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SRNL
SAVANNAH RIVER NATIONAL LABORATORY
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SRNL-STI-2017-00728

Date: November 30, 2017

TO: B. T. Butcher, 773-42A

FROM: J. A. Dyer, 773-42A

REVIEWER: T. L. Danielson, 703-41A

Topic 3.5.1: Vadose Zone Models

Recommendation 150: Decide how to represent intact and subsided conditions for the proposed new conceptual closure cap design for the purpose of calculating infiltration. Produce new intact and subsided infiltration cases based on new conceptual design.

E-Area Low-Level Waste Facility Vadose Zone Model: Confirmation of Water Mass Balance for Subsidence Scenarios

Scope

In preparation for the next revision of the E-Area Low-Level Waste Facility (LLWF) Performance Assessment (PA), a mass balance model was developed in Microsoft Excel to confirm correct implementation of intact- and subsided-area infiltration profiles for the proposed closure cap in the PORFLOW vadose-zone model. The infiltration profiles are based on the results of Hydrologic Evaluation of Landfill Performance (HELP) model simulations for both intact and subsided cases.

Conclusions

The analysis confirmed closure of the infiltration water mass balance to within 0.1% for the 5 percent and 10 percent subsidence cases as currently implemented in the PORFLOW vadose-zone model. In addition, for scenarios where one of the one or more subsided areas is located at the bottom edge of the cap to catch any remaining runoff or drainage from upslope, modeling results revealed that the spatially averaged infiltration rate (or total mass/volume of infiltrating water as a function of time) is independent of percent subsidence for all subsidence scenarios up to and including 100%. Scenarios where a subsided area is located at the cap's bottom edge represent bounding cases at a fixed percent subsidence because they maximize the mass of water that will contact the waste below.

Note that independence with respect to percent subsidence applies to spatially averaged infiltration, not to waste disposal limits. Limits will depend on additional considerations, including percent subsidence and how the subsided areas are distributed across the cap surface. For example, lower percent subsidence and fewer subsided areas mean that less waste will be contacted by the infiltrating water. In addition, the infiltration rates contained in this report are preliminary and should not be used for final design and modeling purposes.

Discussion

A flow and radionuclide transport model of the vadose zone located beneath the proposed E-Area LLWF closure cap is being developed using PORFLOW. Figure 1 displays the approximately 25-acre central slit trench (SLIT or ST) region of the proposed E-Area closure cap. The initial vadose-zone trench model is based on Cross-section E. For the HELP infiltration model simulations, this region is represented as two simplified conceptual model cases (3% slope by 585-foot slope length and 2% slope by 150-foot slope length) as shown in Figure 2 (Dyer, 2017).

Conceptual Model of Cap Subsidence

A generalized conceptual model for cap subsidence is presented by Dyer (2017) as shown in Figure 3. The conceptual model is valid regardless of cap crest orientation with respect to the long axis of the disposal units (i.e., longitudinal or latitudinal). Importantly, the model assumes that 100% of the lateral drainage (i.e., infiltrating water shed through the closure cap drainage layer) and surface run-off from the intact portion of the cap directly upslope of the subsided region (light-blue-shaded areas in Figure 3) enters the subsided region (orange-shaded areas) as run-on. The total run-on (flux) to the subsided region in inches/year, therefore, is directly proportional to the ratio of the

Figure 1. Basis for Vadose-Zone Model (from SRP Drawing Nos. C-CT-E-00083 and C-CT-E-00084)

