RFP--4935
CONF-9505188--2

Modeling One-Dimensional Unsaturated Flow at the Rocky Flats Environmental Technology Site Near Golden, Colorado

J. Scott Thompson[1] and Rose M. Zeiler[2]

---

[1] Environmental Project Manager, EG&G Rocky Flats, Inc., NNFC/T130J, P.O. Box 464, Golden, Colorado 80402, (303) 966-7163, fax (303) 966-6538.

[2] Senior Hydrogeologist, Advanced Sciences Inc., 405 Urban Street, Suite 401, Lakewood, Colorado 80228, (303) 980-0036, fax (303) 980-1206.

J.S. Thompson is the corresponding author.

ABSTRACT

A field investigation characterizing contamination at the Rocky Flats Plant (Rocky Flats Environmental Technology Site) near Golden Colorado revealed unexpectedly high moisture contents in the unsaturated soil column (vadose zone) beneath several of the Plant's Waste Water Treatment Plant (WWTP) sludge drying beds. Because these beds were seldom in use, researchers had hypothesized that the water required to maintain the saturated conditions observed beneath several of the sludge drying beds was coming from sources other than the beds themselves. In an effort to substantiate this hypothesis, a one-dimensional physically-based unsaturated flow model was utilized to simulate the vertical movement of moisture from the sludge drying beds into the unsaturated soil column below. The model was run to simulate vertical flow over a two-year period and results indicated that no significant changes from initial conditions were apparent. This evidence supports the hypothesis that the high moisture contents found beneath the sludge drying beds are being fed by sources other than infiltration of sludge applied to the beds themselves. This paper presents the details of the simulation and provides further evidence of the hypothesized flow regime.

Key Words: One-dimensional modeling, unsaturated flow, vadose zone

SITE DESCRIPTION

The Site's Sanitary Treatment Plant collects, treats, and discharges all sanitary wastes generated from a 384 acre industrial area. The primary mission of the Site was production of components for nuclear weapons and because the WWTP treated radioactive laundry effluent from approximately 1969 to 1973, the sewage sludge is treated as low level radioactive waste (EG&G, 1990). The WWTP utilizes a conventional activated sludge facility where digested sanitary sewage sludge is sent to any one of seven open air drying beds. Each application of sludge to any given drying bed contains approximately 2000 gallons at two to three percent solids to liquids (by weight). The free liquids entrained with the sludge are decanted through an underdrain system and returned to the primary clarifier. Following the decanting of liquids, the remaining solids are air dried until a solid-to-liquid ratio of greater than 43 percent (by weight) is achieved and then is packaged in polyethylene-lined plywood containers at a rate of approximately 90 per year for eventual disposal.

SITE GEOLOGY AND HYDROLOGY

The Site's industrial area is surrounded by a 6550 buffer zone located just east of north-south trending Front Range about 16 miles east of the Continental Divide. The Site's geomorphic surface is a broad, eastward-sloping alluvial fan at an altitude of approximately 6,000 feet above mean sea level. Geologic units at the Site consist of unconsolidated surficial units of Quaternary age (Rocky Flats Alluvium, valley-fill alluvium, and colluvium) which unconformably overlie Cretaceous bedrock (Arapahoe Formation/Laramie Formation and Fox Hills Sandstone). Rocky Flats Alluvium comprises the main alluvial cover at the Site and all other surficial deposits occur topographically below within stream drainages. The Laramie formation is composed of two units; the uppermost containing mostly silty claystones, siltstones, and some fine-grained fluvial channel sandstones, and the lower unit containing mostly coals and sandstone that increase in thickness towards the base of the unit. Three east-flowing, intermittent streams traverse the Site, dividing it into three primary drainages (EG&G, 1993). The geology underlying the Site's WWTP sludge drying beds was evaluated during an earlier study (ASI, 1990) using data from four wells located within a 750-foot radius of the site. A cross-sectional view of the area is depicted in Figure 1.

