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Saturated Zone Modeling for the Clive DU PA

5 June 2014~~28 May 2014~~

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6. Remarks		

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TABLES

1.0 Summary of Parameters and Distributions

This section is a brief summary of parameters and distributions used for modeling saturated zone processes for the Clive Depleted Uranium (DU) Performance Assessment (PA) Model. For distributions, the following notation is used:

- N(μ, σ, [*min*, *max*]) represents a normal distribution with mean μ and standard deviation σ, and optional truncation at the specified *min*imum and *max*imum,
- LN(*GM*, *GSD*, [*min*, *max*]) represents a log-normal distribution with geometric mean GM and geometric standard deviation GSD, and optional *min* and *max*,
- U(*min*, *max*) represents a uniform distribution with lower bound *min* and upper bound *max*,
- Beta(μ, σ, *min*, *max*) represents a generalized beta distribution with mean μ, standard deviation σ, minimum *min*, and maximum *max*,
- Gamma(μ, σ) represents a gamma distribution with mean μ and standard deviation σ, and
- TRI(*min*, *m*, *max*) represents a triangular distribution with lower bound *min*, mode *m*, and upper bound *max*.

Note that a number of these distributions are truncated at a minimum value of 0 and a maximum of Large, an arbitrarily large value defined in the GoldSim model. The truncation at the low end is a matter of physical limits (e.g. precipitation cannot be negative), and in GoldSim's distribution definitions, if truncations are made, they must be made at both ends, so the very large value is chosen for the upper end.

Table 1: Summary of saturated zone parameter distributions

Parameter	Distribution	Units	Comment
Saturated Hydraulic Conductivity	N(9.6e-4, 9.67e-5, min=Small, max=Large)	cm/s	See Section ~~3.1~~
Bulk Density	N(1.57, 0.05, min=Small, max=Large) [standard deviation is a placeholder]	g/cm^3	See Section ~~3.2~~
Porosity	N(0.29, 0.05, min=Small, max=1-Small) [standard deviation is a placeholder]	—	See Section ~~3.2~~
Hydraulic Gradient	N (6.94 x 10^{-4}, 1.27 x 10 $^{-4}$, min=0 , max=Large)	—	See Section ~~3.3~~
Aquifer Thickness	N (16.2, 0.25, min=0, max=Large)	ft	See Section ~~4.1~~

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2.0 Clive Site Hydrogeology

The site hydrogeology for the Energy*Solutions*' Clive facility has been described by Bingham Environmental (1991, 1994) and Envirocare (2000, 2004). The most recently revised

hydrogeologic report prepared by Envirocare (2004) noted that the interpretations of structure and stratigraphy presented in their report were consistent with previous presentations described in Bingham Environmental (1991, 1994) and Envirocare (2000).

The following description of the Clive site hydrology is taken from the review prepared by Envirocare (2004). The site is described as being located on lacustrine (lake bed) deposits associated with the former Lake Bonneville. The sediments underlying the facility are principally interbedded silt, sand, and clay. While the depth of the sediments below the site is not known, the sediments extend to a depth of at least ~~250~~ 620 feet (ft) (DWR 2014, water right number 16-816 and associated well log 11293). This minimum depth is based on a borehole log for ~~the deepest well on the site~~a nearby well ~~which~~ that did not encounter bedrock at its total depth of ~~250~~ 620 ft.

Sediments at the site are described by Bingham Environmental (1991, 1994) and Envirocare (2000, 2004) as being classified into four hydrostratigraphic units (HSU). Predominant sediment textural class, layer thickness range, and average layer thickness for each unit are listed in Table 2~~Table 2~~.

Unit 4: This unit begins at the ground surface and extends to between 6 ft and 16.5 ft below the ground surface (bgs). The average thickness of this unit is 10 ft. This unit is composed of finer grained low permeability silty clay and clay silt.

Unit 3: Unit 3 underlies Unit 4 and ranges from 7 ft to 25 ft in thickness. The average thickness of this unit is 15 ft. Unit 3 is described as consisting of silty sand with occasional lenses of silty to sandy clay.

Unit 2: Unit 2 underlies Unit 3 and ranges from 2.5 ft to 25 ft in thickness. The average thickness of this unit is 15 ft. Unit 2 is described as being composed of clay with occasional silty sand interbeds. A structure map was prepared by Envirocare (2004, Figure 5) with contours representing the elevations of the top of the unit. This map shows that the top surface of Unit 2 slopes downward gradually from east to west in the vicinity of the ~~Class A South cell~~portion of the Federal cell housing DU (Federal DU Cell).

Unit 1: Unit 1 is the bottom layer of this sequence. This unit is described as silty sand interbedded with clay and silt layers. The thickness of this layer ~~has not been estimated~~in the vicinity of the Clive facility is known to be in excess of 620 ft. (DWR 2014, water right number 16-816 and associated well log 11293).

Table 2: Texture class, thickness range, and average thickness for the hydrostratigraphic units underlying the Clive site.

