From: Howard Crabtree
To: Sid Jones; Brad Stephenson; Gareth Davies; Beth Rowan; Abe Almassi; Gerry Middleton; Steven Stout; John Wojtowicz; Hannah Klein
Cc: David C. Foster; Thomas Gebhart; Eddie Worthington; Kristof Czartoryski
Subject: FW: TDEC position on draft responses to D4/D2 EMDF RI/FS comments
Date: Wednesday, August 24, 2016 7:49:03 PM
Attachments: 1) TDEC D4 RI_FS Comments and Draft Responses GROUPED 7-28-16 - TDEC Position_2016-08-24.docx
2) Att A 2016-08-04 TDEC Exception language draft (from Susan DePaoli).pdf
3) Att B Worthington (1999) A Comprehensive Strategy for Understanding Flow in Carbonate Aquifers.pdf
4) Att C Worthington et al. (2016) Enhancement of Bedrock Permeability by Weathering.pdf
5) Att C App A Supplementary Data.pdf
6) Att D TDEC D4 EMDF Comments Final to DOE 5.16.16.pdf
image003.png

FYI. I just emailed DOE the table Brad has been working on with you folks with our position on DOE's draft responses to TDEC comments on the D4 RI/FS (the Word attachment) and supporting information (the PDFs). By separate email, Randy forwarded a letter to DOE earlier in the day outlining a path forward for the informal dispute on the document, which he, Chris, Andy, John, Steve, and Dr. Jones have been putting together. Both look really good to me.

I appreciate the help folks.
Howard

From: Howard Crabtree
Sent: Wednesday, August 24, 2016 6:37 PM
To: Brian Henry; DePaoli, Susan; Jeffery Crane
Cc: Andy Binford (Andy.Binford@tn.gov); Chris P. Thompson; Kristof Czartoryski; Randy Young
Subject: TDEC position on draft responses to D4/D2 EMDF RI/FS comments

Brian and Susan,

Attached is the table requested summarizing the TDEC draft position on the draft DOE responses to comments on the D4/D2 EMDF RI/FS (Word), with supporting attachments (PDFs). Please, distribute as appropriate. The notes below should help with the review. If you have questions, give me a call.

Howard

1) Tracked changes indicate suggested edits to…

    a) corrected errors in TDEC comments, presumably introduced when DOE scanned our original comment letter and

    b) suggest potential editorial revisions to the draft responses for DOE's consideration.

2) To facilitate review by DOE, green shading indicates areas of TDEC agreement, and yellow shading highlight areas of disagreement.

TN Department of Environment & Conservation

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From: DePaoli, Susan [mailto:depaolis@p2s.com]
Sent: Tuesday, August 02, 2016 2:08 PM
To: Howard Crabtree
Cc: 'Henry, Brian'
Subject: FW: D2 EMDF RI/FS Informal Dispute Status - EPA Comments

Howard,
Just a suggestion, but it would be really helpful if TDEC could put another column on the end of the draft comment/response table sent last week on the RI/FS (email on 7/28) like EPA did (see attached) titled "**EPA Informal Dispute Position**" for the Aug 9th meeting.

Thanks!
Susan

From: Crane, Jeffrey [mailto:Crane.Jeff@epa.gov]
Sent: Friday, July 15, 2016 4:15 PM
To: Henry, Brian; 'Howard Crabtree'
Cc: Adler, David Green; Chris P. Thompson; Kristof Czartoryski; Campbell, Richard; Japp, John Michael (John.Japp@orem.doe.gov); Randy Young; Mac' 'McRae (mmcrae@TechLawInc.com); Osteen, Bill; Brock, Martha; Thoms, Sharon; Frederick, Tim; DePaoli, Susan
Subject: D2 EMDF RI/FS Informal Dispute Status - EPA Comments

Brian/Howard,

I took an action item to review the table on the EPA issues at our last meeting. Attached please find the issue table that includes a new rightmost column with issue status and path to closure. I found the table to be very useful and hope the new column helps in that regard as well.

Let me know when we can follow up with further discussion and path forward on informal dispute resolution. It would help if we have a similar table for the FFS.

Jeffrey L Crane
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CERCLA D4 RI/FS COMMENT AND (DRAFT) RESPONSE SUMMARY

Shaded Response Cells are comments selected for July 28th TDEC meeting; Version 7/28/16

Highlights are indications for authors to either update or check that an update has been made.

Green shading indicates TDEC agreement. Yellow shading highlights TDEC disagreement.

Comments by: **Tennessee Department of Environment and Conservation**
Comments Received: May 16, 2016
Title of Document: Remedial Investigation/Feasibility Study for Comprehensive Environmental Response, Compensation, and Liability Act Oak Ridge Reservation Waste Disposal Oak Ridge, Tennessee
Revision No.: D4
Document No: DOE/OR/01-2535&D4
Date: March 18, 2016

NEW D4 Comment #	A B C	D4 Comment	DRAFT DOE D4 Response	TDEC Informal Dispute Position
D4.01		The D4 version of the RI/FS was significantly modified from the D3 version in response to regulatory concerns. The changes provide partial resolution to several issues that have prevented TDEC approval of previous drafts. The inclusion of additional ARARs, particularly those specific to radioactive waste management, has strengthened the legal foundation for authorization of the disposal facility. Additional alternatives were added, including disposal facilities at on-site locations thought to potentially be more compatible with State of Tennessee criteria for siting radioactive waste disposal facilities. An alternative that incorporated more aggressive volume reduction strategies and more off-site disposal was evaluated. Changes to risk assessment methodology were relatively few but had significant consequences for certain important contaminants of concern. The establishment of waste acceptance limits at any on-site disposal facility that would be protective of water resources has been a consistent and significant regulatory concern. While the risk assessment methodology may still not properly address contaminants of concern for which travel time to the receiving stream or aquifer is critical to the risk evaluations, the risk assessment for contaminants that will be limited predominantly by release mechanisms at the source and dilution in the receiving waters has been significantly strengthened. The waste acceptance limits that would be imposed by the PreWAC given on page 77 and on pages 81-83 of Appendix H for relatively mobile contaminants that are assumed to undergo little radioactive decay or reaction throughout the compliance period are arguably within a range that would protect water resources.	No response required.	TDEC agrees.
D4.04		TDEC believes that compliance with siting criteria and developing a WAC protective of human health and environment are necessary for long term protection of human health and the environment. **Page 7-19~~.~~, Section 7.2.2.3 Long-term Effectiveness and Permanence (On-site), Engineering and Institutional Controls**, second paragraph states the leachate collection system and removal system above the primary liner and the leak detection and removal system below the primary liner would be effective for the period of active institutional controls. The period of active institutional controls is not known, but is assumed for design purposes to extend for at least 100 years. Subsequently, the final cover system, secondary liner, and geologic buffer would provide long-term control of leachate release since these engineered features would last minimally for 500 years. **Page 7-31 Cost** discusses a "Perpetual Care Trust Fund" and states said fund is intended to cover certain costs for 1,000 years following closure of the landfill. **Page 7-51~~.~~, Section 7.3.3** states "Off-site disposal of waste at Energy Solutions, WCS, and NNSS in the long-term may be more reliable at preventing exposure than on-site disposal at the ORR, as they are located in arid environments that reduce the likelihood of contaminant migration or exposure via groundwater or surface water pathways. Fewer receptors exist in the vicinity of Energy Solutions, WCS, and NNSS than on the ORR." **Page 7-51 also states that while underdrain networks are necessary and effective in isolating wastes from the underlying saturated zone, they do provide avenues for localized and relatively rapid transport of contaminants in groundwater that could be released below the footprint and discharge at underdrain outfall locations.** **Page 7-52** states that "The extent of the underdrain networks vary among the proposed sites. Assuming some degree of greater mobility is associated with the areal extent of the underdrain, the Hybrid Site 6 has the least underdrain network area (27,000 ft^2) and the EBCV Site has the most area ~~1297~~(297,000 ft^2) with the Dual Site 7a/6b Option (~~1~~132,000 ft^2) and the WBCV Site (259,000 ft^2) of intermediate area." Page 7-52 goes on to state that "while the cover system remains in place, migration of contaminants into groundwater and surface water is the only credible pathway of exposure," implying uncertainty as to whether and how long the cover system will remain in place.	No response required.	TDEC's positions for the comment components are as follows. **Page 7-19, Section 7.2.2.3** TDEC agrees that no response is required. **Page 7-31 Cost** The state is re-evaluating both the terms of the funding agreement and adequacy of the level of the funding given the experience with EMWMF. Because there are significant issues and uncertainties, there is at present time no justification to assume a continuation of the current $1 million annual payments. **Page 7-51, Section 7.3.3** TDEC agrees that no response is required. **Page 7-52** TDEC agrees that no response is required.
D4.03	**A1**	CERCLA Section 121 (d)(1) requires that *"Remedial actions selected under this section or otherwise required or agreed to by the President under this Act shall attain a degree of cleanup of hazardous substances, pollutants, and contaminants released into the environment and control of further release at a minimum which assures protection of human health and the environment. Such remedial actions shall be relevant and appropriate under the circumstances presented by the release or threatened release of such substance, pollutant, or contaminant."* TDEC D3 RI/FS comment TDEC.S.099 in the *CERCLA D3 RI/FS Comment and Response Summary* identified concerns with risk posed	An additional site, Site 7c, has been added to the revised RI/FS (version D5). This site is not expected to rely on the performance of underdrain systems post-closure to maintain a lowered groundwater table, so that flowing water in the underdrain system is not an issue post-closure.	The D4 RI/FS includes an expansion of alternatives to include (1) dual sites, (2) a smaller site that requires a hybrid of on-site disposal, off-site disposal, and more aggressive efforts to minimize waste volume, and (3) a site in central Bear Creek Valley. TDEC agrees that these additional alternatives require less reliance on an underdrain to prevent problems due to groundwater intrusion.

		from an underdrain. TDEC's comment stated that the proposed ESCV site underdrains, like the underdrain at the EMWMF, would presumably be able to supply several gallons per minute of water continuously even during drought conditions, and might be a usable water supply even when individual wells were dry. The D4 RI/FS did not identify the underdrain as a potential exposure pathway in either Appendix H Section 2.2 *Conceptual Model and Exposure Pathways* or Section 2.3 *Hypothetical Receptor*. Further, potential risk posed by an underdrain was neither quantified in theD4RI/FS nor used in PreWAC development. Underdrains are engineered pathways for future release of hazardous substances, pollutants, and contaminants from the landfill. Over time, the underdrains would contain constituents released from the landfill directly overlying the underdrain, as well as from other areas of the landfill where constituents are released to groundwater and the contaminated groundwater subsequently discharges to an underdrain. **Page 7-51** of the RI/FS also states that while underdrain networks are necessary and effective in isolating wastes from the underlying saturated zone, they do provide avenues for localized and relatively rapid transport of contaminants in groundwater that could be released below the footprint and discharge at underdrain outfall locations. Figure H-16 shows the underdrain may have concentrations in the range of 0.1 to 0.9 of the leaching source in areas where underdrains may discharge to surface near the edge of the landfill. Once again, an underdrain that would presumably be able to supply several gallons per minute of water continuously even during drought conditions might be a usable water supply. Further, with the low flow in Bear Creek in the vicinity of the EBCV site, it is conceivable that a future farmer could impound flow from an underdrain to develop a farm pond for livestock watering or irrigation. Fish are common in farm ponds and risk from consuming fish from an underdrain fed farm pond was not evaluated. Underdrains provide a direct conduit to surface water with potentially minimal sorption or other attenuation of constituents. Bear Creek is classified for recreational use, and impact on surface water resources including consumption of fish from Bear Creek was not evaluated. These exposure pathways associated with a flowing underdrain should be added to the maximally exposed individual (MEI) evaluation to verify whether a site with a flowing underdrain meets the CERCLA Section 121(d)(1) threshold requirement for control of further release at a minimum which assures protection of human health and the environment. Further, these exposure pathways should be added to waste acceptance criteria (WAC) development to assure future waste disposed does not pose an unacceptable risk due to a flowing underdrain. TDE's position is that unless and until an acceptable evaluation is performed that demonstrates that an underdrain, releasing water and potentially leachate from under the EMDF, will be protective of human health and environment over the long-term, a design with an underdrain that would produce flowing water once the liner had been fully constructed is unacceptable.		There were discussions on Site 7c at the project team level on June 30, 2016 and July 19, 2016 concerning the collection of site-specific data to verify water levels, verify whether an underdrain would be needed, verify how an underdrain could be avoided, and determine what data may be needed to evaluate alternative landfill layout configurations. When will the site-specific data be collected to answer this question so we are not guessing? TDEC does not support a site with an underdrain that would produce flowing water once the liner is fully constructed. Prior to RI/FS approval, we need site-specific data demonstrating that any underdrain will be temporary and not flow upon liner completion. The FFA parties should conduct a data quality objectives (DQO) meeting to identify data needs. DOE should provide a technical facilitator for this meeting to ensure each party's concerns are acknowledged and appropriately addressed. TDEC expects that the record of decision (ROD) will clearly specify that any flow from an underdrain after liner construction will trigger additional investigation and landfill reconfiguration to eliminate the underdrain.
D4.10	**A2**	During Site Management Team (SMT) discussions between the D3 RI/FS and D4 RI/FS, DOE stated that all sites being considered for the possible waste management facility required underdrains. TDEC suggested that DOE evaluate the extent of underdrain(s) needed for each site and whether any site may require only "minimal underdrains." TDEC offered that "minimal underdrain" refers to siting and constructing a landfill facility over small spring(s) or seep(s) that will dry up, due to capping or cutting off the recharge area, so that the resulting facility will not require a continually functioning underdrain once the facility is constructed. It is believed that a minimal underdrain poses a significantly reduced threat compared to an extensive or flowing underdrain. Both the East Bear Creek Valley (EBCV) site and the West Bear Creek Valley (WBCV) site have groundwater fed creeks flowing through the proposed landfill sites that will require extensive underdrains to convey the water from under proposed future landfills. The D4 RI/FS states (page 6-40) that the EBCV site requires an extensive underdrain system (Figure 6-12). Page 6-41 states that the individual pieces of the WBCV site underdrain system are similar to the EBCV option because the natural drainage ways extend across most of the WBCV site, but fewer areas of underdrain appear to be required than at the EBCV site. The RI/FS also states (page 6-41) that the conceptual underdrain proposed for Site 7a in the Dual Site Option is similar to that for the WBCV site (Figure 6-15). Based on TDEC review of the RI/FS, Site 6b has the smallest underdrain system and is likely to require only minimal underdrains. The D4 RI/FS (page 6-41) states "Site 6b was selected as the onsite location for the Hybrid Alternative based on a conceptual design that requires the least expansive underdrain system. It is likely that these seeps would not produce any water once the liner had been fully constructed for this site. The locations would no longer have available recharge." (Figure 6-14).	A new site, a modification to Site ~~7a~~7c, is proposed in the revision of the RI/FS. Facility conceptual design at this site (designated as Central Bear Creek Valley, CBCV, or Site 7c) indicates underdrain features; however, as indicated in the document, the underdrains are expected to be minimally relied on during construction and operation. Underdrains for this Site 7c are not expected to produce running water or be needed to maintain a lowered groundwater table over the long-term. Permanent reliance on an underdrain at Site 7c is not expected.	See TDEC Informal Dispute Position D4.03 above. TDEC does not support a site with an underdrain that would produce flowing water once the liner is fully constructed. Prior to RI/FS approval, we need site-specific data demonstrating that any underdrain will be temporary and not flow upon liner completion. The FFA parties should conduct a DQO meeting to identify data needs. DOE should provide a technical facilitator for this meeting to ensure each party's concerns are acknowledged and appropriately addressed. TDEC expects that the ROD will clearly specify that any flow from an underdrain after liner construction will trigger additional investigation and landfill reconfiguration to eliminate the underdrain.
D4.11	**A3**	TDEC personnel walked the periphery of sites 7a and 7b to evaluate the need for underdrains and potential for minimal underdrains. Based on TDEC observations, it appears possible that either site 7a, 7b, or both sites 7a and 7b may be configured without extensive underdrains. This would require changing the Site 7a conceptual design to avoid the underdrain. Suitability of sites 7a and 7b would need to be verified by site-specific hydrogeologic assessment. We agree with the D4 RI/FS text on page E-18l that states *"new site specific hydrogeological and geotechnical data will be required to establish key relationships between the base cell elevations and the underlying water table and bedrock configuration, as well as other data required for detailed design, modeling, etc."*	A revision and extension of Site 7a, new Site 7c, has been added to the RI/FS. This site provides a larger capacity than Site 7a alone. Reliance on underdrains for either Site 7a or 7c may be lessened after site characterization; however, based on existing and current documented hydrology at the site, the underdrain configuration presented for Site 7a (and applicable for Site 7c) will be retained and is conservative. It is noted that the reliance on underdrains at these sites is expected to be unnecessary over the long-term, and certainly much less significant compared to WBCV and EBCV underdrain functioning requirements in the long-term.	See TDEC Informal Dispute Position D4.03 above. There were discussions on Site 7c at the project team level on June 30, 2016 and July 19, 2016 concerning the collection of site-specific data to verify water levels, verify whether an underdrain would be needed, verify how an underdrain could be avoided, and determine what data may be needed to evaluate alternative landfill layout configurations. DOE's response indicates that site-specific data are available for Sites 7a and 7c. DOE should provide the data to TDEC as soon as possible as a critical step toward resolving the informal dispute regarding the D4 RI/FS. TDEC does not support a site with an underdrain that would produce flowing water once the liner is fully constructed. Prior to RI/FS approval, we need site-specific data demonstrating that any underdrain will be temporary and not flow upon liner completion. The FFA parties should conduct a DQO meeting to identify data needs. DOE should provide a technical facilitator for this meeting to ensure each party's concerns are acknowledged and appropriately addressed. TDEC expects that the ROD will clearly specify that any flow from an underdrain after liner construction will trigger additional investigation and landfill

				reconfiguration to eliminate the underdrain.
D4.12	**A4**	Calculations for the PreWAC values require clarification and verification. For example, the equation for calculating the peak creek dose (PD'eff) for non-carcinogenic constituents is given on page H-66. Multiple DFcreek and DFwell values are given on pages H-58 and H-64 and it is unclear which dilution factors are used for which calculations. Further, while trying to duplicate the non-carcinogenic PD'eff for uranium in Appendix H, Attachment A, Table 2 and the uranium Adjusted PreWAC in Tables H-12 and H-13, it appeared that a scaled dilution factor for DFcreek may have been used in the D4 RI/FS. This effort was further confused by the acrylonitrile example given on page H-80. The PD'eff for acrylonitrile referenced on page H-80 does not agree with the PD'eff for acrylonitrile in Attachment a, Table 2; utilizing the formula on page H-66 subsequently yielded a third PD'eff value for acrylonitrile. This may be dilution factor uncertainty again. Further, the acrylonitrile example on page H-80 specified dividing by the reference dose and instead of using the reference dose from Attachment A, Table 3-2, the value for the slope factor was used in the example.	The two values for each of DFwell and DFcreek used in the preWAC calculations correspond to two values for infiltration, 0.43 in/year during performance stage 3, and 1.32 in/yr during performance stage 4. Values for DFwell given in Table H-5 are incorrect and do not reflect the final D4 modeling assumptions; these values have been corrected. The values given on page H-64 (0.02 and 0.064) were used in the preWAC calculations. The values of DFcreek given in Table H-5 are those used for the preWAC calculations. No scaling procedure for the DFwell was used in the preWAC calculations. An error in calculating the peak effective dose for a child receptor was identified following the submittal of the D4 RIFS. This error resulted in PD'eff (those given in Appendix H ~~Atttachment~~Attachment B, Table 2) that are a factor of two lower than the correct value, based on the D4 modeled contaminant concentrations and exposure assumptions. Tables H-12 and H-13 as well as Table 2 of Appendix H Attachment B have been corrected in the D5 revision. Errors in the Acrylonitrile preWAC calculation example on page H-80 have been corrected. The values given for the reference dose, PD'eff, and all subsequent derived quantities for Acrylonitrile on page H-80 have been corrected.	TDEC agrees.
D4.18	**A5**	Page 7-17 states that "One siting requirement, TDEC 0400-20-11-.17(1)(h), has been determined to be relevant but not appropriate. See Appendix G Section 4.3 for a discussion," TDEC disagrees and determined siting requirement TDEC 0400-20-11-.17(1)(h) is both relevant and appropriate. TDEC 0400-20-11-.17(1)(h) states "The hydrogeologic unit used for disposal shall not discharge groundwater to the surface within the disposal site." The discussion in Appendix G Section 4.3 on page G-17 and G-18 distinguishes between (1) "shallow land disposal" where packaged waste is placed in excavated trenches and the filled trenches are backfilled with soil, capped, and mounded to facilitate runoff and (2) an engineered disposal facility that incorporates an engineered earthen cover, liner system, and geologic buffer. Further the engineered disposal facility is built above existing grade and utilizes underdrains to mitigate the effects of shallow groundwater. Page G-18 states that "Based on this analysis, the siting requirements appear to regulate a structure/facility that is vastly different from the proposed EMDF .... while it may be relevant in that it applies to LLW disposal, is not appropriate due to the differences in the types of facilities ... " Tennessee is an NRC state, and TDEC 0400-20-11-.17(1)(h) is identical to 10 CFR 61.50(a)(8) which states "The hydrogeologic unit used for disposal shall not discharge groundwater to the surface within the disposal site." 10 CFR 61.50(a) includes criteria for determining whether a disposal site is suitable for near surface disposal. As defined in 10 CFR 61.2: *Near-surface disposal facility* means a land disposal facility in which radioactive waste is disposed of in or within the upper 30 meters of the earth's surface. *Land disposal facility* means the land, building, and structures, and equipment which are intended to be used for the disposal of radioactive wastes. 10 CFR 61.7 Concepts recognizes in (a)(2) that, for near surface disposal, the disposal unit is usually a trench. However, near surface disposal facility is not limited to disposal in trenches as 10 CFR 61.7 (a)(1) states "Part 61 is intended to apply to land disposal of radioactive waste and not to other methods such as sea or extraterrestrial disposal. Part 61 contains procedural requirements and performance objectives applicable to any method of land disposal. It contains specific technical requirements for near-surface disposal of radioactive waste, a subset of land disposal, which involves disposal in the uppermost portion of the earth, approximately 30 meters. **Near-surface disposal includes disposal in engineered facilities which may be built totally or partially above-grade provided that such facilities have protective earthen covers.** Near-surface disposal does not include disposal facilities which are partially or fully above-grade with no protective earthen cover, which are referred to as 'above-ground disposal.'" (emphasis added) TDEC further considered that EMDF is proposed for disposal of long half-life radionuclides, such as, Tc-99 (i.e. half-life 2.13E+5 years) and various uranium isotopes (U-234 with a half-life of 2.45E+05 years, U-235 with a half-life of 7.04E+08 years, U-236 with a half-life of 2.34E+07 years, and U-238 with a half-life of 4.47E+09 years) that will remain in the disposal facility long after engineering components fail. To further clarify 10 CFR 61.50(a)(8) and the identical state requirement. TDEC evaluated NUREG-0902 which deals with Site Suitability, Selection and Characterization and gives background on the purpose for the siting requirement. It states this requirement should provide sufficient space within the buffer zone to implement remedial measures, if needed, to control releases of radionuclides before discharge to the ground surface or migration from the disposal site. It further states the staff prefers long flow paths from the disposal site to the point of groundwater discharge in order to increase the amount of decay of radionuclides, increase the hydrodynamic dispersion within the aquifer, and increase the likelihood of retardation of radionuclides in the aquifer. TDEC rules are consistent with the NRC purpose for this requirement, as disposal means the *isolation of radioactive waste from the biosphere inhabited by man and containing his food chains* by emplacement in a land disposal facility *(emphasis added).* Underdrains (either under or adjacent to the disposal area and that will not dry up due to covering the recharge area) discharge groundwater	DOE has included TDEC 0400-20-11-.17(1)(h) as an ARAR. The various sites will all require an exception to this ARAR, as described in Appendix H, Chapter 4. Each site relies on engineered features to provide the basis for a variance. A more detailed discussion as to the degree to which each site requires this exception based on the long-term underdrain reliance is provided in Chapter 7. See attached draft language emailed by Susan DePaoli 08-04-2016 @ 13:59 ET (Attachment A to this table).	TDEC does not support a site with an underdrain that would produce flowing water once the liner is fully constructed, and TDEC disagrees that deficiencies in site characteristics can be entirely offset by cost-effective engineered features. However, the definition of hydrogeologic unit relevant to TDEC 0400-20-11-.17(1)(h), is: *Hydrogeologic unit – any soil or rock unit or zone which by virtue of its porosity or permeability, or lack thereof, has a distinct influence on the storage or movement of groundwater.* While all alternatives considered in the RI/FS may include at least one area where groundwater discharge was indicated by the presence of a seep or spring, some of these seeps and springs identified (by the USGS) may be fed by shallow and isolated recharge areas. At some sites, these recharge areas may be so limited in size that they have minimal influence on the storage or movement of groundwater. If the recharge area for the discharge is located within the landfill footprint, it would seem that the rule is no longer relevant. The rationale for this rule, given in NRC guidance (NUREG 0902) states: *"This requirement will result in a travel time for most dissolved radionuclides at least equal to the travel time of the groundwater from the disposal area to the site boundary. In addition, this requirement should provide sufficient space within the buffer zone to implement remedial measures, if needed, to control releases of radionuclides before discharge to the ground surface or migration from the disposal site."* TDEC believes that by obtaining more detailed characterization data and modifying the footprint(s) of the proposed landfill, one or more of the alternatives proposed in the RI/FS can be selected that do not include any site-related surface water pathways that might shortcut the migration of contaminants. Seeps that might re-emerge over time would be recharged on the landfill footprint itself. They would be controlled by the conditions on the closed landfill and not dependent on site characteristics. All candidate sites are not equal. Any waiver must be justified by site-specific data, including a determination of whether a waiver is necessary. The need for a waiver will depend on site characterization data and may be a consideration in site selection.

		and any pollution to ground surface. Underdrains may further provide concentrated pathways for conveyance of pollution from under the disposal site to onsite ditches or conveyances to surface water. The effect of extensive or flowing underdrains conflicts with the purpose for this relevant and appropriate requirement. EBCV site (Site 5), WBCV site (Site 14), and Site 7a contain underdrains that conflict with the purpose of this requirement. The effect of this requirement on Sites 6b and 7b with anticipated flow along strike to natural tributaries is not determined.		
D4.19	**A6**	Page 7-17 states that the facility design would also incorporate TSCA requirements for a chemical landfill to accommodate waste containing PCBs at concentrations > 50 ppm. The discussion on page 7-17 further states that this will require waivers of two TSCA technical requirements. The first waiver is required for: "There shall be no hydraulic connection between the site and standing or flowing surface water…The bottom of the landfill liner system or natural in-place soil barrier shall be at least fifty feet from the historical high water table." It further states that Appendix G Chapter 4 provides evidence and rationale in the following three categories to support this waiver: (a) PCB management and disposal practices on the ORR; (b) Equivalent or superior effectiveness of site soils and engineered features on the EMDF; and (c) Results of risk assessment and related fate and transport modeling for PCBs. One basis for this waiver in Appendix G assumes PCBs will be disposed only in bulk waste at concentrations of < 50 ppm. It is unclear that justification for a waiver based on disposing bulk PCB waste with concentrations <50 ppm applies to granting a waiver for disposing PCB >50 ppm. a) PCB management and disposal practices on the ORR discussion: PCB management and practices are described on pages *G-12* and G-13. Third paragraph on G-13 states that as a result of these in-place procedures on the ORR, disposal of PCB waste in the existing EMWMF has been limited to bulk PCB waste disposal <50 ppm), and has been confirmed in Waste lot acceptance documents to date. It further states that it is expected that these procedures will continue in effect throughout operation of a future on-site disposal facility as well, thereby limiting all on-site disposal of PCB waste to <50 ppm. b) Equivalent or superior effectiveness of site soils and engineered features on the EMDF: Discussion on pages G-1 3 and G-14 demonstrate that the liner system proposed for EMDF should be superior to TSCA liner requirements. On page G-14 it also states that "In conjunction with the limitations imposed on the quantities and volume of PCBs allowed for EMDF disposal, these features limit the possibility of PCB releases that would present an "unreasonable risk of injury to health or environment" (emphasis added). The EMDF also relies on an underdrain network to lower the pre-existing water table. Underdrains are engineered pathways for future release of hazardous substances, pollutants, and contaminants from the landfill. Over time, the underdrains would contain constituents that release from the landfill directly above the underdrain and from other areas of the landfill where constituents are release to groundwater and said contaminated groundwater discharges to an underdrain. Underdrains may provide a diluted leachate discharge to surface that may flow in a ditch or tributary to surface water with potentially minimal sorption or other attenuation of constituents. The ditch or tributary may also provide for sediment erosion to Bear Creek. Bear Creek is classified for recreational use. Creation of extensive or flowing underdrains conflicts with the TSCA requirement that "There shall be no hydraulic connection between the site and standing or flowing surface water." c) Results of risk assessment and related fate and transport modeling for PCBs: Pages G-14 and G-15 describe results of risk assessment and modeling. This analysis did not evaluate the effect of an underdrain on PCB risk and transport of PCB contamination to surface water and Bear Creek. Fish downstream in Bear Creek already have PCBs in their tissue. The discussion once more assumes that PCBs are disposed in the future EMDF only in the solid phase and in relatively low bulk concentrations. It also assumes "significantly reduced infiltration rates within the landfill footprint."	TDEC states "It is unclear that justification for a waiver based on disposing bulk PCB waste with concentrations <50 ppm applies to granting a waiver for disposing PCB >50 ppm." A TSCA waiver is granted on the basis of "evidence to the Regional Administrator that operation of the landfill will not present an unreasonable risk of injury to health or the environment from PCBs when one or more of the requirements of paragraph (b) of this section are not met." The logic behind the argument presented in the RI/FS is that a huge majority of waste to be disposed at a future on-site facility will not contain higher than 50 ppm PCB. The disposal of lower concentrations of PCB solids (<50ppm) is more protective of human health and the environment, than disposal of much higher concentrations of PCBs. PCB wastes containing <50 ppm PCBs may be disposed of in municipal solid waste landfills with construction standards and engineered features far less protective than those proposed for the EMDF. Appendix G reviews the compliance agreement between DOE and EPA Region 4 for properly managing and disposing of PCBs on the ORR. The agreement, originally written and signed in 2008 and updated in 2012, places reporting and management requirements on legacy PCB waste on the ORR. It requires that disposition pathways for that legacy waste be identified. The PCB legacy waste is reported in three tables: A, B, and C. To date, all wastes in Tables B and C have been disposed of and the tables are "closed". Table A contains a list of remaining PCB legacy waste on the ORR. Several waste streams on that list are also transuranic waste (in addition to containing PCB contaminants), so they are not eligible for disposal in the proposed (or existing) on-site disposal facility. Another waste is identified as "no path" waste that will likely be disposed offsite, but in any case could not be disposed in an on-site CERCLA landfill. There is one waste stream identified on the list as possibly eligible for disposal in an on-site CERCLA disposal facility, the Disposal Area Remedial Action (DARA) soils. The OREM baseline identified this waste (~4,000 cy) for offsite disposal. However, it may be able to be disposed in an on-site TSCA disposal facility. Detailed characterization must be performed to answer that question. As a percentage of landfill capacity, this waste would only be about 0.2% of the capacity of a 2.2 M yd^3 landfill. In terms of mass of PCB allowable in a TSCA landfill, the mass of PCB contaminants in the DARA waste, assuming it was at the maximum allowable land disposal concentration of 500 ppm, would only be approximately 0.1% of the maximum allowable PCB mass in the landfill. This information provides the basis for demonstrating protectiveness from disposal of PCBs, and requesting a waiver to the two TSCA requirements as discussed in the RI/FS. Language in the RI/FS will be modified as necessary to clarify this position in the document. With regard to potential migration of PCBs via underdrains, the proposed Site 7c, without any significant underdrain system, would preclude this potential pathway.	DARA soils are currently being evaluated for disposal in EMWMF. The 4,000 cubic yards of DARA soils should either be disposed offsite or placed in EMWMF so that a TSCA waiver would not be needed for EMDF.
D4.20	**A7**	Page 7-18, first paragraph, the second TSCA requirement requiring a waiver is needed for EBCV (Site 5) only and requires "The landfill site shall be located in an area of low to moderate relief to minimize erosion and to help prevent landslides or slumping. The discussion on page G-16, Section 4.2.2. states that the majority of the EMDF footprint (about three-fourths of the footprint area) lies on existing slopes of 30% steepness or less, while only about one-fourth of the footprint is developed on steeper slopes of Pine Ridge. Page G- 15, Section 4.2.1 states that PCB limiting procedures are expected to continue thereby *limiting all on-site disposal of PCBs waste* to *<50 ppm.* This information was given as evidence the proposed facility will not pose an unreasonable risk of injury to health or the environment from PCBs when the requirement is not met. The basis for this waiver in Appendix G assumes PCBs will be disposed only in bulk waste at concentrations of < 50 ppm. It is unclear that justification for a waiver based on disposing bulk PCB waste with concentrations <50 ppm applies to granting a waiver for disposing PCBs >50 ppm.	See the response in previous comment. A waiver would not be granted to dispose of PCBs at any particular concentration, rather, based on evidence presented, the waiver would be granted on the ability of the proposed action to "not present an unreasonable risk of injury to health or the environment from PCBs when one or more of the requirements of paragraph (b) of this section are not met." The evidence presented supports the claim that PCBs proposed for disposal will not present an unreasonable risk of injury to health/environment because: (1) PCB concentrations historically, as disposed in the EMWMF, are below concentrations that require the added protection provided by the regulations being waived (e.g., PCB concentrations are < 50 ppm) and future disposal at EMDF is expected to produce similar waste streams also containing PCBs below 50 ppm, (2) disposal of PCBs of higher concentration (> 50 ppm) are under agreements with EPA Region 4 for disposal management, where a single	DARA soils are currently being evaluated for disposal in EMWMF. The 4,000 cubic yards of DARA soils should either be disposed offsite or placed in EMWMF so that a TSCA waiver would not be needed for EMDF.