The stratigraphy and geologic contacts remain partly inferred at depths below the alluvium/colluvium - bedrock zone of contact because drilling conducted during the 1992-1993 study did not extend deep enough for confirmation of all of these contacts. However, the study was able to confirm that artificial fill is approximately 7.0 to 8.5 feet thick beneath the south row of drying beds and 4.0 feet thick beneath the north row of drying beds. The alluvium/colluvium - bedrock zone of contact is approximately 11.1 to 11.7 feet thick beneath the south row of drying beds and 6.8 to 8.0 feet thick beneath the north row of drying beds (ASI, 1994). Previous investigations had estimated mean ground water elevations in the vicinity of the sludge drying beds to be at elevations less than 5910 feet above MSL (17 feet below ground surface), well below the zone of the unconsolidated surficial materials. The 1992-1993 investigation verified this estimate as no ground water was encountered during drilling of the six 45 degree boreholes. The boreholes were terminated when the augers encountered claystone, and appropriate monitoring instrumentation was installed. Confirmation of unsaturated conditions in the

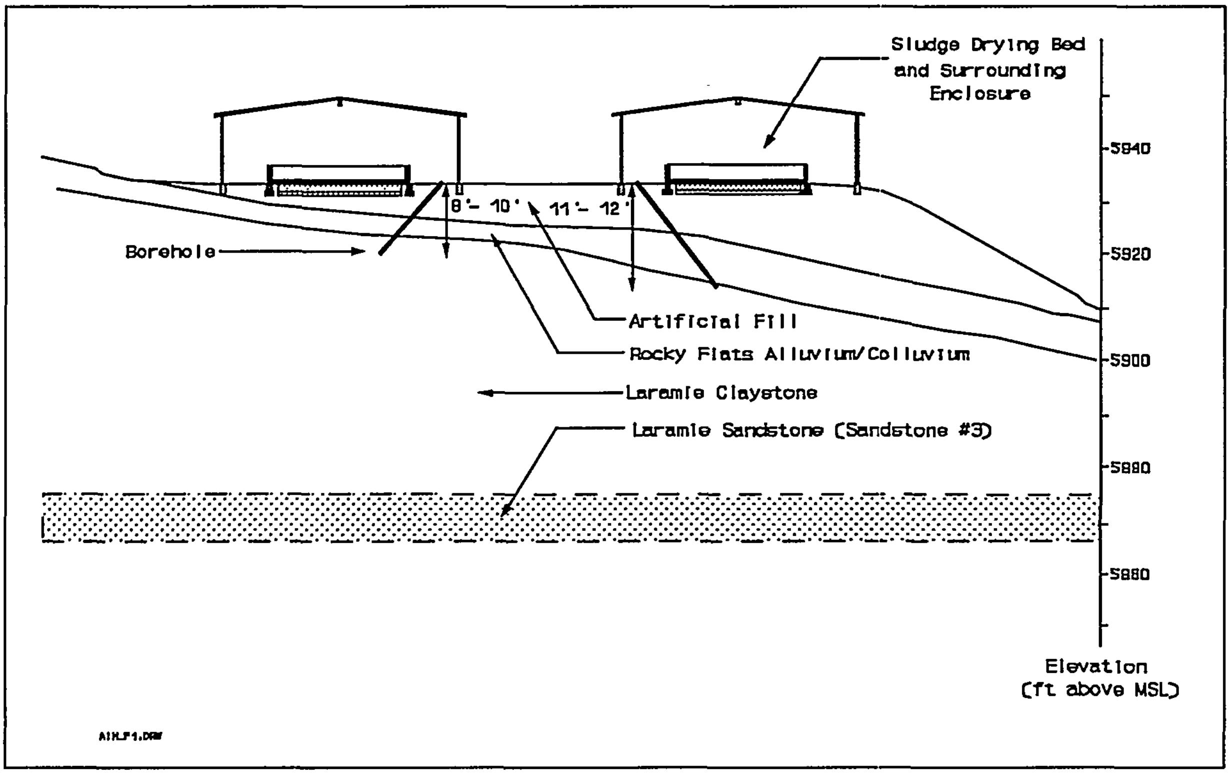


Figure 1. Cross section of the WWTP Sludge Drying Beds, looking east.beneath the sludge beds.