Unit	Sediment Texture Class	Thickness Range (ft)	Average Thickness (ft)
4	silt and clay	6 – 16.5	10

Unit	Sediment Texture Class	Thickness Range (ft)	Average Thickness (ft)
3	silty sand with interbedded silt and clay layers	7 - 25	15
2	clay with occasional silty sand interbeds	2.5 - 25	15
1	silty sand with interbedded clay and silt layers	~~2 -2~~> 620	~~2~~> 620

The aquifer system in the vicinity of the Clive Facility is described by Bingham Environmental (1991, 1994) and Envirocare (2000, 2004) as consisting of unconsolidated basin-fill and alluvial-fan aquifers. Characterization of the aquifer system is based on subsurface stratigraphy observations from borehole logs and from potentiometric measurements.

The aquifer system is described as being composed of two aquifers; a shallow, unconfined aquifer and a deep confined aquifer. The shallow unconfined aquifer extends from the water table to a depth of approximately 40 ft to 45 ft bgs. The deep confined aquifer is encountered at approximately 45 ft bgs and extends through the valley fill (Bingham 1994). The water table in the shallow aquifer is reported to be located in Unit 3 on the west side of the site and in Unit 2 on the east side.

Deeper saturated zones in Unit 1 below approximately 45 ft bgs are reported to show higher potentiometric levels than the shallow unconfined aquifer. Differences in potentiometric levels are attributed to the presence of the Unit 2 clays. These observations are interpreted as indicating that the shallow unconfined aquifer below the site does not extend into Unit 1 but is contained within Units 2 and 3. Unit 1 extends from approximately 45 ft bgs and contains the deep aquifer.

3.0 Groundwater Flow Parameter Distributions

The parameters used to calculate the groundwater flux are the saturated hydraulic conductivity and the hydraulic gradient. The porosity is needed to calculate the mean groundwater velocity from the flux.

3.1 Saturated Hydraulic Conductivity

To develop a distribution for saturated hydraulic conductivity (K_s), 253 measurements were obtained for 122 locations in the vicinity of the cells and ponds. These measurements were provided to N&C by Energy*Solutions* in an Excel spreadsheet named "Hydraulic Cond.xls" prepared by R. Sobocinski.

There are multiple measurements per location. Thus, in order to not over-represent those locations, a random effects analysis of variance model was fitted, treating location as a random effect, to produce estimates of the mean K_s and its associated standard error.

The average K_s across locations ranges from 2.23×10^{-6} cm/s to 5.95×10^{-3} cm/s. There is some right-skew to the average K_s values, which results in a slight overestimate of the standard error in the random-effects model. However, with 122 locations, the distribution of the mean will be

well-approximated with a normal distribution. The random effects model produces a mean K_s of 9.6×10^{-4} cm/s and standard error of 9.67×10^{-5} cm/s.

3.2 Bulk Density and Porosity

Although no data have been provided, Whetstone (2000) provides some values for material properties of the shallow aquifer. In Section 7.1.2 of that report, a deterministic value for bulk density of 1.566 g/cm^3 is ~~is~~ listed as an input for the Whetstone (2000) model. That value was adopted as a mean of a normal distribution, and was assigned a placeholder standard deviation of 0.05 g/cm^3.

Similarly, section 7.1.3 of Whetstone (2000) offers a porosity for the shallow aquifer of 0.29. That value was used as the mean of a normal distribution, and a placeholder standard deviation of 0.05 was assigned.

3.3 Hydraulic Gradient

The statistical distribution for hydraulic gradient developed for the Clive DU PA model is specific to horizontal gradients in the shallow aquifer. Vertical gradients were not considered in the model.

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Monthly averages of the site-wide hydraulic gradient from 1999 through 2010 were calculated by Energy*Solutions* from water level measurements. These data were used to establish a distribution for the mean site-wide gradient. The influence of any off-normal conditions occurring during the time period of the water level measurement data would be included in this data. The uncertainty related to the mean is typically well-modeled by a normal distribution, due to the effect of averaging. A difficulty with the gradient data is in establishing an appropriate standard error for the mean, since there is considerable time correlation in the data. That is, the values change less from month to month than they do over longer time periods. To account for this behavior several auto-regressive, moving-average (ARMA) models (Brockwell and Davis 1996) were fit to determine a model that adequately captured the time with an adequate fit for the time correlation. Amongst these models, a best model was chosen based on the Akaike information criterion (AIC), and a standard error for the mean was established based on this model's fit.

A performance assessment is based on estimates of the expected performance of the site. To achieve a realistic estimate of expected performance, spatio-temporal scaling (upscaling) is needed for defining parameter distributions in probabilistic models. These upscaled distributions represent a large area/volume and time frame instead of only points in time and space. Spatio-temporal scaling is critical for model definition and understanding the impact on uncertainty for estimating 95th percentiles (for example) of model output distributions. Without proper scaling, models outputs are compromised.

