Analysis of Modeling Capabilities to Predict Disposal Facility Cover Design and Performance at DOE sites – 11057

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ABSTRACT

This paper is on the modeling approaches utilized to design final disposal facility cover systems at DOE sites. Predictions from three of the most popular models used to predict the hydrologic performance of disposal facility covers is examined using the uranium mill tailings disposal facility in Monticello, Utah as a case study. Multiple climate scenarios are constructed for the Monticello site and evaluated using each of the three selected models to predict corresponding performance. A comparative analysis of predictions is performed within each model. The extent to which these models appropriately account for the effects of climate change is addressed. HELP provided modest changes in its predictions when synthetic analogues were used instead of temporal. Percolation was highest for simulations using synthetic analogues. UNSAT-H showed changes in its response to synthetic analogues versus temporal analogues. Less percolation was predicted using synthetic analogues than the temporal analogues. Synthetic simulations with Hydrus-1D predicted more percolation than temporal simulations.

INTRODUCTION

The U.S. Department of Energy (DOE) is responsible for the cleanup of nuclear waste at former nuclear weapons sites across the United States (U.S.). The sites actively produced nuclear weapons components and assembled nuclear weapons from the 1940s through the end of the Cold War [20]. DOE's Office of Environmental Management currently oversees environmental restoration activities at more than 80 of these sites. Cleanup activities include decontamination and demolition of buildings, management of contaminated soils and groundwater, containment of radioactive and hazardous chemical waste materials in near surface disposal facilities (e.g., disposal facilities, trenches and vaults), treatment and stabilization of liquid radioactive wastes, and disposal of nuclear materials [20].

With the abundance of sites across the U.S. and the variability in operational management at each site, DOE introduced Order 435.1, *Radioactive Waste Management*, in 1999. The purpose of this order was to establish guidelines for the management of DOE high-level waste, transuranic waste, low-level waste, and the radioactive component of mixed waste [18]. DOE Order 435.1 also states that performance assessments (PAs) are to be conducted for low-level waste disposed and performance objectives should be evaluated for a 1,000-year period to determine potential risk impacts to the public and environment. A PA is “an analysis of a radioactive waste disposal facility conducted to demonstrate there is a reasonable expectation that performance objectives established for the long-term protection of the public and the environment will not be exceeded following closure of the facility” [18]. Long-term features, events and processes at sites that may contribute to the risk of groundwater contamination and human exposure may be considered in PAs [13]. One long-term event is the impact of climate change.

Climate Change Effects

Natural and anthropogenic processes are believed to be causing climate change that includes rises in temperature and variation in precipitation patterns [17]. Increases in average temperature, coinciding with more frequent and extreme weather conditions are anticipated [17].

While the entire U.S. maybe influenced by climate change, the extent of the impact will be regional [17]. Therefore, any approach to understanding how climate change will affect environmental performance of disposal facilities must be performed at a regional level. Numerical models used for design and PAs will be used to assess the impact of climate change. These models must include operational parameters (e.g., temperature) that require initial and boundary conditions (e.g., precipitation) to accurately depict climate change effects.

DOE 435.1 Modeling Approaches

Traditional design guidelines for disposal facility covers often rely on deterministic models of flow and transport processes. The effects of increases in average temperatures or the occurrence of more frequent and extreme weather conditions associated with climate change generally are not considered [21]. This paper will explore and compare predictions from models when climate change effects are considered as well as explore the behavior of these models when input data are altered from temporal analogues to synthetic analogues.

SITE DESCRIPTION

The Monticello uranium mill tailings site is located in southeastern Utah, 1.5 km from Monticello, Utah. In 1941, a uranium ore mill was constructed at the site that processed nearly one million metric tons of ore [4]. Operations were terminated in the early 1960s, leaving approximately 2 million cubic meters of uranium mill tailings that can emit radon gas and gamma radiation [4]. In 1995, DOE began construction of a repository south of the original mill site to contain the mill tailings [4]. The disposal cell design was subject to both minimum technology guidance for hazardous waste disposal facilities under Subtitle C of the Resource Conservation and Recovery Act of 1976 (RCRA), and design guidance for radon attenuation and 200-1,000 yr longevity under the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA) [19; 20].

