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General well function for soil vapor extraction

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ABSTRACT

This paper develops a well function applicable to extraction of groundwater or soil vapor from a well under the most common field test conditions. The general well function (Perina and Lee, 2006) [12] is adapted to soil vapor extraction and constant head boundary at the top. For groundwater flow, the general well function now applies to an extraction well of finite diameter with uniform drawdown along the screen, finite-thickness skin, and partially penetrating an unconfined, confined, and leaky aquifer, or an aquifer underneath a reservoir. With a change of arguments, the model applies to soil vapor extraction from a vadose zone with no cover or with leaky cover at the ground surface. The extraction well can operate in specified drawdown (pressure for soil vapor) or specified flowrate mode. Frictional well loss is computed as flow-only dependent component of the drawdown inside the extraction well. In general case, the calculated flow distribution is not proportional to screen length for a multiscreen well.

1. Introduction

By changing the top boundary condition, this paper modifies the general well function (GWF) of [13] to make it applicable to soil vapor extraction (SVE). Two commonly used conceptual SVE models are considered here: one for a vadose zone with no ground cover [2] and another for a vadose zone capped by a low permeability layer treated as a leaky-boundary flux model [1]. The model for SVE is obtained directly from the GWF through a change of variables. Since fitting to field test data was presented in previous works [e.g., 1,7,12,14], it is not repeated here. The aim of this paper is to develop a single model applicable to a wide range of hydraulic and pneumatic testing.

The GWF for pumping from a confined, unconfined, or leaky-boundary flux aquifer under specified flow or specified drawdown conditions accounts for a partially penetrating extraction well with wellbore storage, finite-thickness skin, and non-uniform radial flux (uniform drawdown) along the screen interval. The GWF reduces to a number of widely used well functions for pumping and slug tests in confined, unconfined, and leaky aquifers as special cases, as discussed in [13]. It is applicable to a wide range of practical field tests, such as constant flowrate, constant drawdown, or instantaneous head change (slug test); if the specified flowrate (or specified drawdown) is time-varying, it can be represented by superposition of steps. A comprehensive summary of common aquifer test types and existing well functions can be found in [18].

SVE is commonly used for the cleanup of vadose zone soils contaminated by volatile organic compounds. Most practical SVE applications in the USA are based on forced flow in the vadose zone resulting from soil gas removal from the subsurface. Description of typical field SVE instrumentation and procedures can be found in [17] or [6]. Other approaches are possible, such as so called "barometric pumping" utilizing diurnal atmospheric pressure variations, which is an effective method for soil cleanup where site conditions are appropriate [e.g., 15,21]. DiGiulio and Varadhan [6] discuss in detail the derivation of equations governing soil vapor flow, boundary conditions, and compare different analytical models for soil gas flow. You and Zhan [19] further discuss and assess the effectss of atmospheric pressure changes on SVE tests.

Perina and Lee [12,14] presented a solution for a SVE well in vadose zone with no cover and non-uniform flow gradient along the extraction well screen under specified pressure or extraction rate. To extend the GWF to the "open domain" model for a vadose zone with no ground cover, the integral transform used in the GWF [13] is replaced by a modified finite Fourier sine (MFFS) transform [4]. The open domain model is also applicable to pumping or permeameter testing in saturated deposits beneath a reservoir. The GWF already includes the leaky-boundary flux top boundary which is applicable to SVE from a vadose zone covered by a low permeability layer.

Most groundwater extraction wells are "flow-controlled", meaning that the flow rate at which the pump operates is the controlled variable. Typical "drawdown-controlled" wells are flowing artesian wells but any extraction well can be operated as drawdown-controlled by maintaining a desired water level in the