The influence of off-normal conditions on shallow groundwater flow is discussed in Envirocare (2004) for two cases. In the first, flow was affected by localized recharge from a surface water retention pond in the southwest corner of the facility in the spring of 1999 and in the second, a ground water mound formed between March 1993 and spring 1997 below a borrow pit excavated

near the 11e.(2) cells that occasionally filled with rain water. The mound decreased and was negligible by the time of the report in 2004. The latter of these conditions was captured by the hydraulic gradient data set used to develop the distribution for the model. The influence of these conditions on the hydraulic gradient appear to be transient and of small magnitude. The development of the distribution for hydraulic gradient did not consider climate change.

The hydraulic gradient (i) is modeled as normal distribution with a mean of 6.9×10^{-4} and a standard deviation of 1.27×10^{-4}. The influence of the range of the gradient given by the distribution can be evaluated by calculating a range of groundwater velocity derived from the gradient using Darcy's law. The saturated hydraulic conductivity (K_s) is modeled as a normal distribution with a mean of 9.6×10^{-4} cm/s and a standard error of 9.67×10^{-5} cm/s. Porosity (φ) is modeled as a normal distribution with a mean of 0.29 and a standard deviation of 0.05. From Darcy's law the groundwater flux (J) is:

$$J = K_s \, i \qquad (1)$$

and the groundwater velocity (v) is:

$$v = J/\varphi \qquad (2)$$

where φ is the porosity.

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The range of groundwater velocity is estimated by choosing values from each distribution corresponding to the mean ± 3 times the standard error and calculating values of *v* from the equations above. Maximum and minimum values for groundwater velocity derived from the hydraulic gradient distribution range from 4.2 times the mean to 1/5th of the mean.

The significance of uncertainty in the value of the hydraulic gradient was evaluated for the Clive DU PA model through a sensitivity analysis. The sensitivity analysis identifies which variables have distributions that exert the greatest influence on the response. The response evaluated in the sensitivity analysis for the PA model was dose. The results showed that hydraulic gradient was quantitatively determined to not be a sensitive parameter.

~~The uncertainty distribution for site-wide gradient was thus established as a normal distribution with a mean of 6.94×10^{-4} and a standard deviation of 1.27×10^{-4}.~~

4.0 Groundwater Transport Parameter Distributions

Calculations in the PA Model that are needed for estimating transport in the shallow saturated zone include the cross-sectional area normal to the flow direction (thickness times width), definitions of the material SatZone_Medium (hydraulic conductivity, porosity, and bulk density of Unit 2), the Darcy velocity (a function of gradient and hydraulic conductivity) and radioelement-specific solid/water partition coefficients (K_ds). The distributions for bulk density and porosity have been described previously in Section 3.2 and the hydraulic gradient in Section 3.3. Aquifer dimensions are described in Section 4.1. Since the flow through the saturated zone is modeled as a horizontal column of discrete GoldSim Cell pathway elements, dispersivity is not explicitly defined as it would be for an analytical solution such as a plume. This is discussed in Section 4.2. The distributions for K_ds are described in the *Geochemical Modeling* white paper.

~~Parameters in the PA model that are needed for estimating transport in the shallow aquifer include the aquifer thickness, porosity, ionic and molecular diffusion coefficients, and the dispersion coefficient. The distribution for porosity has been described previously in Section 3.2. Aquifer thickness and dispersion coefficient parameters are described in following sections. The distribution for ionic and molecular diffusion coefficients is described in the *Geochemical Modeling* white paper.~~

4.1 ~~Aquifer Thickness~~ Saturated Zone Dimensions

The location and extent of the saturated zone modeling domain including the location of the DU waste, the point of compliance monitoring well, the buffer zone of the DU cell, and outer boundaries of property owned and controlled by Energy*Solutions* are shown in Figure 1.

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Both the unsaturated (vadose) and saturated zones are represented in the Clive DU PA Model as GoldSim Cell pathway elements. A Cell pathway is mathematically equivalent to a continuously-stirred tank reactor (CSTR), in which the contents are instantaneously and uniformly mixed throughout the volume. The representation of the saturated zone in the PA Model consists of a series of linked cells. The mass and rate of water flowing through the column of cells depends on the Darcy velocity and the cross-sectional area perpendicular to the flow direction. This area is simply the (stochastic) thickness of the aquifer times its width, which is dependent on the geometry of the embankment. The transport of contaminants in water through the vadose zone and into the saturated zone is modeled as advective mass flux links from the unsaturated zone vertical column into the various cells underlying the embankment. This contaminated recharge is distributed along the saturated zone flow pathway, with a fraction entering each saturated zone cell. The cell pathways and their interconnections are represented schematically in Figure 2. Note that there are no wastes located under the sideslopes in the Clive DU PA model.