			remaining legacy waste stream has been identified as a potential, higher PCB concentration waste to be disposed in the current landfill or a future landfill, and the ORR has completed disposal of the great majority of PCB waste identified under that Compliance Agreement, (3) liquid form wastes (PCB in pure form are liquids) are prohibited from disposal in the proposed on-site facility, and (4) modeling of the disposal of PCBs at 1 kg/m3 (~ 300 ppm) demonstrates that this contaminant does not present a risk to human health or the environment.	
D4.S.02	**A8**	Page 6-9, 2nd paragraph: *"No known federal- or state-listed T&E species have been identified in the EBCV site area (Option 5), except for Northern long-eared bats, which are listed as threatened. An acoustic bat survey conducted by ORNL personnel in August 2013 at and near Site 5 prior to timber recovery did not detect any Gray or Indiana bats that are listed as endangered species, but did identify Northern long-eared bats (See Appendix E for details)."* Did DOE previously notify the U.S. Fish and Wildlife Service regarding timber recovery at this site? Given the threatened Northern Long-eared bat was detected onsite, has DOE been in Section 7 consultations with the USFWS regarding the EBCV site (Option 5)? Under Section 7 of the Endangered Species Act, Federal agencies must consult with the U.S. Fish and Wildlife Service when any action the agency carries out, funds, or authorizes (such as through a permit) *may affect* a listed endangered or threatened species. This process usually begins as informal consultation. A Federal agency, in the early stages of project planning, approaches the Service and requests informal consultation. Discussions between the two agencies may include what types of listed species may occur in the proposed action area, and what effect the proposed action may have on those species.	Timber recovery in the Site 5 area was conducted for trees that had been felled by a downburst in the area. Timber recovery was completed under a different DOE entity than OREM (OREM is not the DOE "owner" of site 5.). As stated in the document: *"Acoustic bat surveys were completed by ORNL around the EBCV Site after the May 2013 downburst there to assess the potential for T&E bat species prior to timber recovery."* (D4 RI/FS page 7-26) and *"An acoustic bat survey was conducted by ORNL Natural Resources Division personnel to determine species of bats present in the windthrow area near Site 5 prior to approving timber recovery (K. McCracken, pers. comm. 2014). Acoustic monitors were placed at the locations shown by green dots in Figure E-56. Six bat species were detected as shown in Table E-15. Of those only one, the Northern long-eared bat, is listed as threatened."* (D4 RI/FS page E-136). If TDEC is interested in further information regarding the survey conducted by ORNL, they are encouraged to contact those personnel referenced here.	TDEC does not agree. The response does not address the question about consultations with the US Fish and Wildlife Service (USFWS) regarding threatened and endangered bat species at Site 5. Little or no data are available regarding the presence of threatened and endangered bat species at Sites 7a, 7b, and 7c. In accordance with Section 7 of the Endangered Species Act, DOE must consult with the USFWS prior to any action in those areas that may affect a listed endangered or threatened species.
D4.S.03	**A9**	Page 6-14. last paragraph titled: Ecological/cultural resources: *"No recent site-specific surveys to identify T&E species have been completed for Site 14. Ecological conditions for the WBCV area were reported in an environmental impact statement data package for the LLWDDD program published in 1988.* This study is outdated for the purpose of establishing current T&E species status. TDEC agrees that detailed assessments to evaluate potential impacts to wetlands and to identify T&E species would be warranted at Site 14 if the site is selected for construction, as stated on page 6-15. Furthermore, as NEPA values are to be incorporated into CERCLA, TDEC expects a thorough evaluation of ecological and cultural resources at any candidate site before approval of an alternative that would authorize construction of a disposal facility on the site.	Yes, DOE agrees that the study is outdated, as the document goes on to state *"Other sites, should one be selected, would have to undergo a detailed T&E species survey, as well as a wetland delineation and hydrologic stream determination survey to determine impacts to these species and areas."* (D4 RI/FS page 7-26) and *"As previously noted, detailed surveys are required early in the planning process and prior to any construction in order to satisfy applicable regulations and statutes, and DOE requirements."* (D4 RI/FS page E-142) Cultural resources have been identified within the Bear Creek Valley area, and are noted on figures (e.g., see Figures E-58, E-59, E-60). See pages E-139 to E-142 for a discussion of those results. DOE recognizes that, once a site is selected, detailed surveys will be required. The previously gathered/reported information (hydrological, geological, ecological, cultural, T&E species) throughout Bear Creek Valley is presented in great detail in the document (Appendix E, 233 pages) to give as complete a picture as possible, and to help in any way differentiate between sites. It should be pointed out that some types of surveys are used to help determine mitigation plans should an issue be illuminated. However, under most circumstances, these types of surveys (T&E, ecological/cultural) would not preclude the use of a site, per se, and thus would only be invested in once the site has been selected.	TDEC agrees.
D4.S.04	**A10**	Page 6-20. 3rd paragraph titled: Ecological/cultural resources: *"Two separate surveys to identify T&E species of vascular plants and fish were completed in 1998 for the EMWMF that included the Site 6b area (see Appendix f for details). Neither survey identified T&E species in the Site 6b area, although recommendations were made to preserve habitats and implement best management practices to protect the Tennessee Dace in downstream areas. ORR ecological surveys mapped a "natural area 28" across and adjacent to the Site 6b area (See Appendix f) that includes wetlands delineated east and west Of the site. Wetlands on the east and west sides of Site 6b along the NT-5 and NT-6 tributaries were delineated by Rosensteel and Trettin (1993) that could be impacted by EMDF construction (See maps and details in Appendix f). Surveys to evaluate potential impacts to wetlands and other T&E species may be warranted at Site 6b if the site is selected for EMDF construction."* As discussed in comment 3 above, the documents cited in this paragraph are outdated for the purposes of establishing the current status of T&E species. Given that the Northern Long-eared bat was detected in an acoustic survey in Bear Creek Valley as recently as 2013, bat survey data for any candidate site should be collected prior to approval of an alternative that would allow a facility to be constructed on the site.	Yes, DOE agrees and has noted that additional surveys will be required once a site has been selected. Refer to the response to Comment D4.S.03 above.	TDEC agrees.

D4.S.05	**A11**	Page 6·81: The PreWAC values listed in Table 6-5 do not include the non-carcinogenic PreWAC for uranium of 52.2 mg/kg identified in Table H-12 (page H-81). Presumably~~.~~, uranium non-carcinogenic PreWAC limits were calculated based on a Hazard Index (HI) of 3. The non-carcinogenic pathway for uranium metal is based on a reference dose of 0.003 mg/kg-day. Since this reference dose is the same for all isotopes of uranium, the PreWAC for the non-carcinogenic threat from uranium metal should be determined by EPA approved analytical methods and reported as total uranium in units of mg/kg instead of speciation into the various uranium isotopes.	DOE agrees that any toxicity-based uranium preWAC should be based on total uranium. See also the response to comment D4.02.	See TDEC Informal Dispute Position D4.02.
D4.S.06	**A12**	Page 6-51. Section 2.2.4.8. Longevity of Engineered Features Cover/Liner Systems: *Geomembrane liners of the landfill liner system at all sites would control releases of leachate to ground water for their design life reported to extend from 500 to 1000 years or more (Koerner, et al. 2011, Rowe, et al. 2009a, Benson 2014, EPA 2000). Both cap and liner systems contain geomembranes to prevent water infiltration into the waste, reduce contact of water and waste, and minimize leachate production and migration. As described by Bonaparte et 01. (2016), it appears that HDPE geomembranes of the type being used in some MLLW disposal facilities are relatively unaffected at total alpha doses of 5 megarad (Mrad), or more. These geomembranes are also reportedly unaffected by radiation from gamma and/or beta sources until total doses reach on the order of 1 to 10 Mrad, which is much higher than what would be expected to be disposed in the EMDF.* TDEC agrees that properly designed and installed geocomposite barriers may control leachate releases to groundwater for many decades or even centuries. However, the difference between a service life of a few hundred years and a thousand years might be critical for isolation of an isotope like strontium 90, which would require 30 to 40 half-lives, or about 1000 years to decay from the proposed limit set by the administrative waste acceptance criteria to levels that would be innocuous in leachate. TDEC also agrees that disposal of waste that could produce a total dose of 1 megarad to the geomembrane in either cap or liner is unlikely, due in part to the small amount of waste that is likely to be generated with high concentrations of beta/gamma emitters and in part to shielding by clay and drainage layers. However, as the proposed administrative WAC would allow 4600 Curies per cubic meter of Cesium 137 and places no limits on Cobalt 60, it is not clear to TDEC that localized liner damage due to radiation fields would be completely impossible without dose calculations and possibly further WAC restrictions.	The RI/FS uses a conservative estimate of 500 years for the lifetime of geosynthetics in modeling the risk to a receptor. This modeling indicates that Sr-90 does not pose a risk to the receptor at any time. The NRC indicates that a time frame of 300 years is sufficient to reduce the concentrations of short-lived isotopes (which includes Sr-90) in a landfill to innocuous levels. ("300 years, approximately the time required for Class-B waste to decay to innocuous levels..." (47 FR 57457). Additionally, recent research by prominent researchers in the field of geosynthetics (C.H. Benson 2016 and Bonaparte et al, 2016)[1], based on CERCLA waste disposal (specific waste contaminants and chemical constituent concentrations present) currently occurring at DOE complexes throughout the country, indicate minimum service lives of 1400 years may be expected. Localized damage to geosynthetics due to high radiation fields is very highly unlikely, nearing impossible. In the event waste with the high rad levels described were received, EMWMF (for example) has several measures in place that would help protect the geomembrane liner. Likewise, a future facility would have the same controls in place. (As an aside, in the event there were some small localized exposure of the liner to a high gamma dose, it would be so small an area compared to the entire landfill/liner system that it would be insignificant in terms of providing a breach of the liner.) • All waste streams must go through a rigorous approval process to ensure it meets the WAC before it is approved for disposal at EMWMF. o Waste with activity exceeding 30,000 pCi/g beta-gamma is evaluated on a case-by-case basis to ensure appropriate precautions are taken for safely handling, transporting, and disposing of such items. o Increased rad levels would likely trigger increased safeguards related to the health and safety of personnel. Not only will these increased safeguards reduce the dose rate during transportation, unloading, and disposal, they will serve to reduce the long-term dose rate to the geomembranes. o Remote-handled waste is not approved for disposal at EMWMF. • As alluded to in the comment, geomembrane in the cell liner system and closure cap is well separated from any significant rad exposure. Geomembrane on the cell floors is beneath at least 2 feet of protective cover (1 foot of siliceous rock and at least 1 feet of soil). Geomembrane on the berm side slopes is beneath at least 1 foot of protective cover (at least 1 feet of soil), but hard containers will not be placed any closer than about 2 feet to the liner on the berm side slopes. Geomembrane in the closure cap will be at least several feet from any waste. o These measures provide distance and shielding. o With the prescribed rock and soil cover, beta activity from isotopes such as those described (i.e., Sr-90 and Cs-137) would not contribute to the geomembranes' total dose. Gamma from isotopes such as Co-60 would be the most likely dose contributor under the circumstances and should be used as the	As pointed out in comment D4.01, TDEC acknowledges that progress was made toward reaching consensus on groundwater modeling. While disagreements between TDEC and DOE remain on groundwater modeling, the intent of this comment is to point out that the risk assessment presented in the D4 RI/FS remains too narrowly focused and is formulated in a manner that is too rigid to provide realistic limits for certain contaminants of concern. TDEC agrees that, generally, there is little candidate waste on the Oak Ridge Reservation that might cause geomembrane damage. However, TDEC also believes that over a timeframe of 10 half-lives necessary to significantly weaken the source, concentrations at the limits imposed by administrative WAC of isotopes such as Cesium 137 (due to the gamma radiation emitted through the short-lived Ba-137m daughter) could result in radiation fields that could damage liner materials. TDEC believes that the proposed administrative WAC that limits isotope concentration based on the requirements for disposal in a geologic repository as opposed to shallow land burial may not be sufficiently protective and that other scenarios and pathways should be evaluated.

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[1] Benson, C.H. *Predicting Service Life of Geomembranes in Low-Level and Mixed-Waste Disposal Facilities*, Webinar Performance and Risk Assessment Community of Practice, May 15, 2016.
Bonaparte, R., M.Z. Islam, V.M. Damasceno, S.A. Fountain, M.A. Othman, and J.F. Beech *Geomembrane-Leachate Compatibility for U. S. Department of Energy CERCLA Waste Disposal Facilities*, Submitted for review, ASCE GEO Sustainability & Geoenvironmental Conference, Chicago, Aug 14-18, 2016.

			limiting factor in this case. Bonaparte et. al.[1] identify gamma doses of 1 to 10 MRad must be experienced to see a detrimental effect on geosynthetics. Current estimated Co-60 waste concentrations do not exceed 1.35e4 pCi/g (converts to 0.024 Ci/m3), and thus do not present a concern considering the distance and shielding provided. While there are no limits on Co-60 in waste according to the analytic PreWAC, dose limits to workers and thus auditable safety analysis (ASA) derived WAC would limit the receipt of waste that might pose a concern.	
D4.S.08	**A13**	Page 7-13. TDEC 0400-20-11-,17(1)(f): *"All proposed sites are situated such that upland drainage areas are minimized by locating the footprints as far upslope as possible."* TDEC is not sure this statement is true since several of the sites are proposed to be located on knobs separated from Pine Ridge.	The language will be reworded to clarify how this is accomplished for each site.	TDEC agrees.
D4.S.09	**A14**	Page 7-18. Section 7.2.2.3 Long-term Effectiveness and Permanence (On-site): The Residual Risk discussion is limited to the 1,000 year compliance period. Residual risk beyond 1,000 years is not considered in the Long-term Effectiveness and Permanence discussion.	Language has been added to this section to address functioning of underdrain systems over longer periods of time. Reliability of modeling and certainly ability to predict effectiveness decreases with time due to the inherent uncertainties associated with the characterization of future environmental conditions and human habits and therefore very limited discussion is presented on times past 1,000 years.	TDEC does not support a site with an underdrain that would produce flowing water once the liner is fully constructed. Prior to RI/FS approval, we need site-specific data demonstrating that any underdrain will be temporary and not flow upon liner completion. The FFA parties should conduct a DQO meeting to identify data needs. DOE should provide a technical facilitator for this meeting to ensure each party's concerns are acknowledged and appropriately addressed. TDEC expects that the ROD will clearly specify that any flow from an underdrain after liner construction will trigger additional investigation and landfill reconfiguration to eliminate the underdrain.
D4.S.10	**A15**	Page E-16. Figure E-l. BCV~~Bev~~ Phase I ROD land use zones ... : Symbols displayed on the map are missing from the legend. Please provide a complete legend that describes all map symbology, including existing streams, roads, and gray polygons west of Site 6b.	These are not symbols (roads and creeks). The roads are labeled on the figure. Bear Creek is labeled on the figure. The grey shaded areas have been added to the legend.	TDEC agrees.
D4.S.11	**A16**	Page E·18. Figure E·2. Existing contaminant source areas ... : A) Symbols displayed on the map are missing from the legend. Please provide a complete legend that describes all map symbology, including existing streams. B) Acronyms on the map (e.g., HCDA) are not defined on the figure or in the Appendix E acronym list. Please define all acronyms.	This map is from another source (as indicated in the figure title), and therefore the legend cannot be modified. Acronym HCDA has been added to the Appendix E list (that was the only acronym in the figure that that could not be found in the Appendix acronym list).	TDEC agrees.
D4.S.12	**A17**	Page E-24. Figure E-7. Potential EMDF sites in BCV with respect to the northern DOE site boundary and nearest Oak Ridge residents: The map is annotated to portray distances between potential disposal sites and existing (current) residences. For protectiveness of future residents, it would be more appropriate to show the distance to the DOE site boundary. Please revise the figure accordingly (and any calculations or estimates based on these distances). At a minimum, revise the figure title to accurately reflect that the map only addresses *current* residents.	Because calculations for particle dispersion during construction are made to existing residents, this map will not be changed. The title has been edited to note this is existing or current residents.	The response is unclear. As noted on page 7-15 of the RI/FS, NUREG 0902 states: "Disposal sites should be located in areas which have low population density and limited population growth potential. Disposal sites should be at least two kilometers from the property limits of the closest population centers." All candidate locations being evaluated for the proposed EMDF are within the corporate boundary of the city of Oak Ridge (population ~29,330). The term "population center" is not defined in NUREG 0902; however, in defining the "Population Center Distance" in 10CFR100.3 the NRC describes a densely populated center as one containing more than 25,000 residents. Otherwise, all the areas under consideration for the EMDF are within 2 km of the property limits of residents of the city in areas that have a potential to grow. Consequently, the interest is not only the current residents, but also the property limits beyond which DOE has no control. TDEC is seeking clarification on the issue.
D4.S.15	**A18**	Page E-32. Section 2.8.2. Hydrogeological Conceptual Models for EMDF Sites in Bear Creek Valley: *"Groundwater and surface water flow paths along and adjacent to the NT valleys adjoining the proposed sites ultimately lead downgradient toward the base level elevations imposed by Bear Creek which drains the entire valley toward the southwest."* As shown on Figure E-3 and other diagrams, the karstic Maynardville Limestone outcrops and dips steeply to the southeast along both sides of Bear Creek. As noted on page E-76: "*Stratigraphically and physically above the Maynardville, the Copper Ridge Dolomite dips to the southeast under the north flank and crest of Chestnut Ridge. Cavities in the Copper Ridge are generally larger than those in the Maynardville… Uncontaminated groundwater from the cavity/fracture network below Chestnut Ridge drains northward and discharges to Bear Creek and probably commingles with groundwater in the Maynardville karst.*" In karst settings such as this, groundwater has been demonstrated to flow beneath surface streams, and surface streams may have losing reaches, as Figure E-32 shows for Bear Creek. If the intent is to communicate that Bear Creek is a hydrogeologic boundary to groundwater flow, please include supporting evidence or cite a document where this is documented.	It is agreed that ground water flows beneath surface streams, etc. There is no intention to communicate anything beyond the statements as written.	TDEC agrees with the DOE response that groundwater may flow beneath surface streams in karstic formations such as the Maynardville Limestone. This means that some reaches of Bear Creek may not serve as a hydrogeologic boundary to groundwater flow. As written, the draft response appears to contradict the quoted statement from the RI/FS. TDEC recommends that DOE revise the response (and the RI/FS) to address the comment.
D4.S.18	**A19**	Page E-43. Figure E-18. Key changes to surface and groundwater hydrology from preconstruction through EMDF construction, capping, and closure: It is not clear how the relatively shallow upslope diversion channel will divert upgradient groundwater around the landfill. The diagram does not indicate how groundwater flow will be prevented from crossgradient (along-strike) areas into the area beneath the landfill, where the water table is predicted to be lowered.	The upslope diversion channel is for surface storm flow diversion and for shallow stormflow zone capture and diversion. This shallow stormflow zone that occurs within the subsurface of the topsoil zone during significant rainfall events is labeled in the Stage I part of the figure in upgradient areas. Capture and diversion of surface runoff and shallow subsurface stormflow zone ground water will reduce the volume of water available for water table recharge in areas upgradient of the footprint. The	TDEC understands that the NTs are natural discharge zones for shallow groundwater but does not accept that they intercept all strike-controlled groundwater flow, some of which is deeper. Regarding the response that "*along-strike underflow…has apparently not been observed at the existing EMWMF,*" it is not clear how available data support this statement. TDEC does not support a site with an underdrain that would produce

			diversion channel is not expected to intercept or divert upgradient groundwater flow at or below the water table to any degree, as illustrated in Figure E-18.There is expected to continue to be groundwater flow as indicated by the blue arrows, which are labeled as "shallow GW flow paths and discharge to NTs". A combination of recharge cutoff in the footprint due to the cover, significant fill areas which raise the geologic buffer and liner up relative to the groundwater table, and the underdrain blanket and trench drainage areas all serve to maintain the lowered water table beneath the landfill. The cross sectional nature of the figure precludes a 3D representation of anticipated flow paths, however, the base level elevations along the valleys of the NT-2 tributary on the east side, and the NT-3 tributary on the west side of the landfill would act as natural discharge zones for ground water to eliminate any significant ground water movement into areas beneath the footprint from along strike pathways from adjacent areas to the east and west. The prompt and steady decline of water levels shown in the water level hydrographs for the Phase I monitoring wells during periods with little or no precipitation indicates that the water table interval is continually draining toward and discharging to the low elevation areas along the NT tributaries. Along strike flow toward these adjacent NT tributaries from adjacent undisturbed areas is likely to follow fracture flow pathways in saprolite and bedrock developed over the eons that naturally converge toward and discharge to the NTs. The potential for significant along-strike underflow beneath the capped landfill therefore appears unlikely, and has apparently not been observed at the existing EMWMF.	flowing water once the liner is fully constructed. Prior to RI/FS approval, we need site-specific data demonstrating that any underdrain will be temporary and not flow upon liner completion. The FFA parties should conduct a DQO meeting to identify data needs. DOE should provide a technical facilitator for this meeting to ensure each party's concerns are acknowledged and appropriately addressed. TDEC expects that the ROD will clearly specify that any flow from an underdrain after liner construction will trigger additional investigation and landfill reconfiguration to eliminate the underdrain.
D4.S.19	**A20**	Page E-46 and Figure E-19. Water table contour map for Site 5 representing the highest groundwater levels for the winter/spring 2015 wet season: *"Of the proposed EMDF sites, the hourly water level data from the Phase I monitoring* at *Site* 5 *provides the only complete record of water table fluctuations over a full year of record. Figure E-19 illustrates the Site* 5 *seasonal high water table measured on April 21, 2015, reflecting the annual wet season peaks observed each year during periods of relatively heavy winter/spring precipitation (see Attachments A and B for details)."* A single year of water level data cannot adequately represent the potentiometric surface range over 1,000+ years. Describe any adjustments or safety factors that were applied to address this discrepancy.	There is no discrepancy and no adjustments or safety factors were applied. The water table map is merely provided to demonstrate reasonably representative seasonal high pre-construction water table conditions for the relatively undisturbed watershed area of the footprint. The purpose of Section 2.9 is to present the anticipated changes to the water table that will occur during and after landfill construction at any of the proposed sites. Once a site is selected and agreed upon, site-specific baseline water level data will be collected and used in engineering design and ~~can be used~~ to simulate and predict changes to the water table through construction phases and into post-closure periods. Also, refer to EPA comment D4.07 response for more information, which does take into consideration water table changes over a 15 year period. Contaminant transport modeling described in Appendix H does include conservative assumptions to account for the possibility of higher than anticipated groundwater elevations beneath the disposal facility. Specifically, the 22 ft thickness of the vadose zone assumed for the PATHRAE model (Table H-5 and Figure H-21) includes only seven feet (an average beneath the cell floor areas) of unsaturated structural fill between the bottom of the geologic buffer materials and the water table. The anticipated average thickness of this vertical interval is 19.5 feet (Figure H-22), based on the EBCV conceptual design and groundwater modeling,	TDEC agrees with EPA's position (see below), with the additional condition that data are collected to verify the seasonal high water table prior to RI/FS approval. The FFA parties should conduct a DQO meeting to identify data needs. DOE should provide a technical facilitator for this meeting to ensure each party's concerns are acknowledged and appropriately addressed. **EPA Position:** Water Table Depth At Alternative Sites - ISSUE OPEN COLLECT FIELD DATA; REVISE AND REVIEW REDLINE EPA recommends DOE ORR collect a round of field data to determine current water table depths at the Alternative Sites. This initial effort and further data collection during design is expected to address this matter.
D4.S.24	**A21**	Page E-74: The text cites Lutz and Dreier (1988), Please list the associated reference in Chapter 7, along with any others that are missing.	All the references made in Appendix E were cross checked to the references. The absent reference was made by a previous author no longer working on the project that was not provided in the D3 version. The full reference could not be located during finalization of the D4 but was left in the report. An appropriate reference was used to replace this reference (Dreier and Koerber 1990). See revised D5 RI/FS.~~.~~	Please provide the full reference (Dreier and Koerber, 1990) in the response and a copy of the document (or a link to its location online). TDEC finds citations of the following reference online, but we do not find the full document. Reference Dreier, R.B. and Koerber, S.M., 1990, Fault Zone Identification in the Area Surrounding the Y-12 Plant and Its Waste Management Areas: Preliminary Investigation, Y/TS 656, Oak Ridge Y-12 Plant.
D4.S.26	**A22**	Page E-78: *"The maximum thickness of this unsaturated zone between the top of the waste and the post closure water table is in the range of 100-150 ft thick at Site* 5 *(See conceptual design cross sections in Chapter* 6 *of the EMDF RI/FS Report)".* Please rephrase this sentence to state the minimum predicted thickness of the unsaturated zone between the bottom of the waste and the post-closure water table, which is the relevant thickness.	The text on page E-78 has been revised to address this comment, and includes the following sentence: "The average estimated post-closure thickness of the vadose zone beneath the disposal cell floors, based on the conceptual design and groundwater modeling for Site 5, is 34.5 ft, and the minimum thickness is ~~20~~ 10 ft. See Figure H-22, p. H-61, in Appendix H for a contour map of Site 5 illustrating the range in vadose thickness between the post-closure water table and the base of the geologic buffer	The response would be acceptable if it were corrected to state that the minimum thickness is 10 ft (not 20 ft), as shown on Figure H-22. The map includes thickness contours labeled 15 ft and at least one unlabeled contour with a value of 10 ft.

			across the site footprint.”	
D4.S.28	**A23**	Page E-94. Hydraulic Conductivity in Relation to Equivalent Porous Media Modeling. Third Paragraph. 9th line: A reference by Worthington (2003) is incompletely used in the D4. The reference is also missing from the references list (note the corrected reference is included below). The original reference that should be used is Worthington (1999) below. In that paper the discussion by Worthington (1999) as used in the D4 is only partially represented and does not advocate assuming that the setting can be assumed to be an equivalent porous medium and can be modeled as such. It is part of a discussion of several techniques typically used.	The reference to Worthington 2003 is a re-published version of the Worthington 1999 reference that TDEC points out in this comment. The 2003 reference has been added to the list of references. No change will be made to the document, as the quote is correctly given.	TDEC disagrees. The correct reference is Worthington (1999) (Attachment B to this table). The RI/FS quotes part of the introduction that is simply a synopsis of what other researchers have commonly done. However, Worthington (1999) says in the abstract that a comprehensive approach is needed where both conduits/channels and other parts of the bedrock must be sampled. It does not say or imply that an equivalent porous medium approach using MODFLOW is advocated.
D4.S.29	**A24**	Page E·102. Section 2.13.4 Groundwater Geochemical Zones. Fourth complete paragraph: TDEC comment TDEC.S.066 discusses deep groundwater circulation on the ORR and points out that Nativ et al. (1998) reply to the rebuttal of their original paper by Moline et al. (1998). The D4 version still does not quote the reply by the original author to the rebuttal. In rocks that have been faulted such as those on the ORR, TDEC would not presume, as stated in the RI/FS, that a finite number of borehole tests would be adequate to determine that permeable fractures at depth were absent or of minimal consequence.	Comment is noted.	The paragraph in the RI/FS is incomplete and misleading, and the DOE response does not address or resolve the TDEC comment. TDEC expects the revised text to acknowledge that the original authors (Native et al., 1998) replied to the comments by Moline et al. (1998) in support of their original position.
D4.S.30	**A25**	Page E-103. Section 2.13.4 Tracer Tests. First paragraph. 10th line. "informal unpublished document" : The results of tracer tests done in Bear Creek Valley are included in the TDEC Environmental Monitoring Report (2001).	DOE was provided with an informal stand alone file in MS Word describing the tracer tests in BCV. We appreciate the identification of the published source noted by TDEC. The reference will be noted in the text and added to the D5 version for clarification. Document was received from TDEC and added to the Administrative Record.	TDEC agrees.
D4.S.31	**A26**	Appendix E. Attachment A. page 1: *"The conceptual design for the EMDF includes the installation of underdrain systems beneath the landfill to ensure surface water and groundwater diversion, drainage, and lowering of the water table below the waste cells. The results of the Phase I site characterization are presented in relation to the existing site topography and proposed conceptual design for the landfill and underdrain system. The results support the concept that the water table can be effectively managed and lowered during and after construction to ensure that the water table does not encroach on the geologic buffer or waste materials placed above the buffer and liner systems."* The document should indicate any lessons learned from the failure of groundwater modeling to predict post-construction groundwater levels at the EMWMF with an acceptable level of certainty, as well as how any such lessons are incorporated in the EMDF conceptual design to ensure that the water table does not encroach on the geologic buffer or waste materials.	The new Section 2.9 in the D4 version of Appendix E, particularly subsection 2.9.1 – *Underdrain Effects*, was intended to more clearly address the use of underdrains to mitigate the problems associated with the rise of the water table that occurred at the EMWMF. Page E-44 in particular describes the following in relation to lessons learned from the EMWMF – *“The underdrains would also be extended far into the uppermost reaches of the headwater NT sub-tributaries to intercept and drain the headwater springs/seeps and ground water discharge zones along the main ravines and stream channels cutting into the southern flanks of Pine Ridge. The extensive underdrain network proposed for Site 5 contrasts greatly with the single straight line underdrain retrofitted for Cell 3 of the EMWMF. Placement of the underdrains along the entire lengths of the former stream channels and ravines is more likely to alleviate the potential for any upward incursions of the water table below the footprint that have been of concern at the EMWMF.”* See the remainder of Section 2.9.1 and 2.9 as a whole for a more comprehensive coverage of anticipated post-construction changes to the water table. With regard to predictive modeling at the EMWMF, it is unclear whether the EMWMF model addressed the backfilling of fine grained materials within the upper part of the former NT-4 valley, but the current EMDF model for Site 5 incorporates drain cells for the entire layout of the underdrain network and is thus believed to accurately reflect the layout and reasonably simulate the effects of the underdrain in lowering and maintaining a lowered water table.	TDEC does not support a site with an underdrain that would produce flowing water once the liner is fully constructed. Prior to RI/FS approval, we need site-specific data demonstrating that any underdrain will be temporary and not flow upon liner completion. The FFA parties should conduct a DQO meeting to identify data needs. DOE should provide a technical facilitator for this meeting to ensure each party's concerns are acknowledged and appropriately addressed. TDEC expects that the ROD will clearly specify that any flow from an underdrain after liner construction will trigger additional investigation and landfill reconfiguration to eliminate the underdrain.
D4.S.32	**A27**	Appendix E. Attachment A, Figure 1. Phase I Monitoring Locations at the Proposed EMDF Site: The Rome formation symbol defined in the legend does not match the symbol shown on the map. Please correct the legend or map for accuracy and consistency. This discrepancy should be resolved on other figures throughout the RI/FS report components (e.g., Appendix E, Attachment B, Plates 5 and 6).	The Cr/Crs notations will be modified for consistency.	TDEC agrees.
D4.S.33	**A28**	Appendix E, Attachment B. Cut/Fill Thickness Map: Symbols displayed on the map are missing from the legend. Please provide a complete legend that describes all map symbology, including existing streams and roads.	The existing legends in the upper left, upper right, and lower left corners appear to identify all relevant information. Roads are labeled and the paths of the NT stream channels should be obvious as shown by the blue line stream paths that are coincident with valleys.	Key roads are indeed labeled satisfactorily on the map. The NTs should also be labeled or identified as streams in the legend. While it may be obvious to technical staff at DOE and TDEC that streams are represented by symbols comprised of blue dashes and dots, this may not be obvious to members of the public. The RI/FS is part of the administrative record and is made available for review by members of the public, who are the ultimate customers.
D4.S.34	**A29**	Page G-13: Part of the discussion to justify a waiver of TSCA requirements is that all onsite disposal of PCB waste at EMWMF and future EMDF is limited to < 50 ppm. A PCB limit of 50 ppm should be established in the WAC for the future EMDF.	See responses to comments D4.19 and D4.20. Additional information has been added to the RI/FS to address the very small volume of PCB contaminated waste expected to require disposal in a future on-site landfill.	DARA soils are currently being evaluated for disposal in EMWMF. The 4,000 cubic yards of DARA soils should either be disposed offsite or placed in EMWMF so that a TSCA waiver would not be needed for EMDF.
D4.S.35	**A30**	Page F·20. Chapter 3. NATURAL PHENOMENA HAZARDS: *"Two natural hazards, tornados and earthquakes, are considered in this evaluation, since these are the most likely potential natural phenomena that could affect the EMDF."* DOE is to be commended for evaluating an air dispersion scenario. However, the source is modeled as being equivalent to waste disposed in EMWMF. While this might be reassuring that risks will be low if waste inventory in a future disposal facility is similar to EMWMF waste, it does not provide a basis for	The purpose of the natural phenomena hazard analysis provided in the RI/FS is to demonstrate the feasibility of siting the landfill based on the probability of a tornado in the region, but is not meant to develop radionuclide limits based on such. A full analysis for a selected site, with calculations that would limit the radionuclide concentrations based on a	As agreed by the FFA parties at the May 24, 2016 EPC meeting, the waste acceptance criteria (WAC) attainment process will be revisited before ROD approval. More scenarios, such as air dispersion, should be evaluated for the purpose of preWAC development.