Climate Conditions

Climate at the Monticello repository is semi-arid, with an average annual precipitation of approximately 381 mm and an average annual temperature of 7.8 ºC [4]. When modeling a disposal facility cover system, historical climate data are examined. Average annual data are often used to select a "typical year" for analysis. The year with the greatest amount of precipitation often serves as the "design year" [3].

The use of historical data (temporal analogues) allows users to capture the historical context of the environment that encompasses both extreme conditions (e.g., wet and dry patterns) and climatic variations. A disadvantage of using solely historical data is that past changes in climate are unlikely to have been caused by mechanisms (e.g., anthropogenic causes) expected to affect future climate [8]. Furthermore, the historical record time period is relatively small compared to the forecast period (1,000 yrs). Palaeoclimatic changes from earlier time periods (e.g., the last Interglacial period) were most likely caused by changes in the Earth's orbit around the sun, while more recent palaeoclimatic changes are presumably related to naturally occurring changes in atmospheric circulation, as are changes in the earlier part of the instrumental record [8]. Because anthropogenic climate changes are not accounted for in this record, the future climate will resemble those of a past climate.

An alternative approach is to use historical records in conjunction with atmospheric models to produce synthetic analogues. General circulation models (GCMs), representing physical processes in the atmosphere, ocean, cryosphere and land surface, are the most advanced tools currently available to produce synthetic analogues [8]. While simpler models have also been used to provide globally or regionally averaged estimates of future climate conditions, only GCMs, often in conjunction with nested regional models or other downscaling methods, have the potential to provide geographically and physically consistent estimates of regional climate change data [8]. GCMs depict the climate using a three dimensional grid over the globe. Many physical processes, such as those related to clouds, also occur at smaller scales and cannot be properly modeled. As an alternative, their known properties must be averaged over the larger scale in a technique known as parameterization [8]. This is one source of uncertainty in GCM-based simulations of future climate.

This paper compares predictions of cover performance using GCM-produced precipitation data and historical records obtained from instrumentation as input. Three hydrological models are used to test the response of the models to the GCM-produced data and the variation in results between the different precipitation data inputs. Table I provides a description of the scenarios used.

Table I: Scenario Descriptions

Scenario	Name	Description
1	Typical Year	Year in which the typical or average amount of precipitation is observed over the given period.
2	Design Year	Year in which the greatest amount of precipitation is observed over the given period.
3	GCM Alternative	Year in which predicted future precipitation data from a GCM is used as input for the given project area.

Annual precipitation presented in Scenario 1 represents average annual totals seen at the facility (402 mm, 1998). A total of 126 days had measureable precipitation with October producing the most precipitation (25.9% of annual total) and December the least (0.5% of annual total). Months that had large amounts of precipitation included March, July, and October. The longest precipitation event occurred in the fall, where 43.7 mm was received over 7 days. The largest span of time with no precipitation occurred in the summer over an 18 day period.

Scenario 2 is the wettest year on record at the facility (550 mm, 1997). A total of 152 days had measureable precipitation with January producing the most precipitation (24.5% of annual total) and March the least (1.02% of annual total). Months that had large amounts of precipitation included January, August, and September. The longest rain event occurred in the spring, when 37.7 mm was received over an 8 day period. The largest span of time with no rain happened in the summer over a 21 day period.