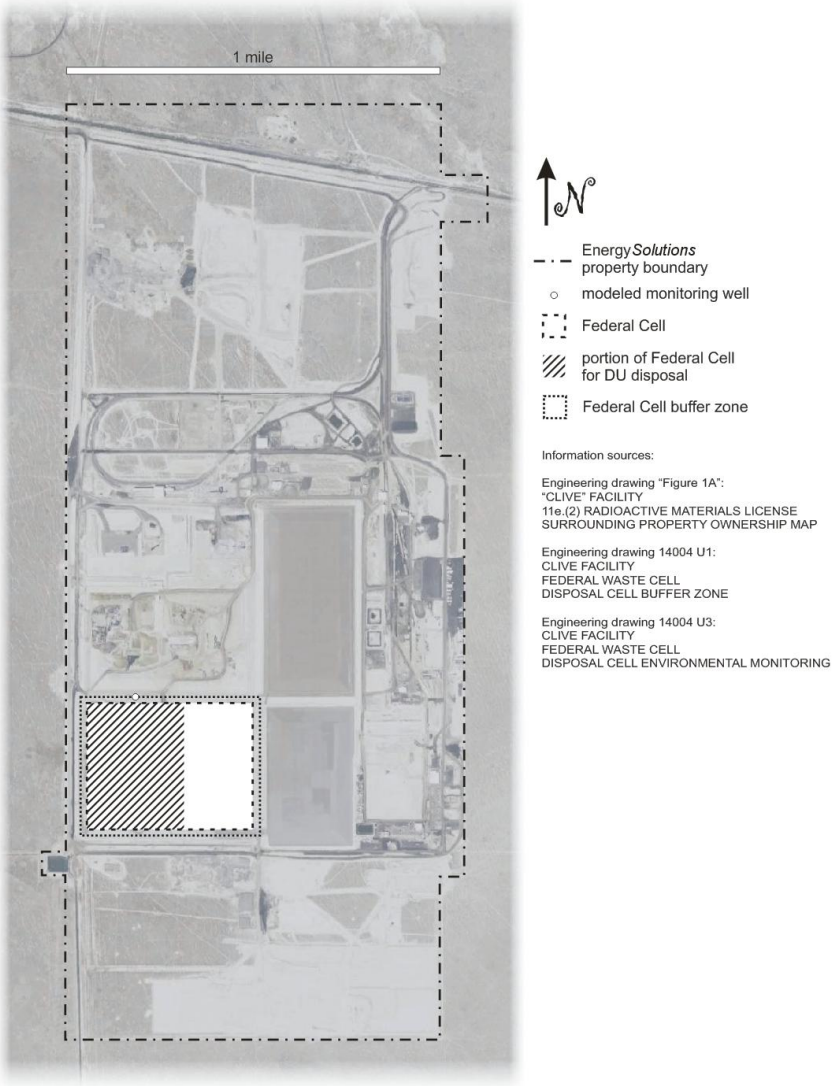

Figure 1. Location and extent of the saturated zone modeling domain including location of the DU waste, the point of compliance monitoring well, the buffer zone of the DU cell, and outer boundaries of property owned and controlled by EnergySolutions.

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~~The unsaturated zone and the shallow aquifer are represented in the Clive PA Model as cell pathways. A cell pathway consists of a series of linked mixing cells. The transport of contaminants in water through the vadose zone is modeled as advective mass flux links from cell to cell though the network to the first cell representing the shallow aquifer. The cell pathways for the unsaturated zone and the shallow aquifer are represented schematically in Figure 1.~~

The advective mass flux in a cell pathway is calculated as the concentration of the contaminant in water multiplied by the rate at which the water is flowing:

$$\text{Advective Mass Flux} = \text{Concentration} \times \text{Flow Rate} \qquad (3\text{~~1~~})$$

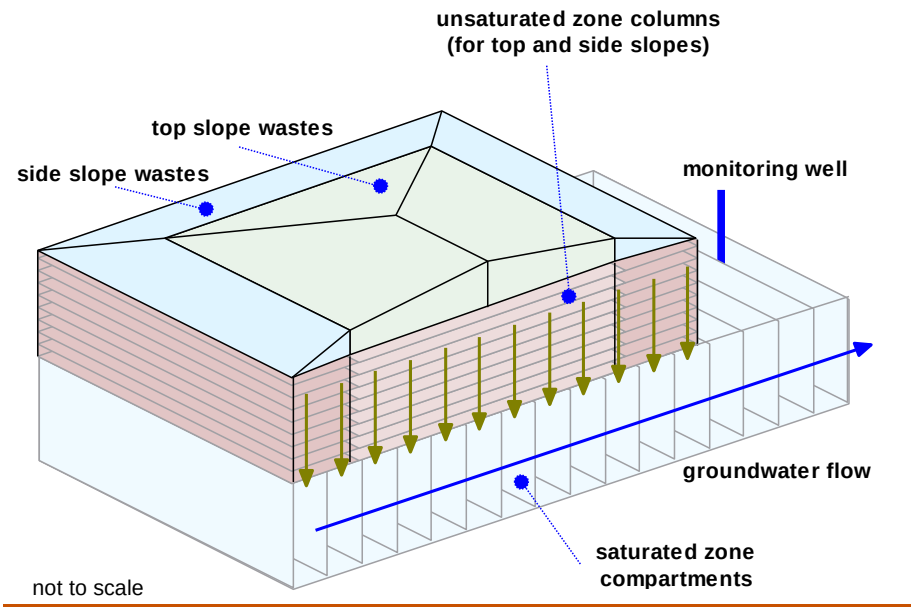

Figure 2~~2~~1: Schematic representation of unsaturated zone and shallow aquifer transport using cell pathways.