		setting limits on concentrations of radionuclides that might contribute to either on-site or off-site risk during a tornado.	tornado is part of the safety basis analysis that is completed outside of the RI/FS. That analysis informs the development of Auditable Safety Analysis (ASA) based waste acceptance criteria, and results will be included in a WAC Attainment (Compliance) Plan that is a primary document subject to TDEC approval.	
D4.S.36	**A31**	Page H-24. Paragraph 3. Second Bullet: " ... *composite barrier layer that consists of a 40 mil thick high density polyethylene (HDPE) geomembrane layer ...* " and Page Ho26. Item 8. First Bullet " ... *proposed geomembrane (40 mil) ...* " and Page H-28. Table H 2. column 'Layer' (#5) and column 'Thickness' *(80* mil). The specified thickness of the composite barrier layer is inconsistent between the text and the table, with the text indicating 40 mil and the table indicating 80 mil. This needs to be corrected. Further, the barrier thickness in the cover layer should normally be the same as that in the liner (as indicated by the thickness of 80 mil shown for Layers 5, 12 and 15 in Table H-2; it is not clear if that is the case here.	The D4 RIFS conceptual design specifies a 40 mil HDPE membrane in the cover and two 60 mil membranes in the liner system. Table H-2 has been corrected.	If a 40-mil HDPE membrane is used for the final cover system and two 60-mil HDPE membranes are used in the liner system, then the revised conceptual plan should discuss how the water infiltration through the cover system will remain less than or equal to flow through the liner system, as stipulated in 40 CFR 264.310.
D4.S.43	**A32**	Appendix H. Attachment B. Table 1: Some of the Peak Effective Risk, PReff, (ELCR) included in Table 1 appear to be PRwell instead of PReff~~.~~. In other words, some of the PReff in Table 1 was derived from drinking from the groundwater well only and does not appear to include the risk from livestock watering and consumption of meat and produce grown on the farm.	The tabulated values are correct. In general, for the revised well location in the D4 RIFS, the dose contribution from food ingestion is very small or negligible in comparison to water ingestion.	TDEC requests additional clarification, as we are unable to verify the tabulated values are correct. It may be possible to resolve the comment through a meeting where DOE explains the calculations and derivation of the tabulated values.
D4.S.45	**A33**	Appendix H - Attachment B. Page 7. Section 2.2 HELP Model Output. Paragraph 1: The text indicates HELP model results for the long-term scenario are presented in Section 2.2.2; however, no Section 2.2.2 is provided in Appendix H - Attachment B. Further, output data for at least one run should be provided for some confirmation of the HELP model output.	This omission has been corrected.	TDEC agrees.
D4.S.46	**A34**	Response to Comment TDEC.S.001-: TDEC should clarify that the purpose of TDEC comment 5.001 was to identify problems with the current disposal facility that have not been resolved to TDEC's satisfaction. The comment response focuses on debating or denying the significance of these problems, and the D4 does not incorporate any major changes that reflect progress on outstanding EMWMF issues. During the five previous years since the FFS was scoped with the regulators, little consideration has been given to issues at EMWMF. DOE has only recently initiated discussions on the problems of elevated groundwater discussed in the comment and there has been little discussion on modifications to the approach to waste acceptance. To address the response to this comment, TDEC first notes that unregulated discharges of radioactive wastewater to Bear Creek occurred very early in EMWMF operations prior to facility expansion. The problems resulted primarily from excessive runoff from a large working face and water pending on a low permeability protective layer in cell 1 of EMWMF rather than the inability of the leachate collection system to convey water. With regard to the second individual comment response, it is true that releases occurring during waste generation and transportation are not directly the results of on-site disposal. However, these releases, such as the contamination of Highway 95 and the contamination of sewage sludge at the Rarity Ridge wastewater treatment plant, were, in part, the result of having abundant on-site disposal capacity and flexibility in the approach to waste characterization, which favored en masse removal actions rather than a more surgical approach to risk reduction. With regard to the groundwater intrusion into the EMWMF buffer and liner, TDEC's concerns were never strictly based on the pneumatic piezometer readings, as DOE has surmised, but on the apparent intrusion of groundwater into the liner prior to underdrain construction and persistent elevated water levels around the northeast end of EMWMF. The hypothesis that elevated piezometer readings resulted primarily from the increase in pore pressure due to the overburden weight of added waste is not consistent with the data that was presented in the referenced UCOR report, or with data collected subsequent to its publication. Pressure in pores under confined conditions increases almost instantaneously (at the speed of sound in water) and decays as consolidation occurs. In clay barriers, this decay may require months or years. The piezometer readings below cell 3 did not rise quickly during the time when cell 3 was most rapidly loaded, and the pressure recorded in the years since loading shows seasonal changes rather than decay. Finally, while the karst system in the Maynardville Limestone in Bear Creek Valley was documented in the BCV RI, as DOE states in the response to comment, no travel times were available except an arrival time for the short trace reported by Geraghty and Miller (1989). The Bear Creek RI does not reference the several tracer studies in west Bear Creek Valley after 1995 or tracing done in similar rocks in Melton Valley, many of which are now summarized in Appendix E of theD4version of this RI/FS. These studies did provide insight concerning the range of first-arrival times and center-of-mass travel times in Conasauga Group rocks such as those underlying the proposed sites. Changes to the fate and transport modeling made in theD4are seen by TDEC as positive and significant, but still don't necessarily provide a conservative assessment of risks to water resources from all contaminants of concern that are of interest. TDEC anticipates working to expand the scope of the risk assessment and ensure that on-site waste disposal can be done compliantly and cost effectively and welcomes the opportunity to work with DOE on improving the analysis of water pathway risk in the 04. As DOE states in the response, TDEC approval of and comments on the work plan (TDEC letter dated November 27, 2013) for the investigation of site 5 did not indicate that the site would be rejected on the basis of its location across the upper NT-3 valley or make any recommendations for avoiding Site 5 on the basis of its footprint across a "blue line" stream. However, TDEC believes that both discussions with DOE and the content of the approval letter made it clear that the site investigation would be made at risk. The letter states, on page 2, *"We appreciate DOE's cooperation with TDEC's request to perform this screening evaluation prior to the proposed plan and it should be understood that TDEC's acceptance of this Limited Phase 1 Site Characterization Plan for the Proposed Environmental Management Disposal Facility Site does not constitute an endorsement of the proposed EMDF location. It should also be understood that where the screening level evaluation should assist in understanding the hydrogeology and characteristics of the site, there are also other concerns that will have to be resolved prior to TDEC acceptance of the RI/FS."* TDEC regrets any miscommunication and has discouraged DOE from further characterization at this site and at other proposed sites until more progress can be made on resolving outstanding issues at EMWMF and agreement reached on issues concerning characterization and	With regard to the elevated water levels below the northeast area of the EMWMF, the extensive underdrain system proposed for Site 5 (EBCV) and the similar underdrain networks proposed for the other potential EMDF sites in BCV are all intended to ensure that the water table issues noted at the EMWMF do not occur at any of the proposed EMDF sites. Please review Section 2.9.1 of Appendix E (p. E-44 and E45) where the layout and properties of the conceptual design for the underdrains are described, and contrasts with the EMWMF underdrain are noted. The proposed underdrains would be laid out to follow existing NT stream valleys and extended up into the uppermost reaches of the NT tributaries to ensure that the water table is effectively drained and groundwater underflow is captured and drained. Upper valleys of the NT tributaries would not be backfilled with low permeability materials that might induce a subsurface damming effect at the level of the water table. Aspects of the underdrain described in Section 2.9.1 are clearly meant to address TDEC/EPA concerns and mitigate the lessons learned at the EMWMF. DOE agrees that no further characterization is warranted until consensus is reached among DOE, EPA, and TDEC on a suitable final site for the EMDF.	TDEC does not support a site with an underdrain that would produce flowing water once the liner is fully constructed. Prior to RI/FS approval, we need site-specific data demonstrating that any underdrain will be temporary and not flow upon liner completion. The FFA parties should conduct a DQO meeting to identify data needs. DOE should provide a technical facilitator for this meeting to ensure each party's concerns are acknowledged and appropriately addressed. TDEC expects that the ROD will clearly specify that any flow from an underdrain after liner construction will trigger additional investigation and landfill reconfiguration to eliminate the underdrain. DOE misquotes the TDEC comment. The TDEC comment states "TDEC regrets any miscommunication and has discouraged DOE from further characterization at this site and at other proposed sites until more progress can be made on resolving outstanding issues at EMWMF and agreement reached on issues concerning characterization and acceptance of waste at any future on-site facility."

<table>
<tr><td></td><td></td><td>acceptance of waste at any future on-site facility.</td><td></td><td></td></tr>
<tr><td>D4.02</td><td>**B1**</td><td>The last paragraph of page ES-4 of the D4 version of the RI/FS states "Based on these results, it can be concluded that most future CERCLA waste to be generated after EMWMF reaches maximum capacity would be able to be disposed at the proposed EMDF." This conclusion is repeated in slightly different but equivalent form throughout the document. including on page 1-8, in section 2.1.3 on page 2-5, in section 2.3, and in Appendix H. However, there is little evidence to back up this assertion in the document.

To the extent that time and resources have been available, TDEC has been able to verify that PreWAC limits for uranium and technetium presented in this RI/FS may fall within a reasonable range of waste acceptance limits that should protect health and environment from risks generated by a 2.2 million cubic yard radioactive waste disposal facility sited in Bear Creek Valley. Based on our current knowledge of contamination levels in future CERCLA waste, the limits suggested by the PreWAC would also preclude much of the projected CERCLA waste from the on-site disposal facility. At EMWMF, waste acceptance has been largely controlled by the levels of uranium and technetium isotopes in the waste. The majority of the waste disposed at EMWMF could not have been accepted under limits similar to those proposed in this PreWAC, 52 mg/kg for uranium and 45 pCi/g for technetium-99.

If the claim that the PreWAC demonstrates that majority of CERCLA generated waste can be disposed safely onsite should prove valid, then it follows that much of the CERCLA waste could also meet disposal limits established for the permitted Y-12 landfill or other permitted solid waste disposal facilities. This can be inferred from a comparison between the waste acceptance limits at the Y-12 permitted landfill and the PreWAC for the proposed facility. The limits imposed on any waste contaminated with depleted uranium (U-234 and U-235 below the naturally occurring isotopic abundance) would be more stringent at the proposed facility than at the Y-12 landfill. The technetium-99 limit at the Y-12 landfill is only 5 picoCuries per gram higher at the proposed facility than at the Y-12 landfill. Much of the projected waste from Y-12, including debris from buildings in the West End Mercury Area, is likely to be contaminated with depleted uranium. Birchfield and Albrecht (2012) report uranium concentrations at the 90 percent upper confidence level for Alpha 5 building structure at approximately 500 mg/kg, an order of magnitude greater than the PreWAC for uranium.

As stated on page G-12 (Appendix G, 4.1.1) of the RI/FS, PCB wastes with a PCB concentration greater than 50 ppm are not anticipated to contribute significantly to the quantity of CERCLA waste generated on the Oak Ridge Reservation. Page 2-4 states that RCRA F listed waste will not be disposed in the proposed CERCLA landfill, and characteristic waste must comply with the treatment standards of 40 CFR 268. Most RCRA and TSCA mixed waste, as well as low level radioactive waste which could be disposed in a future CERCLA disposal facility with PreWAC limits similar to those given in Appendix H, could be disposed in the ORR landfills.

This significant inconsistency between the numbers generated by risk assessment and the conclusions in the text effectively invalidates any cost comparison between the various alternatives set forth in the document. The limits on uranium and technetium, which generally match TDEC's attempts thus far to assess risks imposed by on-site disposal, show that rather severe limitations on waste acceptance will be necessary to ensure protection of human health and the environment at a radioactive waste disposal facility of this size and at these locations. Despite significant changes that address a number of regulator concerns, the D4 version of this document still fails to provide a sufficiently thorough risk assessment and enough additional information on candidate waste streams to form the basis for an informed decision concerning the value added by the proposed disposal facility to the overall remediation goals for the Oak Ridge Reservation.</td><td>Paragraph 1 requires no response.

The toxicity-based PreWAC limit for uranium has been removed because it was based on a hazard index of 3.0 and predicted that uranium concentrations peak in groundwater/surface water well beyond 10,000 years. Due to the extensive time frame considered, this limit has been removed. This modification addresses all concerns voiced in subsequent paragraphs (all of which are based on the toxicity limit for uranium, which was based on uranium concentrations expressed far beyond 10,000 years). Based on expected Tc-99 contaminant concentrations in Y-12 and ORNL future demolition debris and soil waste, DOE is comfortable with the limits associated with that contaminant.</td><td>(1) TDEC believes that modeling of reasonably foreseeable conditions may limit the volume of uranium and other isotopes that can be disposed in a protective manner.

(2) TDEC does not agree to remove uranium.

(3) DOE's response states there is little to no confidence in modeling past 1,000 years. Therefore, the referenced 10,000-year modeling period is suspect. Uranium poses a non-carcinogenic risk, and TDEC does not agree to assume that uranium does not pose a risk just because of uncertainty in modeling.

(4) TDEC believes uranium would pose a risk within 10,000 years and possibly within 1,000 years. TDEC does not agree to remove/ignore non-carcinogenic effects of uranium.

(5) TDEC does not agree that water quality criteria (in this case the MCL for uranium) should be applied for only 1,000 years. Application of the MCL over longer time frames may significantly change the WAC required for protection of water resources.</td></tr>
<tr><td>D4.06</td><td>**B2**</td><td>As stated in General Comment 2, Uranium risk-based PreWAC values may be limiting factors as to what may be placed in a future EMDF. Please see the table below.

<table>
<tr><th>Isotope</th><th>Non-carcinogenic Table H-12 (page H-81) HI=3 (mg/kg)</th><th>Carcinogenic Calculated 10-4 ELCR (pCi/g)</th></tr>
<tr><td>U233</td><td>60.5</td><td>57</td></tr>
<tr><td>U234</td><td>57.6</td><td>55.1</td></tr>
<tr><td>U235</td><td>52.2</td><td>50.7</td></tr>
<tr><td>U236</td><td>52.3</td><td>53.1</td></tr>
<tr><td>U238</td><td>52.2</td><td>55.2</td></tr>
</table>
PreWAC carcinogenic limits for Uranium-238 calculated using the risk-based approach included in the D4 RI/FS and a 10-4 ELCR will be on the order of 50 to 60 pCi/g. Table H-12 includes a non-carcinogenic PreWAC for uranium-238 of 52.2 mg/kg. The amount of future waste that meets uranium risk-based PreWAC limits should be evaluated to refine estimates of additional onsite landfill capacity needed. Risk based limits used for this evaluation must be consistent with CERCLA required carcinogenic risk range (i.e. 10-4 to 10-6) and non-carcinogenic (e.g. HI of 1 to 3) risk.</td><td>An error in calculating the HI-based limits for a child receptor was identified following the submittal of the D4 RIFS. This error resulted in preWAC values (those given in table H-12) that are a factor of two lower than the correct value, based on the D4 modeled contaminant concentrations and exposure assumptions. Tables H-12 and H-13 as well as Table 2 of Appendix H Attachment B have been corrected in the D5 revision.

Additionally, for the D5 RI/FS, EPA has requested that an HI of 3 be removed from the analysis.</td><td>TDEC agrees.

DOE also needs to back-calculate a PreWAC based on the maximum contaminant level (MCL) for uranium. Assessment of future conditions should evaluate against RAOs at the appropriate exposure endpoints.</td></tr>
<tr><td>D4.07</td><td>**B3**</td><td>The waste volume estimates in Chapter 2 and Appendix A include both wastes that may be suitable for disposal at the Y-12 industrial and construction and demolition landfills (ORR landfills), as discussed on pages 1 and 2 of Chapter 6, and an added 25 percent of the projected waste volume to account for uncertainty. Inclusion of landfill waste into the overall waste inventory inflates the quantity of waste requiring disposal in a CERCLA facility by an undetermined amount, as well as the differential cost between the on-site and off-site alternatives. The U.S. Department of Energy Office of Inspector General performed an audit in 2013 that identified 140,000 cubic yards of material disposed in EMWMF that could have been disposed at the ORR landfills.

Based on the candidate waste streams listed in Appendix A, TDEC might expect between 25 and 40 percent of the waste to be acceptable at the ORR landfills, depending on the level of waste segregation used. No characterization data is available to better define this range, which we acknowledge to be not much better than a guess. An effort to better estimate the probable quantity of waste suitable for disposal in the</td><td>Candidate waste streams listed in Appendix A have volumes given only that are associated with waste expected to be disposed via the alternatives presented in this document. Volumes from those candidate waste streams that will be suitable for disposal at ORR landfills were not included in Appendix A totals as explained in the RI/FS (those volumes were subtracted out prior to reporting in Appendix A) because they are not candidates for disposal under these alternatives analyzed.

Refer to response to D4.02 for the response to the remainder of this</td><td>As DOE has implemented their waste management strategy, significant volumes of waste listed Appendix A have already been slated for disposal at Y-12 landfills, including much of the debris from K-1037. Furthermore, DARA soils are currently being evaluated for disposal in EMWMF. The 4,000 cubic yards of DARA soils should either be disposed offsite or placed in EMWMF so that a TSCA waiver would not be needed for EMDF.</td></tr>
</table>

		ORR landfills should have been made, identified separately in Appendix A, and subtracted from the total volume needed for disposal of waste in a CERCLA landfill. In the past, DOE has indicated that radioactive waste disposal under the authority of the Atomic Energy Act as implemented by DOE Orders was impractical due to the anticipated quantities of mixed low level radioactive and TSCA or RCRA waste. As stated elsewhere in these comments, the D4version of the RI/FS states that DOE has no plans to dispose of significant quantities of either TSCA waste (> 50 ppm PCBs) or hazardous waste that exhibits a prohibited characteristic at the point of land disposal. In this case, additional on-site disposal alternatives might include disposal under DOE authority rather than through CERCLA. Also, since risk assessment of on-site disposal in theD4indicates that some key contaminants of concern may have waste acceptance limits similar to those on the ORR landfill, an expansion of current permitted solid waste disposal capacity might prove to be just as feasible as disposal authorized under CERCLA.	comment as it is essentially a repeat of that comment.	
D4.08	**B4**	The Remedial Action Objectives (RAOs) on page 4-1 and goals used to determine PreWAC concentrations on page 4-2 are inconsistent. RAOs on page 4-1 appear applicable as long as CERCLA waste is managed, disposed or entombed at the landfill and do not include a time limit. However, page 4-2 *goals* include a 1,000 year compliance period. Additional discussion of water resource protection on page H-75 references the goal language, not the RAOs, and implies that water resource protection is only accomplished within the 1,000 year compliance period. Similarly, the response to TDEC comment TDEC.S.l00 references protection of water resources and ecological receptors within the 1,000 year compliance period, implying that protection of water quality and the environment after 1,000 years is not necessary. TDEC reads the RAOs on page 4-1 to include protection of water resources as long as CERCLA waste is in the landfill, a time period which presumably extends beyond 1,000 years. Remedial Action Objectives need to be consistent and consistently applied.	The RAOs are applicable as long as CERCLA waste is managed. The 1,000 year goal is in reference to modeling. Meeting RAOs past 1,000 years, because modeling is not to be relied on in decision making processes due to the increase in uncertainty of the predictions, is not assured via the modeling. Follow-on monitoring is required until there is no longer a risk present. Monitoring during operations and post-closure is completed per ARARs. That monitoring will continue, per CERCLA, as long as a risk is present. The language in the RAOs section indicates this, as it states (see bolded language in particular): ***RAOs one and two are partially satisfied for the On-site Disposal Alternative through meeting ARAR location and siting*** *requirements, design and construction requirements,* ***monitoring requirements,*** *and closure/post-closure requirements as summarized in Appendix G. Specifically, these requirements include but are not limited to the following:* • *Avoidance of floodplains; wetlands; archaeological resources; and endangered, threatened or rare species. Where avoidance is not possible, mitigation measures will be taken.* • *Siting requirements (some of which will require waivers that are justified in this document) regarding seismic stability; soil properties; hydrogeologic conditions; presence of natural resources; and capability of the site to be monitored.* • *Design requirements regarding the liner system; leachate detection, collection/storage, and treatment systems; geologic buffer system; run-on/run-off control systems; and final cover systems.* • *Construction requirements regarding installation and quality assurance of components as well as management of storm water.* • *Operational requirements concerning the acceptance and receipt of waste (form, characterization, etc.); emplacement of waste in the landfill; transportation of waste; security systems; storm water management; inspections; training; contingency planning; inventory and record keeping; inspections; and sampling and monitoring of leachate, ground water, and surface water.* • *Closure requirements regarding manner of closure; monitoring; security and land use control; and final cover functioning and design.* • ***Post-closure requirements including institutional controls; maintenance; monitoring; and general care.*** Additionally Section 7.7 of Appendix G states (see bolded language in particular): ***Post-closure care must begin after closure and must continue for a period to be determined by the FFA parties.*** *Property use must be restricted and the facility must be maintained to protect the integrity of the landfill cover and other components. General post-closure care includes site surveillance and maintenance, maintenance and operation of the leachate collection system as long as leachate is being generated,* ***and environmental monitoring, including ground water detection monitoring.*** More detail on the post-closure groundwater monitoring is provided in Section 7.8 of Appendix G. As stated, this monitoring must continue for a period to be determined by the FFA parties.	TDEC agrees with much of this comment: **We agree:** The Remedial Action Objectives (RAOs) are applicable as long as CERCLA waste is managed. Since RAOs are applicable as long as CERCLA waste is managed, we believe that CERCLA requires remedial action to address releases that violate the RAOs, irrespective of when the release occurs. **We agree** that uncertainty is inherent in modeling and that uncertainty increases as predictions are made further into the future. Probabilistic or other methods may be used to support risk-informed decisions. DOE should contract an independent third party to complete such modeling efforts. DQO and scoping meetings should be held to reach triparty consensus on scenarios and exposure pathways that will be used for evaluation of risk, on software choices, and on model input parameters. DOE should provide a technical facilitator for these meetings to ensure each party's concerns are acknowledged and appropriately addressed. Meeting RAOs past 1,000 years is not assured via the modeling because modeling is not relied on in decision making processes due to the increase in uncertainty of the predictions. **We agree:** Follow-on monitoring is required until there is no longer a risk present. **We agree:** Per CERCLA, the monitoring will continue as long as risk is present. **We disagree:** DOE's RTC states: Post-closure care must continue for a period to be determined by the FFA parties. TDEC's position is that CERCLA post-closure care must continue until post-closure care is no longer needed to meet RAOs, and the FFA parties do not have the authority to agree to stop post-closure care if doing so may result in violation of RAOs or CERCLA. **Discussion:** Therefore, when determining the waste acceptance criteria, the FFA parties should determine how long they intend the United States Government and the Department of Energy (DOE) or DOE's successor to perform post-closure care, monitoring, and remedial action. The associated costs of post-closure care, monitoring, and remedial action should be incorporated in any revisions of the RI/FS. For example, a preliminary waste acceptance criteria (PreWAC) for U-238 (depleted uranium) of 3,170 pCi/gram is proposed by DOE. If all of the waste disposed in EMDF were U-238, this would equate to 45 to 46 million pounds of U-238—a quantity comparable to that already disposed in the Bear Creek Burial Grounds (BCBG). U-238 has a half-life of about 4.4 billon years. The EMDF sites are located in Bear Creek Valley, and the combination of local geology, hydrology, and siting criteria should not prevent future releases from entering groundwater and surface water and impacting downstream areas designated for unrestricted use. Remedial action would be required to capture and treat U-238 until sufficient U-238 has leached such that further release would not violate RAOs. With DOE's proposed PreWAC, we suspect remedial action could be needed for tens of thousands to hundreds of thousands of years. TDEC disagrees with several assumptions, such as there will be no differential settling of the waste, in modeling for the 1,000-year compliance period and expects the need to begin perpetual remedial action will be sooner instead of later.
D4.09	**B5**	Disregarding the Remedial Action Objectives, the risk methodology specified in the RI/FS, and the CERCLA 10-4 to 10-6 risk range in	For the EMDF D4 RI/FS, PreWAC for radionuclides predicted to peak	TDEC does not accept the 500 mrem/year dose as a means to develop a

		proposing carcinogenic PreWAC limits for radionuclides is unacceptable. The Remedial Action Objectives (RAOs) specify: Page 4-1 : "1. *Prevent exposure of human receptors* to *CERCLA waste (or contaminants released from the waste into the environment) that exceeds* a *human health risk of 10-4 to 10·6 Excess Lifetime Cancer Risk (ELCR) or hazard index of 1."* Page 4-2: *"These PreWAC waste concentration limits are determined based on demonstrating the following goals are met during the 1,000 year compliance period: l0-4 ELCR and HI of* 1 *...for the compliance period (to 1,000 years) using* a *resident farmer scenario, and 10-4 ELCR and HI of 3 at times exceeding 1,000 year compliance period."* However, on Page H-75: *"A ratio is set up* to *scale this assumed concentration and corresponding risk to the appropriate carcinogenic risk goal (set* as *10-5 for contaminants that peak <1,000 years post closure, and* as *10-4 for those COPCs predicted to peak between 1,000 and 2,000 years, see Table H-1), which allows calculation of the PreWAC limit for each radionuclide COPC. For radioisotopes predicted to peak after 2,000-years post closure, preliminary administrative limits based on modeling exposures at 100* m *have been assigned ... "* The methodology to assign PreWAC limits in the D4 RI/FS is a significant change from the D3 version. The D3 version calculated the PreWAC for carcinogenic radionuclides based on formulas in the RI/FS for all constituents that peak after 1,000 years utilizing a 10-4 ELCR, similar to the approach the D4 utilizes for the time period 1,000 to 2,000 after closure. The D4 RI/FS disregards Remedial Action Objectives and the CERCLA 10-4 to 10-6 risk range for constituents that, according to theD4RI/FS, peak after 2,000 years. There are no analyses that demonstrate risk is within the CERCLA risk range where preliminary administrative limits are assigned for constituents that peak after 2,000 years. For example, using the equations and approach specified in the D4 RI/FS, a carcinogenic PreWAC on the order of 55 pCi/g may be calculated for U-238 utilizing a 10-4 ELCR. The D4 RI/FS includes 3,170 (3.17E+03) pCi/g as the carcinogenic PreWAC limit for U-238 in Table H·l0 (not an Adjusted PreWAC). Table H·10 includes no reference to preliminary administrative limits. A value of 3,170 pCi/g equates to about a 5.75E·03 (5.75 per thousand) ELCR. PreWAC limits for only four carcinogenic radionuclides (i.e. C-14, Cl-36, H-3, and Tc-99), highlighted in bold in the table below, were determined by the risk-based methodology specified in the D4 RI/FS. PreWAC limits for the remaining 28 carcinogenic radionuclides (i.e. Am-241, Am-243, Cf-249, Cf-251, Cm-245, Cm-246, Cm-247, Cm-248, 1-129, K-40, Nb-94, Ni-59, Np-237, Pa-231, Pu-239, Pu-240, Pu-242, Pu-244, Re-187, Se-79, Si-32, Sn-126, U-233, U-234, U-235, U-236, U-238, and Zr-93) are presumably set using preliminary administrative limits. The process and rationale for modifying each carcinogenic radionuclide PreWAC with the administrative limit is not transparent and is not discussed in Appendix H. Risks for these 28 radionuclide PreWAC limits (modified by the administrative limits) range from approximately 2.6E-02 (2 .6 per hundred) to 9.8E-04 (9.8 per ten thousand) ELCR, based on the limited resident farmer scenario. The table below [see pages 13-14 in the original TDEC letter (May 16, 2016); Attachment D to this table] estimates risk-based PreWAC concentrations for radionuclide carcinogenic risk and compares the risk numbers to the D4 RI/FS PreWAC Table H-10 and Table H-13 limits. The calculated ELCR for the D4 Proposed EMDF PreWAC limits are also included.	after 2000 years were based on a risk-informed, 500 mrem/yr radiological dose criterion. The flow and transport model predictions and receptor exposure assumptions utilized were the same as for the risk-based PreWAC, but rather than estimating ELCR with a carcinogenic slope factor (for comparison to a specific target risk level), the peak annual radiological dose was calculated using water ingestion dose conversion factors for each radionuclide. This predicted peak dose corresponding to the assumed unit waste concentration (1 Ci/m3) was then used to estimate the waste concentration limit (PreWAC) corresponding to the 500 mrem/yr criterion. The assumptions underlying this calculation are exactly the same as those made for calculating risk-based PreWAC. Appendix H has been revised to detail the PreWAC approach for radionuclides predicted to peak after 2000 years.	responsible PreWAC and rejects that using the 500 mrem/yr dose as consistent with CERCLA. TDEC's comment included language that excess lifetime cancer risks for the 28 radionuclide PreWAC limits developed using the 500 mrem/yr dose range from approximately 2.6E-02 (2.6 per hundred) to 9.8E-04 (9.8 per ten thousand), based on the limited resident farmer scenario. These risk levels are inconsistent with CERCLA and Remedial Action Objectives (RAOs) for EMDF. The 3,170 pCi/gram U-238 PreWAC concentration discussed in D4.08 was derived from the 500 mrem/year dose. As discussed in D4.08, establishing 3,170 pCi/gram as the U-238 PreWAC will require the United States Government and future generations to perform remedial actions to meet CERCLA Remedial Action Objectives for an extremely long time. Remedial Action Objectives (RAOs) specified on page 4-1 of the RI/FS include: a. Prevent exposure of human receptors to CERCLA waste (or contaminants released from the waste into the environment) that exceeds a human health risk of 10-4 to 10-6 Excess Lifetime Cancer Risk (ELCR) or Hazard Index of (HI) 1. b. Prevent adverse impacts to water resources or unacceptable exposure to ecological receptors from CERCLA waste contaminants through meeting chemical-, location-, and action-specific ARARs, including RCRA waste disposal and management requirements, Clean Water Act (CWA) Ambient Water Quality Criteria (AWQC) for surface water in Bear Creek, and Safe Drinking Water Act (SDWA) MCLs in waters that are a current or potential source of drinking water. An approach the parties should consider is replacing the 500 mrem/year dose with appropriate concentrations derived from the RAOs and back calculating the PreWAC using a process similar to what DOE used to back calculate the PreWAC based on the 500 mrem/yr dose. That process: 1. Should allow for development of a PreWAC for radionuclides and their progeny that does not assume the United States Government will perform perpetual remedial action to control releases and protect the public. 2. Would allow the parties to focus on coming to agreement on modeling that determines dilution or attenuation between the landfill and the well at 100 meters and set aside some of the other modeling issues such as groundwater travel time. 3. Would allow the parties to focus on the waste source term with the goal of not developing a landfill with sufficient mass to require perpetual remedial action when engineering controls fail. This may require utilizing the DOE/NRC RESRAD family of codes to evaluate radionuclides and their progeny in the waste and leachate and potentially other appropriate models. 4. Should be cost effective, if costs of future remedial actions are taken into account. **If DOE is unwilling to develop a PreWAC based on RAOs, then DOE-OR should go forward with submitting the performance assessment (PA) and composite analysis (CA) to LFRG instead of submitting another RI/FS. DOE-OR determines the schedule for submitting the PA to the LFRG, and TDEC understands the LFRG review/approval process takes about 6 months to complete. LFRG would establish a PreWAC for radionuclides for EMDF that the FFA parties could modify to be consistent with CERCLA.**
D4.13	**B6**	Page H-75 of the RI/FS specifies "...water resource protection is accomplished within the 1,000 year compliance period as specified in the RAOs .... These PreWAC waste concentration limits are determined based on demonstrating the following goals are met during the *1,000 year compliance period:* Appropriate AWQC for chemicals (risk-based discharge levels for radionuclides in Bear Creek and tributary surface water are per the *Integrated Water Management Focused Feasibility Study* [UCOR, 2016].)" *(emphasis added).* TDEC comments to the *Integrated Water Management Focused Feasibility Study* (UCOR, 2016) are incorporated into these RI/FS comments by reference.	Comment resolution to the IWM FFS comments are similarly incorporated by reference. Any resolution of comments on the IWM FFS that would affect language in the RI/FS will thus be incorporated; it is noted that the RI/FS was written such that statements incorporating issues dealt with by the IWM FFS referenced the IWM FFS and did not repeat positions that are stated in the IWM FFS.	TDEC believes that preWAC values should be protective of water resources in perpetuity—not just for 1,000 years.
D4.22	**B7**	The Remedial Action Objectives (RAO) on page 4-1 references several RAOs which define protectiveness of the remedy including:	Meeting RAOs is demonstrated for the 1,000 year compliance period based on modeling. However, past 1,000 years, modeling is not to be relied on to	(1) TDEC disagrees with modeling and assumptions, such as there will be no differential settling of the waste, for the 1,000-year compliance period