unconsolidated surficial materials beneath the sludge beds was obtained through laboratory analysis of core samples. A zone of saturation was determined to exist at the top of the uppermost claystone unit. The artificial fill material and the surficial deposits are likely to have been compacted by the overlying structures and have a saturated hydraulic conductivity of approximately 1.0 x 10^{-8} cm/sec. The claystone unit immediately beneath the unconsolidated surficial materials exhibited saturated hydraulic conductivities ranging from 1.8 x 10^{-9} cm/sec to 8.0 x 10^{-9} cm/sec (ASI, 1994). Soil-moisture measurements conducted during the 1992-1993 investigation indicated that volumetric soil-moisture profiles with depth remained relatively constant. Some downward and upward soil-moisture movement has occurred but the quantity (flux) was judged to be very small, due to the very low hydraulic conductivities of the materials beneath the sludge drying beds. Anomalies in the amount of moisture content beneath several of the sludge drying beds became apparent during the course of the 1992-1993 investigation. For example, volumetric moisture contents above 40 percent were consistently noted in the soil column beneath Sludge Drying Bed Number 5 at a depth below 6.5 feet from the ground surface. Measurements above approximately 40 to 45 percent are indicative of saturation. However, WWTP operations records showed that this bed had been unused for at least seven months prior to the 1992-1993 investigation, and adjacent bed (Beds Number 6 and 7) had been used a total of six times during the same period (ASI, 1994). Even if unreported usage of the sludge drying beds was occurring, the bulk of ground water in the unconsolidated surficial materials would not penetrate the claystone because, even under saturated conditions, the claystone is unable to transmit large amounts of water. Instead, ground water flows laterally along the contact of the Alluvium/Fill and Laramie formation in a direction that is controlled largely by the geometry of this contact. Based on this evidence, it was hypothesized that infiltration from the sludge drying beds was not great enough to maintain the observed saturated conditions, and that this moisture must be coming from other sources.

MODELING THE UNSATURATED ZONE

The One-dimensional Princeton Unsaturated Flow and Transport Code (Celia, 1991; Celia and others, 1990) was selected and used for estimating flux rates and moisture contents for selected cases of water input from the WWTP sludge-drying beds. The model simulates the movement of water in both unsaturated and saturated soils. It also simulates the movement of a nonreactive dissolved contaminant in the water phase; however, this model feature was not used in the analysis of the Building 995 sludge-drying beds.

The equation that is assumed to govern the flow of water derives from the basic conservation of mass statements, coupled with specific constitutive relations. Conservation of mass of the water phase, coupled with the Darcy equation and a variety of other assumptions (Hillel, 1980; Celia and others, 1990), leads to the Richards' equation. Because Richards' equation is nonlinear, it may be written in several different forms. In one dimension (the z- or vertical-dimension), Richards' equation may be written as follows:

$$\frac{\partial\theta}{\partial t} + \left(S_s \frac{\theta}{\theta_s}\right)\frac{\partial h}{\partial t} - \frac{\partial}{\partial z}\left[K(h)\,\frac{\partial h}{\partial z}\right] - \frac{\partial K}{\partial z} = 0$$

where:
θ = volumetric moisture content (cm^3/cm^3)
θ_s = saturated volumetric moisture content (cm^3/cm^3)
h = matric potential or pressure head (cm)
S_s = elastic storage coefficient (1/cm)
K(h) = unsaturated hydraulic conductivity (cm/sec)
z = vertical dimension, assumed to positive downward (cm)
t = time (sec).

To solve this equation, constitutive relations between θ and h and between K and h (or K and θ) are needed. While the governing equation written above is essentially independent on the materials within the soil column beneath the sludge-drying beds, the functional relationships $\theta(h)$ and K(h) are strongly material dependent. Therefore, characteristics of the soils beneath the Building 995 sludge-drying beds are reflected in these two relationships. The van Genuchten relationships had been used in the RETention Curve (RETC) computer program (van Genuchten, et al., 1991) during the 1992-1993 investigation to develop moisture-characteristic curves for the soil columns beneath selected sludge-drying beds. Together with saturated hydraulic conductivities from the 1992-1993 investigation, all of the material-specific data required to satisfy inputs to the model was available. Boundary and initial conditions also must be provided for the model and consist of either pressure heads (and related volumetric moisture contents) or fluxes.

CONCEPTUAL MODEL

The conceptual soil profile to be modeled consisted of a one-dimensional column with varying material properties in the z-dimension (Figure 2). The conceptual model was developed

