability estimates differently depending on domain representation. Comparing 1D and 2D homogeneous models shows that 1D models underestimate permeability by 31–40 % in half-layer domains but only 3–4 % in full-domain representations, indicating that the importance of capturing both flow dimensions depends on domain completeness. Moreover, the unexpected finding that the 1D homogeneous full-domain model ($R^2 = 0.8088$) outperformed the 2D heterogeneous model ($R^2 = 0.7611$) suggests that pneumatic tests at the observation distance of 28 m primarily capture bulk or effective properties rather than fine-scale heterogeneities. As mentioned earlier, the pneumatic signal appears to be naturally averaged over heterogeneous features, making the additional complexity of explicit heterogeneity modeling counterproductive for parameter estimation. This finding has important implications for pneumatic test design and interpretation, suggesting that simpler models with appropriate domain representation may be more reliable than complex heterogeneous models for characterizing effective subsurface properties.

The modeling framework presented here offers a practical approach for improving pneumatic test interpretation, particularly at sites characterized by layered vadose zone structures and significant atmospheric variability. Subsurface permeability heterogeneity has long been recognized as a key factor limiting effective groundwater contamination cleanup (Carroll et al., 2024), including in the vadose zone (Brusseau et al., 2013). Our findings suggest that, despite this inherent heterogeneity, pneumatic test signals are naturally averaged over spatial variations. This implies that simpler models, when appropriately designed, can capture effective parameters reliably, providing a practical approach for parameter estimation and remediation planning in complex vadose zone environments. It should be noted that while CCU parameters show low sensitivity in pneumatic test interpretation, this layer remains crucial for SVE design as it controls long-term flow patterns and contaminant accessibility. The low sensitivity reflects limited pressure communication during test timeframes rather than insignificance for remediation planning. In addition, our finding that full-domain representation exceeds explicit heterogeneity in importance should apply broadly to gas-phase contaminant characterization, as pneumatic tests measure bulk flow properties regardless of contaminant type. However, multiphase systems or liquid contaminants might show different sensitivities to heterogeneity due to capillary effects and saturation-dependent flow properties not captured in gas-phase testing.

While this study highlights the benefits of barometric correction in pneumatic test analysis, several limitations must be acknowledged. Our analysis is based on a single pneumatic pumping test at one location, which limits our ability to fully assess both the spatial variability of subsurface properties across the Z-9 Trench area and the performance of our correction methodology under diverse atmospheric conditions. The magnitude and nature of systematic bias we observed may vary with geological setting, vadose zone characteristics, local barometric patterns, and seasonal meteorological conditions, requiring site-specific evaluation of correction benefits. Furthermore, the barometric correction method used (multiple regression) is just one of several possible approaches for removing atmospheric pressure effects and comparing it with other correction techniques would be valuable. Moreover, our numerical model assumes isothermal conditions, while actual field settings experience temperature variations that can influence gas density, viscosity, and flow behavior. Daily temperature variations of 10–20 °C could change gas properties by 2–7 %, potentially introducing another source of error in parameter estimation. Additionally, the computational burden of complex heterogeneous numerical models may limit practical application in routine site characterization, particularly for real-time monitoring scenarios where rapid parameter estimation is required. Integration of data-driven machine learning approaches in SVE characterization could address these computational limitations while maintaining parameter estimation accuracy (Zhang et al., 2024; Li et al., 2024). Future research should address these limitations through several key directions: (1) conducting multi-well pneumatic tests at different locations and across varying seasonal conditions to assess spatial variability and validate our correction framework under diverse atmospheric scenarios, (2) comparing alternative barometric correction methods beyond multiple regression technique to optimize correction accuracy, (3) developing coupled thermal-pneumatic models to account for temperature effects on gas properties and barometric interactions, (4) creating automated real-time barometric correction algorithms for continuous monitoring applications, and (5) applying our methodology to sites with more complex contamination scenarios involving multiple VOCs or varying saturation conditions to enhance practical utility for diverse remediation settings.