		a. Prevent exposure of humans receptors to CERCLA waste (or contaminants released from the waste into the environment) that exceeds a human health risk of 1 0-4 to 10- 5 Excess lifetime Cancer Risk (ELCR) or Hazard Index of (HI) 1. b. Prevent adverse impacts to water resources or unacceptable exposure to ecological receptors from CERCLA waste contaminants through meeting chemical-, location-, and action specific ARARs, including RCRA waste disposal and management requirements, Clean Water Act (CWA) Ambient Water Quality Criteria (AWQC) for surface water in Bear Creek, and Safe Drinking Water Act (SDWA) MCLs in waters that are a current or potential source of drinking water. Other goals are identified on page 4-2 that page 4-1 states do not define protectiveness. Page 4-2 states that "PreWAC waste concentration limits are determined based on demonstrating the following goals are met *during the 1,000 year compliance period"* (emphasis added). • 10-5 ELCR and HI of 1 based on a human receptor's (direct) ingestion of groundwater from a drinking water well and (indirect) uptake of surface water for the compliance period (to 1,000 years) using a resident farmer scenario, and 10-4 ELCR and HI of 3 at times exceeding 1,000 year compliance period • Appropriate AWQC for chemicals (risk-based discharge levels for radionuclides in Bear Creek and tributary surface water are per the *Integrated Water Focused Feasibility Study* (UCOR, 2016) • MCLs in groundwater present in drinking water well of the resident farmer scenario. Therefore, the PreWAC as identified in the D4 RI/FS should be consistent with RAOs during the 1,000 compliance period, *but not necessarily thereafter.* CERCLA 121(d)(1) requires the remedial action "shall attain a degree of cleanup of hazardous substances, pollutants, and contaminants released into the environment and of control of further release at a minimum which assures protection of human health and the environment." RAOs should also include protection of environmental receptors allowing for environmental risk assessment or screening. We found no timeframe in either CERCLA or the NCP that specifies that after a specified number of years it is no longer necessary to assure protection of human health and the environment under CERCLA. CERCLA 121(d)(2) discussed ARARs for any hazardous substance, pollutant, or contaminant that will remain onsite. We found no timeframe in either CERCLA or the NCP that says that ARARs are no longer applicable or relevant and appropriate after a specified timeframe. CERCLA utilizes a review process every 5 years to determine whether remedial actions remain protective. As a follow-up for the May 3rd meeting discussing changes from the 03 toD4 RI/FS DOE's contractor sent TDEC and EPA the following: *"For the EMDFD4RfFS, PreWAC for radionuclides predicted to peak after 2,000 years were based on a risk-informed, 500 mrem/yr radiological dose criterion. The flow and transport model predictions and receptor exposure assumptions utilized were the same as for the risk-based Pre WAC, but rather than estimating ELCR with a carcinogenic slope factor (for comparison to a specific target risk level), the peak annual radiological dose was calculated using water ingestion dose conversion factors for each radionuclide. This predicted peak dose corresponding to the assumed unit waste concentration (1 Ci/m3) was then used to estimate the waste concentration limit (PreWAC) corresponding to the 500 mrem/yr criterion. The assumptions underlying this calculation are exactly the same as those made for calculating risk-based PreWAC."* This methodology developed PreWAC limits for 28 radionuclide with excess lifetime cancer risk (ELCR) in the range from about 2.6E·02 (2.6 per hundred) to 9.8E·4 (9.8 per ten thousand) based on the limited resident farmer scenario. Much of this risk results from drinking from the residential water well. The ELCR may be higher if additional pathways of exposure are considered. CERCLA and the RAOs reference SDWA MCLs. SDWA MCLs are identified in the RAOs for waters that are a current or potential source of drinking water. The future farmer scenario assumes drinking from a residential water well in the exposure risk scenario and development of the PreWAC. Potential use of groundwater for a drinking water supply does not end at the end of the 1,000 year compliance period and may increase farther out in the future. MCLs for radionuclides include beta/photon emitters (4 mrem/yr), gross alpha particle (15 pCi/L), Radium-226 and Radium-228 (5 pCi/L) and Uranium (30 µ~~u~~g/L). The MCL for uranium limits toxicity of uranium as a heavy metal in addition to effects as a radionuclide. It should be verified that PreWAC limits will result in groundwater concentrations at the residential water well that are less than or equal to the appropriate MCLs irrespective of how far in the future modeling predicts a peak concentration in surface water.	demonstrate protectiveness due to the increased uncertainty associated with the results. Past 1,000 years, continued monitoring (post-closure monitoring) is relied on to demonstrate protectiveness, and the time for which that monitoring must continue to be performed is determined by the triparties. ARARs (e.g., SDWA MCLs, CWA AWQC) dictate the allowable limits of contaminants in water bodies as indicated through monitoring. As stated in Section 7.7 of Appendix G (see bolded language in particular): ***Post-closure care must begin after closure and must continue for a period to be determined by the FFA parties.*** *Property use must be restricted and the facility must be maintained to protect the integrity of the landfill cover and other components. General post-closure care includes site surveillance and maintenance, maintenance and operation of the leachate collection system as long as leachate is being generated,* ***and environmental monitoring, including ground water detection monitoring.*** As indicated by the commenter, CERCLA does not specify a time frame, but requires 5-year reviews "***CERCLA utilizes a review process every 5 years to determine whether remedial actions remain protective.***"	and does not agree that the modeling demonstrates RAOs will be achieved. (2) TDEC disagrees that the triparties have authority to decide how long monitoring will be required. The ROD will include language requiring 5-year reviews, as required by the National [Oil and Hazardous Substances Pollution] Contingency Plan (NCP). (3) Likewise, the post-closure care period is determined by CERCLA and is not a FFA-party decision. (4) In accordance with the NCP, reviews are required at least every 5 years as long as contaminants remain at the site above levels that allow for unlimited use and unrestricted exposure. Effectively, with disposal of long-half-life radionuclides such as uranium, this requires reviews through geologic time. (5) TDEC believes modeling should evaluate conditions beyond 1,000 years in the future. If DOE is relying on modeling to evaluate meeting RAOs for the first 1,000 years, then there is no reason to avoid modeling beyond that time period. All of the evaluations are for future (not current) conditions, and increased uncertainty regarding future conditions is no reason to avoid modeling those periods. Probabilistic modeling methods provide the means to evaluate conditions where uncertainties are greater.
D4.S.01	**B8**	Page 4-1 , RAO 2: The RAO to protect ecological receptors includes ARARs that may not include radionuclides. Protection of ecological receptors from radionuclides should also be established through ecological risk assessment.	Ecological protection is provided through meeting radionuclide concentration discharge limits during operations (see the Integrated Water Focused Feasibility Study that contains the appropriate RAO and sets Radionuclide discharge limits. This reference to the IWM FFS is stated in the RAO chapter 4 of the RI/FS.) For long-term operation, RAO #1, which limits radionuclide concentrations via human health cancer risk, also therefore protects ecological receptors as well (ecological receptors have relatively short life-spans and are therefore not as susceptible to chronic radiation exposure).	TDEC agrees with EPA's position (see below). **EPA Position:** Derived Eco risk PRGs or RGOs - ISSUE OPEN UPDATE RAO & PRE-WAC MODEL/DISCHARGE CRITERIA: REVISE AND REVIEW REDLINE The RI/FS will clearly demonstrate how ARAR-based or derived ecological risk-based PRGs are used for each COC for both the Pre-WAC and discharge criteria. The footnote as written implies protectiveness is assumed when ARAR-based PRGs are not available for each COC and the burden is on a finding of insufficiency. Rather, this RI/FS must demonstrate sufficiency of protectiveness (human and ecological) when PRGs are not identified for COCs. If the remedy is deemed protective without a COC-specific ecological PRG, then a justification will be demonstrated for each COC, similar to the approach for human health. Confirm that human health PRGs (ARAR-based or derived) are being used

				for all COCs for the Pre-WAC and discharge criteria, otherwise include human health PRGs in the revised footnote below. The DOE ORR RAO Footnote is acceptable as revised: "For all COCs ~~W~~where ARARs (e.g., F&AL AWQCs) are deemed insufficient or are not available for ~~in~~ protect~~ing~~ion of ecological receptors, ~~alternate remediation levels~~PRGs for the Pre-WAC ~~or~~and discharge criteria for wastewater will be ~~defined~~derived using a risk-based approach. COCs without human health or ecological PRGs (ARARs or derived risk-based) will be demonstrated to be protective." EPA Risk-based Calculators - ISSUE OPEN UPDATE RAO & PRE-WAC MODEL/DISCHARGE CRITERIA: REVISE AND REVIEW REDLINE DOE ORR took an action item to provide sample calculations to show that the exposure point model calculations used in PATHRAE resulted in risk levels at or level lower than or equal to the PRG and RSL Calculators. This demonstration may be helpful but for consistency, EPA expects use of the PRG and RSL calculators where ARARs are not available for all COCs to derive discharge criteria and Pre-WAC concentration limits. Additionally, the RAOs should include a description of how PRGs are considered in finalizing the Pre-WAC limits and discharge criteria for both human and ecological protection. DOE ORR has proposed to make unsolicited changes to the Pre-WAC - ISSUE OPEN JUSTIFY DOE ORR PROPOSED PRE-WAC MODEL CHANGE(S); REVISE AND REVIEW REDLINE The U Pre-WAC concentration limit is proposed to be revised by DOE ORR. Confirm why this change to the D4 document is appropriate and that no other unsolicited changes are being proposed.
~~e4~~D4.05	**C1**	TDEC does not agree that the risk assessment presented in Appendix H provides reasonable assurance that the proposed facility will be protective of human health and the environment, a threshold criterion for actions authorized under the Comprehensive Environmental Response, Compensation, and liability Act (CERCLA). The risk assessment in this RI/FS is based on the same general approach and the same set of software packages used for modeling risk at the EMWMF nearly two decades ago. TDEC has made numerous comments, both written and verbal, expressing both lack of confidence in the approach to risk assessment and concerns with the applicability of the models over the past five years. However, the methodology has changed little through the various documents that have been written to initiate the process to authorize a new disposal facility for radioactive, hazardous and toxic waste. As DOE has not suitably addressed these comments, some of which were first given informally to DOE in 2012 after the submission of the Focused Feasibility Study for Comprehensive Environmental Response, Compensation, and liability Act Oak Ridge Reservation Waste Disposal, Oak Ridge, Tennessee *(DOE/OR/01-2535&DO)*, it will be incumbent upon TDEC to ensure that independent verification of the risk assessment is performed and to confirm that CERCLA waste can be compliantly and cost effectively disposed on the Oak Ridge Reservation. Whether this is carried out by a group chosen by the FFA parties, an independent contractor answering directly to TDEC, or TDEC staff, this is will require independent re-calculation of the PreWAC using a substantially different approach to that used in this and in the previous versions of this RI/FS. Proper verification of the risk assessment will require that sufficient scenarios and pathways be evaluated to substantiate that the threshold criteria of CERCLA can be met while allowing acceptance of sufficient candidate waste to render the proposed facility viable. Some of the additional scenarios and exposure pathways that should be considered, at least at the screening level, include: • Ecological and recreational risks in Bear Creek due to bioaccumulative hazardous substances, including radionuclides • Radon flux through the facility cap to demonstrate compliance with 40 CFR 61.192, listed as an applicable requirement in Appendix G • Air dispersion modeling to demonstrate compliance with 40 CFR 61.92, listed as an applicable requirement in Appendix G • Direct exposure pathways For exposure pathways where multiple sources may impact a receptor, such as radionuclide emissions to ambient air or recreational use of Bear Creek below BCK 9.2, cumulative risk from EMWMF and any proposed disposal facility should be evaluated. A resident farmer scenario similar to that reported in this RI/FS, along with the remedial action objectives that require compliance with maximum contaminant limits (MCLs) in groundwater and ambient water quality criteria (AWQC) in surface water, could be used to ensure protection of water resources. However, other methods would need to be used to predict many key components of contaminant fate and	DOE disagrees. The modeling parameters and results presented in the D4 RI/FS were significantly changed from the D3 RI/FS; those changes were discussed at length in Project Team Meetings and are documented in responses provided to TDEC's D3 comments. DOE maintains that risk assessment presented in the D4 RI/FS, while acknowledging that it employs simplified representations of flow and contaminant transport, is in fact conservative. A demonstration of its conservativeness has been documented by Dr. Painter, a ground water modeling expert, in a recently completed report (ORNL-TM2016/235). Additionally, DOE points out that the results (PreWAC) presented in the D4 RI/FS are considered preliminary. DOE is required to complete a Performance Assessment (PA) under DOE O 435.1, and is in the process of doing so. That effort involves employing a different fate and transport model, and will provide further verification of the RI/FS modeling. Additional scenarios and exposure pathway analyses are required under the Order, including probabilistic treatment of key uncertainties. Ultimately, the results of the RI/FS modeling and the PA efforts will be captured in the final WAC, which are presented in a Primary FFA document, the WAC Compliance (Attainment) Plan that requires approval by the FFA parties.	TDEC's D4 RI/FS comment begins: "TDEC does not agree that the risk assessment presented in Appendix H provides reasonable assurance that the proposed facility will be protective of human health and the environment, a threshold criterion for actions authorized under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)." (1) TDEC does not agree that the risk assessment is conservative. In addition to problems with modeling that have been discussed in TDEC comments on the D4 and earlier versions of the RI/FS, DOE apparently does not like the modeling results and substitutes an administrative PreWAC based on 500 mrem/year for 28 of the 32 radionuclides addressed in the D4 RI/FS. See TDEC's position regarding comment/response D4.09. (2) **DOE argues that they are preparing a performance assessment (PA) under DOE O 435.1 incorporating different modeling and exposure scenarios to demonstrate that the RI/FS modeling provides reasonable assurance.** This argument does not make sense. TDEC needs the modeling being performed for LFRG and LFRG review/approval to make that determination. The PA appears to require at least some of the evaluations that TDEC has been requesting. The PA and composite analysis (CA) should be developed and approved by LFRG prior to the next version of the RI/FS to stop the RI/FS comment/response do-loop. Cumulative dose/risk is evaluated in the CA to assure future remedial action will not be required at the disposal facility due to cumulative dose/risk from multiple source areas. TDEC understands that DOE will submit the PA to LFRG, using different modeling and additional exposure scenarios. DOE-OR determines the schedule for submitting the PA to LFRG, and TDEC understands the LFRG review process takes about 6 months to complete. LFRG should also establish a PreWAC for radionuclides for EMDF that the FFA parties could modify to be consistent

		transport. The software used in this RI/FS, with reasonable assumptions for key parameters, might yield a credible hydrologic balance, including estimates of release rates from the proposed facility and dilution factors in groundwater and in Bear Creek. Unfortunately, the models are too limited to predict accurate travel times for water or contaminants. The HELP model cannot account for the effect of a sloping landfill base, which will lead to ponding and a distribution of travel times through even a uniform liner. The flow field through the liner would not be uniform even if the water pooled above it were of uniform depth, since flow through the geomembrane is controlled by orifice flow through discrete holes or tears, usually with an equivalent radius not greater than a few millimeters (Rowe, 2012). Several studies. including that of Giraud and Bonaparte (1989), showed that the greatest hydraulic resistance to leakage through composite liners is generally at the interface between the geomembrane and underlying clay liner. Until the geomembrane deteriorates considerably, which, as noted in the RI/FS, may take decades or even centuries, leakage rates depend primarily on such unpredictable variables as the care taken to prevent holes and wrinkles during installation of the barrier (Rowe, 2012). As TDEC has expressed on numerous occasions, deterministic prediction of contaminant travel times in fractured media on the ORR, such as the bedrock in Bear Creek Valley, and, to a lesser extent, the saprolite and weathered residuum, does not seem viable. Tracing results in the bedrock and residuum of the Conasauga group yield travel times that are highly variable and clearly dependent on the specific location and design of the test (c.f. Spalding, 1987). A realistic prediction of travel times for contaminants is probably not feasible, and estimating travel times using consistently conservative assumptions may limit waste acceptance unnecessarily, perhaps to the point of indicating that the facility is not cost effective. It would seem that a stochastic approach to contaminant fate and transport prediction might provide a better basis for risk assessment.		with CERCLA and include in the D5 RI/FS. DOE-OR could accelerate this schedule by completing and submitting the PA earlier to LFRG. **If DOE intends for the PA, CA, and LFRG review/approval to resolve any of the modeling problems identified by TDEC, then those documents and reviews should be completed before DOE submits another RI/FS for TDEC review.** (3) TDEC disagrees with DOE's response that "…those changes [referring to model parameters in the D4 RI/FS] were discussed at length in project team meetings…". At least during recent project team meetings, TDEC efforts to seek clarification of why/how certain values were applied/changed in the models were cut off as being outside the purpose of the meetings. (4) The groundwater flow velocities evaluated by Dr. Painter are on the low end of the range documented by tracer studies in similar settings on the ORR. Use of groundwater flow velocities more representative of flow through fractures may demonstrate that the modeling needs to be more conservative.
D4.14	**C2**	The conceptual site model assumes a surface water pathway where a future farmer utilizes surface water at BCK 11.54 for irrigating vegetation and watering livestock. In the D4 RI/FS modeling analysis, one input parameter required for PATHRAE is the river flow rate (the annual flow in Bear Creek). An annual flow of 736,000 cubic meters was input into the PATHRAE model in the D4 RI/FS to calculate the concentration of pollutants in surface water, while an annual flow of 491,000 cubic meters was used in the D3 RI/FS. Use of a total annual flow rate appears to underestimate the risk. Evaluating streamflow data for BCK 11.54, TDEC calculated average median flows for June 1 through November 30 and December 1 through May 31 as 155 L/minute and 1160 L/minute respectively. Converting median flow in L/minute to total flow in cubic meters yielded an average of 40,845 cubic meters for the period of June 1 through November 30 and 304,012 cubic meters from December 1 through May 31; this results in an average annual cumulative median flow on the order of 344,858 cubic meters. Similarly, plotting BCK 11.54 on USGS StreamStats[1] shows BCK 11.54 has a drainage area of about 0.6 square miles. Evaluation of DOE flow data for BCK 11.54 shows that, over the five year period analyzed, 37% to 53% (average of 45%) of the total annual flow occurred over a 25 day period each year. The sensitivity analysis table on page H-71 shows there is a linear relationship between stream flow rate and peak concentration - if the flow is reduced in half, the calculated peak stream concentration doubles. In conclusion, peak stream concentrations reported in the D4 RI/FS are low by about a factor of about 2. Doubling the peak steam concentration will double the peak effective risk for the carcinogenic pathway (see equations on page H-65 and H-66) and will double the peak effective dose for the non-carcinogenic pathway (see equations on page H-66.) [1] USGS StreamStats is found at http://streamstatsags.cr.usgs.gov/v3_beta/viewer.htm?stabbr=TN.	DOE agrees that using median flows as the basis for the annual average flow rate calculation will result in lower values. Median-based values cannot be used to correctly calculate the total flow volumes or the average flow rates. Given the RIFS modeling assumption that the total mass of contamination released from the disposal cell is transported without dilution via groundwater to the surface water point of exposure (PATHRAE), and the results of the advective contaminant transport modeling (MODFLOW+MT3D) indicating that less than 95% of the contaminant mass is discharged upstream of BCK 11.54, the use of an annual average flow rate for calculating surface water concentrations in PATHRAE is reasonably conservative.	TDEC disagrees. While TDEC agrees that using the annual average flow is conservative for 25 days per year, the risk is underestimated during the rest of the year.
D4.15	**C3**	Utilizing C'creek calculated from PATHRAE and the annual river flow rate input into PATHRAE, the peak flux/load per year and peak average flux/load per day to Bear Creek can be calculated. This flux may be used to evaluate EBCV site impact on capture and subsequent consumption of fish downstream of BCK 11.54. For example, utilizing assumptions in PATHRAE for U-238, including a basis of 1 kg/m3 in the waste, PATHRAE yields a peak concentration in Bear Creek of 5.97E-2 mg/L. Utilizing an annual flow of 7.36E+5 m3/yr, an annual peak load/flux of 4.39E+7 (43,900,000) mg/yr or 1.2E+5 (120,000) mg/day or 83.6 mg/min can be calculated. For U-238 with a specific activity of 3.36E-7, 83.6 mg/min equates to about 28,089 pCi/min. Adding this flux/load to calculated flux provided in TDEC comments on the *Integrated Water Management Focused Feasibility Study* (UCOR, 2016) shows concentrations exceed recreational use calculated risk standards based on capture and consumption of fish in Bear Creek at BCK9.2 without additional future release from EMWMF. (It is assumed that by the time EMDF is releasing constituents to Bear Creek, EMWMF will also be releasing constituents to Bear Creek.) This analysis should be redone using the PreWAC concentrations to evaluate loading/flux resulting from the landfill and whether the landfill WAC would potentially impact downstream water resources.	This comment refers to contaminant release expected to occur far in the future (>> 10,000 years). As stated by DOE many times and as indicated by the NRC and the IRPC, there is little to no confidence in model predictions at these time frames. Protective criteria (PreWAC, resource protection) for such late time frames are not based on fate and transport modeling.	TDEC agrees that modeling uncertainty increases as predictions are made further into the future. DOE should contract an independent third party to complete modeling with probabilistic or other methods to support risk-informed decisions. Based on DOE's response, modeling of time-to-peak concentration has little meaning.
D4.16	**C4**	PreWAC development for constituents that peak after 200 years after maintenance of a dense fescue ground cover is discontinued or 4,000 years in the future, whichever is earlier, should be recalculated using infiltration rates consistent with a cover where the four foot vegetation layer and sand from the underlying one foot sand/gravel layer have been totally removed by erosion, evapotranspiration is negligible, and the amended clay layer and underlying compacted clay layer are compromised. TDEC utilized the Revised Universal Soil Loss Equation 2 (RUSLE2) to evaluate soil loss on the East Bear Creek Valley (EBCV) Site. Soil loss may be used to estimate future erosion in tons per acre of the engineered cover. Erosion of the cover affects infiltration through the cover and performance of remaining cover components. The model was run utilizing 5% slope for the first 100 feet and 25% slope for the next 635 feet for a total of 735 feet with grade channels at 265 feet, 475 feet and 735 feet. Management of activities and vegetation on the cover and erosion of the cover are important considerations in long term effectiveness of the cover. Page H-24 discusses the importance of the upper part of the cover to support root systems for evapotranspiration, drain away water to remove chances of deeper root penetration, create a barrier for deep root development, prevent long term erosion and protect the underlying clay barrier from degrading effects of desiccation and the freeze thaw cycle. RUSLE2 modeling indicated that maintaining a dense fescue grass cover is needed to prevent substantial erosion of the portion of the cover with the 25% slope. It was estimated that within 200 years after maintenance of a dense fescue groundcover is discontinued or 4,000 years in the future, whichever is earlier, the four feet thick vegetative cover and sand from the underlying one foot sand/gravel layer could be removed through erosion. This increased infiltration will significantly change leachate volume, leachate concentrations, peak concentrations in surface	DOE has performed cover erosion modeling with RUSLE2 utilizing parameter values similar to those cited in this comment and obtained much lower estimated soil loss rates than are suggested by this comment. DOE results suggest that complete erosion of the cover above the drainage layer would require greater than 20,000 years, based on the assumptions inherent in the model and the parameter values chosen. An effort to review and reconcile these differences between the regulator and DOE analyses may be productive.	TDEC disagrees that the cover erosion modeling presented in the D4 RI/FS is representative of likely conditions and welcomes an effort to work with DOE to reconcile the disagreement. RUSLE2 models for 100 years and extrapolates after that. A number of variables affect soil loss and erosion. TDEC's comment is that erosion of the cover could occur within 200 years after maintenance is discontinued or 4,000 years, whichever is earlier. We appreciate that DOE intends to maintain the dense fescue groundcover for over 20,000 years in the future to prevent erosion to the drainage layer. How does removal of the cover to the drainage layer affect water entering the landfill? DOE's modeling assumes erosion stops with 24 inches of top soil remaining for one million years. As stated before, there is little to no confidence in model predictions far in the future. This includes DOE's modeling of time-to-peak concentration in surface water.

		water, groundwater well dilution rates and other factors. Summary of PATHRAE Model sensitivity analyses in Table H-9 on page H-71 shows that if the infiltration rate increases by a factor of 3, the peak concentration in surface water will increase by a factor of three or higher and the time to reach the peak concentration decreases by a 40 to 65%. Similarly, if the infiltration rate increases by a factor of 8.2, the peak concentration in surface water increases by a factor of 8 to 10 or higher and the time to peak concentration decreases by 65 to 85%.		
D4.17	**C5**	Bear Creek is classified for recreational use. Human health risk from the capture and consumption of fish living in water polluted by site constituents and decay products (such as Po-210) is needed. Polonium-210 (Po-210) is in the decay chain for U-238, is highly toxic, and bioaccumulates in fish.	Fish populations currently existing in the area of Bear Creek where surface water is being utilized in the resident farmer scenario are not of sufficient size for consumption; therefore, this scenario is not applicable at that location. Additionally, the future concentration of Po-210 in surface water was considered based on D3 RI/FS comments and found to be of insufficient concentration to pose a risk to the future farmer based on even less stringent preWAC concentrations than are currently posed in the D4 RI/FS.	TDEC disagrees. In addition to the fact that farmers could fish downstream, downstream Bear Creek is a fishery and is being posted by the Division of Water Resources for fish consumption. Capture and consumption of fish in Bear Creek is relevant to protection of water resources and protecting public health and has to be adequately evaluated in the risk assessment. Further, Site 7c is closer to the fishery, if not within the fishery.
D4.21	**C6**	Consensus has not been reached on input parameters to the modeling. These parameters control the calculated amount of leachate, the calculated leaching rate, and time to peak concentration in surface water.	Several requested changes to the assumed exposure scenario and modeling parameter values were made for the D4 revision, based on several meetings and extensive discussion of various issues. DOE does not plan on additional modifications to modeling parameters and assumptions contained in the D4 RIFS.	TDEC agrees that several requested changes were made and improved the modeling. However, other requested changes were ignored, and discussions during meetings were cut off by DOE without resolution. TDEC has identified problems with the models, assumptions, and results of the risk assessment. In response to comment D4.05, DOE indicates it will work through a series of these issues in the PA and CA for DOE HQ LFRG. TDEC understands that DOE will submit the PA to LFRG, using different modeling and additional exposure scenarios. DOE-OR determines the schedule for submitting the PA to LFRG, and TDEC understands the LFRG review process takes about 6 months to complete. LFRG should also establish a PreWAC for radionuclides for EMDF that the FFA parties could modify to be consistent with CERCLA and include in the D5 RI/FS. DOE-OR could accelerate this schedule by submitting the PA earlier to LFRG. **If DOE intends for the PA, CA, and LFRG review/approval to resolve any of the modeling problems identified by TDEC, then those documents and reviews should be completed before DOE submits another RI/FS for TDEC review.**
D4.23	**C7**	Of note is the fact that, for the different proposed disposal sites, there are different lithological and formation contact areas for different sites. This may be more significant than initially appears, particularly when there are formations that contain more carbonate. If the streams on the sites are walked and water quality parameters are measured along them, it is apparent that when, for example, a stream crosses a carbonate unit, say the Dismal Gap Formation (formerly Maryville limestone), there is a measurable change in electrical conductivity of the water. This means that a higher dissolved load is in the water, which means that channels or conduits are developing in the subsurface.	Plate 2 in the EMDF Phase I report for Site 5 (EBCV) illustrates the measured borehole thicknesses of limestone beds in the rock core sequence in GW-976(I) within the Dismal Gap (Maryville LS) formation. The limestone (carbonate) beds comprise only 12.2% of the total cored interval (8.8 ft total limestone beds/71.8 ft total rock core). The remainder of the rock core consists of predominantly clastic rocks (shale/mudstone/siltstone). The suggestion that the Dismal Gap formation in BCV is a "carbonate unit" is misleading. Dr. Robert Hatcher in fact proposed renaming the Maryville Limestone on the ORR to the Dismal Gap formation to be more consistent with a formation that is predominantly clastic with some limestone beds. DOE has presented information on lithological and formation contacts for each site in the RI/FS. See Appendix E which, at 233 pages, expends a good amount of effort describing conditions for BCV and for each site. In particular, the relative location of the footprints with respect to the Maynardville (which *is* a predominantly carbonate unit prone to dissolution and karst flow characteristics) is addressed for each of the proposed sites. Appendix E notes that the predominantly clastic rocks north of the Maynardville/Nolichucky contact provide a probable buffering effect for contaminant transport in ground water (slower travel times and greater attenuation), relative to more rapid flow rates and commingling of surface water in Bear Creek within the karst of the Maynardville Limestone. Site footprints located farther north from the Maynardville and Bear Creek offer a greater opportunity for contaminant attenuation prior to reaching the Maynardville karst than footprints located further south in closer proximity to the Maynardville.	TDEC agrees with the portion of the DOE response that acknowledges that the Dismal Gap formation has some limestone beds. The presence of carbonate rock can be verified by field measurements and observations at Dismal Gap and other outcrops. Even relatively thin carbonate rock layers can be very important for groundwater flow because their greater solubility allows the creation of enlarged channels. Moreover, clastic rocks adjacent to carbonates typically have some carbonate cement. A paper just published (Worthington et al., 2016; Attachment C to this table) discusses the nature of silicate rocks and in terms of channeling and rapid flow. This paper documents that silicate rocks are remarkably like carbonates, with rapid velocities and long flowpaths (sometimes many kilometers long), despite differences in mineralogy and solubility. Reference Worthington, S.R.H., Davies, G.J., and Alexander, E.C., Jr., 2016, Enhancement of bedrock permeability by weathering, Earth Science Reviews, 160:188-201, Elsevier.
D4.24	**C8**	The general groundwater situation in this part of Bear Creek Valley needs to be described in a clearer way. The document is written such that a "pick and choose" method is used to obtain supporting materials to justify the position. Sometimes references are quoted out of context, and previous comments were made about this, but have not been rectified.	DOE disagrees with this comment; see Figure E-9 and accompanying text as an example of the general groundwater situation for Bear Creek Valley described and illustrated. The RI/FS has presented significant quantities of information and data, and does not agree that it is presented in a "pick and choose" way. Appendix E is in fact more detailed and comprehensive than any previous versions of the RI/FS. Existing sections were expanded and revised and new sections were added to Appendix E to address TDEC/EPA comments and concerns, including conceptual model descriptions for BCV and each of the proposed sites, effects of landfill construction on the water	The groundwater situation as investigated in BCV does include a lot of valuable information. However, the "pick and choose" in the TDEC comment refers to the way some references continue to be used incompletely to justify a position that is not supported if the references are quoted in context. As noted in TDEC comment and position D4.S.29, citations of Worthington (1999), Nativ et al. (1998), and Moline et al. (1998) seem to be used in a way that seems to justify a certain position that is not supported when the references are presented completely.

			table, and detailed presentations of tracer tests completed in BCV and elsewhere on the ORR. The information provided draws on the findings from extensive research, ORNL/Y-12 reports, and peer-reviewed journal publications by ORNL scientists, many in collaboration with a host of academic researchers from UTK and other universities. References are extensive and were carefully cited throughout the report.	
D4.S.07	**C9**	**Page 7-10. Section 7.2.2.2.3 Action-specific ARAR. first bullet. TDEC 0400-20-11-.17(1)(b) Disposal site shall be capable of being characterized, modeled, analyzed and monitored:** "*All sites selected for consideration meet this ARAR. All sites under consideration in this RI/FS as locations for an on-site disposal facility - EBCV Site, WBCV Site, Dual Site (Site 6b and Site 7a) - are located in BCV, which has been extensively characterized over the last 40-50 years. More than 1,000 groundwater wells have been installed and monitored many of which continue to be monitored, multiple characterization events have been executed and documented, and over 900 acres of the valley are incorporated in the BCV model (see Appendix E and Appendix H), Additionally, an effort is underway within OREM to develop a more detailed groundwater model at BCV outside of this RI/FS.* ***The current BCV model, a porous media model, has been questioned in terms Of its ability to adequately predict groundwater movement in Bear Creek. Discrete fracture flow models have been suggested to be more applicable for this area. However, development of a fracture-based flow model would take a large amount of capital and time, without any guarantee of producing a successful accurate model. The scale of fractures compared to the scale of the current porous flow model grid is such that this approximation is appropriate, and modeling calibration efforts and results support that conclusion. See further discussions in Appendix H.***" The approach cited above assumes a porous medium. In other parts of the document the equivalent porous medium approach is promoted. A porous medium has: areal recharge (no losing or sinking streams), parallel flow lines, with laminar flow, (no convergent flow, no turbulent flow, no troughs, valley or ridges in the potentiometric surface), discharge across the entire downgradient face of the aquifer (no springs or seeps) and a convex profile to the water table (in cross section), or a steepening hydraulic gradient towards the discharge. So, do any of the proposed sites deviate from any of the ideal criteria? If so, the porous medium assumption is invalid. A5TM (1995) state in fractured rocks the porous medium is poorly approximated, and should be avoided. It appears that the settings proposed fail for most if not all of these fundamental porous medium test criteria. An equivalent porous medium is: "a homogeneous setting with parameters chosen to be characteristic of the fissured rock" (Barker, 1993) - essentially an ideal porous medium with the chosen parameters assumed if they are not measured. The term equivalent porous medium appears quite straightforward. However, further in Barker (1993) there is a discussion and it is such that there are different scenarios to choose from, that involve various characteristics about the transport mechanisms in the rock matrix and the fissures, for example, whether transport is diffusive or advective, whether there is flow in the matrix and fissures or only in the fissures, but still diffusive exchange between the two. When the time scale is small with respect to the diffusion across the fissures and the effects of matrix porosity can be ignored, (conditions he suggests are probably restricted to the laboratory) an equivalent porous medium model might work, using just the fissure porosity. This might also work if diffusive equilibrium exists, with the time scale small, the setting behaving like a homogeneous medium and using the total porosity, with alternatively a double porosity approach (flow in only the fissures). If there is a wide distribution of timescales, then only diffusive double permeability approaches can be envisioned (flow in both the fissures and the matrix and diffusive exchange). This discussion hopefully shows the complex interactions that have to be determined when using what appears to be a relatively simple: "equivalent porous medium" approach. In reality it involves choosing a complex and interwoven set of assumed conditions, of which most are impossible to validate, unless they are measured directly. It is often suggested that large scale can allow a better fit to such approaches. This may be the case with general parameters to determine mass balance, but then tested with methods not buried in the same assumptions details emerge that usually result in a model more closely approximating a discrete situation that defies equivalence with anything but reality. There are numerous traces in fractured non-carbonate/clastic rocks that have been done kilometers in length with velocities of > 100 m/day (Worthington et al., 2016 [in review]). When the proportions of flow in different porosity elements (matrix, fissure and channel/conduit) are included, it is obvious that the concept of any type of porous medium is much less likely. It is overly simplistic to assume that fissured rock can be modeled as a porous medium. One alternative is to use parameters determined directly by groundwater tracing, although tracing is likely to prove that rock is not a porous medium. Another alternative is to apply parameters derived by tracing in similar settings on the ORR (e.g., Gwo et al., 2005) and to assume those values are representative. Convergent flow to major fissures must be considered and thus the inclusion of channeling must be included in the thought process. Channeling will obviously result in more rapid velocities, which will result in any dissolved solutes or contaminants reaching users more rapidly and in higher concentrations.	The question regarding use of porous media modeling versus fractured flow modeling was fully addressed in D3 responses to EPA questions on the matter. DOE response to the D3 RIFS comment EPA.G.025 outlines the challenges and limitations of discrete fracture flow models and the characterization efforts required to support them. DOE does not propose to revise the fundamental approach to groundwater modeling for the RIFS.	If an equivalent porous medium (EPM) approach is used, parameters need to be determined that are representative of the fractured media present at the candidate sites. TDEC continues to recommend that DOE involve an independent group acceptable to the FFA parties to complete the modeling necessary to develop a defensible PreWAC. It is TDEC's expectation that this will result in using a substantially different approach to that used in this and previous versions of this RI/FS.
D4.S.13	**C10**	Page E-26. Paragraph 2: " ... *the proposed sites (Option 5) and physically and hydrologically separated from this community by Pine Ridge.*" Freeze and Cherry (1979) and Fetter (1980) show the effect of topography and geology/hydrogeology on groundwater flow nets. Without tracer test information, it cannot be stated or claimed in this type of topographic setting in fractured rocks that the site is hydrologically separated from the (scarp side of the ridge) i.e., Scarboro community side of the ridge. Tracer testing from both sides of the ridge must be done to prove that there is a groundwater divide. This would be considered a common practice in carbonate settings and would be prudent in clastic and other similar settings also (Worthington et al., 2016 (in review]). Note: the higher up in the dip slope of the ridge the proposed site is increases the probability that the assumption that no groundwater will pass beneath the ridge is more likely to be incorrect.	Field studies supporting the site conceptual model for predominantly clastic rock formations on the ORR proposed by Solomon et al. (1992), Moore and Toran (1992), and Clapp (1998) suggest that over 98% of ground water flux occurs via the shallow stormflow zone and the water table interval. It is clear from decades of water table measurements and mapping that the water table within the predominantly clastic rock formations (i.e. – the formations encompassing the Rome through the Nolichucky) conforms consistently with surface topography. The water table occurs at or near the ground surface along stream valley floors and generally increases in depth below surface toward and below ridgeline areas. The water table is constrained by discharge zones along surface water streams and mimics surface water runoff divides. In addition, the	The paper cited in the TDEC comment (Worthington et al., in review) has now been published (Worthington et al., 2016; Attachment C to this table). Regardless of that paper, the only way to establish the position of a basin boundary in terrain like Oak Ridge is to trace from both sides of the assumed divide under various groundwater stage conditions. Monitoring wells are imperfect for sampling channels or zones of discrete flow because of the low probability of intersecting main channels. Subsidiary (tributary) channels are more likely to be intersected, but they may provide irrelevant or misleading results. The best and most direct way to study channels is by tracing.