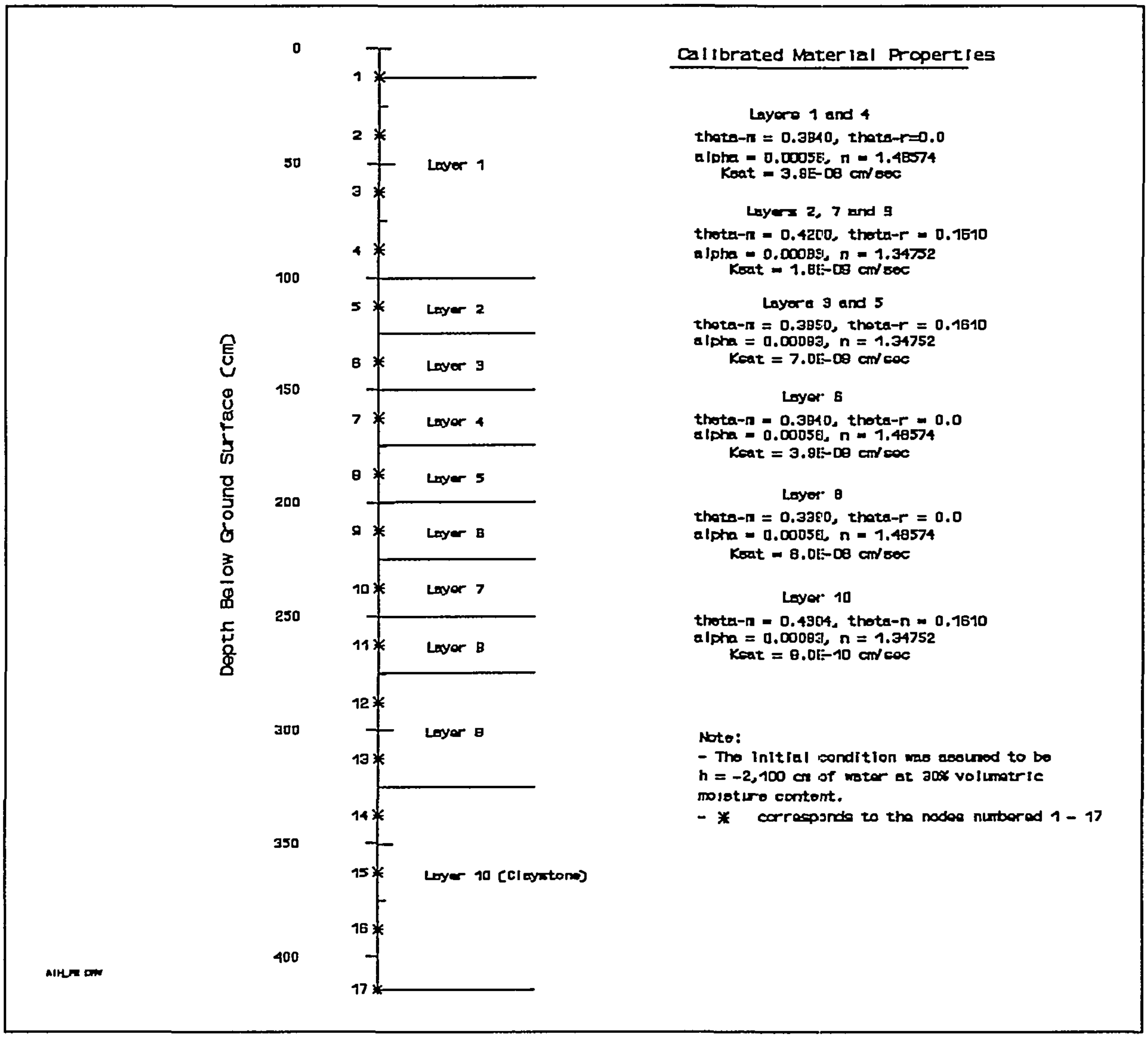


Figure 2. Conceptual profile beneath sludge-drying Bed 5.