An assumption of the mixing cell approach is that all contaminant mass that enters the cell is completely mixed and equilibrated among all media in the cell, consistent with the mathematical representation of a CSTR. To provide contaminant mass balance, GoldSim requires information specifying the volume of the cells. For the Clive DU PA model, the extent of the saturated zone below the Federal DU cell and the distance from the toe of the waste in the disposal cell to the compliance point are represented as a horizontal network of linked cells (Figure 2). GoldSim requires the specification of the length of the cell in the direction of flow and the cross-sectional

area of the cell. The length of each cell is the transport distance divided by the number of cells. The choice of the number of cells used is based on standard modeling practice, with more discussion provided in Section 4.2. The cross sectional area is the product of the cell width and height. For the Clive DU PA model, the cell width is set to the width of the Federal DU cell perpendicular to the direction of flow ("length overall" in Figure 3 of the *Embankment Modeling* white paper). The height of the cell corresponds to the aquifer thickness.

~~An assumption of the mixing cell approach is that all mass that enters the cell is completely mixed and equilibrated among all media in the cell. To provide contaminant mass balance, GoldSim requires information specifying the volume of the cells. For the Clive PA model, the extent of the saturated zone below the Class A South cell~~Federal DU ~~cell and the distance from the toe of the disposal cell to the compliance point are represented as a horizontal network of linked cells (Figure 1). GoldSim requires the specification of the length of the cell in the direction of flow and the cross-sectional area of the cell. The dimensions of the cell are determined in the following manner. The length of the cell is determined by the selection of the number of cells used to represent the transport distance. The length of each cell is then the transport distance divided by the number of cells. The choice of the number of cells used is arbitrary. The cross sectional area is the product of the cell width and height. For the Clive PA model, the cell width is set to the width of the Class A South cell~~Federal DU cell ~~perpendicular to the direction of flow. The height of the cell corresponds to the aquifer thickness.~~

Aquifer thickness in the subsurface at the ~~Class A South cell~~Federal DU cell was estimated considering water table elevations, mapped stratigraphy, and interpretations described in Envirocare (2000, 2004). Water table maps provided in Envirocare (2000, 2004) indicate that the flow in the shallow aquifer in the vicinity of the ~~Class A South cell~~Federal DU cell is generally to the north. This northerly flow direction is representative of the current conditions reflecting the effects of mounding due to surface water infiltration. The natural gradient is approximately to the northeast. Given the predominant flow direction, wells GW-19B, GW-27D, GW-25, and GW-1 were selected as locations providing the best available borehole logs for estimating the elevation of the bottom of the aquifer. Well construction details are provided in Table 3 and well locations are shown in ~~Figure 2~~Figure 3.

Table 3. Construction details for selected wells used for estimating the elevation of the bottom of the shallow aquifer.

Well Number	State Plane Coordinates (NAD 83)		Surface Elevation (ft)	Well Depth (ft bgs)	Date Drilled
	Easting (ft)	Northing (ft)			
GW-19B	1189865	7420999	4269	102	02/06/91
GW-27D	1190080	7423071	4270	100	12/28/98
GW-25	1191693	7423029	4274	34	12/19/91
GW-1	1191843	7420942	4273	42	03/03/88