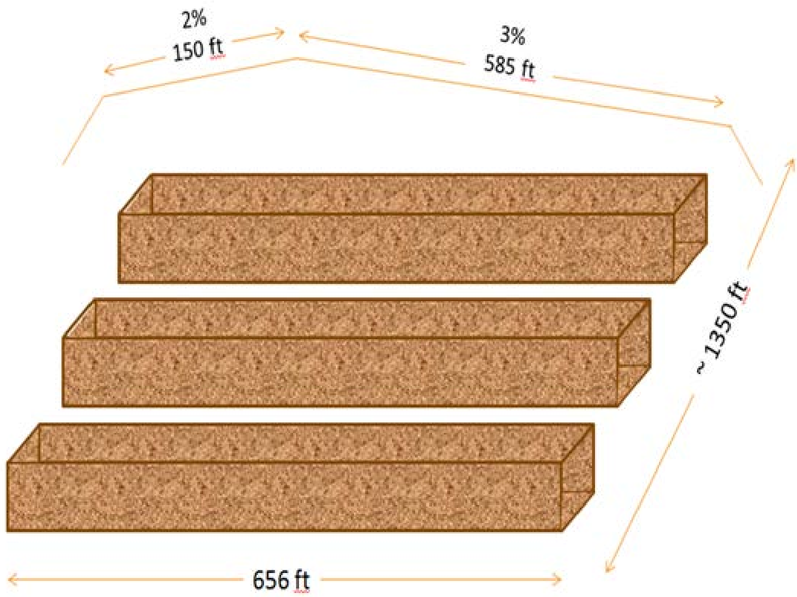

Figure 2. HELP Model Simulation Cases for Section E in Figure 1

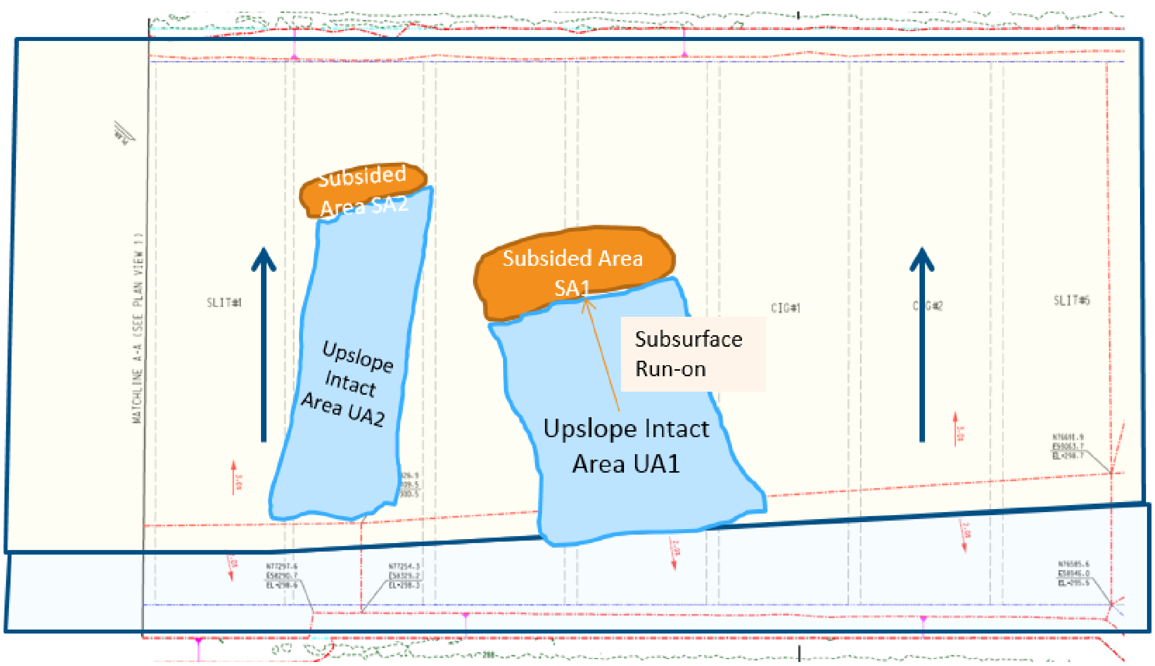

Figure 3. Conceptual Approach to Cap Subsidence

upslope intact area (UA1 or UA2) to the downslope subsided area (SA1 or SA2) as given by:

$$\text{Run-on} = (\text{Area}_{UAi}/\text{Area}_{SAi})(\text{Lateral Drainage} + \text{Surface Run-off})_{\text{HELP Intact Case}} \quad (1)$$

Figure 4 displays one implementation of this conceptual model in the PORFLOW vadose-zone trench model where multiple subsided regions are evenly spaced on either side of the cap crestline and one subsided area is located at the bottom edge of the cap on each side.