4. Conclusions

This study examined the effects of barometric pressure on pneumatic pumping tests at the Hanford Site's Z-9 Trench, revealing that neglecting atmospheric pressure variations introduces significant estimation errors in subsurface parameter estimation. Through five increasingly complex numerical modeling scenarios, we demonstrated a systematic underestimation of air permeability by approximately 20 % when barometric pressure corrections were not applied. Key findings include: (1) barometric corrections improve model fit with RSE reductions of two orders of magnitude while maintaining parameter sensitivity hierarchies, (2) full domain representation is more critical than explicit heterogeneous modeling for accurate parameter estimates, with full-domain models achieving R^2 values of 0.81–0.87 compared to half-layer models ($R^2 =$ 0.54–0.70), and (3) the 1D homogeneous full-domain model outperformed complex 2D heterogeneous representations, indicating that pneumatic tests measure effective bulk properties rather than fine-scale heterogeneities. Sensitivity analysis confirmed permeability as the dominant parameter (Sobol index ≈ 0.7–1.0) followed by anisotropy ratio (Sobol index ≈ 0.3). The study establishes a practical framework for barometric correction in pneumatic test interpretation that enhances accuracy without fundamentally altering parameter importance rankings. These improvements are essential for optimal SVE system design, preventing overconservative approaches that result in unnecessary infrastructure and extended remediation timeframes. The framework provides actionable guidance for practitioners conducting pneumatic tests in layered vadose zones, ultimately supporting more cost-effective and reliable subsurface remediation strategies.

CRediT authorship contribution statement

Farzad Moeini: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kenneth C. Carroll:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation. **Zhenxue Dai:** Writing – review & editing, Investigation, Conceptualization. **Mohamad Reza Soltanian:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

Akara, M.E.M., Kuhlman, K.L., Bowman Ii, D.O., Jackson, R.S., 2025. Factors controlling groundwater response to earth and atmospheric tides. J. Hydrol. 657, 133088. https://doi.org/10.1016/j.jhydrol.2025.133088.

Boudouch, O., Kacem, M., Benadda, B., 2020. Soil **v**apor **e**xtraction: **f**undamentals, **t**heory (**p**ermeability and **g**as–**n**on-aqueous **p**hase **l**iquid **m**ass **t**ransfer **c**oefficient) and **a**pplications. https://doi.org/10.1039/9781788016261-00088.

Brusseau, M.L., Rohay, V., Truex, M.J., 2010. Analysis of soil vapor extraction data to evaluate mass-transfer constraints and estimate source-zone mass flux. Groundw. Monit. Remediat. 30 (3), 57–64. https://doi.org/10.1111/j.1745-6592.2010.01286.x.

Brusseau, M.L., Carroll, K.C., Truex, M.J., Becker, D.J., 2013. Characterization and remediation of chlorinated volatile organic contaminants in the vadose zone. Vadose Zone J. 12 (4). https://doi.org/10.2136/vzj2012.0137.

Butler Jr., J.J., Jin, W., Mohammed, G.A., Reboulet, E.C., 2011. New insights from well responses to fluctuations in barometric pressure. Groundwater 49 (4), 525–533. https://doi.org/10.1111/j.1745-6584.2010.00768.x.

Cao, W., Zhang, L., Miao, Y., Qiu, L., 2021. Research progress in the enhancement technology of soil vapor extraction of volatile petroleum hydrocarbon pollutants. Environ. Sci.: Processes Impacts 23 (11), 1650–1662. https://doi.org/10.1039/D1EM00170A.

Carroll, K.C., Oostrom, M., Truex, M.J., Rohay, V.J., Brusseau, M.L., 2012. Assessing performance and closure for soil vapor extraction: integrating vapor discharge and impact to groundwater quality. J. Contam. Hydrol. 128 (1–4), 71–82. https://doi.org/10.1016/j.jconhyd.2011.10.003.

Carroll, K.C., Truex, M.J., Brusseau, M.L., Parker, K.R., Mackley, R.D., Rohay, V.J., 2013. Characterization of persistent volatile contaminant sources in the vadose zone. Groundw. Monit. Remediat. 33 (2), 68–84. https://doi.org/10.1111/gwmr.12006.