Scenario 3 annual precipitations (521 mm) is derived from data obtained from a GCM. Only 74 days had measureable precipitation with August having the most precipitation (25.1% of annual total) and December the least (0% of annual total). Months that had large amounts of precipitation included August, September, and October. The longest precipitation event occurred in the fall, when 36.6 mm was received over a period of 7 days. The largest span of time with no precipitation occurred in the summer over a 42 day period. The next largest span of time with no precipitation occurred in the spring over a 38 day period. Scenario 3 has no precipitation in July, which is followed by the month with the greatest precipitation (August). The extremely dry conditions followed by extremely wet conditions occur only a month prior to the first hard freeze in the region (late September) [4]. Runoff is expected to be minimal and less than 10% of precipitation and evapotranspiration is expected to account for most of the removal of water from the soil profile [1]. Additional details on the development of precipitation values for Scenario 3 are discussed in the next section.

GCM Scenario Selection

The Data Distribution Centre (DDC) provides data resources for several GCMs produced by various countries. The GCM used for this analysis is the GFDL R30 climate model, a U.S. based, coupled atmosphere-ocean GCM (AOGCM). The four major components are an atmospheric spectral GCM, an ocean GCM and relatively simple models of sea ice and land surface processes [8]. This model was selected based on its geographical focus on the U.S., the availability of variables needed for input in hydrologic models (e.g., precipitation, temperature, humidity), as well as the accessibility of future predictions spanning 100+ years.

The model uses storylines to produce various data outputs of future conditions. The storylines encompass scenario families that are based on various social and economic conditions that drive GHG emissions. The *A1B* storyline predicts emissions will increase very rapidly until 2030, continue to increase until 2050 and then decline [17]. The *A2* storyline predicts emissions will continue to increase rapidly and steadily throughout the twenty-first century. The *B1* storyline predicts emissions will increase very slowly for a few more decades, then level off and decline. The B1 storyline and scenario family describes a convergent world with the same global population as in the A1B storyline (one that peaks in mid-century and declines thereafter), but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The *B2* storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels. Even as all storylines are unique and can produce a range of data outputs, developers have defined storyline B2 as a low emission scenario, A1B as a moderate emission scenario and A2 as a high emission scenario.

With a total of four possible scenarios, accompanied by unique data conditions for both temperature and precipitation, up to 28 plausible scenarios could be developed for this analysis. If an uncertainty, sensitivity, and/or alternative design analysis was desired, over 100 scenarios are possible. As a result, a single representative storyline was selected that allows a direct comparison of results between “typical year” and “wettest year” model outputs. To be conservative, the moderate or A1B storyline was chosen.

Hydraulic Properties

Construction of the Monticello tailings disposal cell was completed in 2000. The final cover is a composite design that exceeds the Environmental Protection Agency (EPA) minimum technology guidance for hazardous waste disposal facilities regulated under RCRA Subtitle C and exceeds UMTRCA radon attenuation requirements [2]. The design includes a compacted soil liner (CSL) which serves as a radon barrier directly above the tailings. The CSL is covered with a high-density polyethylene (HDPE) geomembrane, which separates the CSL from a sand layer. The fine-textured soil and rock layer overlying the capillary barrier layer serves as a water storage layer where water is either removed by evapotranspiration or remains in the liner system. Table II provides hydraulic properties of the cover design, obtained from the risk-based performance assessment developed for the Monticello Repository [4].

Table II: Monticello Soil Hydraulic Properties

Layer	1	2	3	4
Thickness (mm)	1676	305	1.52	610
Porosity	0.456	0.375	-	0.343
Field Capacity	0.380	0.150	-	0.200
Wilting Point	0.180	0.040	-	0.150
Initial Soil Water Content	0.300	0.080	-	0.310
K_{sat} (cm/sec)	1.00E-03	1.00E-01	2.00E-13	1.00E-06
Slope (%)	-	3.00	-	-
Drainage Length (m)	-	549	-	-
Pinhole Density (holes/acre)	-	-	1.00	-
Installation Defects (holes/acre)	-	-	1	-
Placement Quality	-	-	Good	-