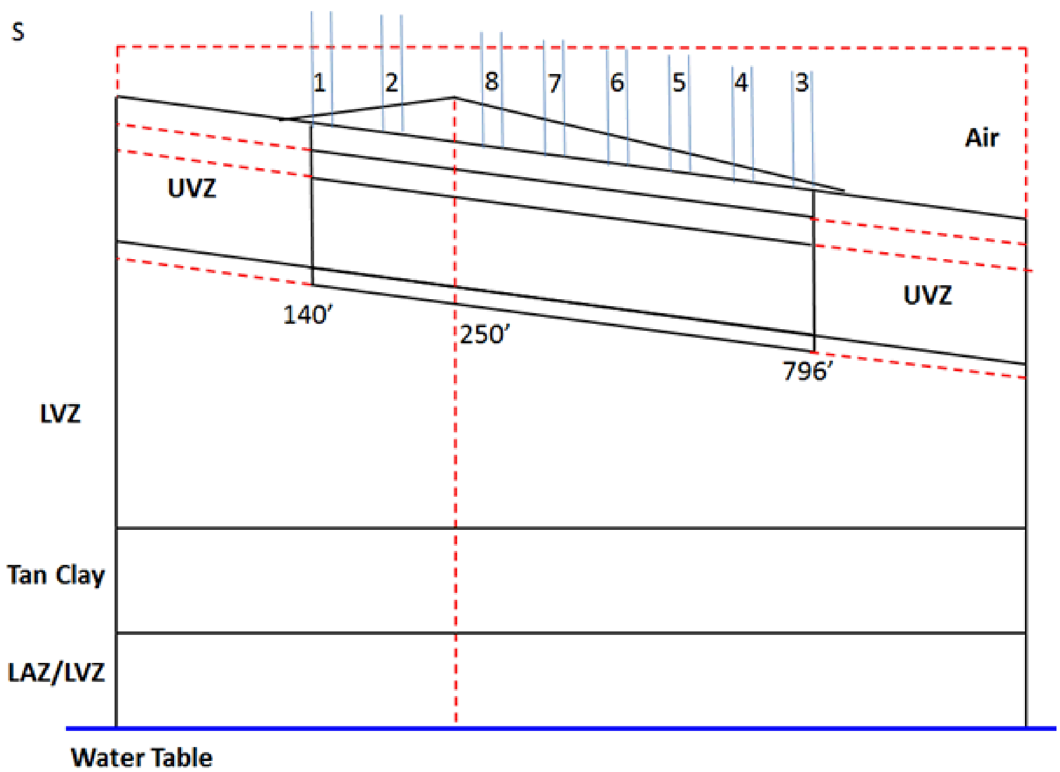

Figure 4. Implementation of Evenly Spaced Subsided Areas in PORFLOW Vadose-Zone Model

Water Mass Balance

For the conceptual subsidence model adopted here where a subsided area is located at the bottom edge on each side, the total mass of water infiltrating the surface of the closure cap (i.e., the sum of intact plus subsided area infiltration) is essentially equal regardless of the assumed number and percentage of subsided areas. This approximate equality holds because the area-averaged infiltration rate of water at the cap surface (i.e., mass rainfall minus mass evapotranspiration) for subsided cases ($M_{\text{TOT X\% SUBSIDENCE}}$) is approximately equal to the quantity "rainfall minus evapotranspiration" for the 100% intact case ($M_{\text{TOT INTACT}}$) where the drainage and barrier layers have been removed from the HELP model.

$$M_{TOT\ INTACT} = M_{TOT\ 3\%\ SUBSIDENCE} = M_{TOT\ 5\%\ SUBSIDENCE} = M_{TOT\ 10\%\ SUBSIDENCE} \quad (2)$$

$$M_{TOT\ INTACT} = \text{Mass Rainfall}_{intact} - \text{Mass Evapotranspiration}_{intact} \quad (3)$$

$$M_{TOT\ X\%\ SUBSIDENCE} = \sum_i^{n_{intact}} I_{i\ intact} A_{i\ intact} + \sum_j^{n_{subsided}} I_{j\ subsided} A_{j\ subsided} \quad (4)$$

where I_i and I_j are the infiltration rates and A_i and A_j are the areas for each intact and subsided segment, respectively. A demonstration of this equality concept is provided below in the sections *Mass Balance Model* and *Relationship to the Intact Case*.