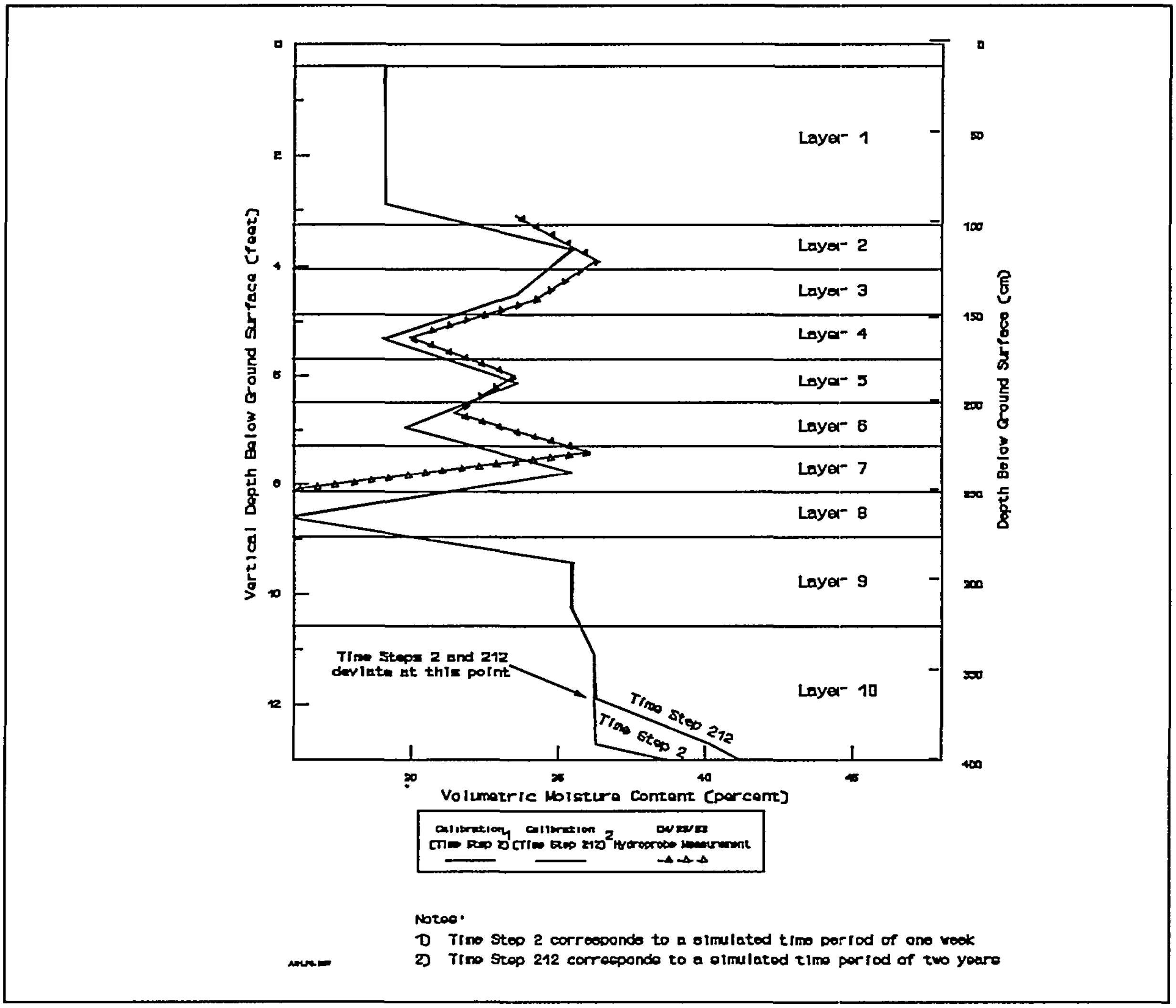
using data from the 1992-1993 investigation. A single borehole for which all required physical data was available was selected for modeling. The moisture content profile of this borehole (Borehole AB3N) was expected to represent worst-case conditions, because the bed above this borehole (Sludge-drying Bed 5) is unlined. Additionally, because no sludge had been added to Bed 5 during the entire two-year interval of observation, the soil-moisture profiles are believed to be most representative of initial conditions. Although each borehole was sampled for geotechnical data, continuous geotechnical characterization for the length of the borehole was not practical. Because the boreholes are in a radiologically controlled area, detailed geological logging of the samples was not carried out. Bi-weekly soil-moisture profiles collected over a one-year period in borehole AB3N indicated that multiple heterogeneities existed. It was noted that soil-moisture profiles in AB3N appear to change little, that is, there appears to be a signature to the profile that remains essentially unchanged even as soil-moisture contents change along the profile. Therefore, characterization of the heterogeneities in the soil was built upon differentiation of layers within the borehole using soil-moisture profiles. Using similar moisture contents, the ten layers were grouped into six material types. Geotechnical analyses of three samples within the borehole were used to assign values to each of the material types as detailed in Figure 2. The assigned values for each material type were later adjusted based upon the model calibration.

The material properties for the 10 layers shown on Figure 2 are represented by 17 nodes. Where no geotechnical data were available for a material type, values for the van Genuchten parameters of θ_m, θ_r, α, and n were extrapolated from other samples with similar grain size distributions from data developed during the 1992-1993 investigation (ASI, 1994). Although no data were collected for the claystone (Layer 10), a saturated hydraulic conductivity one order of magnitude smaller than the smallest measured value from the 1992-1993 investigation was used.