			structural dip of the formations toward the southeast acts to limit the potential for any migration (shallow or deep) toward the northwest beyond Pine Ridge. Stratabound flow and contaminant migration has been documented on the ORR (Kettelle et. al., 1992). Perhaps the most convincing evidence comes from existing contaminant plumes in BCV which all have migrated downgradient to the southeast away from source areas (i.e. – Bear Creek Burial Grounds, etc. – see Figure E-2 in Appendix E). If contaminants have been migrating to the northwest below Pine Ridge, they have not been detected to date in site monitoring wells. Water table mapping based on the many monitoring wells installed on the ORR at the scale of the proposed EMDF sites, in similar terrain, and within the clastic formations noted above have reliably demonstrated these conditions. The results are also consistent with the flow nets and discussions provided in the ground water textbooks by Fetter and Freeze and Cherry.	TDEC also notes that Figure E-2, cited in DOE's response, does not indicate the existence of any groundwater monitoring locations northwest of the source areas that would confirm or deny the presence of any plumes that may exist in that direction. Reference Worthington, S.R.H., Davies, G.J., and Alexander, E.C., Jr., 2016, Enhancement of bedrock permeability by weathering, Earth Science Reviews, 160:188-201, Elsevier.
D4.S.14	**C11**	Page E-30. 2.8.1 Hydrogeological Conceptual Model for Bear Creek Valley: The concepts of the hydrogeology of fractured rock settings used in this document have not moved with the progress made within the discipline and throughout the profession in general across the globe through the decades. For example, it is now acknowledged that it is not possible to assume that carbonate or fractured rocks behave as a porous medium (ASTM, 1995). Many papers through several decades have been written that describe rapid flow of recharge, groundwater flow and discharge in non-carbonate clastic rocks. They assume the characteristics of carbonate rocks, because there are obviously preferential flow paths, i.e., channels, the only difference being that the diameters of the channels in clastic rocks are probably less than those in carbonate rocks, because the dissolution rates are less (Worthington et al., 2016 [in review]). Fractured rocks have relatively long groundwater flowpaths and relatively deep flowpaths because the specific surface area contacted by water and other dissolved solutes is low as compared to the specific surface area of a well-sorted sand or gravel. This means that fractures tend to alter (or weather) along their length. With a positive feedback loop where in an open fracture within which water moves, if it becomes widened, it will take more water and thus will widen more and so on. This is one of the few reasonable explanations for deep contamination of classic rock settings. In addition the mineral assemblages of sandstones and shales dissolve incongruently, where a relatively insoluble clay mineral is formed after, e.g., feldspar minerals dissolve, which is different that when a carbonate rock dissolves and almost all the existing rock is transported away in solution. These scenarios in clastic rocks cause miscalculations in groundwater velocity, underestimations in contaminant transport, and other potentially problematic modeled predictions. At the end of the first paragraph therein (Section 2.8.1) a differentiation is made between karst and clastic rocks, evaluate the comments here and that statement, and in particular with regards to Worthington et al. (2016 [in review~~)).~~]).	No references are provided by TDEC for the "many papers through several decades" that are noted, so it is unclear the sources of the information that TDEC has summarized in the comment. In addition, the Worthington et al paper is "in review" and therefore is presumably unavailable as it has yet to be formally published. Thus it cannot be reviewed by DOE unless provided to DOE by Mr. Davies, the secondary author. The ASTM website notes the following withdrawal for ASTM D5717-95: *"Formerly under the jurisdiction of ASTM Committee D18 on Soil and Rock, this guide was withdrawn in May 2005 in accordance with section 10.5.3.1 of the Regulations Governing ASTM Technical Committees, which requires that standards shall be updated by the end of the eighth year since the last approval date." The ASTM standard from 1995 (21 years ago and not so recent)*. DOE disagrees with the comment that the concepts "have not moved with the progress", etc., and TDEC has provided only two references to support this broadly stated contention – one of which is 21 years old and withdrawn from current ASTM standards, and the other single reference which has yet to be published. The conceptual models are in fact based on the best available site-specific data and research conducted on the ORR and in BCV over several decades by many researchers from ORNL, from university research teams, and from qualified and respected environmental engineering firms. Site conceptual models (SCMs) are always site-specific and based on the unique conditions at and near the site. SCMs are formulated based on local topography, meteorology/climate, geology, hydrology (surface and subsurface), etc., and generally do not draw conclusions from other sites and conditions that are not site-specific. The site conceptual models developed for the ORR by Solomon et al (1992) and Moore and Toran (1992), and research conducted by many others, are based on solid scientific research, published by ORNL and in important respected journals (Ground Water, Ground Water Monitoring Review, Water Resources Research, Journal of Environmental Engineering, Journal of Contaminant Hydrology, U.S. Geological Survey, etc.). Their fundamental work and conclusions have not been significantly disproven. The fact that much of the work was completed in the 1980s and 1990s in no way discounts the results. The SCM presented in the BCV RI Report built upon the fundamental research and findings reported by Solomon et al and Moore and Toran and addressed the unique hydrogeological and contaminant fate and transport conditions associated with BCV. The current RI/FS report for the EMDF incorporates the collective findings from these previous efforts and presents SCMs for the proposed sites. These SCMs can in turn be refined and presented in more detail once a final site is selected for the EMDF and when site-specific data are collected and interpreted. Refinements to the SCM can then be used to adjust modeling assumptions and model construction as the EMDF project proceeds into the design phase.	TDEC provides the following information as a potential pathway to reconcile the original comment and DOE's response. The Worthington et al., (2016) paper is now published. The author of this comment helped write ASTM (1995). That document was written because the consensus of the scientific (academic, state government, federal government, private industry and military) community acknowledged that karst, carbonate, and fractured rocks have conditions that deviate from porous media. Even though all ASTM documents are now taken off active status after 8 years without updating, it does not invalidate the original standard guide as implied by DOE's response. Many papers and chapters in books have been published on flow in carbonates and karst since about 1990. They actually use concepts that date back many decades earlier. They show consistently that deep flow (up to several thousands of meters) in long systems (some >1,100 km) exist (Banner et al., 1989). Worthington (1991) rethinks the concept of groundwater flow in carbonates and uses investigation data that were not available previously. The site conceptual model was addressed in the groundwater strategy meetings and has several obvious problems. The main problem is that the nature and extent of groundwater contamination has not been characterized fully, but the SCM implies such characterization. This is true almost everywhere on the ORR. There is a regional aspect to Oak Ridge hydrogeology that must be addressed (Davies et al., 2012). References Banner, J.L., Wasserburg, G.L., Dobson, P.F., Carpenter, A.B., Moore, C.H., 1989, Isotopic and trace element constraints on the origin and evolution of saline groundwaters from Central Missouri, Geochimica et Cosmochimica Acta, 53:2, 383-398. Davies, G.J., Worthington, C.E., and Sebastian, J.E., 2012, Deep circulation of meteoric water in carbonates in East Tennessee: Is this a 50 m.y. old groundwater system that is still active? Geological Society of America Abstracts with Programs. Vol. 44, No. 7, p.298. Worthington, S.R.H., 1991, Karst Hydrogeology of the Canadian Rocky Mountains, Ph.D. Thesis, School of Geography and Geology, McMaster University, Hamilton, Ontario, Canada, 391 p. Worthington, S.R.H., Davies, G.J., and Alexander, E.C., Jr., 2016, Enhancement of bedrock permeability by weathering, Earth Science Reviews, 160:188-201, Elsevier.
D4.S.16	**C12**	Page E-33. 2.8.2 Hydrogeological Conceptual Models for EMDF Sites in Bear Creek Valley: "*As shown in Figure E-11, Solomon et al (1992) defined hydrologic subsystems for areas underlain by predominantly clastic (non carbonate) rocks referred to on the ORR as aquitards . ... The subsystems include ... an aquiclude at great depth where minimal water flux is presumed to occur.*" Given that 1) releases of radioactive constituents from EMDF have the potential to impact human health and the environment for thousands of years and 2) groundwater flow is one of the most significant potential transport pathways, reliance on general statements made more than a quarter century ago should be supported with site-specific data from a thorough hydrogeological investigation of the candidate sites. It is not	As previously noted, the hydrogeological conceptual models developed for the ORR and BCV and adapted to the EMDF sites are based on sound scientific research and site investigations and do not rely on general statements. The earliest research to assess water flux was completed in watersheds very similar to those at each of the proposed EMDF sites and	TDEC's position is that: 1) Siting regulations require geologic buffers for radioactive waste disposal facilities to protect human health and the environment. Suitability of the geologic buffer is particularly critical on the ORR and within BCV because

		sufficiently protective to refer to predominantly clastic rocks as aquitards or to presume minimal groundwater flux at depth. In a region with a significantly more stable tectonic history than the ORR, Anthony Runkel, Chief Geologist of the Minnesota Geological Survey, has demonstrated that conceptual hydrogeologic models used for decades are indefensible (Bradbury and Runkel, 2011 ; Runkel, 2010). In particular, he finds little support for historical assumptions that groundwater flow in siliciclastic strata is primarily intergranular and that "aquitards" have uniformly low conductivity. Specifically, he finds that discrete intervals of exceptionally high conductivity, commonly bedding-plane fractures and fractures perpendicular to bedding, can dominate the hydraulics of siliciclastic strata previously presumed to be aquitards. If intervals of high conductivity dominate groundwater flow in the relatively undeformed strata of Minnesota, such intervals are more likely to influence flow in the highly deformed bedrock of Bear Creek Valley.	included tubes placed in the shallow stormflow zone and monitoring wells at and below the water table along with hydrograph analysis to evaluate the response of surface water and ground water flow conditions during and between rainfall events. That work, along with other research and investigations that followed through several decades should not be trivialized, but rather should be used as most accurately representing the unique and site-specific surface water and groundwater flow conditions for BCV and the ORR. The commenter is encouraged to review or re-review the numerous publications cited extensively in Appendix E. A wealth of hydrogeological research and data are available for BCV and the ORR that provide the most reliable foundations for a site-specific hydrogeological conceptual model for the EMDF sites. The fact that much of the work was completed in the 80's and 90's in no way negates its validity. The several tracer tests completed at sites on the ORR, and in particular those completed in BCV provide solid evidence to demonstrate that contaminant migration within the saturated zone of saprolite and fractured rocks of the predominantly clastic rock formations of the Conasauga Group is orders of magnitude less than that within the carbonate formations of the Maynardville and Copper Ridge. Use of the term aquitard does not imply that fracture flow is not occurring along bedding planes and joints in the saprolite and bedrock of the ~~Conasagua~~Conasauga clastics. DOE has used available hydraulic conductivity data in BCV at and near the proposed sites to estimate ground water flow rates. Per previous responses, DOE feels the most cost effective approach is to reach triparty agreement on a site for the EMDF prior to investing millions of dollars in extensive characterization of a specific footprint location. TDEC concerns regarding the identification and characterization of high hydraulic conductivity fractures should be expressed during DQO scoping sessions and integrated with work plan development for future site characterization of the selected EMDF site, where the details and specific methods of data collection are actually defined.	of the humid environment and vulnerable hydrogeologic setting. 2) Characterization of the candidate sites is a fundamental component of a remedial investigation. Characterization includes the collection of site-specific data from a thorough hydrogeological investigation of the sites and defensible risk assessments. 3) Site-specific data and defensible risk assessments are necessary to support the meaningful comparison of alternatives in a feasibility study—in this case, to select one or more candidate sites for disposing radioactive waste in a manner that protects human health and the environment. As noted by DOE's response, a vast amount of hydrogeological research data are available for BCV and the ORR. TDEC believes the available data are useful for developing *preliminary* conceptual site models, and TDEC also believes the data demonstrate that site-specific data are needed because of the wide ranges of hydrogeological conditions (heterogeneity) in BCV. Also, as noted in TDEC's position regarding D4.S.14, considerable progress has been made to better understand groundwater flow and contaminant transport in settings like the ORR within recent decades. 4) The FFA parties should conduct a DQO meeting to identify data needs. DOE should provide a technical facilitator for this meeting to ensure each party's concerns are acknowledged and appropriately addressed.
D4.S.17	**C13**	Page E-33. 2.8.2 Hydrogeological Conceptual Models for EMDF Sites in Bear Creek Valley: *"Detailed water budget research on ORR watersheds that are similar to those of the EMDF sites ... "* Please cite the reference(s) supporting similarity between the candidate EMDF sites and watersheds where detailed water budgets were developed. As written, the paragraph containing the quoted statement is confusing, as it presents different findings from two studies and then speculates about groundwater flow conditions at various depths and future impacts of landfill construction on groundwater flow.	The statement quoted by TDEC has been modified to state "detailed water budget research, hydrograph analysis, and other methods .." See p. 3-5 through 3-28 of Solomon et al 1992 for complete descriptions of research methods, locations, interpretations, and findings completed in the headwaters areas of Melton Branch underlain by the same Conasauga Group formations in BCV. Studies were also completed in the Ish Creek Basin. The water budget analysis by Clapp is referenced in Section 2.8.2. Solomon et al (1992) and Moore and Toran (1992) provide complete references for published works supporting the conceptual model. In addition, the BCV RI Report (DOE 1997) includes additional references and appendices documenting details of the conceptual model and water budget analyses for BCV. The RI/FS Report for the EMDF project need not reproduce the extensive and original results of research and investigations in BCV and at areas on the ORR with similar characteristics to those in BCV. The original reports must be reviewed to fully appreciate the detailed basis for the site conceptual models presented for the proposed EMDF.	Please cite the appropriate references in the RI/FS—not just in the response. Removing the reference to "*ORR watersheds that are similar to those of the EMDF sites*" does not resolve the comment, and removal of that phrase makes it difficult for the reader to understand how the historical research applies to the candidate sites under evaluation. In the RI/FS, comment responses, and project team meetings, DOE has stated that the data needed to support characterization of the candidate EMDF sites can be extrapolated from historical investigations of other areas within BCV and elsewhere on the ORR. The RI/FS should document clearly and specifically the contributions made by previous investigations at other locations to the characterization and evaluation of candidate sites. As stated previously, the FFA parties should conduct a DQO meeting to identify data needs. DOE should provide a technical facilitator for this meeting to ensure each party's concerns are acknowledged and appropriately addressed.
D4.S.20	**C14**	Pages E-46 and E-52: *"If Site* 5 is *selected for the EMDF~~.~~, additional hydrogeological data will be needed to more completely establish baseline conditions for groundwater in, adjacent to, and upgradient of the Site* 5 *footprint...."* and *"Additional site characterization and water table monitoring at Site* 5 *in conjunction with more detailed engineering analysis are envisioned to resolve whether the conceptual base elevations would need to be raised in this area* or *whether dewatering before or during construction would be required."* Such fundamental baseline groundwater conditions should be characterized before selecting candidate sites and developing conceptual designs.	In reference to the first quote on page E-46, as TDEC is fully aware and previously agreed to, there was an inability to locate a Phase I well pair in the Rome formation upslope of Site 5. Therefore, this statement was made to acknowledge this fact, and that data collection from such a well/well pair would still be necessary if the site were to be selected. In reference to the second quote, as the quote indicates, a particular area of the footprint is being discussed; this is a relatively small area located at the southern portion of the footprint~~,~~. The quote has been taken out of context, and isolated here in the comment. The entire discussion from page E-52 is: *The current conceptual design for Site 5 requires that a portion of the north side of the spur ridge* [located in the southern portion of the footprint] *be excavated down to elevations below the water table mapped during the 2015 Phase I investigation. The remaining undisturbed southerly section of the spur ridge would remain as a natural buttress along the southern edge of the landfill. It is assumed that the water table within this local area*	TDEC disagrees. That was the EMWMF approach. It was necessary to retrofit Cell 3 with an underdrain due to the high groundwater levels. Long-term implications of the Cell 3 underdrain have not been determined. There are also elevated hydraulic heads at several pneumatic piezometers under the landfill and elevated water levels in monitoring wells on the Pine Ridge side of Cells 1 and 2. There are ongoing discussions to figure out water level issues at EMWMF. TDEC does not want to replicate that approach. Site-specific data are required prior to RI/FS approval to verify there will not be surprises similar to what happened at EMWMF. There were discussions on Site 7c at the project team level on June 30, 2016 and July 19, 2016 concerning the collection of site-specific data to verify water levels, verify whether an underdrain would be needed, verify how an underdrain could be avoided, and determine what data may be needed to evaluate alternative landfill layout configurations. When will the site-specific data be collected to answer this question so we are not guessing? TDEC does not support a site with an underdrain that would

			of the footprint could be effectively dewatered and reduced during landfill construction. Additional site characterization and water table monitoring at Site 5 in conjunction with more detailed engineering analysis are envisioned to resolve whether the conceptual base elevations would need to be raised in this area or whether dewatering before or during construction would be required. This type of detailed consideration of a relatively small area of the site is not warranted unless the site is selected. Should the site be selected, as the discussion suggests, this area should be investigated further to clarify the situation and how the construction/final design should accommodate the issue. It is not an issue that would preclude the use of the site under any circumstances. Relatively shallow water table conditions are known to exist at each of the proposed sites. As a steward of government spending, DOE feels it would be wasteful to spend millions of dollars on site characterization at proposed sites that are not ultimately selected as the disposal site. The most cost effective approach is to reach agreement among DOE, TDEC, and EPA on a site(s) among those proposed and then proceed with detailed site characterization to support design and other project needs.	produce flowing water once the liner is fully constructed. Prior to RI/FS approval, we need site-specific data demonstrating that any underdrain will be temporary and not flow upon liner completion. The FFA parties should conduct a data quality objectives (DQO) meeting to identify data needs. DOE should provide a technical facilitator for this meeting to ensure each party's concerns are acknowledged and appropriately addressed. TDEC expects that the record of decision (ROD) will clearly specify that any flow from an underdrain after liner construction will trigger additional investigation and landfill reconfiguration to eliminate the underdrain.
D4.S.21	**C15**	Pages E-72 and E-76: *"Geologic structures provide the fundamental pathways for groundwater flow and contaminant transport. Structures most relevant to the site conceptual model and fate and transport modeling include ... macropores and relict fractures within saprolite .... " "Descriptions and detailed systematic analyses of fracture sets are generally not provided in site investigation reports or in boring log or test pit descriptions, so that the nature of fracture systems and the detailed geometry of fracture networks remain nebulus [sic] and undefined at most sites. This is true for the EMWMF and for the proposed EMDF sites .... These uncertainties and limitations are necessarily reflected in fate and transport simulations in fractured media on the ORR."* If geological structures provide the fundamental pathways for groundwater flow, understanding of those fracture systems should be defined to a higher standard than "nebulous" to reduce uncertainties and limitations of the fate and transport modeling.	Hydrogeologic site characterization will include reasonable efforts to quantify structural and lithologic properties, commensurate with the level of detail required for the conceptual and mathematical models employed. DOE response to the D3 RIFS comment EPA.G.025 outlines the challenges and limitations of discrete fracture flow models and the characterization efforts required to support them. DOE does not propose to revise the fundamental approach to groundwater modeling for the RIFS.	TDEC's position is that characterization of the candidate sites is a fundamental component of a CERCLA remedial investigation. Characterization includes the collection of site-specific data from a thorough hydrogeological investigation of the candidate sites. The FFA parties should conduct a DQO meeting to identify data needs. DOE should provide a technical facilitator for this meeting to ensure each party's concerns are acknowledged and appropriately addressed.
D4.S.22	**C16**	Page E-72. Section 2.12.3.2 Bedrock Fractures in Predominantly Clastic Formations of the Conasauga Group: It should be recognized that the flowmeter readings are from boreholes that may not be connected to macrofeatures, as is often the case, simply because there is a low probability of these zones being intersected by chance (Benson and LaFountain, 1984). The only way to reliably demonstrate that hydrogeology from boreholes correctly represents a site is to test the conceptual model with tracers.	The limitations of boreholes intersecting (or not intersecting) the most hydraulically conductive and interconnected fractures is certainly recognized. An entirely new section addressing the tracer tests completed in BCV and elsewhere on the ORR was added to the D4 version of Appendix E (Section 2.13.5). The results of those tests provide useful information applicable to the EMDF project. The most intensively studied of those tracer tests, which was conducted at the proposed WBCV site (Site 14), required more than 72 monitoring wells/well clusters at 45 locations encompassing a relatively small area roughly 150 ft long by 70 ft wide. The tracer plume required 370 days to migrate a distance of 108 ft (at 100 ppb) in fractured rocks of the ~~Conasagua~~Conasauga clastics similar to those at each of the proposed EMDF sites. This would suggest that an enormous and prohibitive investment of resources and time would be required to complete tracer tests across the much larger areas of the proposed EMDF sites encompassing tens of acres.	TDEC's position is that tracing directly measures the groundwater flow velocities needed for transient modeling of contaminant transport. The cost of tracing to develop a protective WAC will be small compared to additional remediation if the site conceptual model is inadequate and releases occur.
D4.S.23	**C17**	Page E-73. Section 2.12.3.2 Bedrock Fractures in Predominantly Clastic Formations of the Conasauga Group: First paragraph, last sentence: How do you corroborate a notion? It is more logical to rationalize that, since the water table has not been in the same place, it settles in the zone of maximum porosity and permeability. It is also likely that there is more flow parallel or aslant the strike as in other locations that have been tested with injected tracers. The remaining and previous discussion about groundwater flow should consider that there will be convergent flow in larger fractures simply because of a positive feedback loop that develops. This could easily lead to small diameter channeling (a few mm to cm) that can be missed by boreholes, but that carry leachate or groundwater + dissolved solutes related to the waste cell to impact users probably many kilometers (miles) away.	The last sentence of paragraph 1 on page E-73 states, "The ORNL report by Moore and Young (1992) should be referenced for additional details." It is unclear to what the comment refers. It is certainly possible that convergent flow occurs in larger fractures, and such fractures may be feeding into the spring and seep areas found along the flanks and floors of the NT valleys. However, the accurate identification and 3D delineation of fracture networks including those of larger fractures is for practical purposes nearly impossible at the size and scale of the proposed EMDF sites and adjacent downgradient areas. See previous comment regarding the level of effort and timeframe required to intensively investigate a relatively small area that is a fraction of the size of the proposed EMDF footprints.	TDEC's position is presented above (D4.S.22).
D4.S.25	**C18**	Page E-76. Section 2.12.3.3. Karst Hydrology in the Maynardville Limestone and Copper Ridge Dolomite: There is a discussion about karst, karstification, etc., which segregates karstification into only these two formations. A modern approach to this should be considered. Worthington et al., (2016 [in review]) show that dissolution actually occurs in non-carbonate rocks, because of geological time, almost as commonly as it does in carbonates. They cite many examples of tracer tests that show rap id velocities (>150 *m/day* [~500 ft/day]) and long pathways (> 3 km [~2 miles]) e.g., in arkosic sandstones (quartz, feldspar and some mica minerals). Other examples they cite show similar parameters and suggest that at the scale of contaminant groundwater and migration (dissolved solutes and colloids) in narrow channels that can permit turbulent flow at 0.001 *m/s* (about 90 m/day [-300 ft/day]) (Quinlan et al., 1996) there is comparability between clastic and	As noted in previous responses, tracer tests conducted in BCV and elsewhere on the ORR are reviewed in detail in Appendix E Section 2.13.5 and support the fact that flow rates in the Maynardville and Copper Ridge are orders of magnitude greater than those in the predominantly clastic rock formations underlying the proposed footprints. The tests provide site-specific results directly applicable to the EMDF sites and areas downgradient of the sites, indicating measured tracer travel times. The	TDEC's position is presented above (D4.S.22). Additionally, TDEC notes that DOE cited various papers that present valuable tracing data, but those results were not adequately incorporated in the modeling.

		carbonate rocks. Lowe and Waters (2014) state that there are lithological conditions that promote development of subsurface channels, conduits and karst. These are: shale beds, faults and unconformities. The first of these is because sulfide minerals are often present in shales and thus can be oxidized after being in contact with meteoric waters to produce a groundwater that contains sulphuric acid, which can Significantly enhance dissolution. Faults and unconformities always have some sort of void spaces formed along them, and thus can allow groundwater or formation water and thereafter meteoric water to penetrate. This can have the effect of pre-conditioning the setting so that when it is subjected to uplift and subaerial exposure and attacked by meteoric water, dissolution processes can proceed at higher rates. Degrees of karstification are hard to quantify. Quinlan et al., (1996) provide the only numerical basis for describing the minimum size for conduits (a few mm [a few fractions of an inch] in diameter).	ORR test results from the tracer tests completed in the predominantly clastic rock formations do not indicate travel times anywhere near rates of 500 ft/day. As previously noted the test conducted at the WBCV site required 370 days to migrate a distance of 108 ft, an average rate of 0.3 ft/day. See Section 2.13.5 for additional details and summary findings from the tracer tests. It is acknowledged that travel times greater than those measured in the ORR tracer tests are possible, but in lieu of additional tests to demonstrate higher rates, the existing research provides the best available evidence directly applicable to the EMDF sites. Alternatively, it is also possible that the environmental and hydrogeological conditions at the sites noted in the comment are unique to the local conditions where they occur, and may not occur locally or be applicable to the environmental setting of the EMDF sites.	
D4.S.27	**C19**	Pages E-80 and E-81 : *"The hydraulic characteristics of unsaturated (and saturated) in-situ materials can be currently estimated based on available data at and near the proposed EMDF sites but most field investigations have not involved any direct measurements of unsaturated zone hydraulic parameters." "If unsaturated zone characteristics are required to support modeling, engineering design, or other project needs, they can be addressed in future work plans or site characterization."* If most investigations have not involved direct measurement, does this mean that some direct measurement data are available? If so, how are those data factored into the evaluation? If not, collection of such data is warranted to support a defensible evaluation of site suitability even before it is needed for detailed engineering design.	Site characterization will occur after the EMDF site is selected and agreed upon by the FFA parties. TDEC will be provided the opportunity to actively participate in DQO sessions and work plan development defining the specifics of that site characterization, including the acquisition of data on the hydraulic characteristics of the unsaturated zone as needed.	See TDEC's position regarding comment/response D4.S.20. RI/FS approval requires site-specific data to verify there will not be surprises similar to what happened at EMWMF.
D4.S.37	**C20**	Page H-30. Table H-3. Amended Clay Hydraulic Conductivity. Stage 4: The basis for adjusting the hydraulic conductivity of the amended clay layer by a factor of 2 should be provided.	The factor of two reduction in hydraulic conductivity is based on the following assumptions: • Limited long term changes in regional climate characteristics • Limited erosion of the protective cover layers overlying the amended clay barrier (HELP model assumes 24" thickness is retained) • Impacts of any differential settlement of the cover barrier system components is limited to reduction in lateral drainage efficiency • Limited impacts related to root penetration or other bioturbation processes on the compacted clay cover components Appendix H Section 4.1.2 has been revised to explain the linkages among various assumptions regarding barrier system component performance over time. Additional evaluation of uncertainty in hydraulic performance of the cover system is planned for the DOE O435.1 Performance Analysis.	These are very favorable assumptions. For example, Bullet 2 conflicts with DOE RTC D4.16, and Bullet 3 assumes there is no differential settling of underlying waste. In the RI/FS comment resolution discussion on August 9, 2016, DOE's contractor stated that the modeling did not incorporate differential settling of the waste because that result in cover failure and they did not model cover failure. The contractor's assumption was that differential settling of waste under the cover would be identified during each five-year review and would be repaired each five years. TDEC's concern is that if repairs do not occur, the cover could fail and the drainage layer could discharge water into the waste from areas of differential settling, in addition to other mechanisms of water percolating into the waste due to the cover failure. This would severely alter assumptions of water percolating through the waste. It would significantly reduce the time required for pollution to be released from the landfill and would increase concentrations of released pollutants or contaminants. It is overly optimistic to assume that all differential setting in waste is always identified in a timely manner and repaired every five years for the 1,000-year modeled period, much less thereafter. This questions validity of the first 1,000-year modeling results.
D4.S.38	**C21**	Page H-32. Section 4.2.1.2 Model Boundary Conditions: *"The UBCV Model has* a *no-flow boundary at the top of Pine Ridge to the north of the proposed facility ... "* and Page H-3St Figure H-9: The no-flow boundary assigned north of the proposed facility in the MODFLOW model appears to be only a few hundred feet away from the unit. Assigned boundary conditions should be tested to demonstrate that the boundary assignment does not have a significant influence on the calculated water levels - especially when the model boundary is in relatively close proximity to the area of interest in the model. This is particularly important since the model is used to estimate post-construction water level declines at the EMDF for comparison to the base of the landfill liner system. A no-flow boundary can enhance calculated declines by inhibiting flux into the model area. The assumption of a no-flow boundary underlying the ridge is a theoretical guideline, but field data has not been presented to support the boundary definition.	Based on the EBCV site Phase 1 monitoring data, changes in the assumed groundwater recharge rate were made for the Rome formation to improve prediction of water table elevations on the upslope portion of the EBCV site. This adjustment may be viewed to account for both uncertainty in the location of the groundwater divide under Pine Ridge and uncertainty in groundwater recharge within the Rome formation at the EBCV site. During groundwater model development for the DOE Order 435.1 Performance Assessment, sensitivity of modeled water table elevations to the recharge rate assigned to the Rome formation will be evaluated to address uncertainty in the location of the groundwater divide.	**If DOE intends for the PA, CA, and LFRG review/approval to resolve any of the modeling problems identified by TDEC, then those documents and reviews should be completed before DOE submits another RI/FS for TDEC review.** Moreover, sensitivity analysis is needed to understand how the boundary affects the calculated water levels.
D4.S.39	**C22**	Page H-43, Section 4.2.1.4 Model Calibration: Since the numerical model is used as the basis for establishing pre-design components of the landfill facility as well as PreWAC values, knowledge of specific calibration results is warranted to gage the suitability of the model for the applications. Calibration details, however, are not presented in this RI/FS. Information normally required includes the distribution of calibrated heads, minimum/maximum residuals, calibration statistics (such as root mean square error, absolute error, mean error) and the spatial distribution of the head residuals. It is not clear if any of this information, specific to this model for the proposed EMDF, is presented in other reports; nonetheless, some of the basic calibration information should be included in the RI/FS to allow confirmation that the model calibration is adequate for this application.	Information on past calibration efforts for this model is provided in Appendix H Section 4.2.1.4 (Page H-43). Based on the EBCV site Phase 1 monitoring data collected between December 2014 and November 2015, changes in the assumed groundwater recharge rate were made for the Rome formation to improve prediction of water table elevations on the upslope portion of the EBCV site. A figure has been added to Appendix H illustrating modeled and observed water table elevations at the EBCV site. Once a site is selected for the EMDF, and adequate site characterization data are available, additional groundwater model performance information and calibration metrics will be provided. This information can also be referenced or included in the appropriate CERCLA documentation.	We need sufficient information and characterization prior to RI/FS approval to assure we are basing decisions on reliable data and are not just guessing. No documentation on the model calibration was provided, other than a paragraph that parameters were validated previously (including a report reference, which TDEC has not been able to find) and general statements that "…well head values were in general agreement…" among other statements. Generally, standard calibration statistics are reported (perhaps in a simple table) to allow the reader to gauge the suitability of the model for representing the system being modeled. The modeled vs. observed water table figure may help, but it is not a substitute for actual calibration statistics.
D4.S.40	**C23**	Page H-50. Section 4,3,2 MT3D Model Assumptions: The MT3D model setup includes withdrawal of water from layers 3-6 - presumably with one well node assigned in each of the 4 model layers representing the pumping of a water supply well. However, the summary of	There were two wells represented in the MODFLOW and MT3D models, each at a distance of 100 m from the waste disposal facility. These two	TDEC requests further clarification.