When considering radionuclide transport and waste disposal limits, however, percent subsidence as well as the number and distribution of subsided areas will matter. For example, lower percent subsidence and fewer subsided areas mean that less waste will be contacted by the infiltrating water. The water mass balance provides a convenient reality check for any proposed subsidence scenario implemented in PORFLOW, and is demonstrated in more detail below.

Mass Balance Model

A water mass-balance model based on Figure 4 was developed in Microsoft Excel. The bases for the model were:

- 5% and 10% subsidence cases.
- Upslope intact area to downslope subsided area ratio is 18.6:1 and 8.9:1 at 5% and 10% subsidence, respectively
- Width of cap slice is 1 foot (ft.).
- Percent slope and slope lengths are as shown in Figures 2 and 4.
- Cap extends beyond (overhangs) waste disposal unit footprint by 40 ft. on each end.
- Locations of subsided regions are as shown in Figure 4.
- Infiltration rate (I) is a normalized volumetric flux expressed in units of inches (in.) per year (yr.) [volume (V_i) per yr. per unit area].
- Surficial area of Section i of cap surface is slope length L_i x slope width 1 ft. = L_i square feet (ft^2).
- Mass of water infiltrating Section i is (I_i)(L_i)(1 ft./12 in.)(62.43 pounds/cubic feet) = m_i pounds (lbs.).
- Total mass of water infiltrating through the cap is the $\Sigma\ m_i$.

For illustration purposes, infiltration rates were generated by HELP v4.0 (Dixon, 2017) using the same design (number, type, and material properties of layers) as the F-Area Tank Farm (FTF) closure cap (Phifer et al., 2007 and Phifer et al., 2009). The infiltration rates are preliminary and should not be used for final design and vadose zone modeling purposes.

The water mass balances at three points on the infiltration-rate-versus-time curve were analyzed: 0 hours, 1,000 hours, and 10,000 hours following installation of the closure cap system. Subsidence is conservatively assumed to occur immediately at time zero.

Figures 5, 6, and 7 compare the mass balance results for 5% and 10% subsidence at 0, 1,000, and 10,000 years following cap installation, respectively. At each time step, the difference in the total volume of infiltration water between the 5% and 10% subsidence scenarios is less than 0.1% as shown in Table 1.

Figure 8 displays the results of the water balance for all time steps in the infiltration rate curve (0 to 10,000 years) assuming 10% subsidence. The last two columns in the table shown in Figure 8 compare the area-averaged infiltration rate calculated across the entire cap surface area (including the 40-foot overhangs) and across the total footprint of the waste zone only. The area-averaged infiltration rates are independent of percent subsidence for all subsidence scenarios up to and including 100% because one of the subsided areas is located at the bottom edge of the cap.

5% Subsidence
Time = 0 yr after cap installation

	Section #	Intact/ Subsided	I_i (in/yr)	L_i (ft)	V_i (ft^3)	m_i (lb)
	1	I	0.00008	40	0.000267	0.016648
	2	S	323.72238	2.806	75.69708	4725.769
2%, 150 ft	3	I	0.00008	52.194	0.000348	0.021723
	4	S	323.72238	2.806	75.69708	4725.769
	5	I	0.00008	52.194	0.000348	0.021723
	6	I	0.00037	87.2	0.002689	0.167853
	7	S	323.64999	4.634	124.9828	7802.679
	8	I	0.00037	86.2	0.002658	0.165929
	9	S	323.64999	4.634	124.9828	7802.679
	10	I	0.00037	86.2	0.002658	0.165929
	11	S	323.64999	4.634	124.9828	7802.679
3% 585 ft	12	I	0.00037	86.2	0.002658	0.165929
	13	S	323.64999	4.634	124.9828	7802.679
	14	I	0.00037	86.2	0.002658	0.165929
	15	S	323.64999	4.634	124.9828	7802.679
	16	I	0.00037	86.2	0.002658	0.165929
	17	S	323.64999	4.634	124.9828	7802.679
	18	I	0.00037	40	0.001233	0.076997
	Sum			736.0	901.3094	56268.74

Average Infiltration Rate Over Total Cap Surface **14.70** in/yr
Σ Vi / (Σ L_i * 1.0 ft) * 12.0 in/ft