The next step was to determine an initial flux rate. It was known that each sludge-drying bed has a capacity of approximately 7500 gallons, but rarely is more than 2000 gallons of sludge pumped to any given bed. A conservative number of 3740 gallons (approximately one-half full capacity) was picked and calculations of the maximum amount of liquids that could decant and be available for infiltration over the entire surface area of the bed were made. This total discharge "Q" (cm^3/sec) was converted to a flux per unit area "q" (cm/sec) by dividing by the surface area of the sludge-drying bed. Because it takes approximately two weeks to one month for the sludge to dry (ASI, 1994), the initial flux rate was applied for the first two weeks and for all times after this, the flux was set equal to the saturated hydraulic conductivity of Layer 1 (at a gradient of one).

MODEL CALIBRATION

The uniform initial moisture content was obtained from a typical single soil-moisture profile (the 04/28/93 Hydroprobe Measurement on Figure 3) by relating the moisture-characteristic curve developed for a sample within Layer 4 to the moisture content at that point in the soil moisture profile. As shown on Figure 3, a volumetric moisture content of 30 percent is found midway through Layer 4. Then a corresponding matric potential of -1200 cm of water was obtained from the moisture-characteristic curve (not shown). The model was calibrated to the initial conditions by varying the maximum moisture content of each material type until the simulated soil moisture profile matched the measured soil moisture profile. The results of this calibration are readily apparent when one compares the 04/28/93 Hydroprobe Measurement representing the actual moisture profile to the Calibration (Time Step 2 and Time Step 212) representing the modeled moisture profiles both before and two years after the simulated application of sludge to Bed 5. Note that the data points representing Time Step 2 and Time Step 212 do not diverge until Layer 10 which will be discussed further in the next section.



Notes:
1) Time Step 2 corresponds to a simulated time period of one week
2) Time Step 212 corresponds to a simulated time period of two years

Figure 3. Model calibration results.

RESULTS

The model was run to simulate a two-year period of vertical flow. As depicted on Figure

3, the soil moisture profile at the end of the two-year simulation period (Time Step 212) was nearly identical to initial conditions (Time Step 2). No significant, and only marginally discernible, changes from initial conditions were apparent. These results support the position that infiltration from the WWTP sludge-drying beds under worst-case conditions, that is, maximum application rates, unlined sludge beds, and maximum possible infiltration rates, cannot account for the changes in elevation of the water table on top of the claystone. Perched water-table fluctuations and "wetting" of the soil-moisture profile observed during the 1992-1993 investigation are most likely due to sources other than the sludge drying beds themselves. Possible sources of this moisture could include other leaking WWTP vessels in the immediate vicinity or upgradient lateral inflow.

REFERENCES

Advanced Sciences, Inc. (ASI). 1990. "Draft Final Groundwater Monitoring Plan for the Rocky Flats Plant Sanitary Treatment Plant Sludge Drying Beds." Prepared for EG&G Rocky Flats, Inc., July 25, 23 p., 12 figures, 3 tables.

Advanced Sciences, Inc. (ASI). 1994. "Final Vadose Zone Monitoring Report, Sanitary Treatment Plant Sludge Drying Beds, Rocky Flats Plant ." Prepared for EG&G Rocky Flats, Inc., September 30, 1994, 99 p., 68 figures, 17 tables, Appendixes A through H.

Celia, M.A., E.T. Bouloutas and R. Zarba, 1990, A General Mass-Conservation Numerical Solution for the Unsaturated Flow Equation: *Water Resources Research*, vol. 26, no. 7, pp. 1483-1496.

Celia, M.A., 1991, Water Resources Program, The One-Dimensional Princeton Unsaturated Code: Distributed at the Princeton University Short Course on Fundamentals of Unsaturated Zone Modeling, 24 June - 28 June, 1991, 29 p., 2 Attachments.

EG&G Rocky Flats, Inc., 1993b, Background Geochemical Characterization Report: Report prepared for the U.S. Department of Energy, Rocky Flats Plant, Golden, Colorado, September 30, 5 sections, 6 plates, Appendices A through F.

Hillel, D., 1980, Fundamentals of Soil Physics: New York, Academic Press, Inc.

Richards, L.A., 1931, Capillary Conduction of Liquids in Porous Mediums: *Physics*, vol. 1, pp. 318-333.

van Genuchten, M.The., Leij, F.J., and Yates, S.R., 1991, The RETC Code for Quantifying the Unsaturated Functions of Unsaturated Soils: Ada, Oklahoma, Robert S. Kerr Environmental Research Laboratory, EPA/600/2-91/065, December, 85 p.