		MODFLOW parameters for the Future Condition scenario (Table H-4, page H-41) lists 8 well nodes used in the model. Please clarify the representation of the pumping and number of well nodes assigned.	wells represented the two locations that were considered for the drinking water well in the resident exposure scenario during discussions with the project team. The two modeled wells each correspond to 4 well nodes, for a total of 8 nodes, and the assumed pumping rate was 240 gal/day at each well. Modeled wellhead concentrations for the receptor well location indicated in the RIFS main text and Appendix H were used to derive preliminary WAC. Modeled withdrawal of water at the other well location has no impact on the predicted development of the plume at the receptor well location.	
D4.S.41	**C24**	Page H-64. second complete paragraph: "…*dilution factors for the creek (surface water source) and residential well (see Section* 4.3.3) *were used for scaling the constituent concentrations in the creek* to *corresponding well concentrations."* The surface water concentrations and the residential well (groundwater) concentrations used in the scaling calculations have each been developed using different modeling approaches and assumptions (the surface water concentrations are developed using PATHRAE with consideration of advection, dispersion, and sorption, while the groundwater concentrations are developed based on advection only). The comparability of the modeled values for use in scaling calculations is questionable.	The cited text has been revised to clarify the meaning. The difference in the derivation of the dilution factors for the creek and well does add some uncertainty to the predicted well concentration. This simplification is addressed in the text on page H-64.	Response noted.
D4.S.42	**C25**	Page H·69. Table H·7: Response to TDEC comment TDEC.S.106 stated that differential settling is assumed post-1,000 years and is accounted for by clogging the drainage layer of the cap (decrease in hydraulic conductivity of 100), HELP model sensitivity analysis presented in Table H-7 includes a 2 order of magnitude reduction of hydraulic conductivity in the lateral drainage layer post-1000 years. TDEC does not understand the technical basis for postponing differential settling to greater than 1,000 years after closure.	The PATHRAE contaminant transport model does not accommodate transient infiltration rates, so the performance scenario and approach to transport modeling releases utilizes constant infiltration rates for each performance stage, with instantaneous increases occurring at 500 and 1000 years. Although substantial differential settling of the cover system components may occur prior to 1000 years, the conceptual landfill performance scenario includes no significant reduction in drainage efficiency due to the combined effects of clogging and differential settling within that timeframe, based on the assumptions of limited degradation of the protective cover layers that overlie the lateral drainage layer.	Differential settling was included in the D4 as a two-order-of-magnitude decrease in lateral drainage (see D4.S.37) because of TDEC comments on the D3 RI/FS. TDEC's comment on the D4 RI/FS included the question for the technical basis for postponing differential settling for 1,000 years. TDEC's D3 comments included discussion of both differential settling of the cap and of the waste under the cap. It appears from the DOE response that the D4 RI/FS only included differential settling of the cover above the drainage layer and then only beginning at 1,000 years. Differential settling of the 50-foot-thick waste section below the two (2) feet of compacted clay cover may also be substantial. The part of the cover that acts as a barrier to prevent water from percolating into the waste is essentially a 40-mil HDPE liner overlying two feet of clay. If voids occur under the cover that cause the clay to drop into the void, how long will the 40-mil HDPE support the four (4) feet of rock and four (4) feet of soil cover overlying it without leaking or tearing? It appears that three (3) to five (5) feet of differential settling could cause cover failure and result in the drainage layer discharging into the waste zone. There is no technical basis to assume differential settling of waste would not occur for 1,000 years. TDEC D3 RI/FS comment 106 includes in part: "Waste assumed to be placed in EMDF was modeled as a soil-like material and consequently differential settling or differential compaction was not mentioned in Appendix H. Modeling the 50 foot thick waste layer as a soil-like material is inconsistent with many of the materials needing disposal. Further, based on experience with EMWMF, DOE will not perform size reduction of the waste placed in EMDF. Lack of size reduction could result in long term differential compaction/differential settling that disturbs cap drainage layers and causes ponding or micro-fractures in cap layers. Differential compaction/ differential settling could result in DOE's predicted volume of leachate entering groundwater or the underdrain being low by an order or more. If sensitivity analyses were run to evaluate differential compaction and settling, it was not referenced in the RI/FS Appendix H. DOE's worst case scenario (Table H-2) did not assume differential compaction." In the RI/FS comment resolution discussion on August 9, 2016, DOE's contractor stated that the modeling did not incorporate differential settling of the waste because that result in cover failure and they did not model cover failure. The contractor's assumption was that differential settling of waste under the cover would be identified during each five-year review and would be repaired each five years. TDEC's concern is that if repairs do not occur, the cover could fail and the drainage layer could discharge water into the waste from areas of differential settling, in addition to other mechanisms of water percolating into the waste due to the cover failure. This would severely alter assumptions of water percolating through the waste. It would significantly reduce the time required for pollution to be released from the landfill and would increase concentrations of released pollutants or contaminants. It is overly optimistic to assume that all differential setting in waste is always identified in a timely manner and repaired every five years for the 1,000-year modeled period, much less thereafter. This questions validity of the first 1,000-year modeling results.
D4.S.44	**C26**	Appendix H - Attachment B. Page 7. Section 2.1 .3 General Design and Evaporative Zone Data: The SCS runoff curve number of 49.3 seems	HELP sensitivity runs for curve number (CN) = 60, 70, and 80 have been	TDEC still believes that the selected curve number of 49.3 is too low. The

		low when compared to curve numbers presented for Pasture, grassland, meadow or brush in Table 2-2c of the US Department of Agriculture Technical Release 5S (Natural Resources Conservation Service, *Urban Hydrology for Small Watersheds*, 210 VI TR-55, June 1986). In that document, the majority of the runoff curve numbers are greater than 60, with values less than 50 associated with good hydrologic conditions in generally sandy soils. Additionally, the assumption of 100% runoff for the 'Fraction of Area Allowing Runoff' in the HELP model seems optimistically (and non-conservatively) high.	performed and result in very small increases in predicted surface runoff (4% of precipitation for CN=80 vs 1.3% for the base case CN=49.3) for the highly permeable cover soil type selected in the model. The relatively high infiltration provided by the cover soil in the conceptual design limits the magnitude of surface runoff and erosion. HELP predicted total runoff (surface runoff plus lateral drainage) exceeds 40% of precipitation, comparable to water balance results for many small watersheds.	conceptual design should discuss the infiltration rate of the cover soil, the hydrologic soil group (A, B, C, and D), cover type, and the slope of the cover soil. If a high-permeability soil (k greater than 1x10^{-5}cm/sec) is used, then the transmissivity of the geocomposite drainage layer must be specified to ensure that the head over the geocomposite layer is limited to the thickness of the geocomposite drainage layer. In addition, four assumptions should be considered in the HELP model run for determining the maximum leachate quantity: A) Open cell condition with no cover soil, assuming no (zero) runoff. B) Open cell with daily cover soil, assuming partial runoff. C) Open cell with intermediate cover, assuming partial runoff. D) Portion of the site is fully closed (if applicable).

See pages 39-41 in the original TDEC letter (May 16, 2016; Attachment D to this table) for references cited in D4 comments.

ATTACHMENT A

DRAFT LANGUAGE FOR EXCEPTION (IN D5 RI/FS APPENDIX G ARARS)
[Emailed by Susan DePaoli 08-04-2016 @ 13:59 ET]

DRAFT LANGUAGE FOR EXCEPTION (IN D5 RI/FS APPENDIX G ARARS)

TDEC 0400-20-11-.17(1)(h)

This TDEC requirement, an NRC-based low level waste (LLW) disposal siting criterion, states "*The hydrogeologic unit used for disposal shall not discharge groundwater to the surface within the disposal site***.**" The following definitions are given:

- Hydrogeologic unit – *any soil or rock unit or zone which by virtue of its porosity or permeability, or lack thereof, has a distinct influence on the storage or movement of groundwater."*
- Disposal site – *portion of a land disposal facility which is used for disposal of waste. It consists of disposal units and a buffer zone.*
    - Disposal unit – *discrete portion of the disposal site into which waste is placed for disposal.*
    - Buffer zone – *portion of the disposal site that is controlled by the licensee and that lies under the disposal units and between the disposal units and the boundary of the site.*

NRC guidance (NUREG 0902) states the rationale of this criterion: "*This requirement will result in a travel time for most dissolved radionuclides at least equal to the travel time of the groundwater from the disposal area to the site boundary. In addition, this requirement should provide sufficient space within the buffer zone to implement remedial measures, if needed, to control releases of radionuclides before discharge to the ground surface or migration from the disposal site."*

Sites proposed for an on-site disposal facility do not consistently (e.g., based on seasonal precipitation) meet this criterion for the current (pre-construction) site hydrogeologic features. Varying degrees of groundwater discharge to the surface at the proposed sites depending on seasonal rainfall contributions. Discharge of groundwater through seeps/springs/intermittent streams may range from zero discharge during dry seasons to continuous discharge during wet seasons. LLW land disposal facilities designed for this type of hydrogeologic setting rely on maintaining a sufficient thickness of unsaturated material between the waste and the water table to isolate the waste from groundwater, provide extended contaminant travel times, and ensure protection of human health and the environment.

All sites proposed for consideration will require grading to create a level base for construction. Site grading will raise the base of the landfills above the pre-construction high water table, by significant amounts in some areas. A geologic buffer of either in place soil, fill from cut areas, or purchased fill (all of which must meet specific low permeability requirements) is placed to ensure a minimum unsaturated material thickness of 10 feet above the seasonal high water table of the uppermost unconfined aquifer or the top of the formation of a confined aquifer [TDEC 0400-11-01-.04(4)(a)(2)]. Above this geologic buffer, the liner system is installed. The liner system includes three feet of compacted clay, geosynthetic layers, a one foot leachate collection drainage layer, and a final one foot protective material layer (five feet total), above which the waste is placed (consistent with RCRA requirements). The geosynthetic layers are water impermeable materials that have been simulated in multiple independent tests to function for many centuries. These features will isolate the short-lived radionuclides so that decay occurs in place; therefore, they will not present a risk to human health or the environment (see discussion in main document Section 6.2.2.4.8). The geosynthetic materials ensure that leachate does not contaminate the underlying groundwater during the service life of the synthetic liner components. These three features (geologic buffer, liner, and geosynthetics within the liner) along with the material specifications they must meet (e.g., per RCRA) exceed design requirements specified in the TDEC NRC-based *Licensing Requirements for Land Disposal of Radioactive Waste* (TDEC 0400-20-11), which does not require any material, liner, or other engineered feature between the waste and the hydrogeologic unit used for disposal.

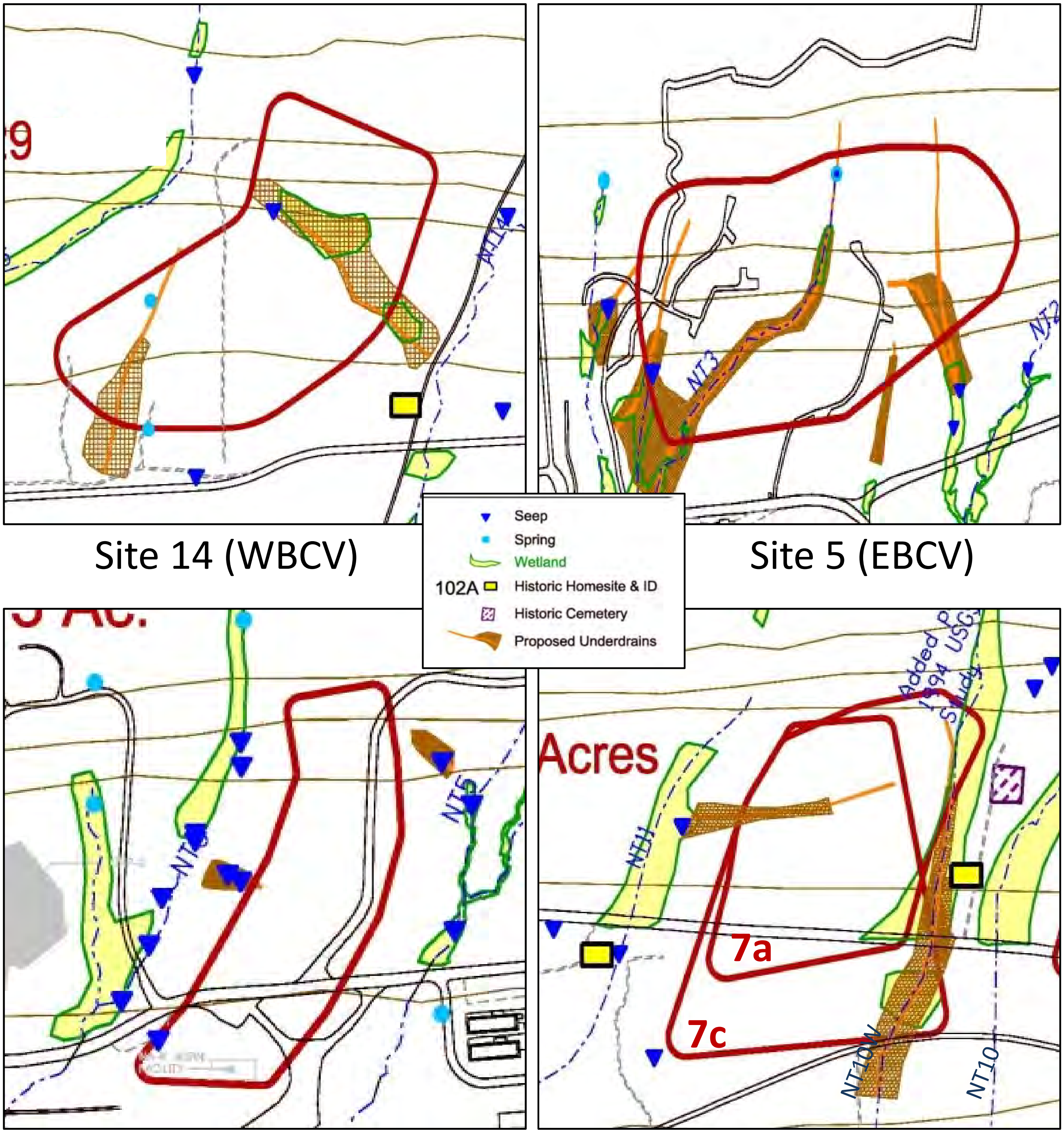
As explained, the conceptual design for the EMDF at all BCV candidate sites incorporates a minimum 15 ft vadose (unsaturated) zone, comprised of the liner and geobuffer between the waste and high water table. Conceptual designs of all sites proposed for consideration include engineered underdrain systems installed beneath the geobuffer to capture and divert groundwater discharge and maintain the minimum thickness of the vadose interval. In addition, in-situ and structural fill materials incorporated to level the footprint provide additional vadose zone thickness beneath a significant portion of the waste for all sites, increasing average depths to groundwater to approximately 25-30 ft. Minimally, vadose zone depths are thus 15 ft, with maximum depths in isolated areas at some sites reaching 90 ft. In the event that contaminants are released from the waste, the underlying vadose zone depth provides an extended travel time that would greatly exceed the travel time of the groundwater from the disposal area to the site boundary as targeted by the siting criterion.

After closure of the landfill facility, the 11 foot final cover system, which also includes geosynthetic layers, ensures that recharge to the footprint is severely limited for hundreds and up to thousands of years, minimizing release of contaminants and further ensuring that groundwater tables remain lowered. During the post-closure period of DOE institutional control of the facility, maintenance and monitoring of the leachate collection and leak detection systems along with required groundwater monitoring (e.g., RCRA Subpart F) will provide indications of potential releases of radionuclides to groundwater and permit the implementation of remedial measures prior to discharge to the ground surface or migration from the disposal site.

In totality, the facility conceptual design’s engineered features for all sites ensure protection of ground water above and beyond the NRC requirement’s intended outcome. Given the unique nature of this CERCLA remedy, coupled with the substantive means by which the NRC-derived requirements are met or exceeded, DOE would suggest that no waiver of TDEC 0400-20-11-.17(1)(h) is required. If TDEC or EPA insists that, given the above a waiver is still suitable and appropriate, then DOE would offer the following.

An exception to the TDEC siting criterion for all proposed sites is requested, as allowed under TDEC 0400-20-04-.08 (Division of Radiological Health General Provisions) whereby *“The Department may, upon application by any person or upon its own initiative, grant exemptions, variances, or exceptions from the requirements of these regulations which are not prohibited by statute and which will not result in undue hazard to public health and safety or property*.” This exception is requested based on the ability of engineered features to fulfill the intent of the siting criterion, and therefore not result in undue hazard to public health and safety or property.

Per CERCLA, a waiver for this requirement may be requested on the basis of “equivalent protectiveness”, under 40 CFR 300.430 (f)(1)(ii)(C)(4) *The alternative will attain a standard of performance that is equivalent to that required under the otherwise applicable standard, requirement, or limitation through use of another method or approach*. As discussed above, the additional engineered features (geologic buffer, liner, and geosynthetics within the liner and cover systems) are over and above design requirements noted in TDEC 0400-20-11, and along with additional vadose zone thickness provided through site grading provide an equivalent protectiveness to that intended by the siting criterion**.**



Site 14 (WBCV)

Site 5 (EBCV)

Site 6b (Dual Site)

Site 7a (Dual Site) and 7c (CBCV)

ATTACHMENT B

A Comprehensive Strategy for Understanding Flow in Carbonate Aquifers
Worthington (1999)

KARST WATERS
INSTITUTE

Special Publication 5

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Karst Modeling
Karst Waters Institute Special Publication 5

A COMPREHENSIVE STRATEGY FOR UNDERSTANDING FLOW IN CARBONATE AQUIFERS

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Abstract

Studies of carbonate aquifers usually either concentrate on sampling the channel flow (e.g. sink-to-spring tracer testing, spring monitoring) or on sampling the non-channel flow (e.g. borehole measurements). A comprehensive approach is advocated here, involving the integration of both sources of information, as well as measurements of the porosity and permeability of the unfractured rock. Representative sampling can be achieved by treating carbonates as triple-porosity aquifers, with one-, two-, and three-dimensional porosity elements. The division of carbonate aquifers into "karstic" or "non-karstic" types is unwarranted.

Introduction

In the past three decades, carbonate aquifers have usually been considered in one of three ways. The simplest and most commonly used approach has been to assume that fractures may be locally important, but that fracture density is great enough that the aquifer can be treated as an equivalent porous medium and can be modeled using a package such as MODFLOW. A second approach has been to recognize that fractures may be laterally continuous for considerable distances and that these are much more conductive than the matrix of the rock. In this case a double-porosity (or double-permeability) model is used for the aquifer. In both cases it is assumed that boreholes facilitate representative sampling of the aquifer. A third approach has been to recognize the existence of a high-permeability network of conduits within the aquifer, and to concentrate on studying the conduits. Techniques include tracer testing from dolines or sinking streams to springs and monitoring of spring discharge or hydrochemical parameters. This approach is most commonly used where there are abundant surficial karst landforms.

The use of *a priori* assumptions on the behavior of carbonate aquifers tends to result in studies that only partially characterize an aquifer. Studies of spring flow or tracer testing from sinkholes to springs succeed in characterizing channel flow in the aquifer, but little is learned about non-channel flow. Conversely, studies using wells as sampling and monitoring points may characterize fracture and matrix flow but often give little or no indication of the rapid solute transport that is occurring in the channel network located between the wells. A full understanding of flow in carbonate aquifers can only be gained by studying all the flow components in the aquifer.

The conceptual model described below incorporates the techniques used for monitoring wells and those used for monitoring springs to gain a more holistic understanding of carbonate aquifers.

A conceptual model for carbonate aquifers

One way of studying carbonate aquifers that may prove useful is to consider aquifers in terms of the three fundamental geometric elements that can exist within it. These are shown in Figure 1 and are: (i) One-dimensional, or linear elements. These are often referred to as *channels*. In carbonate aquifers, large channels in which there is turbulent flow are commonly termed *conduits*, and if they are accessible by people they are called *caves*. (ii) Two-dimensional, or planar elements, such as bedding planes, joints and faults. (iii) The three-dimensional matrix.

Carbonate aquifers can be considered as triple-porosity aquifers since they contain these three porosity elements. Analysis of an aquifer in terms of three porosity elements results in a better understanding of flow and storage than if the aquifer is treated as having only two porosity components. Furthermore, there have been two different ways in which two porosity components in carbonate aquifers have been studied; a double-porosity aquifer is not the same as a conduit and diffuse-flow aquifer (Table 1). Analysis as a triple-porosity aquifer can avoid potential confusion and lead to more accurate insights on aquifer behavior.

Formation, size and distribution of channels

Fracture planes commonly have variable apertures, and most of the flow is concentrated along the more open portions of fractures, which are called channels. For instance, in granites in Great Britain and in Sweden it has been found that such channels may occupy 5-20% of a given fracture plane (Tsang, 1993). However, in carbonate rocks some channels may be greatly enlarged by solution processes. This is due to two factors:

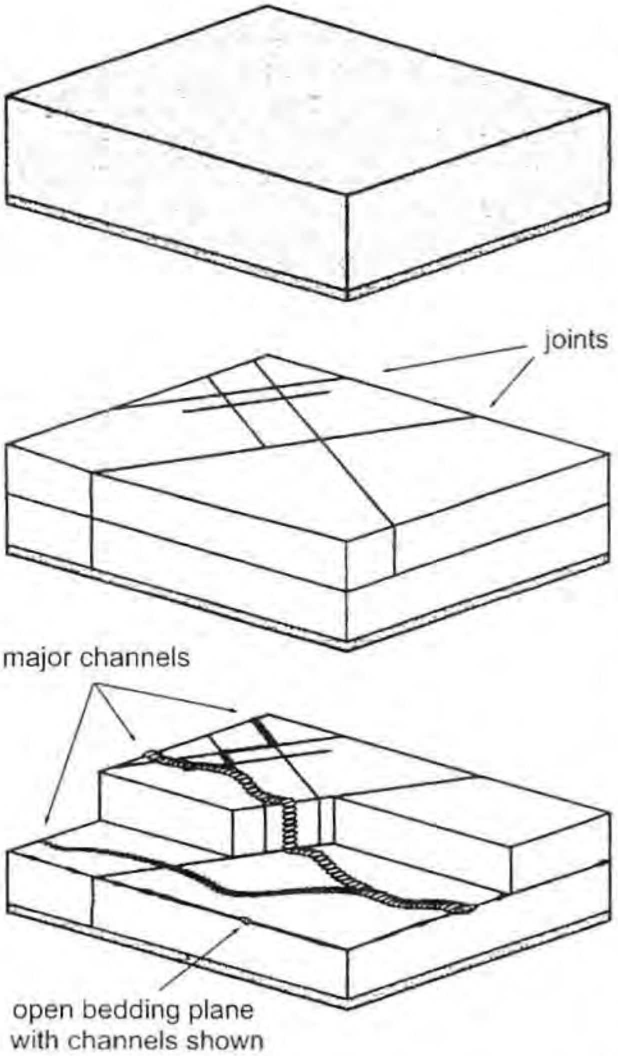

Figure 1: Model for a single-porosity aquifer with matrix flow (top), a double-porosity aquifer with matrix and fracture flow (center), and a triple-porosity aquifer with matrix, fracture, and channel flow (bottom).

(a) The non-linear nature of carbonate dissolution. As thermodynamic equilibrium is approached, the solution rate decreases by several orders of magnitude (Plummer and Wigley, 1976). This results in carbonate groundwater being slightly undersaturated with respect to calcium (or magnesium) carbonate at most sites where there is notable flow.

(b) The positive-feedback relationship between dissolution rate and discharge, which permits larger channels to grow at the expense of smaller ones (Ford and Williams, 1989, p. 249 *et seq.*).

These two factors combine to create broadly dendritic networks of channels. In unconfined carbonate aquifers in moist climates, channeling should always develop. An example of a dendritic channel network is shown in Figure 2. Fifty-three small tributaries converge in this well-mapped cave to form a flow path which discharges to the surface at a spring. The channels shown in Figure 2 are all accessible to people, and are all >0.3 m in diameter.

There are also smaller channels than cave passages. These channels are sometimes encountered in boreholes (Waters and Banks, 1997), but are better visible in quarry walls, outcrops and in cave passages. Figure 3 shows the calculated apertures of two sets of small channels. The "minor flows" are from measurements at 44 drip points from stalactites into four New Zealand caves (Gunn, 1978), and the "major flows" are from the 25 largest flows into GB Cave, England (Friederich and Smart, 1982). Apertures were calculated using the Hagen-Poiseuille equation and the maximum recorded discharge at each flow point, assuming a hydraulic gradient of unity and a circular channel shape. The calculated apertures are only estimates, as channel roughness and surface-tension effects are ignored, and the measured flow may be much less than the channels are capable of delivering. However, the calculated values are likely to be fairly accurate, since discharge varies with the fourth power of pipe diameter. Natural-gradient tracer tests were carried out from the surface to the input points in GB Cave, which were on average 60 m below the surface. Tracer arrival times varied from less than one day

Element geometry	Flow regime	Karst spring studies	Double porosity	Triple porosity
3D	laminar	diffuse	matrix	matrix
2D	laminar	diffuse	fracture	fracture
1D	laminar	diffuse	not included	channel
1D	turbulent	conduit	not included	channel (conduit)

Table 1: Comparison of classification schemes for porosity elements in carbonate aquifers.

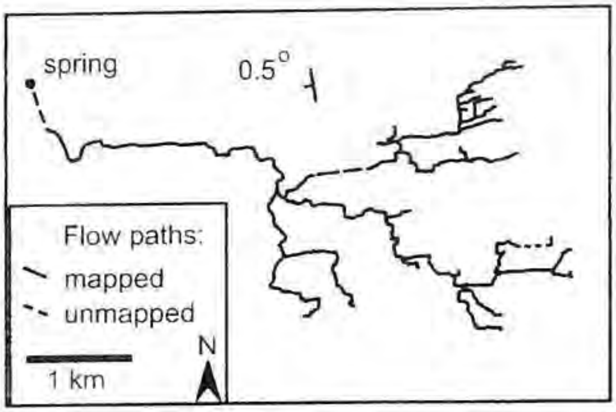

Figure 2: Convergent flow paths draining to a spring, as mapped in Blue Spring Cave, Indiana (after Palmer, 1969).

to several weeks, giving velocities mostly in the range of 10-100 m/day (Friederich and Smart, 1981). These velocities are between the 1700 m/day average velocity for sink-to-spring tracer tests (Worthington et al., 1999a) and calculated velocities of a meter per day or less derived from equivalent porous-medium analysis.

Dolines are input points to channels. The channel at the base of a doline is an efficient drain point which promotes centripetal drainage and facilitates the enlargement of the doline. The channels draining dolines are likely to be at least some millimeters in diameter, and are often found to be much larger. Such channels not only must be able to carry the discharge from the depression, but also the suspended load of insoluble material resulting from erosion of the bedrock within the doline. Furthermore, the channels must be part of a continuous channel network with its outlet at a spring; if this were not the case, then the doline-draining channels would becomes choked with insoluble material, and doline formation would be halted at an early stage.

Sampling and monitoring the three porosity components

(i) Channels: Springs in carbonate strata represent the output points for channel networks and provide a sampling point that integrates the groundwater flow from what is often a considerable area, e.g. 10-1000 km^2. They are thus ideal for sampling off-site migration from contaminant sites. Tracer testing from dolines or sinking streams to springs is common and serves to establish flow direction and velocity. If both spring discharge and the hydraulic gradients in the aquifer are known, then an "equivalent hydraulic conductivity" for the aquifer can be calculated (Worthington and Ford, 1999a). This is an average value across the cross section of the catchment draining to a spring, and ignores turbulent flow, which may be important. The use of an equivalent hydraulic conductivity facilitates comparisons of channel flow with matrix and fracture flow.

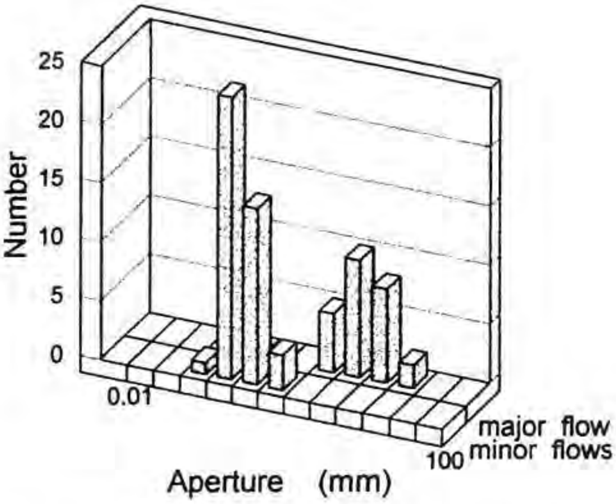

Figure 3: Calculated apertures of minor flows into four New Zealand caves and major flows into GB Cave, England (calculated from measurements by Gunn (1978) and Friederich and Smart (1982).

Boreholes are of limited use in studying channeling. Table 2 gives data on channeling in a number of well-studied carbonate aquifers where extensive caves have been found. From this data set, a borehole would have a probability of only 0.0037 - 0.075 of intercepting one of these mapped cave passages. In volumetric terms the caves only occupy between 0.004% and 0.48% of the bedrock in which they are located. Thus it would be fallacious to assume that an absence of major bit drops in drilling a number of wells at a study site signifies an absence of channeling.

(ii) Fractures: The permeability of horizontal or sub-horizontal fractures (usually bedding planes) is routinely determined from hydraulic testing (e.g. packer, slug, or pump tests) in vertical boreholes. Fracture aperture can be determined by the cubic law from narrow-interval packer testing. The permeability of vertical or sub-vertical fractures is usually estimated rather than measured. For instance, in horizontally-bedded strata it is often assumed that vertical permeability is 10 or 100 times less than horizontal permeability.

(iii) The matrix: The matrix is the solid unfractured rock. Samples may be collected from boreholes, quarry walls, or natural outcrops for testing porosity and permeability. Alternatively, *in situ* packer testing in unfractured sections of boreholes will give values of matrix permeability (Price et al., 1982).

Cave	Volume of rock length x width x height m (1)	Volume of cave x 10^6 m^3 (2)	Length of cave km (2)	Cave porosity % (3)	Areal coverage of cave % (4)
Ogof Agen Allwedd - Ogof Daren Cilau, Wales	6200 x 1900 x 50	0.9	75	0.15	1.7
Blue Spring Cave, Indiana	5100 x 2600 x 45	0.5	32	0.08	1.1
Kingsdale Cave System, England	2600 x 1500 x 100	0.17	20	0.04	1.8
Nohoch Nah Chich, Mexico	5500 x 1900 x 80	4	39	0.48	6.5
Mammoth Cave, KY, USA	11000 x 9000 x 90	8	550	0.09	1.4
Castleguard Cave, Canada	6500 x 1200 x 400	0.12	20	0.004	0.51
Friars Hole System, WV, USA	6000 x 2000 x 80	2.7	70	0.28	2.5
McFail's Cave, New York	3500 x 2300 x 90	0.12	11	0.016	0.37
Skull Cave, New York	1300 x 940 x 60	0.046	6	0.064	1.2
Caves in Southern Gunung Api, Malaysia	7000 x 2500 x 400	30	110	0.43	7.5

Table 2: Cave porosity and areal coverage for some well-mapped caves. **(1)** This represents the minimum rectangular block of rock that can contain the 3-D array of mapped passages in each cave. **(2)** These refer to the explored and mapped cave passages. Increases in these values are likely as the caves are more completely explored. **(3)** Cave porosity is defined as the volume of mapped cave divided by the minimum rectangular block of rock that can contain the cave. **(4)** The areal coverage is the plan area of the cave divided by the minimum rectangular area that can contain the cave, which represents the probability of a borehole intersecting the cave.

The extent of channel networks

Dolines represent the upgradient ends of channels, and it is possible to gain a better understanding of channel distribution by using doline distribution to construct a model of the channel network. For instance, Figure 4a shows the northeast portion of Blue Spring Cave, Indiana (Figure 2), with the doline watersheds shown. A simple map of channeling could be constructed by linking the low points in each of the 38 dolines with either the eight major inputs into this section of the cave or into other major channels (Figure 4b). Such a procedure obviously simplifies the geometry of the major channels and ignores smaller channels (e.g. channels feeding drip points at stalactites), but it does represent an important fraction of flow in the aquifer.

The above procedure is a starting point to modeling channeling in a polygonal terrain such as at Blue Spring Cave, where the whole surface is occupied by contiguous dolines. However, many surfaces above carbonate aquifers have dolines that are widely spaced. These can be linked in the same fashion as at Blue Spring Cave to give a channel network draining to a spring, but this network will be a great simplification of the true channel network. Furthermore, some carbonate aquifers have no dolines overlying them, such as where the aquifer is overlain by non-carbonates or by glacial sediments. Prominent examples are the most extensive cave in Canada (Castleguard Cave) and the most extensive cave in the USA (Mammoth Cave); the majority of both caves underlie surfaces where dolines are absent, so the channel network in these aquifers cannot be inferred from the surface landforms. However, in both cases channel networks have been demonstrated from tracer testing (Smart, 1988; Quinlan and Ray, 1981) as well as from cave exploration.

Where there are no dolines or sinking streams above a carbonate aquifer, then it is most difficult to estimate the extent of channeling. If there are no faults or high-permeability facies at a spring to explain the concentration of aquifer discharge at one point, then the best explanation is that the spring is the outlet for a channel network, and this is likely to extend throughout the spring's catchment. Some carbonate aquifers discharge into thick alluvium, lakes, or the sea, so that the location of springs may be extremely difficult, as will the characterization of channeling.

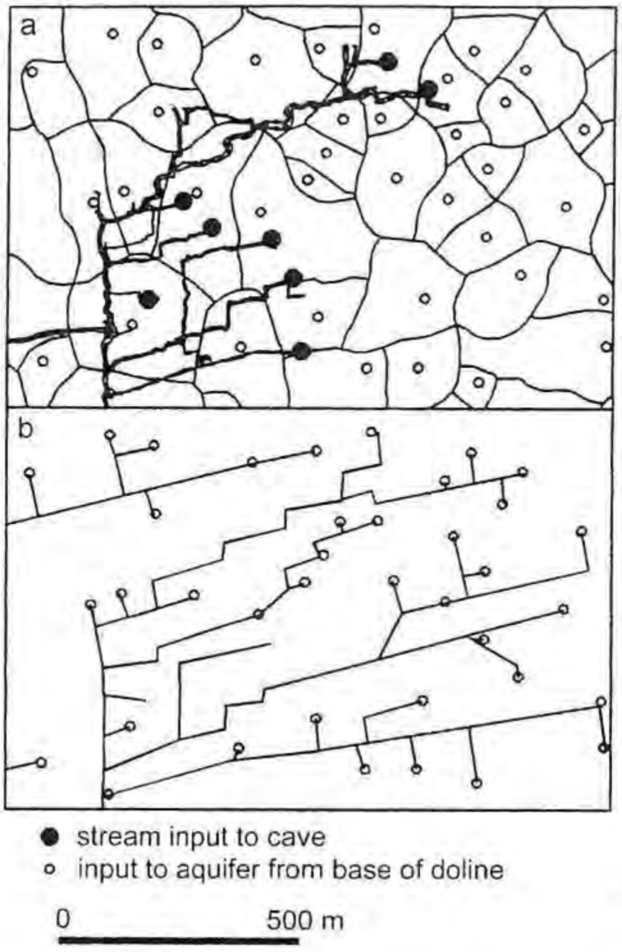

Figure 4: Channeling in the northeast section of Blue Spring Cave, Indiana, showing (top) doline watersheds and underlying cave passages (after Palmer, 1969); and (bottom) a dendritic network of the major channels

Sampling boreholes for channeling

Boreholes are not ideal for investigating channeling because of the low probability of intercepting channels, as explained above. However, there are some aquifer testing and monitoring techniques that can give an indication that there may be channels close to the borehole. The following list of the techniques for inferring channeling is based on the discussion in Worthington and Ford (1995):

(a) Well-to-well or well-to-spring tracer tests. Tracer tests from sinking streams or dolines to springs were established in the 1870s as an excellent method of determining channel velocities and connections. Well tests are much more problematic, as wells may be poorly connected to channels. It is likely that longer-distance traces (e.g. >100 m) are more likely to show evidence of channeling than shorter-distance traces, as the widely spaced channels are more likely to be encountered along a longer tracer path.

(b) Combination of core, packer, slug, and pump tests. Kiraly (1975) first suggested that there is a scaling effect in carbonate aquifers, with larger-scale tests encountering more permeable fractures and channels.

(c) Variable-rate pumping tests. Hickey (1984) showed that the pumping rate should be proportional to the drawdown in observation wells if Darcy's Law is valid within the cone of depression. If there are major channels within the cone of depression, and if these are well-connected to the pumping well, then there should be a non-linear pumping-rate / drawdown response.

(d) Matrix and fracture packer tests to calculate fracture extent. Price (1994) described a method for estimating the extent of interconnected fractures intersected by wells by using steady-state packer testing.