10% Subsidence
Time = 0 yr after cap installation

	Section #	Intact/ Subsided	I_i (in/yr)	L_i (ft)	V_i (ft^3)	m_i (lb)
	1	I	0.000080	40	0.000267	0.016648
	2	S	163.37029	5.55555	75.63432	4721.85
2%, 150 ft	3	I	0.000080	49.44445	0.00033	0.020579
	4	S	163.37029	5.55555	75.63432	4721.85
	5	I	0.000080	49.44445	0.00033	0.020579
	6	I	0.00037	82.658249	0.002549	0.159111
	7	S	163.33606	9.1750842	124.8852	7796.581
	8	I	0.00037	81.658249	0.002518	0.157186
	9	S	163.33606	9.1750842	124.8852	7796.581
	10	I	0.00037	81.658249	0.002518	0.157186
	11	S	163.33606	9.1750842	124.8852	7796.581
3% 585 ft	12	I	0.00037	81.658249	0.002518	0.157186
	13	S	163.33606	9.1750842	124.8852	7796.581
	14	I	0.00037	81.658249	0.002518	0.157186
	15	S	163.33606	9.1750842	124.8852	7796.581
	16	I	0.00037	81.658249	0.002518	0.157186
	17	S	163.33606	9.1750842	124.8852	7796.581
	18	I	0.00037	40	0.001233	0.076997
	Sum			736.0	900.597	56224.27

Average Infiltration Rate Over Total Cap Surface **14.68** in/yr
Σ Vi / (Σ L_i * 1.0 ft) * 12.0 in/ft

Figure 5. Results of Water Mass Balance 5% and 10% Subsidence at 0 Years

5% Subsidence
Time = 1,000 yr after cap installation

	Section #	Intact/ Subsided	I_i (in/yr)	L_i (ft)	V_i (ft^3)	m_i (lb)
	1	I	2.47387	40	8.246233	514.8123
	2	S	278.20209	2.806	65.05292	4061.254
2%, 150 ft	3	I	2.47387	52.194	10.7601	671.7529
	4	S	278.20209	2.806	65.05292	4061.254
	5	I	2.47387	52.194	10.7601	671.7529
	6	I	5.56575	87.2	40.44445	2524.947
	7	S	219.39183	4.634	84.72181	5289.183
	8	I	5.56575	86.2	39.98064	2495.991
	9	S	219.39183	4.634	84.72181	5289.183
	10	I	5.56575	86.2	39.98064	2495.991
	11	S	219.39183	4.634	84.72181	5289.183
3% 585 ft	12	I	5.56575	86.2	39.98064	2495.991
	13	S	219.39183	4.634	84.72181	5289.183
	14	I	5.56575	86.2	39.98064	2495.991
	15	S	219.39183	4.634	84.72181	5289.183
	16	I	5.56575	86.2	39.98064	2495.991
	17	S	219.39183	4.634	84.72181	5289.183
	18	I	5.56575	40	18.5525	1158.233
	Sum			736.0	927.1033	57879.06

Average Infiltration Rate Over Total Cap Surface **15.12** in/yr
Σ Vi / (Σ L_i * 1.0 ft) * 12.0 in/ft

10% Subsidence
Time = 1,000 yr after cap installation

	Section #	Intact/ Subsided	I_i (in/yr)	L_i (ft)	V_i (ft^3)	m_i (lb)
	1	I	2.47387	40	8.246233	514.8123
	2	S	141.58746	5.55555	65.54968	4092.267
2%, 150 ft	3	I	2.47387	49.44445	10.19326	636.3653
	4	S	141.58746	5.55555	65.54968	4092.267
	5	I	2.47387	49.44445	10.19326	636.3653
	6	I	5.56575	82.658249	38.33793	2393.437
	7	S	113.44933	9.1750842	86.74226	5415.319
	8	I	5.56575	81.658249	37.87412	2364.481
	9	S	113.44933	9.1750842	86.74226	5415.319
	10	I	5.56575	81.658249	37.87412	2364.481
	11	S	113.44933	9.1750842	86.74226	5415.319
3% 585 ft	12	I	5.56575	81.658249	37.87412	2364.481
	13	S	113.44933	9.1750842	86.74226	5415.319
	14	I	5.56575	81.658249	37.87412	2364.481
	15	S	113.44933	9.1750842	86.74226	5415.319
	16	I	5.56575	81.658249	37.87412	2364.481
	17	S	113.44933	9.1750842	86.74226	5415.319
	18	I	5.56575	40	18.5525	1158.233
	Sum			736.0	926.4467	57838.07