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Nomenclature

b	saturated thickness, m
b_c	thickness of confining layer, m
C	frictional well loss coefficient (units depend on κ)
c_v	vertical leakance of confining layer, s^{-1} (water), m (air)
ΔH	drawdown within the extraction well, m
ΔH_c	constant drawdown applied at the extraction well, m
ΔH_d	initial displacement applied within the tested well during slug test, m
Δh^a	drawdown within the aquifer, m
Δh^s	drawdown within the well skin, m
I_n	modified Bessel function of the first kind and nth order
K_n	modified Bessel function of the second kind and nth order
k_c	vertical air permeability of confining layer, m^2
k_{os}	horizontal air permeability of observation well skin, m^2
k_r	horizontal air permeability of vadose zone, m^2
k_z	vertical air permeability of vadose zone, m^2
K_r	horizontal hydraulic conductivity, $m\ s^{-1}$
K_z	vertical hydraulic conductivity, $m\ s^{-1}$
N	number of well screen segments, –
N_0	nearest integer of $2/\Delta\eta + 0.5$
p	Laplace transform variable $(t \rightarrow p)$, s^{-1}
P	pressure, Pa
P_a	atmospheric pressure, Pa
Q	extraction rate, $m^3\ s^{-1}$
Q_c	constant flowrate from the extraction well, $m^3\ s^{-1}$
q	radial flux across the pumping well screen per unit screen length, $m^2\ s^{-1}$
q_j	radial flux across the jth screen segment, $m^2\ s^{-1}$
R	universal gas constant, $kg\ m^2\ K^{-1}\ s^{-2}\ mol^{-1}$
r	radial distance, m
r_c	radius of extraction well casing, m
r_{oc}	radius of observation well casing, m
r_{os}	radius of observation well skin, m
r_{ow}	radius of observation well screen, m
r_s	radius of extraction well skin, m
r_w	radius of extraction well screen, m
S_s	specific storage, m^{-1}
T	temperature, K
t	time, s
W	molecular mass, $kg\ mol^{-1}$
z	depth below the top of the aquifer, m
z_b	z to the bottom of the extraction well screen, m
z_{ob}	z to the bottom of the observation well screen, m
z_{ot}	z to the top of the observation well screen, m
z_t	z to the top of the extraction well screen, m
α	factor resulting from the wellbore storage condition, see (38) and (59)
ΔP	gauge pressure, Pa
ΔP_{ow}	gauge pressure inside observation well, Pa
$\Delta\eta_j$	dimensionless length of the jth screen segment, –
μ	dynamic viscosity of air, $kg\ m^{-1}\ s^{-1}$
η	dimensionless depth $\left(\eta = \frac{z}{b}\right)$, –
λ_n	roots of (13)
θ	air-filled porosity of soil, –
κ	power of Q in frictional well loss term
ρ	air density, $kg\ m^{-3}$
ζ_{ow}	quantity related to air pressure inside an observation well (16), $kg\ s^{-1}\ m^{-4}$
ξ_n	quantity resulting from the modified Bessel equation (16), m^{-1}

The overbar stands for the Laplace transform and subscript n for the MFFS transform.

Superscripts a and s stand for properties of the aquifer and skin, respectively.

well during pumping with the aid of appropriate instrumentation; this is a common operating mode for dewatering. Injection tests can also be conducted in drawdown-controlled mode [3]. SVE wells are typically operated with wellhead pressure as the controlled variable during field testing. Both extraction modes can be used in hydraulic and pneumatic testing for determination of aquifer and vadose zone properties, respectively. The majority of existing mathematical models for SVE use the product of applied pressure and volumetric extraction rate as the source term for the well boundary condition [e.g., 6,7,20]; Perina and Lee [12,14] demonstrated the advantages of separating the two quantities and treating one as dependent variable.

The change of variables for transforming the boundary value problem for ground water flow to a well into an equivalent problem for soil gas leads to simple substitutions for the arguments of the GWF. The GWF for the open domain model is derived first, followed by the substitutions to convert the groundwater flow model to an equivalent one for soil gas flow. In the following discussion, the terms soil gas, soil air, and soil vapor are used interchangeably with the understanding that they represent a mixture of air, water vapor, methane, and volatile organic vapors.

Perina and Lee [12,14] compared the soil vapor flow models resulting from the governing equation linearized in terms of pressure (P) and square of pressure (P^2). Both linearizations can be justified and the pressure distributions in the vadose zone near a SVE well predicted by both models are similar, but because the P^2 model leads to ambiguity in calculating pressure along observation well screen [12], the P model is adopted here and the P^2 model is included for completeness only. Li et al. [11] compared the results of analytical solutions to the linearized equation (in terms of P^2) and numerical solution to the exact (non-linear) equation for one-dimensional air flow in a porous medium. They showed that the error of the linearized model increases with pressure; for pressure increase up to $1.5P_a$ at the flow domain boundary, the difference in pressures calculated by the exact and linearized models is less than 2%. Thus a model based on the linearized equation is adequate for analysis of field SVE tests.

2. General well function for an open domain

The following is a brief summary of the conceptual model and solution presented in [13] with the top boundary replaced by one of constant head (zero drawdown).

Consider an aquifer of thickness b. Its properties (K_r^a, K_z^a, S_s^a, and b) are uniform within the zone influenced by the pumping. The initial condition is taken as zero drawdown everywhere in the aquifer prior to the test. A reservoir overlies the aquifer so that the aquifer top can be represented by a constant head boundary.

The extraction well has a finite diameter and partially penetrates the aquifer (Fig. 1). The test is conducted under the condition of either specified flowrate or specified drawdown instantaneously applied at the extraction well at time zero. The term “specified” as used here implies that the quantity be known (or measured); in general, it does not have to be constant in time.

A finite-thickness skin with properties K_r^s, K_z^s, and S_s^s extending from r_w to r_s ($r_s > r_w$) is considered. This concentric shell can