Carroll, K. C., Brusseau, M. L., Tick, G. R., Soltanian, M. R., 2024. Rethinking pump-and-treat remediation as maximizing contaminated groundwater. **Sci. Total Environ.**, 918, 170600, ISSN 0048-9697. Doi:https://doi.org/10.1016/j.scitotenv.2024.170600.

Dai, Z., Samper, J., Wolfsberg, A., Levitt, D., 2008. Identification of relative conductivity models for water flow and solute transport in unsaturated bentonite. Phys. Chem. Earth, Parts A/B/C 33, S177–S185. https://doi.org/10.1016/j.pce.2008.10.012.

Ding, X.H., Feng, S.J., Zheng, Q.T., Peng, C.H., Zhu, Z.W., Yang, C.B.X., 2022. Transient migration behavior of VOC vapor in layered unsaturated soils subjected to multiple time-dependent point pollution sources: analytical study. Sci. Total Environ. 806, 150370. https://doi.org/10.1016/j.scitotenv.2021.150370.

Eklund, B., 2024. Climatic effects on vapor flow and behavior in the vadose zone. Groundw. Monit. Remediat. 44 (4), 80–91. https://doi.org/10.1111/gwmr.12682.

EPA, 2001. Development of Recommendations and Methods to Support Assessment of Soil Venting Performance and Closure (EPA/600/R-01/070). Environmental Protection Agency, Massachusetts, p. 394.

Esrael, D., Kacem, M., Benadda, B., 2017. Modelling mass transfer during venting/soil vapour extraction: Non-aqueous phase liquid/gas mass transfer coefficient estimation. J. Contam. Hydrol. 202, 70–79. https://doi.org/10.1016/j.jconhyd.2017.05.003.

Falta, R.W., 1996. A program for analyzing transient and steady-state soil gas pump tests. Groundwater 34 (4), 750–755. https://doi.org/10.1111/j.1745-6584.1996.tb02064.x.

Feng, S., Liu, H.W., Chiu, A.C.F., Ng, C.W.W., 2019. A steady-state analytical profile method for determining methane oxidation in landfill cover. Sci. Total Environ. 646, 1528–1535. https://doi.org/10.1016/j.scitotenv.2018.07.097.

Forde, O.N., Cahill, A.G., Beckie, R.D., Mayer, K.U., 2019. Barometric-pumping controls fugitive gas emissions from a vadose zone natural gas release. Sci. Rep. 9 (1), 14080. https://doi.org/10.1038/s41598-019-50426-3.

Gee, G.W., Oostrom, M., Freshley, M.D., Rockhold, M.L., Zachara, J.M., 2007. Hanford site vadose zone studies: An overview. Vadose Zone J. 6 (4), 899–905. https://doi.org/10.2136/vzj2006.0179.

Gephart, R.E., 2010. A short history of waste management at the Hanford Site. Phys. Chem. Earth, Parts A/B/C 35 (6–8), 298–306. https://doi.org/10.1016/j.pce.2010.03.032.

Hammond, G.E., Lichtner, P.C., Mills, R.T., 2014. Evaluating the performance of parallel subsurface simulators: an illustrative example with PFLOTRAN. Water Resour. Res. 50 (1), 208–228. https://doi.org/10.1002/2012WR013483.

Huang, J., Goltz, M.N., 2017. Analytical solutions for a soil vapor extraction model that incorporates gas phase dispersion and molecular diffusion. J. Hydrol. 549, 452–460. https://doi.org/10.1016/j.jhydrol.2017.04.013.

Kennel, J., Parker, B., 2024. Characterizing water level responses to barometric pressure fluctuations from seconds to days. J. Hydrol. 641, 131843. https://doi.org/10.1016/j.jhydrol.2024.131843.

Khaleel, R., Freeman, E.J., 1995. Variability and Scaling of Hydraulic Properties for 200 Area Soils, Hanford Site (No. WHC-EP–0883). Westinghouse Hanford Co., Richland, WA (United States). https://inis.iaea.org/records/8cj7w-ddh76.