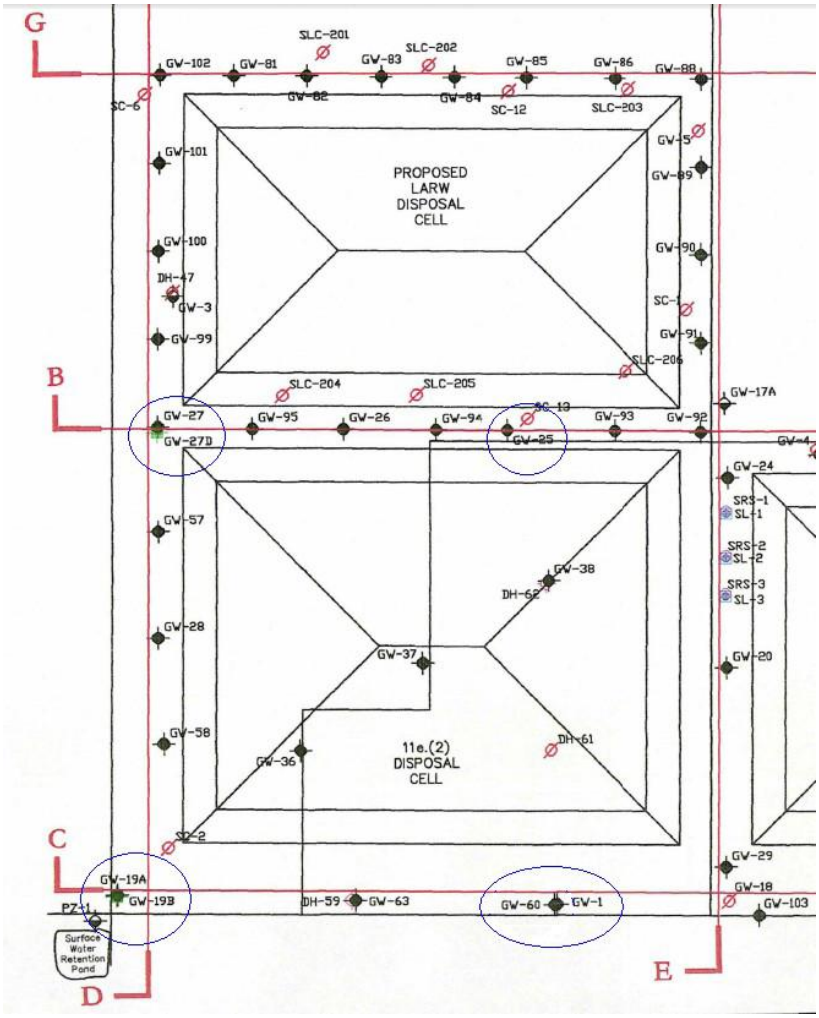

Figure 3~~3~~2. Well locations used for estimating shallow aquifer thickness. Diagram is modified from Envirocare (2004).

Since the shallow aquifer is described as unconfined, the elevation of the top of the aquifer is determined by the water table elevation. At three of the locations, nearby wells with shallow screened intervals were used to obtain more representative values for the shallow water table elevation. Well construction details for the wells used for measurement of water level elevations are provided in Table 4~~Table 4~~ and well locations are shown in ~~Figure 2~~Figure 3. Well GW-19A is located 8 ft from well GW-19B, well GW-27 is located 45.6 ft from well GW-27D, and well GW-60 is located 37.6 ft from well GW-1. Given the average hydraulic gradient of 6.94×10^{-4},

the maximum error in water table elevation due to distance between the wells will be 0.03 ft. This error was considered small enough to be neglected in the estimate of aquifer thickness.

Table 4. Construction details for selected wells used for water table elevations.

Well Number	State Plane Coordinates (NAD 83)		Screened Interval (ft bgs)	Well Depth (ft bgs)	Date Drilled
	Easting (ft)	Northing (ft)			
GW-19A	1189866	7421007	18 – 27.5	31.5	02/07/91
GW-27	1190121	7423091	20 – 29.5	32	12/11/91
GW-25	1191693	7423029	24 – 33.5	34	12/19/91
GW-60	1191832	7420906	22.5 - 27	28	02/02/93

A map of the shallow aquifer showing fresh water equivalent head surface elevation contours was prepared by Envirocare (2004) using groundwater elevation measurements from February, 2004. These elevations are used for this analysis to provide continuity with past work describing the shallow aquifer. The fresh water elevations for the four wells were taken from Table 4 of Envirocare (2004) and are listed in Table 5~~Table 5~~.

Table 5. Water table elevations, aquifer bottom elevations and estimated saturated thickness of the shallow aquifer.

Well Number	Water Table Elevation (ft)*	Bottom Elevation of Shallow Aquifer (ft)	Saturated Thickness (ft)
GW-19B	4251	4229	22
GW-27D	4250	4238	12
GW-25	4250	4240	10
GW-1	4251	4231	20

*GW-19B, GW-27D, and GW-1 water table elevations estimated from the elevation in nearby shallow aquifer wells.

The bottom elevations of the shallow aquifer at wells GW-19B and GW-27D were estimated from hydrologic cross-sections described in Envirocare (2000, 2004). A south to north cross-section on the west side of the ~~Class A South cell~~Federal DU cell is shown in ~~Figure 3~~Figure 4~~Figure 4~~. At well GW-19B the elevation of the bottom of the aquifer is estimated to be where the silty sand interval grades into a clay interval. The borehole log for this well indicates that this transition occurs at an elevation of 4,229 ft.

The lower boundary is extended to the top of an extensive clay layer mapped in well GW-27D shown in ~~Figure 3~~Figure 4~~Figure 4~~. The borehole log for this well indicates that the top of the clay layer occurs at an elevation of 4,238 ft.