In 2008, hydrological and geomorphological properties of the final cover at the Monticello Repository were examined [6]. Field tests for saturated hydraulic conductivity were performed, large-scale undisturbed samples were collected and tested for hydraulic properties, and geomorphological surveys were conducted. The upper 200 mm of the cover consisted of a gravel-amended surface layer intended to limit erosion. The 900 mm thick layer beneath the gravel-amended surface layer is the storage layer. These two layers were the primary focus of the study. Based on the testing that was conducted, typical conditions can be represented using 1.5 X 10^{-4} cm/s as the saturated hydraulic conductivity and the following van Genuchten parameters: $\theta_s = 0.41$, $\theta_r = 0.00$, $\alpha = 0.021$ kPa^{-1}, and n = 1.30 [6]. An 1100 mm single layer will be used in this analysis with the above mentioned hydraulic properties to simulate actual conditions at the repository.

HYDROLOGIC MODELS

Many hydrologic models exist that are capable of determining the performance of disposal facility cover systems. For this analysis, the Hydrologic Evaluation of Landfill Performance (HELP), UNSAT-H, and Hydrus-1D models were chosen. Below is a discussion of each model and various input parameters used in the analysis.

HELP Model

The HELP model requires the input of weather, soil and design data, and provides estimates of runoff, evapotranspiration, lateral drainage, vertical percolation (i.e., infiltration), hydraulic head and water storage for the evaluation of various landfill designs based on a water routing approach. Additional inputs for HELP include the Soil Conservation Service (SCS) curve number, which is used to estimate runoff. The curve number was set at 92 based on recommendations in the DOE 435.1 PA [4]. Table III provides plant input parameters needed for

HELP evapotranspiration calculations. HELP is the only landfill-specific water balance model available. Version 3.07, issued on November 1, 1997, is the latest version of the model.

Table III: HELP Plant Input Parameters [4]

Input Parameter		Value
Evaporative Zone Depth (mm)		1676
Max Leaf Area Index (LAI)		1.00
Growing Season	Start - DOY	74.0
	End - DOY	319
Average Wind Speed (km/h)		12.0
Average Relative Humidity (%)	1st Quarter	58.5
	2nd Quarter	30.7
	3rd Quarter	32.8
	4th Quarter	50.8

UNSAT-H and HYDRUS-1D

UNSAT-H is a one-dimensional unsaturated soil-water and heat flow model based on Richard's Equation that contains transpiration, thermal and isothermal vapor flow models in addition to a range of hydraulic functions. The UNSAT-H model was developed at Pacific Northwest National Laboratory to assess the water dynamics of arid sites and, in particular, estimate recharge fluxes for scenarios pertinent to waste disposal facilities [11].

Hydrus-1D is a one-dimensional finite element model based on Richard's Equation that is used for the analysis of water flow and solute transport in variably saturated porous media [16]. Like UNSAT-H, Hydrus-1D accounts for transpiration and permits various hydraulic functions. A discussion of all three models can be found in Orgorzalek et. al (2008) and Bohnhoff et. al (2009) [7;14].

Upper and Lower Boundaries

An atmospheric boundary was applied at the surface for both models. Daily precipitation was applied using default conditions in each model (10 mm/h in UNSAT-H; uniformly throughout the time steps in Hydrus-1D). Potential evapotranspiration (PET) was computed by both UNSAT-H and Hydrus-1D using the modified Penman equation in Doorenbos and Pruitt [10]. PET was partitioned into potential evaporation and potential transpiration using the Ritchie–Burnett–Ankeny equation [9]. Daily meteorological properties were input to each model, when necessary, to define the atmospheric boundary. On-site measurements were used for wind speed and direction, air temperature, relative humidity, and solar radiation. The maximum suction at the surface used in Hydrus-1D was set at 100 MPa. Nodes in the soil layer were assigned a matric suction based on results obtained from 5 year simulations of precipitation data for each scenario. Matric suction predictions from Hydrus-1D were input not only in simulations for Hydrus-1D but also in UNSAT-H. Simulations were conducted using a unit gradient lower boundary condition for both models, as recommended in practice [5].