Kuang, X., Jiao, J.J., Li, H., 2013. Review on airflow in unsaturated zones induced by natural forcings. Water Resour. Res. 49 (10), 6137–6165. https://doi.org/10.1002/wrcr.20416.

Li, H., Liu, W., Zhan, H., Sun, S., Wang, X., Wang, S., Li, F., Wang, X., 2022. Effect of barometric pumping on relative humidity in the loessal soil of the loess plateau. Geoderma 424, 116008. https://doi.org/10.1016/j.geoderma.2022.116008.

Li, X., Nieber, J. L., Kumar, V. 2024. Machine learning applications in vadose zone hydrology: a review. **Vadose Zone J.**, 23(4), e20361. Doi:https://doi.org/10.1002/vzj2.20361.

Lutes, C., Stewart, L., Truesdale, R., De Loera, J., Zimmerman, J.H., Schumacher, B., 2022. Cost comparison of soil vapor extraction and subslab depressurization for vapor intrusion mitigation. Groundw. Monit. Remediat. 42 (4), 43–53. https://doi.org/10.1111/gwmr.12510.

Mackley, R.D., Spane, F.A., Pulsipher, T.C., Allwardt, C.H., 2010. Guide to using Multiple Regression in Excel (MRCX v. 1.1) for Removal of River Stage Effects from Well Water Levels (No. PNNL-19775 Rev. 1.). Pacific Northwest National Lab.(PNNL), Richland, WA (United States). https://doi.org/10.2172/1000163.

McAlary, T., Wertz, W., Mali, D., Nicholson, P., 2020. Mathematical analysis and flux-based radius of influence for radon/VOC vapor intrusion mitigation systems. Sci. Total Environ. 740, 139988. https://doi.org/10.1016/j.scitotenv.2020.139988.

Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. 12 (3), 513–522. https://doi.org/10.1029/WR012i003p00513.

Oostrom, M., Truex, M.J., Tartakovsky, G.D., Wietsma, T.W., 2010. Three-dimensional simulation of volatile organic compound mass flux from the vadose zone to groundwater. Groundw. Monit. Remediat. 30 (3), 45–56. https://doi.org/10.1111/j.1745-6592.2010.01285.x.

Oostrom, M., Truex, M.J., Rice, A.K., Johnson, C.D., Carroll, K.C., Becker, D.J., Simon, M. A., 2014. Estimating the impact of vadose zone sources on groundwater to support performance assessment of soil vapor extraction. Groundw. Monit. Remediat. 34 (2), 71–84. https://doi.org/10.1111/gwmr.12050.

Ouoba, S., Bénet, J. C. 2023. Numerical modeling and simulation of water transfer in soil with low water contents. **Int. J. Environ. Sci. Technol.**, 20(1), 341–352. Doi:https://doi.org/10.1007/s13762-022-04460-w.

Peterson, R.A., Buck, E.C., Chun, J., Daniel, R.C., Herting, D.L., Ilton, E.S., Lumetta, G.J., Clark, S.B., 2018. Review of the scientific understanding of radioactive waste at the US DOE Hanford Site. Environ. Sci. Technol. 52 (2), 381–396. https://doi.org/10.1021/acs.est.7b04077.

Powell, M.J., 2009. The BOBYQA algorithm for bound constrained optimization without derivatives. *Cambridge NA Report NA2009/06*, 26. University of Cambridge, Cambridge, pp. 26–46. https://www.damtp.cam.ac.uk/user/na/NA_papers/NA2009_06.pdf.

Pruess, K., Yabusaki, S., Steefel, C., Lichtner, P., 2002. Fluid flow, heat transfer, and solute transport at nuclear waste storage tanks in the Hanford vadose zone. **Vadose Zone J.**, 1(1), 68–88. Doi:https://doi.org/10.2113/1.1.68.

Qi, S., Luo, J., O'connor, D., Wang, Y., Hou, D., 2020. A numerical model to optimize LNAPL remediation by multi-phase extraction. Sci. Total Environ. 718, 137309. https://doi.org/10.1016/j.scitotenv.2020.137309.