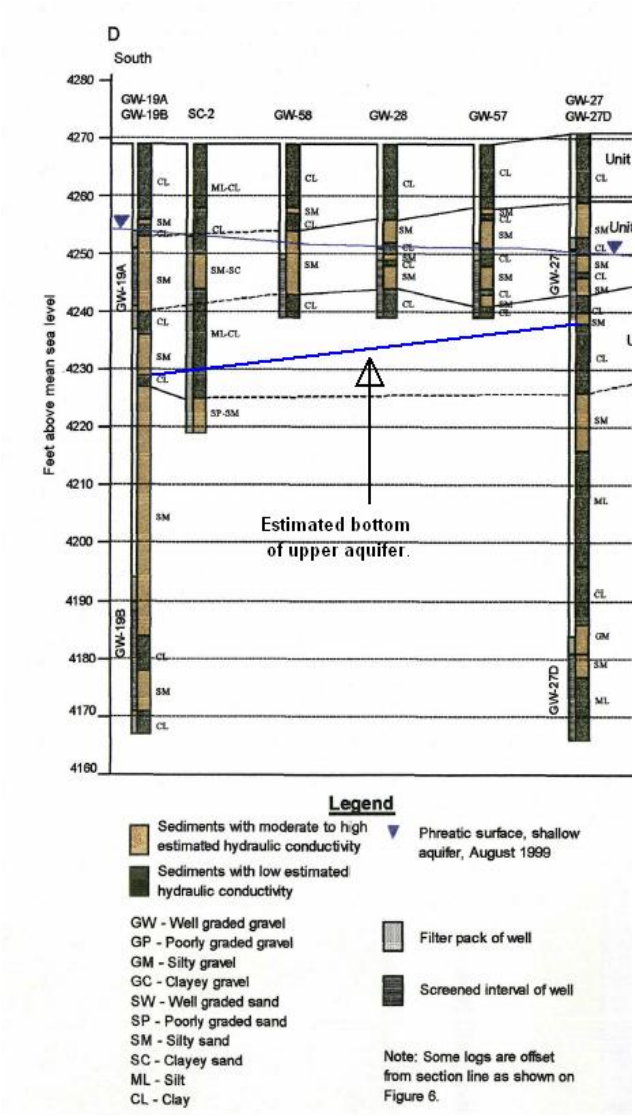

Figure ~~443~~: Cross-section D-D' modified from Envirocare (2004) showing estimated elevation of the bottom of the shallow aquifer.

Well GW-25 is 40 ft deep and screened in the bottom 10 ft of the well in a unit described as silty clay. The elevation of the bottom of the well is 4,240 ft. The saturated hydraulic conductivity measured in this well is reported by Envirocare (2004) as 1.05×10^{-3} cm/s. Comparing this result with a site-wide mean value of saturated hydraulic conductivity of 9.6×10^{-4} cm/s indicates that this well is completed within the shallow aquifer. The elevation of the bottom of the aquifer at this well may be deeper than the bottom of the well but is conservatively taken as 4,240 ft, the elevation of the bottom of the well.

Well GW-1 is 41.5 ft deep and is screened from 20 ft bgs to 40 ft bgs. The driller's log describes the sediments as a silty sand from 14 ft to 29 ft depth and sandy clay from 29 ft to the bottom of the borehole at 41.5 ft. Well GW-60 located 37.6 ft from well GW-1 is completed to a depth of 28 ft in sediments described as a silty clay. The interval from 22.5 ft bgs to 27 ft bgs within the silty clay is screened. Saturated hydraulic conductivity in well GW-60 was determined to be 3.4×10^{-3} cm/s or three times the site-wide average. This relatively high value of saturated hydraulic conductivity measured in a silty clay indicates the ~~the~~ shallow aquifer extends at least as deep as the bottom of well GW-1. Given this interpretation, the elevation of the bottom of the aquifer at this borehole is estimated to be 4,231 ft. The estimated elevations of the bottom of the shallow aquifer and the resulting saturated thicknesses are listed in Table 5~~Table 5~~.

A distribution for the thickness of the saturated zone was established based on four location measurements (GW-19B, GW-27D, GW-25, and GW-1), and professional judgment regarding the accuracy of the measurements. An aquifer thickness for each of the four locations was calculated as the difference between the recorded elevation of the water table and the elevation of the bottom of the shallow aquifer. Since the four locations do not quite form a square, triangulation was used to calculate an average thickness across the region. Only two possible triangulations exist for these four points, so both were computed, and the average of the two was used as the mean of the distribution for saturated zone thickness. Professional judgment was that the measurements are accurate to within 1 foot. Thus, 1 foot was interpreted as a two standard deviation range, giving a measurement standard deviation of 0.5 ft. Since four measurements are being averaged (with nearly equal weights), the resulting standard error for the mean is then 0.5 ft divided by the square root of 4. The resulting distribution for the mean thickness of the saturated zone was thus chosen as a normal distribution with mean equal to 16.2 ft with a standard deviation of 0.25 ft.