Soil Properties

The van Genuchten-Mualem function was used for the unsaturated hydraulic conductivity function in UNSAT-H and Hydrus-1D. The pore interaction term was set at 0.5 in the van Genuchten–Mualem function. As previously noted, the cover will be modeled as one single layer using data obtained from the hydrological and geomorphological properties study of the Monticello repository.

Vegetative Properties

The LAI function was defined using the peak LAI measured in the field and end points of the growing season recommended by the SCS for the vegetation at the field site. The LAI was assumed to increase from 0.0 to 1.0 during the first 30 days of the growing season, decrease from 1.0 to 0.0 over the last 30 days of the growing season, and remain constant in between. For Hydrus-1D and UNSAT-H, the root depth was assumed to increase 1 mm/day during the growing season until the root barrier was reached. Root density was fit with the normalized root density exponential model using coefficients obtained from samples collected from the field [6]. Water uptake was defined in Hydrus-1D and UNSAT-H using the Feddes plant limiting function [12]. The wilting point was defined by the highest matric suction (50,000 cm). The limiting point was set at 600 cm and the anaerobiosis point was set at 25 cm.

Spatial and Temporal Domain and Discretization

In Hydrus-1D and UNSAT-H, a nodal spacing or element thickness as small as 1 mm was used at the ground surface and at soil interfaces, with a total of 101 nodes used. The maximum time step used in UNSAT-H was 0.25 h and the minimum time step required for convergence was 1.0E-05 h. For Hydrus-1D, the maximum time step was set at 24 h and the minimum time step was 6.6 E-05 h. All simulations were conducted for one calendar year.

APPROACH TO WATER BALANCE SIMULATIONS

The objective of the water balance simulations was to compare and contrast the response of each model to a change from temporal analogues to synthetic analogues. Replicating the analysis conducted for the DOE 435.1 PA was not within the scope. The predictions are indicative of initial conditions set within each model and may not be representative of mechanistic aspects of the three models. The following is a presentation of results obtained.

HELP

Daily precipitation and temperature data from the Utah State University Climate Center (USUCC) database (weather station Monticello 2E) were input into the model for Scenario 1 and 2 simulations. Monthly average precipitation and temperature data obtained from the DDC was input into the model to produce synthetically generated daily precipitation and temperature data for Scenario 3. Solar radiation inputs for all scenarios were based on synthetic generations of the temperature data, as outlined in the HELP engineering documentation [15].

Results are presented in Table IV. As expected, evapotranspiration increases as water availability increases for both Scenarios 1 and 2. The rise in precipitation also increases the amount of runoff, thus reducing infiltration rates. Scenario 3 predicts more percolation than Scenarios 1 and 2 (approximately 4 mm).

Table IV: HELP Preliminary Analysis Results

	HELP		
	Scenario 1	Scenario 2	Scenario 3
Precipitation (mm)	402	550	521
Evapotranspiration (mm)	378	492	424
Runoff (mm)	10.4	51.5	55.2
Percolation (mm)	5.78	7.61	11.1
Δ Storage (mm)	13.7	5.49	31.1

UNSAT-H

Similar to HELP simulations, daily precipitation and temperature data from the USUCC database were input into the model for Scenario 1 and 2 simulations. Daily precipitation and temperature data generated by the HELP model for Scenario 3 were input into the UNSAT-H model, as well as synthetically generated solar radiation from the HELP simulations.

Results are presented in Table V. Evapotranspiration increases 19% between Scenarios 1 and 2 and 20% between Scenarios 1 and 3. These increases are consistent with the slight difference in precipitation between Scenarios 2 and 3. This is seen in runoff predictions, as well. Scenario 3 predicts less percolation than Scenario 1.