Average Infiltration Rate Over Total Cap Surface **15.11** in/yr
Σ Vi / (Σ L_i * 1.0 ft) * 12.0 in/ft

Figure 6. Results of Water Mass Balance 5% and 10% Subsidence at 1,000 Years

5% Subsidence
Time = 10,000 yr after cap installation

	Section #	Intact/ Subsided	I_i (in/yr)	L_i (ft)	V_i (ft^3)	m_i (lb)
	1	I	10.46534	40	34.88447	2177.837
	2	S	130.48732	2.806	30.51228	1904.882
2%, 150 ft	3	I	10.46534	52.194	45.519	2841.751
	4	S	130.48732	2.806	30.51228	1904.882
	5	I	10.46534	52.194	45.519	2841.751
	6	I	11.47058	87.2	83.35288	5203.72
	7	S	103.84832	4.634	40.10276	2503.615
	8	I	11.47058	86.2	82.397	5144.045
	9	S	103.84832	4.634	40.10276	2503.615
	10	I	11.47058	86.2	82.397	5144.045
	11	S	103.84832	4.634	40.10276	2503.615
3% 585 ft	12	I	11.47058	86.2	82.397	5144.045
	13	S	103.84832	4.634	40.10276	2503.615
	14	I	11.47058	86.2	82.397	5144.045
	15	S	103.84832	4.634	40.10276	2503.615
	16	I	11.47058	86.2	82.397	5144.045
	17	S	103.84832	4.634	40.10276	2503.615
	18	I	11.47058	40	38.23527	2387.028
	Sum			736.0	961.1367	60003.77

Average Infiltration Rate Over Total Cap Surface **15.67** in/yr
Σ Vi / (Σ L_i * 1.0 ft) * 12.0 in/ft

10% Subsidence
Time = 10,000 yr after cap installation

	Section #	Intact/ Subsided	I_i (in/yr)	L_i (ft)	V_i (ft^3)	m_i (lb)
	1	I	10.46534	40	34.88447	2177.837
	2	S	70.91422	5.55555	32.83062	2049.616
2%, 150 ft	3	I	10.46534	49.44445	43.12108	2692.049
	4	S	70.91422	5.55555	32.83062	2049.616
	5	I	10.46534	49.44445	43.12108	2692.049
	6	I	11.47058	82.658249	79.0115	4932.688
	7	S	58.16453	9.1750842	44.47204	2776.389
	8	I	11.47058	81.658249	78.05562	4873.013
	9	S	58.16453	9.1750842	44.47204	2776.389
	10	I	11.47058	81.658249	78.05562	4873.013
	11	S	58.16453	9.1750842	44.47204	2776.389
3% 585 ft	12	I	11.47058	81.658249	78.05562	4873.013
	13	S	58.16453	9.1750842	44.47204	2776.389
	14	I	11.47058	81.658249	78.05562	4873.013
	15	S	58.16453	9.1750842	44.47204	2776.389
	16	I	11.47058	81.658249	78.05562	4873.013
	17	S	58.16453	9.1750842	44.47204	2776.389
	18	I	11.47058	40	38.23527	2387.028
	Sum			736.0	961.145	60004.28

Average Infiltration Rate Over Total Cap Surface **15.67** in/yr
Σ Vi / (Σ L_i * 1.0 ft) * 12.0 in/ft

Figure 7. Results of Water Mass Balance 5% and 10% Subsidence at 10,000 Years

Table 1. Comparison of Water Balance for 5% and 10% Subsidence Scenarios

Time after Cap Installation (Years)	5% Subsidence Total Volume Infiltration Water (ft^3)	10% Subsidence Total Volume Infiltration Water (ft^3)	Difference
0	900.5970	901.3094	0.079%
1,000	926.4467	927.1033	0.071%
10,000	961.1450	961.1367	-0.001%