(e) Symmetry of cones of depression at pumping wells. The cone of depression at a pumping well is symmetrical in a homogeneous porous medium. However, the cone of depression is likely to be irregular if there is extensive channeling nearby.

(f) Continuous water-level monitoring. Interconnected channel networks transmit water quickly, so a prompt water-level response following rainfall can be expected in boreholes that are well connected to the channel network.

(g) Frequent water-quality monitoring. Precipitation that rapidly infiltrates along channel networks commonly has a much lower solute concentration than long-residence matrix water. Thus variation in solute concentration at a well should be an indicator of connectivity to major channel networks. Frequent sampling (e.g. at least daily) is necessary to detect the rapid response following rainfall. Continuous measurement of electrical conductivity is ideal.

(h) Troughs in the water table. The combination of high permeability in channels and tributary flow to channels means that there are lower heads in channels than in the surrounding aquifer. Quinlan and Ray (1981) showed that such water-table troughs correspond to flow in channels and that they terminate in the downstream direction at springs.

(i) Decreasing hydraulic gradients in the downflow direction. The water-table map of the Central Kentucky karst, which is based on measurements in 1500 wells, the results from 500 dye traces, and the mapping of 700 km of cave passage (Quinlan and Ray, 1981) shows that there are decreasing hydraulic gradients in the downflow direction along water-table troughs. This contrasts with flow in a porous medium, where increasing gradients are needed in a downflow direction to drive the increasing discharge.

(j) Use of environmental isotopes to characterize age distribution of water in the aquifer. In a porous medium there will be increasing age with depth in recharge areas. Where channels provide rapid recharge to the subsurface, then younger water in channels will underlie older water in overlying fractures and the matrix.

The problem with all of these tests is that they cannot unequivocally demonstrate the presence of channeling. For instance, major fractures opened by tectonic forces could give many of the above results. However, the evidence from caves, from tracer testing, and from the kinetics of dissolution suggest that channeling is ubiquitous in unconfined carbonate aquifers. Thus the first assumption in a carbonate aquifer should be that a well-developed channel network is likely to be present.

Examples of triple-porosity analysis of carbonate aquifers

Worthington et al. (1999b) examined matrix, fracture and channel flow in four carbonate aquifers. The four aquifers are **(a)** a Silurian dolostone aquifer in a glaciated area, where there have been a large number of studies at a PCB spill site (Smithville, Ontario); **(b)** the Mississippian aquifer at the world's most extensive known cave (Mammoth Cave, Kentucky); **(c)** the most important aquifer in Britain (the Cretaceous Chalk); **(d)** a tropical Cenozoic limestone aquifer (Nohoch Nah Chich, Yucatan, Mexico); in recent years scuba divers have mapped more than 60 km of submerged channels in this cave.

Porosity and permeability measurements from these four aquifers are given in Tables 3 and 4, respectively. In all four cases more than 90% of the aquifer storage is in the matrix and more than 90% of the flow is in channels (Table 5), with fractures playing an intermediate role. Thus there are considerable similarities between the four aquifers. However, only the aquifer at Mammoth Cave has been traditionally treated as a karst aquifer. The majority of studies of the other three aquifers have treated them as double-porosity aquifers or equivalent porous media.

Discussion and conclusions

It has often been considered that there is a range in carbonate aquifers between "karstic" and non-karstic" end members. For instance, Atkinson & Smart (1981) classify the English Chalk as being close to the "non-karstic fissured aquifer" end of the spectrum, while the Carboniferous Limestone in England (in which most of the well-known caves are found) is classified as being closer to the

Area	Porosity (%)		
	Matrix	Fracture	Channel
Smithville, Ontario	6.6	0.02	0.003
Mammoth Cave, Kentucky	2.4	0.03	0.06
Chalk, England	30	0.01	0.02
Nohoch Nah Chich, Mexico	17	0.1	0.5

Table 3: Matrix, fracture, and channel porosity in four carbonate aquifers.

Area	Hydraulic conductivity (m s^{-1})		
	Matrix	**Fracture**	**Channel**
Smithville, Ontario	1×10^{-10}	1×10^{-5}	3×10^{-4}
Mammoth Cave, Kentucky	2×10^{-11}	1×10^{-5}	3×10^{-3}
Chalk, England	1×10^{-8}	4×10^{-6}	6×10^{-5}
Nohoch Nah Chich, Yucatan, Mexico	7×10^{-5}	1×10^{-3}	4×10^{-1}

Table 4: Matrix, fracture, and channel permeability in four carbonate aquifers.

Area	Fraction of storage in the matrix %	Fraction of flow in channels %
Smithville, Ontario	99.7	97
Mammoth Cave, Kentucky	96.4	99.7
Chalk, England	99.9	94
Nohoch Nah Chich, Yucatan, Mexico	96.6	99.7

Table 5: Principal flow and storage components in four carbonate aquifers.

"karstic" end of the spectrum. Worthington et al. (1999b) compared inflow data to adits in the two aquifers. Both had irregularly spaced inputs, and in both cases there were water-yielding fissures with discharges up to several hundred liters per second. Most of the permeability in both adits is attributable to widely spaced inputs. Consequently, dissolution in both aquifers has resulted in channel networks that contribute minimally to enhancing aquifer porosity, but which have greatly enhanced aquifer permeability. Therefore these aquifers have marked similarities in terms of hydraulic functioning.

One reason why these two limestone aquifers have been viewed differently is the presence of surficial karst features and of known caves in the Carboniferous Limestone and their scarcity in the Chalk. The presence or absence of the surficial features has led to assumptions about aquifer behavior. A second reason is the lack of comprehensive sampling and monitoring in either aquifer in most studies. Few wells have been drilled in the Carboniferous Limestone, and most aquifer studies have used springs. Conversely, most aquifer studies in the Chalk have used wells, and the many springs that exist have been ignored in most hydrogeological studies. Consequently, there is widespread knowledge of channel flow in the Carboniferous Limestone, and of fracture and matrix flow in the Chalk.

The similarity between the matrix, fracture and channel flow and storage proportions in the four contrasting carbonate aquifers, documented in Tables 3, 4 and 5, suggests there is likely to be a similarity between all unconfined carbonate aquifers. This can be explained by fracturing and followed by dissolution, resulting in low-porosity, high-permeability channel networks. Differences cited in the literature are often largely attributable to sampling differences. This problem can be diminished by considering carbonate aquifers as triple-porosity aquifers. Data collection and analysis of the three components of matrix, fracture, and channel flow can give an overall understanding of how a carbonate aquifer functions.

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ATTACHMENT C

Enhancement of Bedrock Permeability by Weathering
Worthington et al. (2016)

ATTACHMENT D

TDEC Comment Letter on the D4 RI/FS
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Enhancement of bedrock permeability by weathering

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ABSTRACT

The permeability of bedrock aquifers varies by more than four orders of magnitude between different lithologies, but the reasons for this large range remain unexplained. In this review, we examine the role that weathering plays in enhancing the permeability of the five major hydrolithologies, represented by limestone, basalt, granite, sandstone and shale. In limestone aquifers, rapid dissolution kinetics and congruent dissolution result in widespread permeability enhancement. Weathering is usually focused along fractures, and feedbacks between flow and dissolution result in self-organization into networks of channels that discharge at springs. Caves represent prominent examples of weathering. In silicate aquifers, slower dissolution kinetics and incongruent dissolution make it more difficult to predict permeability enhancement. However, positive correlations between permeability and both the solute concentrations and the dissolution rates of the five major lithologies suggest that weathering is a major factor that enhances permeability in silicate as well as in carbonate aquifers. This explains why the largest springs occur in the most permeable lithologies, why groundwater velocities >10 m/d are common, and why microbial contamination is more common in bedrock aquifers than in unconsolidated sediments. Differences in weathering rates explain why limestone is much more permeable than shale, and why mafic igneous rocks such as basalt have higher permeabilities than felsic igneous rocks such as granite. Weathering appears to play an important role in enhancing permeability in most bedrock aquifers.

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1. Introduction

Weathering of rocks transforms primary minerals into secondary minerals such as clay, as well as solutes that are carried away by groundwater and rivers to the oceans. Weathering often occurs at or close to the surface, where it is usually considered to be a geomorphic process (Neuendorf et al., 2005). Weathering can also be an important hydrogeologic process because it can occur at greater depths and enhance the permeability of bedrock aquifers, but the extent to which this occurs is poorly known.

Much hydrogeological research has involved aquifers in unconsolidated sediments, which are largely composed of low-solubility quartz and clay minerals. In such cases, there is little need to consider weathering as a factor that affects permeability. On the other hand, bedrock aquifers are more complicated. They are composed of minerals that weather more easily than quartz and clay minerals (Goldich, 1938; Berner and Berner, 2012), and in addition they are usually fractured (Neuman, 2005). Both fracturing and weathering may enhance permeability, but the relative importance of these two factors is unknown. This uncertainty provides a reason why “groundwater processes in [fractured rock and karst] are still largely an open research question” (Anderson, 2008, p.1).

Permeability averages of the major lithologies provide a useful data set to test different hypotheses for permeability enhancement in bedrock aquifers, due to the substantial differences in the physical and chemical properties of the different lithologies, and the large contrasts in permeability between different lithologies. This large range has long been recognized (e.g. Freeze and Cherry, 1979), but has recently been quantified by Gleeson et al. (2011), using results from calibrated groundwater models.

Flow in bedrock aquifers is commonly through fractures, and much of the literature has concentrated on the characterization of their apertures, connectivity, and spatial distribution, as well as the numerical modeling of flow and transport through them (Long and Witherspoon, 1985; Tsang and Neretnieks, 1998; Bonnet et al., 2001; Berkowitz, 2002; Neuman, 2005; Renard and Allard, 2013; Tsang et al., 2015). There are also studies on the effect of stress fields on fracturing (Min et al., 2004; Baghbanan and Jing, 2008; Latham et al., 2013; St Clair et al., 2015) and on modeling the enhancement of fracture apertures by dissolution (Dreybrodt, 1996; Dreybrodt et al., 2005; Kaufmann et al., 2010). However, the reasons for the wide variation in permeability between different lithologies are not explained in the above studies.

Fracturing clearly enhances permeability in most bedrock aquifers, suggesting a positive correlation between permeability and fracturing. However, shales are typically thin-bedded and have more fractures than other lithologies, yet have very low permeability, suggesting an inverse correlation between fracture density and permeability. This implies that fracture apertures or fracture connectivity are likely to be more important factors than fracture spacing in determining permeability. Furthermore, it is possible that fractures, after being created by physical processes, are subsequently enlarged by chemical processes.

Shales are composed primarily of low-solubility quartz and clay minerals. These rocks also have the lowest permeability of the five major lithologies (Table 1). Carbonates have the highest permeability, and permeability enhancement due to weathering is well documented in carbonate aquifers, with caves forming the most prominent examples (Ford and Williams, 2007; Palmer, 2007; White and Culver, 2012). However, weathering is not restricted only to where caves are present, and is often manifested by networks of solutionally-enlarged channels that have modest dimensions but significantly enhance permeability (Price et al., 1993; Worthington and Ford, 2009; Maurice et al., 2012). Weathering can also enhance permeability in sandstone, shale, and in igneous and metamorphic rocks (Tuttle and Breit, 2009; Aubrecht et al., 2011; Comte et al., 2012; Lachassagne et al., 2011; Sauro, 2014).

These examples raise the possibility that weathering may play a substantial role in enhancing permeability in many bedrock aquifers, and that is the focus of this review paper. We compile and interpret a range of data sets to shed light on this issue, including solute concentrations, dissolution rates, groundwater velocities, the presence of bacteria, and flowmeter measurements in wells. The physical aspects of the characterization and modeling of fracture flow have been well covered in a number of reviews (e.g., Berkowitz, 2002; Neuman, 2005; Welch and Allen, 2014; Tsang et al., 2015). Consequently, we do not refer to these physical aspects except where they shed light on permeability contrasts as a function of lithology, but focus instead on chemical aspects of preferential flow in bedrock aquifers.

2. Weathering processes in bedrock aquifers

2.1. Correlation between permeability and solute concentrations

The term weathering encompasses a number of processes that bring about the chemical and physical breakdown of rocks and sediments (Ollier, 1969; Neuendorf et al., 2005). Physical processes such as frost shattering may be important at or close to the surface, but generally in aquifers the principal weathering process is dissolution, which may be congruent or incongruent. Many of the major rock-forming minerals weather incongruently, producing iron oxides or clay minerals in addition to ions in solution (Berner and Berner, 2012). Congruent weathering, producing only solutes (ions, molecules and colloids that can then be removed by groundwater flow), occurs where low-mobility elements such as Fe and Al are absent. Among the common rock-forming minerals, quartz, calcite, dolomite, and also some amphiboles, pyroxenes, and olivines weather congruently. The description of chemical weathering here focuses on the principal reactions, which are congruent or incongruent dissolution by acids, although other processes such as oxidation and hydration do also play a role (Ford and Williams, 2007; Anderson and Anderson, 2010; Berner and Berner, 2012).

Solute concentrations in groundwater reveal the relative magnitude of chemical weathering in different lithologies. The solubility of the common rock-forming minerals varies by about an order of magnitude.

Table 1
Permeability data from groundwater models for the five major bedrock hydrolithologies (modified from Gleeson et al. (2011)).

Hydrolithology	Representative rock	Permeability m^2
Carbonate	Limestone	$10^{-11.8}$
Coarse-grained sedimentary siliciclastic	Sandstone	$10^{-12.5}$
Volcanic	Basalt	$10^{-12.5}$
Crystalline igneous and metamorphic	Granite	$10^{-14.1}$
Fine-grained sedimentary siliciclastic	Shale	$10^{-16.5}$

Silica is the least soluble, with concentrations of 6–10 mg/L as Si (or 13–21 mg/L as SiO_2), and the carbonate minerals calcite and dolomite are the most soluble, with concentrations ranging from 55 mg/L (at PCO_2 of 0.03%) to 300 mg/L (at PCO_2 of 3%) (Ford and Williams, 2007).

Average concentrations of solutes in the major lithologies were compiled from reports of the British Geological Survey and U.S. Geological Survey, using data that was considered to be representative of groundwater that is utilized for water supplies in the respective countries. These data sets were the largest compilations that we found in the literature. The median depth to the top of the open interval for American domestic and public supply wells was 25 m and 68 m, respectively (DeSimone, 2008; Toccalino et al., 2010). Statistics for well depth were not given for the British data, but it is probable that the depth to the top of the open interval is <50 m for most wells sampled. A small percentage of the British samples are from springs. Total dissolved solids (TDS) was listed in the U.S. reports, but not in the British reports, so TDS values were calculated from major ion concentrations (Table S1 in the online Supplementary Data). Median values for the five major lithologies ranged from 62 mg/L for shale to 379 mg/L for carbonates, and are listed in Table 2.

Solute concentrations are dependent not only on lithology, but also on other factors such as soil CO_2 concentrations. Growth of vegetation is positively correlated with both temperature and precipitation, and higher values result in higher soil CO_2, more acidic soil water, more dissolution, and a positive correlation between TDS and both precipitation and temperature (Drake and Wigley, 1975; White and Blum, 1995). On a global scale, 87% of TDS in river water is derived from chemical weathering of rocks, 10% from anthropogenic pollution (principally agricultural nutrients and sewage), and 3% from oceanic salt (via precipitation, with Na and Cl dominating) (Gaillardet et al., 1999; Berner and Berner, 2012). The solutes from the chemical weathering of rocks largely follow groundwater flow paths to rivers, with the result that the relative proportions of solutes are similar in groundwater and river water.

To calculate the fraction of solute concentrations derived from chemical weathering in groundwaters, correction factors were applied to the data in Table 2. TDS concentrations in precipitation are typically a few mg/L, but evapotranspiration increases solute concentration in recharge by a factor of 2.2 on average (Berner and Berner, 2012). A deduction of 10 mg/L to TDS values was made to account for anthropogenic pollution and sea salt. In river water, bicarbonate constitutes 52% of solute concentrations, and TDS values in granite, basalt and shale were reduced by 50% to account for the bicarbonate, all of which is derived from carbonic or biogenic acids (Berner and Berner, 2012). In the dissolution of carbonate minerals, half the bicarbonate is derived from carbonic or biogenic acids, and half from the minerals themselves. Consequently, TDS concentrations were reduced by 25% in carbonate rocks and also in sandstone, where solutes in groundwater are usually dominated by ions from carbonate mineral dissolution. The carbon in carbonic and biogenic acids is ultimately derived from atmospheric CO_2, with most being fixed by plants during photosynthesis, and with the organic matter subsequently decomposing and raising soil acidity. The above correction factors are only approximations, but they do show that the rank of TDS concentrations by lithology remains the same as in the uncorrected data (Table 2).

Numerous authors have used solute data from rivers to establish the relative solute concentrations among different lithologies. In order of decreasing TDS, three of these results are: 1) carbonate > crystalline > argillaceous (Garrels and Mackenzie, 1971); 2) sedimentary > volcanic > plutonic and highly metamorphic (Walling and Webb, 1986); and 3) evaporite > carbonate > silicate, and granite > basalt (Berner and Berner, 2012). The order of weathering rates in these studies is essentially the same as the order of TDS concentrations in groundwater in Table 2.

The link between solute concentration and permeability was tested by regressing permeability values against the solute concentrations of the major lithologies. Permeability values were taken from the compilation by Gleeson et al. (2011), which were derived from numerical model simulations. These values are broadly similar to earlier permeability compilations such as in Freeze and Cherry (1979). Both scaling effects and reduction of permeability at crustal depths are important factors that contribute to permeability differences (Schulze-Makuch et al., 1999; Ranjram et al., 2015). However, Gleeson et al. (2011) largely avoided these complicating factors by using permeability values from aquifers with an upper contact that is within 100 m of the surface and that extend laterally for >5 km. The permeability and solute concentration data are taken from comparable settings, with relatively shallow groundwater (upper contact of aquifer <100 m below surface). Furthermore, both data sets are dominated by data from temperate climates, with the TDS data being from the USA and UK, and 100 of 117 permeability values being from the USA and Europe.

Results show that there is a strong correlation between the log of permeability and the log of TDS concentrations for both the uncorrected data (Fig. 1a; $r^2 = 0.93$) and the corrected data (Fig. 1b; $r^2 = 0.89$). This suggests that weathering may be a major factor in determining aquifer permeability. The dissolutional enhancement of permeability is well recognized for carbonate rocks, but the results suggest that dissolution may also be a significant factor in enhancing the permeability of silicate aquifers.

2.2. Correlation between permeability and dissolution rates

Data on dissolution rates as a function of pH were compiled from the reviews by Morse and Arvidson (2002) and Brantley et al. (2008). The data represent average values derived from many lab experiments. Results show that there is a wide range of dissolution rates (Fig. 2). Dissolution of most common rock-forming minerals is enhanced in the presence of carbonic or biogenic acids (Berner and Berner, 2012). Consequently, these minerals have higher dissolution rates at lower pH values (Fig. 2). The combination of slow dissolution kinetics and rapid groundwater flow along fractures can result in deep penetration of groundwater that is slightly undersaturated with respect to mineral equilibria. Fig. 2 shows reaction rates far from chemical equilibrium,

Table 2
Average total dissolved solids (TDS) concentrations in the five major hydrolithologies in the USA and UK.

Rock	USA data		UK data		Median TDS (mg/L)	Median TDS from weathering (mg/L)[a]
	TDS (mg/L)	Number of samples	TDS (mg/L)	Number of samples		
Carbonate	271	296	486	1363	379	277
Sandstone	328	356	386	990	357	260
Volcanic	280	43	N.D.	N.D.	280	135
Crystalline	118	242	89	195	104	47
Shale	N.D.	N.D.	62	105	62	26

Note: Data for the USA are from Toccalino et al. (2010) and DeSimone (2008). Data for the UK are from a compilation by Shand et al. (2007) and from 30 regional studies (see Table S1). Averages are calculated by calculating the median TDS for each data set (from 40 data sets in the UK and from two data sets in the USA), then the median values for the UK and USA, and finally the median for the two countries. Details are given in the Supplementary Data (Table S1).

[a] The TDS from weathering assumes that 10 mg/L is derived from precipitation, that bicarbonate is 50% of TDS, that the bicarbonate in carbonates and sandstone are derived from dissolution of carbonate rocks, and that the bicarbonate in volcanic and crystalline rocks and shale are derived from dissolution of silicate rocks. See the text for further details. N.D. No data.

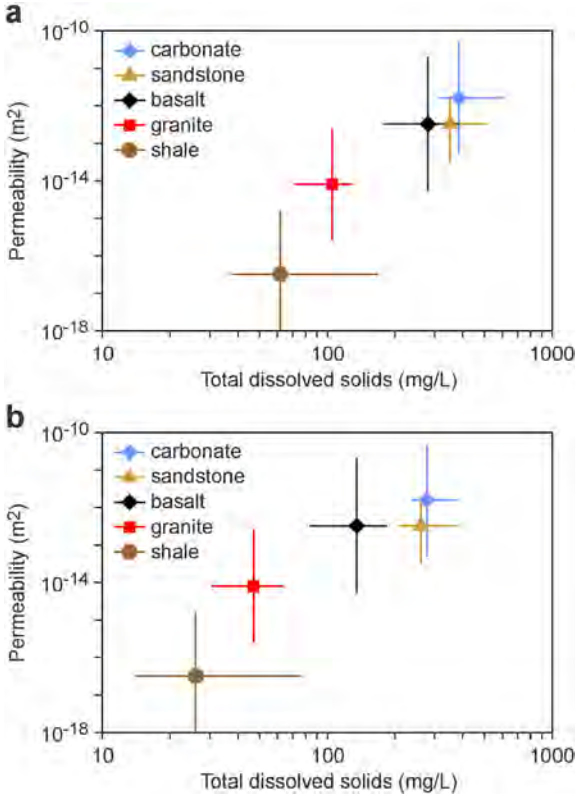

Fig. 1. Correlation of permeability with total dissolved solids (TDS), with (a) uncorrected TDS values and (b) TDS values corrected to show only the weathering component. Geometric mean and standard deviation of log permeability (vertical bars) are from Gleeson et al. (2011). Median and quartile TDS data are from Table 2 and Table S1 in the Supplementary Data.

and reaction rates typically drop by several orders of magnitude as equilibrium is approached. This occurs in both carbonate rocks (Berner and Morse, 1974; Plummer and Wigley, 1976; Morse and Arvidson, 2002) and in silicate rocks (Drever and Clow, 1995; White and Brantley, 2003; Zhu, 2005; Brantley et al., 2008).

The rapid initial dissolution rates of carbonate minerals result in most weathering taking place in the upper part of the bedrock. However, lab experiments have shown that chemical equilibrium is approached asymptotically (Eisenlohr et al., 1999; Worthington, 2015a). These non-linear kinetics have been incorporated into numerical models that simulate dissolution, and show that dissolution and concomitant increases in permeability can take place deep below the surface (Dreybrodt, 1990, 1996; Romanov et al., 2003).

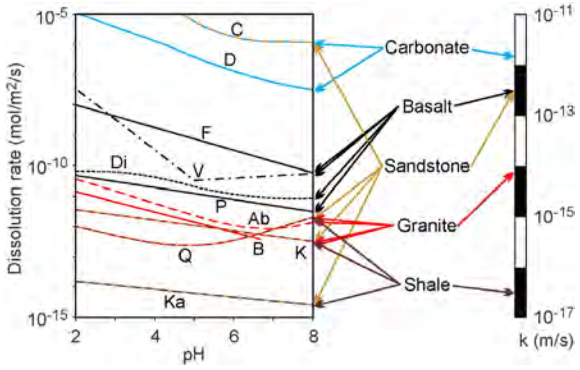

Fig. 2. Correlation between dissolution rates of major rock-forming minerals with permeability (k) of major lithologies. Lines link rocks to the minerals that comprise >5% of each rock (Table 3). The dissolution rates are from Morse and Arvidson (2002) and Brantley et al. (2008), and the permeabilities are from Gleeson et al. (2011). The minerals are calcite (C), dolomite (D), forsterite (F), volcanic glass (V), diopside (Di), Ca-Na plagioclase (P), albite (Ab), K feldspar (K), biotite (B), quartz (Q), and kaolinite (Ka). The dissolution rate of forsterite is assumed to be representative for olivine, diopside for pyroxene, and kaolinite for clay minerals.

The much higher dissolution rates for calcite and dolomite than for silicate minerals suggest that weathering might be much more important in carbonate than in silicate aquifers (Fig. 2). However, there are much smaller contrasts between the solute concentrations of the different lithologies (Table 2). This shows that the low dissolution rates of silicate minerals do not prevent substantial dissolution from taking place in silicate aquifers.

Just a few minerals dominate the composition of the five rocks most representative of the five major lithologies (Table 3). These are also shown in Fig. 2, together with permeability averages for the five rocks. A striking pattern emerges. Most rocks are composed of minerals with a narrow range of dissolution rate, and the more soluble rocks are more permeable. The order of mineral dissolution rates for the igneous rocks is similar to the order in Bowen's reaction series, with minerals such as forsterite that form at high temperature weathering more rapidly than minerals such as quartz that form at low temperature (Goldich, 1938). Regression of the log of mineral dissolution rate against the log of rock permeability gives a positive correlation, with $r^2 = 0.57$ (Fig. 3). Thus, both solute concentrations (Fig. 1) and dissolution rates (Fig. 3) suggest that dissolution may substantially enhance permeability in bedrock aquifers.

2.3. Reactive transport models

The chemical evolution of water as it passes through aquifers has been studied using a wide range of reactive transport models. Much of the focus has been on the evolution of water quality along flowpaths (Clement et al., 1998; MacQuarrie and Mayer, 2005; Steefel and Maher, 2009). However, some studies have focused on changes in permeability as a result of dissolution, and it is these studies that are of interest here (e.g., Dreybrodt, 1996; Dreybrodt et al., 2005; Kaufmann et al., 2012).

Simulation of permeability changes in carbonate aquifers is more straightforward than in silicate aquifers, because many carbonate rocks are composed almost entirely of just one mineral, calcite, which dissolves congruently. The earliest reactive transport models simulated dissolution along single, constant-aperture fractures over distances up to 50 km (Dreybrodt, 1990; Palmer, 1991). This was followed by 2D models of fracture networks (Groves and Howard, 1994; Siemers and Dreybrodt, 1998), and the addition of exchange between the matrix

Table 3
Composition of representative rocks of the five major lithologies.

Mineral and dissolution rate at pH of 7 ($mol/m^2/s$)	Carbonate %	Basalt %	Sandstone %	Granite %	Shale %
Calcite ($10^{-5.9}$)	56.7	–	11.3	–	3.6
Dolomite ($10^{-7.2}$)	36.4	–	–	–	–
Olivine ($10^{-9.9}$)	–	6.7	–	–	–
Volcanic glass ($10^{-10.3}$)	–	21	–	–	–
Pyroxene ($10^{-11.0}$)	–	30.6	–	–	–
Ca Na plagioclase ($10^{-11.3}$)	–	41.7	–	10.3	–
Albite ($10^{-12.0}$)	–	–	–	20.6	–
Quartz ($10^{-12.1}$)	3.7	–	70.7	27.9	31
K feldspar ($10^{-12.1}$)	2.2	–	10.4	36	4.5
Biotite ($10^{-12.5}$)	–	–	–	5.2	–
Kaolinite ($10^{-14.4}$)	–	–	7.6	–	60.9
Geometric mean dissolution rate ($mol/m^2/s$)	$10^{-6.84}$	$10^{-10.92}$	$10^{-11.56}$	$10^{-12.02}$	$10^{-13.30}$

Note: Data on dissolution rates are from Morse and Arvidson (2002) and Brantley et al. (2008). Data on mineralogical composition are from Pettijohn (1975); Blatt et al. (1980), and Wood and Low (1986). Kaolinite has the most comprehensive data available on dissolution rates and is assumed to be representative for all clay minerals.

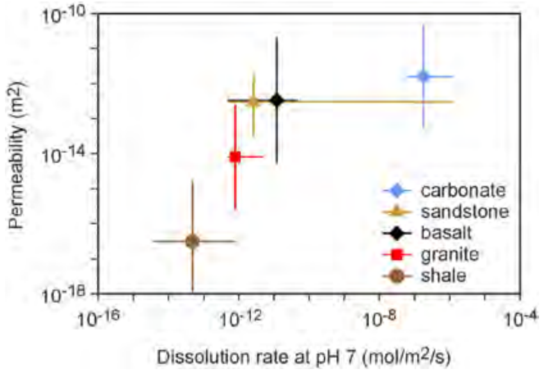

Fig. 3. Correlation of permeability with dissolution rate. Geometric mean and standard deviation of log permeability (vertical bars) are from Gleeson et al. (2011). Weighted mean dissolution rate is based on data in Table 3. The horizontal bars extend to the 10th and 90th percentiles, based on the abundance of mineral in rocks in Table 3. The permeability of basalt and sandstone are the same, but are slightly offset to aid visibility of the data.

and fractures (Kaufmann and Braun, 2000; Liedl et al., 2003; Kaufmann et al., 2010).

The above models incorporated the non-linear dissolution kinetics of calcite, but it was also found that preferential flow results from dissolution where there are variable-aperture fractures (Hanna and Rajaram, 1998), where there is mixing of two solutions at equilibrium with Ca but with different partial pressures of CO_2 (Gabrovšek and Dreybrodt, 2000; Romanov et al., 2003), and where instabilities produce fingering of dissolution fronts (Cheung and Rajaram, 2002; Szymczak and Ladd, 2011). With these complementary dissolution processes, enlargement of fractures or connected vugs is common in carbonate aquifers. A major success of reactive transport models in carbonate aquifers has been their ability to simulate emergent properties that were not present initially in the aquifer. These include turbulent flow, channel networks, caves, and springs (Palmer, 1991, 2007; Dreybrodt et al., 2005; Worthington, 2015a).

Modeling has shown that the channel networks in carbonate aquifers vary between two end-members, one where there are simple tributary systems with the largest channels being enlarged to cave size, and the other where there is more even enlargement of channels, with caves being rare. Both end-members form hierarchical networks, with channel size enlarging in a downgradient direction. Factors influencing the type of channel network include fracture density, fracture aperture variability, matrix porosity, type of aquifer recharge, and solute concentrations in aquifer recharge (Romanov et al., 2003; Bloomfield et al., 2005; Dreybrodt et al., 2005; Worthington and Ford, 2009; Hubinger and Birk, 2011). This modeling of the dissolutional enlargement of fractures in carbonate aquifers has answered the most important questions about how dissolution transforms a low-permeability carbonate aquifer into one with high permeability over timescales of 10^4–10^6 years (Romanov et al., 2003; Dreybrodt et al., 2005; Palmer, 2007).

Numerical simulation of permeability changes as a result of dissolution is challenging in silicate aquifers because most silicate rocks are composed of a number of minerals, each dissolving at a different rate (Table 3). This means that considering weathering as the advance of a single weathering front may be too simplistic, and that there may be multiple fronts (Goldich, 1938). Examples include preferential weathering of olivine in basalt aquifers (Wood and Low, 1986), and of carbonate minerals in sandstone and shale aquifers (Einsele et al., 1995; Shand et al., 2007; Brantley et al., 2013). Furthermore, many silicate minerals dissolve incongruently, with solute concentrations influencing which secondary minerals are stable (Tardy, 1971; Langmuir, 1997). In addition, hydration and the production of secondary minerals can result either in an increase or a decrease in mineral volume, depending on whether the weathering products have a greater or lesser volume than their unweathered precursor minerals and whether the weathering products are mobilized, for instance as colloids. These factors make it difficult to predict whether weathering of silicate rocks will produce a net increase or decrease in aquifer porosity and permeability.

A case study that simulated reactions along flowpaths to thermal springs in the Idaho batholith (USA) illustrates this uncertainty (Mayo et al., 2014). Modeling using PHREEQC gave increased porosity as a consequence of dissolution of the granitoid bedrock in 15 out of 86 simulations. However, it was also found that particles rich in Si and Al and with diameters of 1–10 μm were being transported in the thermal waters. This implies that some of the secondary clay minerals were being transported out of the aquifer, producing an increase in porosity. It was concluded that self-organization was occurring in the aquifer. The increased dissolution along the fractures that were more efficient for transport and precipitation of minerals occurring in the less efficient fractures provided a positive feedback mechanism that developed an integrated channel network.

3. Permeability structure of weathered bedrock aquifers

A common approach to studying aquifers in unconsolidated sediments is to assume that the permeability varies randomly in space, and that the variability can be described in terms of heterogeneity and anisotropy (Freeze, 1975; Freeze and Cherry, 1979). However, these terms are less apt when considering bedrock aquifers, where most flow is often through fractures and so their apertures and connectivity are of prime importance. Laterally-extensive pathways with high permeability include open bedding planes and channel deposits in sedimentary rocks and both interflow zones and lava tubes in volcanic rocks, and these can extend for distances of kilometers (Meinzer, 1927; Anderson, 1989; Muldoon et al., 2001, Swanson et al., 2006). Furthermore, there may be faults and fracture zones with enhanced permeability (Gascoyne and Cramer, 1987; Bense et al., 2013).

In the above cases, the high permeability is caused by physical processes. However, chemical processes can also enhance permeability, and these help produce self-organized permeability structures (Section 3.1) and contrasting weathering profiles that are a function of the lithology (Section 3.2).

3.1. Self-organization

Self-organization in bedrock aquifers results from the positive-feedback process that couples increasing flow with increasing dissolution (Theis, 1936; Ortoleva et al., 1987; Worthington and Ford, 2009; Hartmann et al., 2014). The simplest way to analyze flow along fractures is to assume constant apertures, but variation of fracture apertures is inevitable, and causes most flow to be focused on channels that occupy only part of a fracture plane (Tsang and Neretnieks, 1998). Weathering results in selective enlargement of these channels (Hanna and Rajaram, 1998), which produces a large increase in permeability but only a small increase in porosity because of the focused nature of the dissolution. For instance, dissolution in a Paleozoic carbonate aquifer increased the permeability by two orders of magnitude, but only raised the total porosity from 7% to 7.05% (Worthington et al., 2012).

Simulations of carbonate aquifers have shown how this focused dissolution produces integrated channel networks (Section 2.3). Although smaller channels predominate in number (Curl, 1986), the largest channels become enlarged in some situations to become caves. The smaller channels provide most of the flow in wells, where they are clearly seen in video or televiewer images (Price et al., 1982; Schürch and Buckley, 2002; Maurice et al., 2012). Extensive caves and large springs represent the most noteworthy examples of self-organization. Most caves are formed principally by dissolution and exhibit a tributary pattern, draining to springs (Palmer, 1991, 2007; Worthington, 2015a).