Table V: UNSAT-H Preliminary Analysis Results

	UNSAT-H		
	Scenario 1	Scenario 2	Scenario 3
Precipitation (mm)	402	550	521
Evapotranspiration (mm)	355	423	426
Runoff (mm)	26.7	78.3	72.6
Percolation (mm)	186	239	185
Δ Storage (mm)	-164	-183	-160

Hydrus-1D

Similar to the other model simulations, daily precipitation and temperature data from the USUCC database was input into the Hydrus-1D model for Scenario 1 and 2 simulations. Daily precipitation and temperature data generated by the HELP model for Scenario 3 were input into the Hydrus-1D model, as well as synthetically generated solar radiation from the HELP simulations.

Results are presented in Table VI. Evapotranspiration increases 39% between Scenarios 1 and 2 and 19% between Scenarios 1 and 3. The evaporation component of evapotranspiration for Scenario 3 was nearly 80 mm less than Scenario 2. This can be attributed to the drought conditions present in Scenario 3 which caused a decrease in the amount of moisture available for evaporation. Scenario 3 predicts twice as much percolation as Scenario 1.

Table VI: Hydrus-1D Preliminary Analysis Results

	Hydrus-1D		
	Scenario 1	Scenario 2	Scenario 3
Precipitation (mm)	402	550	521
Evapotranspiration (mm)	350	488	416
Runoff (mm)	0	0	0
Percolation (mm)	49.7	16.2	104
Δ Storage (mm)	0	44.61	0.01

CONCLUDING REMARKS

The objective of the water balance simulations was to compare and contrast the response of each model to a change from temporal analogues to synthetic analogues representative of climate change. Results of the analysis reported herein suggest the findings:

- HELP provided modest changes in its predictions when synthetic analogues were used instead of temporal. Percolation was highest for simulations using synthetic analogues.

- UNSAT-H showed changes in its response to synthetic analogues versus temporal analogues. Less percolation was predicted using synthetic analogues than the temporal analogues.

- Synthetic simulations with Hydrus-1D predicted more percolation than temporal simulations.

As we continue to explore this area of research, our goal is to provide further understanding of appropriate techniques for predicting disposal facility cover performance in response to future climate conditions. Future work will entail studying the behavior of episodic events seen in Scenario 3 over larger time spans (10+ years), in addition to the sensitivity of hydraulic and vegetative parameters to anticipated anthropogenic climate change in conjunction with episodic precipitation events.

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REFERENCES

1. Albright, W.H, Benson, C.H., Gee, G., Abichou, T., Tyler, S., Rock, S. "Field Performance of Three Compacted Clay Landfill Covers." Vadose Zone Journal, 5(6), 1157-1171 (2006).

2. Albright, W.H., Benson, C.H., Mushovic, P.S., and Waugh, W.J. "Monitoring the Performance of an Alternative Landfill Cover at the Monticello, Utah, Uranium Mill Tailings Disposal Site." Proceedings of the Waste Management Symposia 2008 Conference, Phoenix, AZ (2008).

3. Albright, W.H., Benson, C.H., and Waugh, W.J. "Water Balance Covers for Waste Containment: Principles and Practice." American Society of Civil Engineers Press, Reston, VA (2010).

4. Arnold B.W., Ho, C. K., Cochran J.R., Taira R.Y., and Webb S.W. "Development of a Risk-Based Performance-Assessment Method for Long-Term Cover Systems – Application to the Monticello Mill Tailings Repository," SAND2001-3032, Sandia National Laboratories (2001).

5. Benson, C. H., Thorstad, P. A., Jo, H. Y., and Rock, S. A. "Hydraulic performance of geosynthetic clay liners in a landfill final cover." *J. Geotech. Geoenviron. Eng.*, 133(7), 814–827 (2007).

6. Benson, C. H., Albright, W.H., Waugh, W. J. "Hydraulic Properties and Geomorphology of the Earthen Component of the Final Cover at the Monticello Uranium Mill Tailings Repository," Geo Engineering Report No. 08-04, (2008).

7. Bohnhoff, G.L., Ogorzalek, A.S., Benson, C.H., Shackelford, C.D., Apiwantragoon, P. "Field Data and Water-Balance Predictions for a Monolithic Cover in a Semiarid Climate." *J. Geotech. Geoenviron. Engineering,* 135(3), 333-348, (2009).