Area-Averaged Infiltration Rates as a Function of Time for Subsided Cases

Average infiltration rates are independent of percent subsidence

Assumes 40 ft intact overhang on both ends of cap

736 total length of cap including overhang

	Left Side of Cap				Right Side of Cap						
Time after Installation of Cap (yr)	Intact Infiltration Rate Left Side(in/yr)	10% Subsided Infiltration Rate Left Side (in/yr)	Length Intact Segment Left Side (ft)	Length Subsided Segment Left Side (ft)	Intact Infiltration Rate Right Side (in/yr)	10% Subsided Infiltration Rate Right Side (in/yr)	Length Intact Segment Right Side(ft)	Length Subsided Segment Right Side (ft)	Length Overhang (ft)	Average Infiltration Rate Over Total Cap Surface (in/yr)	Average Infiltration Rate Over Total Waste Zone (in/yr)
0	0.00008	163.37	49.444	5.556	0.00037	163.34	81.658	9.175	40	**14.68**	**16.47**
100	0.00047	163.36	49.444	5.556	0.0038	163.29	81.658	9.175	40	**14.68**	**16.47**
180	0.0068	163.38	49.444	5.556	0.065	162.82	81.658	9.175	40	**14.69**	**16.48**
290	0.014	163.42	49.444	5.556	0.15	162.09	81.658	9.175	40	**14.70**	**16.49**
300	0.070	162.90	49.444	5.556	0.27	161.05	81.658	9.175	40	**14.71**	**16.49**
340	0.14	162.24	49.444	5.556	0.55	158.51	81.658	9.175	40	**14.73**	**16.48**
380	0.22	161.59	49.444	5.556	0.83	156.11	81.658	9.175	40	**14.75**	**16.49**
560	0.64	157.81	49.444	5.556	2.08	144.83	81.658	9.175	40	**14.84**	**16.48**
1000	2.47	141.59	49.444	5.556	5.57	113.45	81.658	9.175	40	**15.11**	**16.46**
1800	7.32	98.40	49.444	5.556	10.03	71.54	81.658	9.175	40	**15.46**	**16.28**
2623	9.88	75.39	49.444	5.556	11.24	59.09	81.658	9.175	40	**15.53**	**16.14**
3200	10.04	74.02	49.444	5.556	11.31	58.63	81.658	9.175	40	**15.56**	**16.15**
5600	10.33	71.69	49.444	5.556	11.42	58.09	81.658	9.175	40	**15.62**	**16.19**
10000	10.47	70.91	49.444	5.556	11.47	58.16	81.658	9.175	40	**15.67**	**16.24**

Figure 8. Area-Averaged Infiltration Rates as a Function of Time for Subsidence Scenarios

Relationship to the Intact Case

The area-averaged infiltration rates across the waste zone footprint (last column in Figure 8) should be close in value to predicted infiltration rates for an intact scenario where the drainage and barrier layers have been removed from the HELP model. For this alternate intact cap configuration, the water mass balance reduces to:

$$\text{Rainfall} = \text{Evapotranspiration} + \text{Infiltration} \quad (5)$$

Surface runoff is predicted to be negligible because the barrier layers impeding downward flow of percolating water have been removed from the HELP model. For this alternate intact-cap configuration, HELP v4.0 calculates an area-averaged infiltration rate equal to approximately 16.5 inches per year. This is a second confirmation that the intact- and subsided-area infiltration profiles for the proposed closure cap have been correctly implemented in the PORFLOW vadose-zone model.

Summary

The analysis confirmed closure of the infiltration water mass balance to within 0.1% for the 5 percent and 10 percent subsidence cases as currently implemented in the PORFLOW vadose-zone model. In addition, for scenarios where one of the one or more subsided areas is located at the bottom edge of the cap to catch any remaining runoff or drainage from upslope, modeling results revealed that the spatially averaged infiltration rate (or total mass/volume of infiltrating water as a function of time) is independent of percent subsidence for all subsidence scenarios up to and including 100%. Scenarios where a subsided area is located at the cap's bottom edge represent bounding cases at a fixed percent subsidence because they maximize the mass of water that will contact the waste below.

Note that independence with respect to percent subsidence applies to spatially averaged infiltration, not to waste disposal limits. Limits will depend on additional considerations, including percent subsidence and how the subsided areas are distributed across the cap surface. For example, lower percent subsidence and fewer subsided areas mean that less waste will be contacted by the infiltrating water. In addition, the infiltration rates contained in this report are preliminary and should not be used for final design and modeling purposes.

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