4.2 Dispersion

The process of spreading of a contaminant in groundwater that occurs in addition to movement by advective flow is represented in mathematical models by the dispersion coefficient. The dispersion coefficient represents both the mechanical (hydrodynamic) and chemical components of mixing and is written as:

~~The process of spreading of a contaminant in groundwater that occurs in addition to movement by advective flow is represented in mathematical models by the dispersion coefficient. The dispersion coefficient represents both the mechanical and chemical components of mixing and is written as:~~

$$D_l = \alpha_l \bar{v} + D_m \qquad (42)$$

~~Where~~where

D_l = longitudinal dispersion coefficient

α_l = longitudinal dispersivity

$\bar{v}$~~v~~ = mean pore water velocity

D_m = molecular diffusion coefficient

Only longitudinal dispersion is considered for this discussion because of the geometry of the transport pathway. The width of the disposed waste is the dimension perpendicular to the groundwater flow direction. This distance is 1,429.6 ft ("length overall" in Figure 3 of the *Embankment Modeling* white paper). The distance from the edge of the waste to the compliance point is 90 ft as required by the groundwater discharge permit. The entire horizontal length of the saturated zone cells is this 90 ft plus the footprint of the embankment parallel to the direction of water flow (1775.0 ft, the "width overall" in Figure 3 of the *Embankment Modeling* white paper), making a total length of 1865 ft. With this geometry, the width of the source is more than 5 times the distance from the edge of the source to the point of compliance, making transverse dispersion insignificant.

In a numerical model such as the Clive DU PA Model, the discretization of the flow path into cells results in an effective (numerical) longitudinal dispersion (parallel to the flow direction) due to the full mixing of a CSTR even with no additional dispersivity defined. Because of this inherent numerical dispersion, no additional dispersion coefficient is included in the saturated zone transport calculations in the Clive DU PA Model.

Dispersion is discussed in the User's Guide for the GoldSim Contaminant Transport Module (GoldSim 2010) in the context of the GoldSim Aquifer pathway element. The Aquifer element is a collection of linked Cell elements, and the saturated zone in the Clive DU PA Model is also represented as a collection (column) of Cell elements, which is somewhat more flexible than the predefined GoldSim Aquifer element. Longitudinal dispersivity is commonly approximated as 0.1 times the length of the transport path (GoldSim 2010). For the Clive DU PA Model the point of compliance is a fixed location 232 ft from the edge of the DU waste, since the length travelled under the side slope of the embankment, which contains no DU waste (142 ft), is added to the standard 90 ft. The estimated value of the dispersivity would then be 232 ft /10 = 23 ft. In order to reduce unwanted numerical dispersion, GoldSim (2010) recommends that the number of Cell elements used in the column be greater than the transport path distance divided by twice the dispersivity. For the Clive DU PA Model geometry, the number of cells should therefore be greater than 232 ft / (2×23 ft) = 5. The horizontal column of Cell elements that represents the saturated zone to the well in the Clive DU PA Model contains 20 cells and there are 2 cells under the side slope. The number of cells making up the transport path exceeds the minimum recommended.

The mass balance of water flow is not in question, since it is up to the GoldSim programmer (the model author) to assure that all flows are properly accounted for. GoldSim performs no solutions whatsoever to the hydraulics of the model. In the case of the saturated zone, the water flow through the horizontal column is defined as a constant value all the way through the column.

Since there are no numerical calculations in GoldSim with respect to water flow calculations, mass balance of water has no mass balance error.

The mass balance of contaminants (radionuclides) is determined internally by the GoldSim software as part of its proprietary solution algorithms. The internal solver accounts for advective flows, diffusion in air and water (where applicable), partitioning between air, water, and solid phases, as well as radioactive decay and ingrowth. The modeler and the user are not privy to the internal mass balance calculations, but a good indication of how well the model is performing can be had by experimenting with the settings for solution precision, which are accessible to the user. Using the GoldSim interface, go to Model | Options dialog, and select the Contaminant Transport tab. Under the first set of options, General Options, there is a drop-down box where the user can set the solution precision, in qualitative terms: low, medium, and high. If choosing a higher solution precision does not result in substantially different results, then the user has an indication that the mass balance is acceptable, since refining the precision does not improve the calculation.

~~Only longitudinal dispersion will be considered for this discussion because of the geometry of the transport pathway. The width of the disposed waste is the dimension perpendicular to the groundwater flow direction. This distance is 1,276.4 ft (Whetstone 2007, Figure 6). The distance from the edge of the waste to the compliance point is 250 ft (Whetstone 2007). With this geometry, the width of the source is more than 5 times the distance from the edge of the source to the point of compliance, making transverse dispersion insignificant.~~

~~In a numerical model such as the Clive DU PA Model, the discretization of the flow path into cells results in an apparent dispersion due to small numerical errors even with a value of zero for the dispersivity. Because of the inherent numerical dispersion, the dispersion coefficient is not explicitly included in the shallow aquifer transport calculations in the Clive DU PA Model.~~

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