8. Carter, T.R., Alfsen, K., Barrow, E., Bass, B., Dai, X., Desanker, P., Gaffin, S.R., Giorgi, F., Hulme, M., Lal, M., Mata, L.J., Mearns, L.O., Mitchell, J.F.B., Morita, T., Moss, R., Murdiyarso, D., Pabon-Caicedo, J.D., Palutikof, J., Parry, M.L., Rosenzweig, C., Seguin, B., Scholes, R.J. and Whetton, P.H. "General Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment." Task Group on Data and Scenario Support for Impact and Climate Assessment, Helsinki, Finland (2007).

9. Chadwick, D., Ankeny, M., Greer, L., Mackey, C., and McClain, M. "Field test of potential RCRA-equivalent covers at the Rocky Mountain Arsenal." *Proc., SWANA 4th Annual Landfill Symp.*, SWANA Publication No. GR-LM-0004, Silver Spring, Md., 12–33 (1999).

10. Doorenbos, J., and Pruitt, W. "Guidelines for predicting crop agriculture requirements." *FAO Irrigation Paper No. 24*, 2nd Ed., Food and Agricultural Organization of the United Nations, Rome (1977).

11. Fayer, M.J., "UNSAT-H Version 3.0: Unsaturated Soil Water and Heat Flow Model." Pacific Northwest National Laboratory, Richland WA. PNNL-13249 (2000).

12. Feddes, R., and Zaradny, H. "Model for simulating soil water content considering evapotranspiration—Comments." *J. Hydrol.*, 37 (3–4), 393–397 (1978).

13. Meyer, P. D. and Gee, G. W. "Information on hydrologic conceptual models, parameters, uncertainty analysis, and data sources for dose assessments at decommissioning sites, NUREG/CR-6656," U.S. Nuclear Regulatory Commission, Washington, D.C. (1999).

14. Ogorzalek, A. S., Bohnhoff, G.L., Shackelford, C.D., Benson, C.H., Apiwantragoon, P. "Comparison of Field Data and Water-Balance Predictions for a Capillary Barrier Cover" Journal of Geotechnical and Geoenvironmental Engineering, ASCE (2008).

15. Schroeder, P.R., Dozier, T.S., Zappi, P.A., McEnroe, B.M., Sjostrom, J.W. and Peton, R.L. "The Hydrologic Evaluation of Landfill Performance (HELP) Model: Engineering Documentation for Version 3", EPA/600/R-94/168b, US. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Cincinnati, OH (1994).

16. Šimůnek, J., Šejna, M., Saito, H., Sakai, M. and van Genuchten, M. Th. "The Hydrus-1D Software Package for Simulating the Movement of Water, Heat, and Multiple Solutes in Variably Saturated Media, Version 4.08, HYDRUS Software Series 3." Department of Environmental Sciences, University of California Riverside, Riverside, CA (2009).

17. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. "Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change" Cambridge University Press, Cambridge, United Kingdom and New York, NY (2007).

18. U.S. Department of Energy. "Implementation Guide for use with DOE M 435.1-1, DOE G 435.1-1, Chapter IV Low-Level Waste Requirements," U.S. Department of Energy Office of Environmental Management, Washington, DC (1999).

19. U.S. Department of Energy. "Technical Approach Document, Revision II, UMTRA−DOE/AL 050425.0002, Uranium Mill Tailings Remedial Action Program," Albuquerque, NM (1989).

20. U.S. Environmental Protection Agency. "Technical Guidance Document, Final Covers on Hazardous Waste Landfills and Surface Impoundments," EPA/530–SW–89–047 (1989).

21. U.S. Nuclear Regulatory Commission. "A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities - Recommendations of NRC's Performance Assessment Working Group," NUREG-1573, U.S. Nuclear Regulatory Commission, Washington, DC (2000).