Rasmussen, T.C., Crawford, L.A., 1997. Identifying and removing barometric pressure effects in confined and unconfined aquifers. Groundwater 35 (3), 502–511. https://doi.org/10.1111/j.1745-6584.1997.tb00111.x.

Rohay, V.J., 2008. Performance Evaluation Report for Soil Vapor Extraction Operations at the 200-PW-1 Operable Unit Carbon Tetrachloride Site, Fiscal Year 2007 (No. SGW-37111 Rev 0). Hanford Site (HNF), Richland, WA (United States). https://doi.org/10.2172/938405.

Shi, J., Yang, Y., Li, J., Xi, B., Wang, Y., Wang, Y., Tang, J., 2020. A study of layered-unlayered extraction of benzene in soil by SVE. Environ. Pollut. 263, 114219. https://doi.org/10.1016/j.envpol.2020.114219.

Sobol, I.M., 1993. Sensitivity estimates for nonlinear mathematical models. Math. Model. Comput. Exp. 1 (4), 407–414.

Spane, F.A., 1999. Effects of Barometric Fluctuations on Well Water-Level Measurements and Aquifer Test Data (No. PNNL-13078). Pacific Northwest National Lab.(PNNL), Richland, WA (United States). https://doi.org/10.2172/15125.

Spane, F. A., 2002. Considering barometric pressure in groundwater flow investigations. **Water Resour. Res.**, 38(6), 14–1. Doi:https://doi.org/10.1029/2001WR000701.

Stewart, L., 2022. Analytical solutions for steady-state gas flow in layered soils with field applications. Groundw. Monit. Remediat. 42 (2), 35–46. https://doi.org/10.1111/gwmr.12496.

Sun, C., Xu, C., Zhao, Y., Zhang, W., Li, X., Zhang, Q., Wu, B., Ma, F., Gu, Q., 2023. A numerical simulation of thermally-enhanced soil vapor extraction with a validation of an actual contaminated site. Chemosphere 338, 139413. https://doi.org/10.1016/j.chemosphere.2023.139413.

Toll, N.J., Rasmussen, T.C., 2007. Removal of barometric pressure effects and earth tides from observed water levels. Groundwater 45 (1), 101–105. https://doi.org/10.1111/j.1745-6584.2006.00254.x.

Tong, C., 2005. PSUADE User's Manual. Lawrence Livermore National Laboratory (LLNL), Livermore, CA, p. 109.

Truex, M.J., Oostrom, M., Brusseau, M.L., 2009. Estimating persistent mass flux of volatile contaminants from the vadose zone to ground water. Groundw. Monit. Remediat. 29 (2), 63–72. https://doi.org/10.1111/j.1745-6592.2009.01236.x.

Truex, M.J., Carroll, K.C., Rohay, V.J., Mackley, R.D., Parker, K.R., 2012. Treatability Test Report: Characterization of Vadose Zone Carbon Tetrachloride Source Strength Using Tomographic Methods at the 216-Z-9 Site (No. PNNL-21326). Pacific Northwest National Lab.(PNNL), Richland, WA (United States). https://doi.org/10.2172/1063738.

USACE, 2002. Engineering Design: Soil Vapor Extraction and Bioventing. USACE EM 1110-1-4001. U.S. Army Corps of Engineers, Washington, D.C.. **https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-1-4001.pdf**

Van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44 (5), 892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x.

Wang, C.Y., Manga, M., 2021. Response to tides, barometric pressure and seismic waves. In: Water and Earthquakes, pp. 83–153. https://doi.org/10.1007/978-3-030-64308-9_5.

Yeh, T.C., Khaleel, R., Carroll, K.C., 2015. Flow through Heterogeneous Geologic Media. Cambridge University Press.

You, K., Zhan, H., 2012. Can atmospheric pressure and water table fluctuations be neglected in soil vapor extraction? Adv. Water Resour. 35, 41–54. https://doi.org/10.1016/j.advwatres.2011.10.008.

Zhang, S., Zhao, J., Zhu, L., 2024. Predicting removal efficiency of organic pollutants by soil vapor extraction based on an optimized machine learning method. Sci. Total Environ. 927, 172438. https://doi.org/10.1016/j.scitotenv.2024.172438.