Much less is known about self-organization in silicate aquifers, where the evidence of weathering is in general more subtle than in carbonate aquifers. However, the major weathering process is dissolution by carbonic and biogenic acids in both aquifer types, and furthermore dissolution rates reduce substantially as chemical equilibrium is approached in both aquifer types. However, TDS concentrations in silicate aquifers are generally somewhat less than in carbonate aquifers (Table 2), so it might be expected that permeability enhancement by dissolution would be somewhat less in silicate aquifers than in carbonate aquifers of similar age. Consequently, it is possible that dissolution patterns, including self-organized channel networks, are broadly similar in both carbonates and silicates, though generally with smaller apertures in the latter. Further evidence of self-organization will be examined in Section 5, using data from large springs, tracer tests, flowmeter measurements in wells, and the frequency of bacterial contamination.

3.2. Weathering profiles

The principal weathering reactions in carbonate and silicate rocks are the dissolution of minerals by carbonic or biogenic acids that are ultimately derived from atmospheric CO_2 (Berner and Berner, 2012). Most weathering takes place close to the surface, in the soil zone or uppermost bedrock. Factors favoring this include low solute concentrations in infiltrating waters and high concentrations of CO_2 and biogenic acids in soil water. However, weathering may extend to considerable depths and facilitate deep groundwater flow (Neuendorf et al., 2005). In general, the depth of weathering is poorly known (Calmels et al., 2011; West, 2012). However, in carbonate rocks, the >100 mapped caves that extend to depths >1000 m illustrate the depth that weathering can extend to (Gulden, 2016). Almost all of these caves are explained by dissolution by infiltrating precipitation, with the dissolution process often being termed karstification or speleogenesis in the karst literature (Klimchouk et al., 2000; Dreybrodt et al., 2005; Palmer, 2007). It has been found that the depth to which caves extend below the water table is a function of flow path length and stratal dip (Worthington, 2001). Other potential factors that may affect the depth to which weathering occurs include topography, erosion rates, and climate.

Where the uppermost bedrock is composed of minerals that dissolve incongruently, then a saprolite will be formed. There may be a distinct zonation of primary and secondary minerals with depth, and Goldich (1938) established the relative weatherability of silicate minerals from such profiles. Climate is an important factor in determining the depth of weathering, with warm and humid climates favoring deeper weathering than cold and arid climates (Strakhov, 1967).

The area of the mineral-water interface per unit volume or unit mass is called the specific surface area (SSA), and it affects the extent of dissolution reactions (Morse and Arvidson, 2002; Brantley and Lebedeva, 2011). The SSA for different aquifers can be compared by making the simplifying assumption that the interface is smooth at a microscopic scale. For instance, a sand aquifer with spherical grains 0.3 mm in diameter and a porosity of 0.3 has an SSA of 14,000 m^2 per cubic meter of aquifer volume (i.e. 14,000 m^{-1}). In comparison, if all the flow in a bedrock aquifer is concentrated on three sets of orthogonal fractures spaced 10 m apart, then the SSA is 0.6 m^{-1}, which is 23,000 times lower than the sand example. The much lower SSA in the bedrock example enables water to penetrate much deeper down fractures before coming to chemical equilibrium compared to an aquifer with only intergranular flow. Consequently, this produces very different weathering profiles in aquifers with only intergranular flow and those where fracture flow is important.

Weathering profiles also differ as a function of whether mineral weathering is congruent or incongruent. The two variables of aquifer structure and type of mineral weathering combine to give four contrasting weathering profiles (Fig. 4). The simplest situation occurs where there is intergranular flow and weathering is congruent (e.g., sand). The dissolution rate of quartz is very low but not zero (Fig. 2), and in the long term the only consequence would be a reduction in grain size, some settling, and a small decrease in permeability associated with the reduction in grain size (Fig. 4a). Such effects might not be evident in near-surface sand deposits which are commonly late Pleistocene or Holocene in age, and thus too young to have had substantial weathering. The second situation occurs where there is intergranular flow and incongruent weathering (e.g., silt, loess). In this case, a weathered zone that is enriched in low-solubility minerals will develop in the uppermost sediments (Fig. 4b).

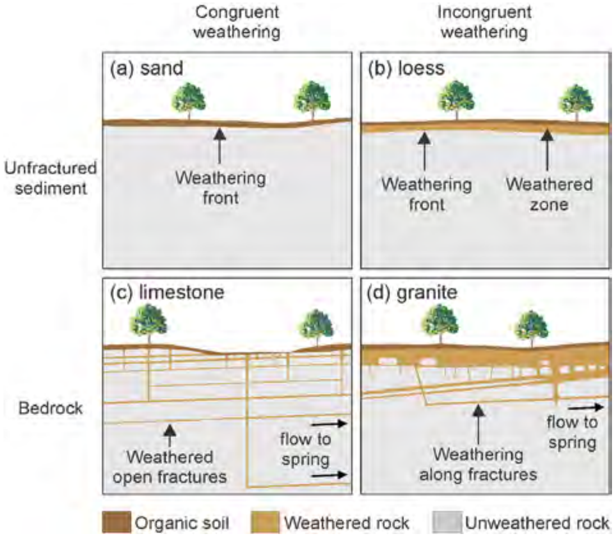

Fig. 4. Profiles of idealized weathered zones for aquifers dominated by (a) congruent dissolution and intergranular flow e.g., sand, (b) incongruent dissolution and intergranular flow e.g., silt, (c) congruent dissolution and fracture flow e.g., limestone, quartzite, and (d) incongruent dissolution and fracture flow e.g., granite, basalt, shale, arkose. The figures show only a small fraction of the overall flow paths from recharge to discharge locations.

The third situation occurs where fracture flow is important and where the minerals dissolve congruently (e.g., limestone, quartzite). Fracture permeability may be several orders of magnitude greater than matrix permeability (Price et al., 1993; Worthington and Ford, 2009). This permits weathering to extend further down fractures than in the matrix (Fig. 4c). At depth, dissolution becomes focused on more widely-spaced fractures, and the weathering front can advance along fractures to the discharge point for the aquifer at a spring. This is shown particularly well by the presence of caves that extend from sinking streams to springs, especially in carbonate aquifers, but also occasionally in quartzite aquifers (Aubrecht et al., 2011; Sauro, 2014). The resulting high-permeability aquifers are common in carbonate rocks, but also occur in quartzites, and at the surface there is often a karst landscape (Wray, 1997; Gunn, 2004; Young et al., 2009; White and Culver, 2012).

The final situation is where fracture flow is important and where the minerals dissolve incongruently (e.g., granite, basalt, shale, arkose). Fracture permeability can again be several orders of magnitude greater than matrix permeability (Reimus et al., 2003). Near the surface, a saprolite develops, but the contrasts in permeability can permit weathering to extend down fractures (Fig. 4d). This can form a high-permeability zone (Lachassagne et al., 2011).

Overall, there are three major factors that explain how weathering enhances permeability in bedrock aquifers. The non-linear dissolution kinetics of carbonate and silicate minerals produce an asymptotic approach to chemical equilibrium, so that there is a progressive reduction in dissolution rates as equilibrium is approached. This means that flow can penetrate substantial distances into the bedrock before chemical equilibrium is reached. Second, the low specific surface area associated with widely-spaced preferential flow paths concentrates dissolution on those selected flow paths. Finally, positive feedback resulting from the coupling of dissolution and flow increases the apertures and hence permeability even more.

An analysis of the data on solute concentrations (Table 2) and dissolution rates (Fig. 2) suggests that there is no simple division of bedrock aquifers into those where weathering has enhanced permeability and those that can be treated as inert. In fact, the substantial increase in solute concentration between the infiltration of water into the ground and its discharge to rivers in all lithologies raises the possibility that it may be common for weathering to increase permeability. Examples of such increases in permeability are given in the next section.

4. Weathering in the five major lithologies

4.1. Carbonate rocks

The enhancement of permeability by weathering is particularly evident in carbonate rocks, resulting in a high-permeability zone in the upper part of unconfined aquifers (Ford and Williams, 2007). This makes them the most productive of bedrock aquifers (Table 1; Freeze and Cherry, 1979). This zone usually extends to depths of tens to hundreds of meters below the surface (Price et al., 1993; Worthington, 2001). However, it can extend to even greater depths. For instance, the city of San Antonio (Texas, USA) derives almost all its water supply from the confined Cretaceous limestone of the Edwards Aquifer; the top of this highly-productive 200 m-thick aquifer is in places >1200 m below the surface (Sharp and Banner, 1997; Hovorka et al., 1998; Lindgren et al., 2004). Enhancement of permeability by dissolution in carbonate aquifers is usually especially high near the bedrock surface (Williams, 1983), in the zone of water-table fluctuation (Rushton, 2003), and at the interface between fresh and saline water (Sanford and Konikow, 1989; Smart et al., 2006).

Caves, by definition, are cavities that are accessible by people, and solution caves have been enlarged by dissolution from interconnected fractures or pores with small apertures (e.g., 0.1 mm). Cave maps illustrate the patterns of such integrated channel networks, which drain to springs (Gunn, 2004; Palmer, 2007; White and Culver, 2012). However, caves represent only the largest channels, and smaller channels are many orders of magnitude more numerous (Curl, 1986). These smaller, dissolutionally-enlarged preferential flowpaths have more modest apertures (e.g., 1 mm–10 cm; Fig. 5a), but significantly enhance permeability and commonly account for most of the flow into wells in carbonate aquifers (Price et al., 1982, 1993; Maurice et al., 2012). Rapid groundwater flow associated with well-developed channel networks can result in short residence times, leading to low TDS values at springs following major recharge events (Ryan and Meiman, 1996; Vesper and White, 2003).

In Cenozoic aquifers there may be interconnected vugs (Cunningham et al., 2009), but in older rocks dissolutional enlargement is usually concentrated on fractures. Modeling of dissolution and flow has shown that dissolution always enhances the permeability in unconfined carbonate aquifers, and also in confined aquifers where there is substantial groundwater flow (Dreybrodt, 1996; Romanov et al., 2003; Worthington, 2015a).

4.2. Crystalline rocks

The crystalline rock hydrolithology comprises plutonic and metamorphic silicate rocks, with granite being the most common plutonic rock (Blatt et al., 1980; Dürr et al., 2005; Lachassagne et al., 2011). Hydration and dissolution are the main weathering processes, enhancing the permeability in the upper part of the bedrock (Davis and Turk, 1964). Weathering of the bedrock can produce visible staining from the oxidation of iron-rich minerals (Fig. 5b), and the transformation of the rock to a saprolite (Fig. 5c), with unweathered corestones (Fig. 5d). Below the saprolite, weathering along fractures forms a zone that has higher permeability than the overlying saprolite (Jones, 1985; Chilton and Foster, 1995; Dewandel et al., 2006; Singhal and Gupta, 2010; Lachassagne et al., 2011; Welch and Allen, 2014).

The much higher permeability of fractures than of the matrix in crystalline rocks permits weathering to extend substantial distances along fractures (Fig. 4d). For instance, detailed analysis of fractures at a depth of 260 m below the surface in a granite showed evidence of early hydrothermal alteration that was most easily recognized by distinctive color changes. This was followed by later cooler-water alteration that resulted in the deposition of clay minerals adjacent to the fracture (Gascoyne and Cramer, 1987). Similar alteration zones in micaceous gneiss at depths of >1000 m below the surface were described by Stapff (1891, p. 139) in the 15 km-long St Gotthard tunnel (Switzerland). Distinctive color changes in the rock occurred up to tens of centimeters from productive fractures, and clay minerals and unaltered quartz were found in the immediate vicinity of the fractures. A century later, construction of the 57 km-long Gotthard Base Tunnel was delayed for several months on three occasions when hydrothermally-altered fracture zones with flows into the tunnel of up to 13 L/s were encountered in granite and gneiss at depths of 1500–2200 m below the surface (Ehrbar et al., 2013). These examples of deep hydrothermal alteration would normally be classified as diagenetic alteration rather than weathering, but they do illustrate that water-rock interaction can occur at great depths and be associated with elevated permeability.

4.3. Volcanic rocks

Basalt is the most common volcanic rock, and is composed of volcanic glass and minerals that crystallized at high temperatures such as olivine (e.g., forsterite) and Ca-Na plagioclase feldspar (e.g., labradorite) (Table 3; Wood and Low, 1986; Singhal and Gupta, 2010). These minerals weather more rapidly than the low-temperature minerals that characterize granite, such as albite, K feldspar and quartz (Fig. 2). Consequently, basalt aquifers have much higher solute concentrations than granite aquifers (Table 2). The Eastern Snake River Plain aquifer in Idaho (USA) is a well-documented example of an extensive high-permeability basalt aquifer. A study of weathering reactions in the aquifer concluded that it “is not an ‘inert bathtub’ that simply stores and transmits water but is undergoing active diagenesis” (Wood and Low, 1986). Weathering reactions include dissolution of pyroxene, olivine, and labradorite to give smectite plus Ca^{2+}, Na^{+}, Mg^{2+}, HCO_3^-, and H_4SiO_4 in solution. A substantial fraction of the weathering products are in solution or otherwise mobilized and are removed by groundwater flow, with a loss of 14 Mg/km^2/year of minerals from the aquifer (Wood and Low, 1986).

Flowmeter logging in basalt aquifers has shown that most flow is often in rubbly zones that occur between lava flows and are associated with surface weathering (Paillet and Hess, 1995; Buckley, 2000; Paillet et al., 2002). Similarly, many of the large springs of the eastern Snake Plain discharge from pillow lavas or basaltic sands at the base of lava flows (Fig. 5e; Stearns, 1936; Stearns et al., 1938; Covington and Weaver, 1991). Discharge from the aquifer is principally at large springs such as Thousand Springs, where 42 m^3/s discharges from pillow lavas at an interflow zone. At Thousand Springs, dissolution appears to have enlarged apertures to at least several millimeters at the contacts between pillows (Fig. 5e). Individual lava flows may extend over distances of many kilometers, and so productive interflow zones may also extend over such distances. Lava tubes may also offer preferential pathways over great distances (Wood and Fernandez, 1988, Allred and Allred, 1997). It is possible that some of the large springs are associated with lava tubes or rubbly zones associated with collapsed lava tubes. Preferential flow has been demonstrated in the Eastern Snake Plain aquifer, where tracer testing has shown that groundwater velocities average hundreds of meters per day over distances of kilometers (Farmer et al., 2014; see also online supplementary data, Table S2). This rapid flow is most likely along interflow zones or lava tubes, but the extent

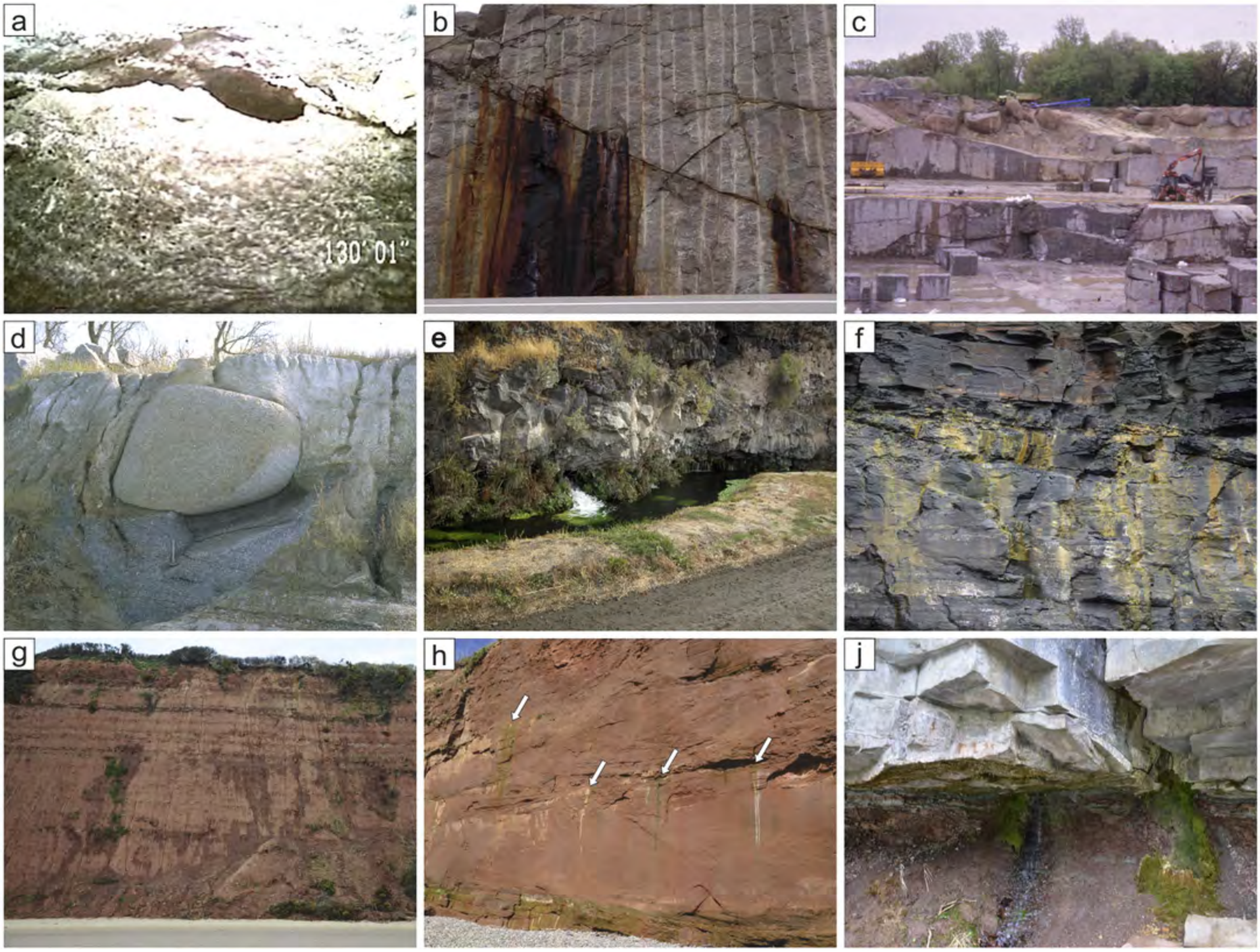

Fig. 5. Examples of weathering and preferential flow in bedrock aquifers: (a) channel with a height of ~5 mm at a depth of 39.6 m (130′ 1″) in a borehole in Silurian dolostone in Hamilton, ON, Canada; (b) iron oxide staining on road cut in gneiss, Sundridge, ON, Canada; (c) saprolite ~5 m thick above Proterozoic granite, Rockville, MN, USA; (d) In situ granite corestone in saprolite, Rockville, MN, USA; (e) discharge from pillow lavas at Thousand Springs, ID, USA, captured by an aqueduct; (f) coastal cliff with iron staining from discharges from Kimmeridge Clay, Kimmeridge, UK; (g) coastal cliff 50 m high of Permian Aylesbeare Mudstone east of Exmouth, UK, with the dark areas indicating discharge which appears to be predominantly from bedding planes; (h) coastal cliff 10 m high of Triassic Otter Sandstone at Ladram Bay, UK. Arrows indicate discharge from channels on bedding planes, as revealed by algae (green) and precipitates (white). In addition there is less focused discharge at the base of the cliff; (j) flow from channels (indicated by flowing water and by moss) at the contact between the Ordovician Queenston Shale and the Silurian Whirlpool Sandstone, Niagara Glen, ON, Canada. (For interpretation of the references to in this figure legend, the reader is referred to the web version of this article.)

to which weathering may have contributed to the preferential flow is unclear.

4.4. Fine-grained siliciclastic sedimentary rocks

Fine-grained siliciclastic sedimentary rocks such as shales and mudstones are composed principally of clay minerals and quartz (Table 3). These minerals constitute the low-solubility residue that remains from the weathering of rocks after the more mobile elements have been removed in solution. Compared to igneous rocks, they are enriched in the lower-mobility elements (principally Al, Fe, K) and depleted in the higher-mobility elements (principally Ca, Na, Mg: Berner and Berner, 2012). Consequently, dissolutional enlargement of fractures is less than in rocks that are more soluble, and they represent the low-permeability end-member of bedrock aquifers. Nevertheless, shale is not inert, and it has been shown that weathering can produce an increase in both porosity and permeability (Tuttle and Breit, 2009; Jin et al., 2013).

Studies of shale aquitards have shown that preferential flow can occur over distances of hundreds to thousands of meters (Michalski and Britton, 1997; Eaton et al., 2007; Green et al., 2012). Iron oxide staining on outcrops reveals the results of weathering (Fig. 5f), and preferential flow on bedding planes can occur even where there are poorly-lithified mudstones (Fig. 5g). In some cases, it has been shown that high permeability coincides with more calcareous beds, where more weathering would be expected (Eaton et al., 2007). However, the overall importance of permeability enhancement by weathering in shales and mudstones is an open question.

4.5. Coarse-grained siliciclastic sedimentary rocks

Coarse-grained siliciclastic sedimentary rocks such as sandstone range widely in solubility because the cement between the quartz grains varies widely in composition (Table 3). Dissolved silica concentrations in groundwater are typically in the range 10–30 mg/L (Davis, 1964; Shand et al., 2007; DeSimone, 2008; Toccalino et al., 2010), and so quartzites can have very low TDS concentrations. However, dissolution can still be important even where the cement is quartz. For instance, there are some extensive caves in quartzite in cratons, where stable conditions over many millions of years have facilitated substantial dissolution (Piccini and Mecchia, 2009; Wray, 2009; Aubrecht et al., 2011; Sauro, 2014). However, TDS concentrations in sandstone aquifers are often >300 mg/L (Table 2). The principal solutes are usually calcium and bicarbonate, reflecting preferential dissolution of calcite, which is a common cement (Table 3; Shand et al., 2007).

Preferential flow on fractures may be focused on channels, where its presence may sometimes be identified in sandstone outcrops by precipitates, algae, or moss (Fig. 5h and j). Flow through the matrix in sandstone aquifers is often important in addition to flow along fractures (Singhal and Gupta, 2010). This contrasts with other lithologies where flow is predominantly through fractures. In some cases, dissolution of the cement releases sand grains which are then physically removed by flowing water. This enhances the permeability (Einsele et al., 1995; Sauro, 2014).

If a sandstone aquifer has interconnected fractures, then a dual-porosity response can be expected from pumping tests, with early values coming from fracture flow and the late response being with the additional contribution of flow from the matrix (Kruseman and de Ridder, 1990). Such a response is seen in Permo-Triassic sandstones in England. These have a median porosity of 26%, but pumping tests where the aquifer is unconfined typically give an early response that lasts hours to months and give a storage of 10^{-4} to 10^{-3} (Allen et al., 1997). These values may well reflect the response of the fracture network to pumping because they are within the range of 10^{-5} to 10^{-2} that Freeze and Cherry (1979, p. 408) give for fracture porosity in bedrock. Results from a natural-gradient tracer test, with a travel time of less than two days over a distance of 280 m, show that there can be fast pathways in English sandstones over substantial distances (Barker et al., 1998). The presence of preferential flow in open fractures (Reeves et al., 1975; Price et al., 1982) and of fecal bacteria at depths >60 m (Powell et al., 2003; Morris et al., 2006) also provide evidence for fast pathways.

Similar results have been found in the Cambrian and Ordovician sandstones of Wisconsin and Minnesota (USA). Logging in wells has shown that there can be substantial preferential flow through fractures (Swanson et al., 2006; Runkel et al., 2006; Leaf et al., 2012). Similarly to the English findings, surface-sourced microbes have been found at depths that would not be anticipated if the aquifer only had intergranular flow, thus indicating preferential pathways (Bradbury et al., 2013; Gellasch et al., 2013). However, the extent to which weathering may have enhanced the permeabilities of the sandstone aquifers in England, Wisconsin, and Minnesota is uncertain.

5. Assessment of preferential flow and weathering

The high correlations between permeability and both TDS and dissolution rates (Figs. 1 and 3), and the case studies described in Section 4 support the hypothesis that weathering often enhances permeability in bedrock aquifers. In this section, we discuss four data sets that help demonstrate the nature of flow and transport. The extent of preferential flow is addressed by compiling and analyzing flowmeter data (Section 5.1). Next, fracture connectivity is addressed by considering data from tracer tests (Section 5.2), microbes in wells (Section 5.3), and large springs (Section 5.4).

5.1. Flowmeter data from wells

Weathering can extend deep into bedrock aquifers where there are interconnected fractures (Fig. 4c and d). However, it is unclear from the literature as to how frequently bedrock aquifers are dominated by intergranular flow and how frequently there is preferential flow along fracture networks or interconnected vugs. Flowmeter data provides a way to assess the relative importance of these two types of flow. This is because results show whether there are slow changes in flow as the flowmeter is lowered or raised in a well, or whether there are sharp changes at specific depths. These two cases represent intergranular flow and fracture flow, respectively. Differentiating the two cases is the easiest where the flowmeter logs are supplemented by other logs such as video, acoustic or optical televiewer, caliper, electrical conductivity, or temperature (Paillet, 1995; Buckley, 2000). However, in a few cases, it is unclear whether the flow is entering the well from intergranular flow in a zone a few meters thick, or from a number of closely-spaced fractures. Most commonly, the flowmeter is used while the well is being pumped, but the addition of measurements under ambient flow conditions can aid interpretation (Paillet, 2000).

Suitable flowmeter data were found from 96 wells, in 77 of which all the measurable flow is from a number of fractures. The wells comprise 18 in carbonates, 9 in basalt, 8 in sandstone, 15 in shale, mudstone or a range of sedimentary siliciclastic rocks, and 27 in crystalline rocks. The wells range in depth from 10 m to 1031 m, with median and mean depths of 62 m and 91 m, respectively. The remaining 19 wells have intergranular flow, a combination of intergranular and fracture flow, or flow from closely-spaced fractures that cannot be individually resolved. Details are given in the online supplementary data (Table S3). A compilation of the flowmeter measurements by lithology shows that almost all flow is usually associated with just a few open fractures, with typically >80% of the flow into wells coming from the three most productive fractures in all five major lithologies (Fig. 6). Furthermore, a number of studies have found that only a small proportion of fractures (commonly ~10%) have measurable flow (Paillet and Ollila, 1994; Morin et al., 1997; Audouin et al., 2008; Boutt et al., 2010; Worthington et al., 2012).

The mean fraction of the total flow for the dataset of 77 wells is 55.2%, 22.9%, 9.9%, 4.7%, and 2.3%, respectively, for the five highest-discharge fractures. Regression of discharge against rank gives the equation $Q = 116 \exp(-0.797n)$, with $r^2 = 0.994$, where Q is the discharge from a fracture and n is the rank of the fracture. The equation $Q = 100\ 0.5^n$ provides a good approximation for the results, giving flow for the five highest-flow fractures of 50%, 25%, 12.5%, 6.25%, and 3.125%, respectively. The limited number of wells in some lithologies means that they may not provide a representative sample.

Assuming that half the flow in a bedrock aquifer occurs in the most productive fracture, then the aperture of this fracture can be calculated by using the cubic law, which can be expressed as

$$k = \frac{Nb^3}{12} \tag{1}$$

where k is the average permeability of each lithology (Table 1), N is the number of fractures per unit distance, and b is fracture aperture (Freeze and Cherry, 1979, p. 74). Eq. (1) can be rearranged to

$$b = \sqrt[3]{\frac{12k}{N}} \tag{2}$$

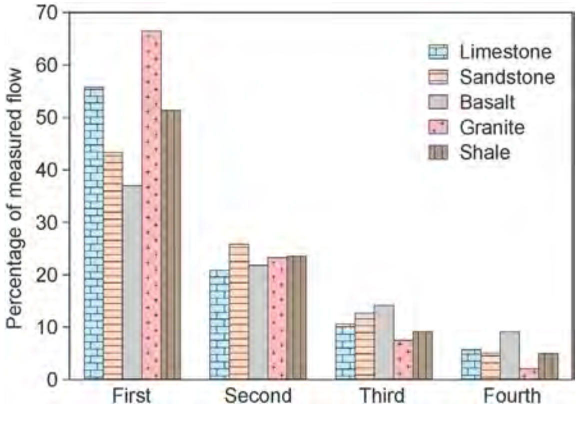

Fig. 6. Average percentage of flow from the four most productive fractures into wells in the five major lithologies, based on flowmeter data from 77 wells (see Table S3 in online supplementary data for details).

Results are shown in Table 4. Calculations of the largest apertures range from 0.018–0.027 mm for shale to 0.66–0.98 mm for limestone (Table 4). Eq. (2) applies to fractures that are straight and have smooth walls, but actual fractures are not smooth, and dissolution often produces elliptical channels that occupy only a part of a fracture (Hanna and Rajaram, 1998). These two differences cause actual apertures to be larger than the calculated values. Downhole images in carbonates and sandstones provide examples of such channels, with apertures in the mm–cm range being most common (Fig. 5a; Price et al., 1982, Schürch and Buckley, 2002; Runkel et al., 2006; Maurice et al., 2012).

The results from the compilation of flowmeter data clearly show that fracture flow is very common in all lithologies, and that most of the flow in most wells is from just a few widely-spaced fractures. Furthermore, the similar distributions of preferential flow in all five lithologies (Fig. 6) suggests that similar chemical and physical processes are at work in these aquifers. Simulations of flows in fractured-rock aquifers often utilize fracture apertures in the range 0.01–0.1 mm (Long et al., 1982; Hyman et al., 2015). The calculated fracture apertures for the most permeable fractures in wells in limestone, basalt, sandstone, and granite are substantially larger than such model values (Table 4). This implies that measured groundwater velocities may be greater than is generally assumed, and this topic is explored in the next section.

5.2. Groundwater velocities

It was shown in the last section that half the flow into bedrock wells is often delivered by a single fracture. However, it is uncertain from measurements in single wells whether these are discrete fractures that are only connected to smaller-aperture fractures, or whether these fractures form parts of laterally-extensive preferential-flow networks. Tracer tests provide direct measurements of groundwater velocity and provide the best way to determine fracture connectivity (Payne et al., 2008). Taking the fracture apertures determined in Table 4 for the different lithologies, groundwater velocities can be estimated by using the cubic law, which can be expressed as

$$Q = \frac{-i\rho g b^3 w}{12\mu} \tag{3}$$

where Q is the fracture discharge, g is the acceleration due to gravity, w is the fracture width, i is the hydraulic gradient, and μ is the dynamic viscosity (Domenico and Schwartz, 1998, p. 50). This can be combined with the continuity equation

$$Q = vbw \tag{4}$$

where v is the groundwater velocity, and then rearranged to give

$$v = \frac{-i\rho g b^2}{12\mu} \tag{5}$$

Results suggest that fracture velocities in shale are likely to be <1 m/d, but may be >100 m/d in limestone, basalt, and sandstone (Table 5). These velocities assume constant-aperture fractures, but weathering enhances channeling of flow on only part of a fracture plane. Consequently, channel apertures and thus velocities are likely to be greater than the values given in Table 5.

Table 4
Apertures of the largest fractures for the major lithologies in 30 m and 100 m deep wells.

Lithology	Aperture of largest fracture (mm)	
	For 30 m deep well	For 100 m deep well
Limestone	0.66	0.98
Basalt	0.38	0.57
Sandstone	0.38	0.57
Granite	0.11	0.17
Shale	0.018	0.027

Note: the calculations assume (i) aquifer permeability is the geometric mean value calculated by Gleeson (2011) for each lithology, (ii) that half the total flow into a well comes from a single fracture, and (iii) that the fracture is smooth and has a constant aperture.

Table 5
Groundwater velocities for the largest fracture for the major lithologies in 30 m-thick and 100 m-deep wells.

Lithology	Well depth (m)	Groundwater velocity (m/d) with hydraulic gradient = 0.001	Groundwater velocity (m/d) with hydraulic gradient = 0.01
Limestone	30	27	270
	100	60	600
Basalt	30	9.2	92
	100	20	200
Sandstone	30	9.2	92
	100	20	200
Granite	30	0.79	7.9
	100	1.8	18
Shale	30	0.02	0.2
	100	0.044	0.44

Note: the calculations assume that (i) aquifer permeability is the geometric average value calculated by Gleeson (2011) for each lithology, (ii) that half the total flow into a well comes from a single fracture, (iii) that the fracture is smooth and has a constant aperture, and (iv) that the groundwater temperature is 15 °C.

These calculated velocities may be compared with measured velocities from artificial tracer tests. There have been many thousands of such tests in carbonate rocks, and these have helped to show the extent of rapid flow. For instance, a compilation of 3015 tracer tests between sinking streams and springs gave a median groundwater velocity of 1940 m/d, where the median traced distance was 4000 m (Worthington and Ford, 2009). Furthermore, a set of 53 sink-to-spring tracer tests over distances >25 km gave a median groundwater velocity of 2200 m/d (Worthington, 2015a). These rapid velocities clearly reflect the effectiveness of self-organization in carbonate aquifers in creating connected open pathways that extend over great distances.

There have been far fewer tracer tests in silicate aquifers, especially over the substantial distances (e.g., >100 m) where one would expect the effects of self-organization to become clearer than over short distances. Nevertheless, data were found in the literature for 49 tests over distances >100 m in crystalline, volcanic, and both coarse-grained and fine-grained siliciclastic sedimentary rocks. Details are given in the online supplementary data (Table S2). Such tests often have groundwater velocities of tens to hundreds of meters per day (Fig. 7). These results are derived from only ten areas, and may not be representative of all silicate aquifers. Consequently, many more tracer tests in silicate aquifers are needed.

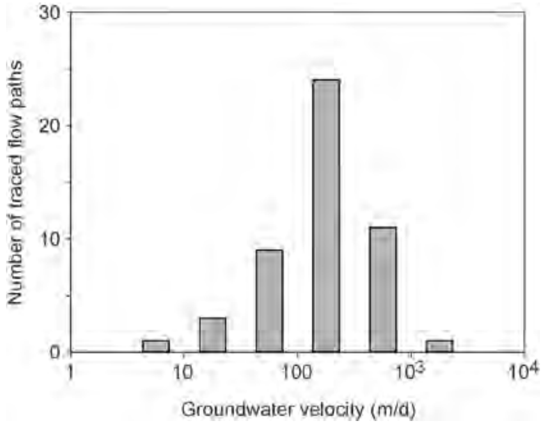

Fig. 7. Groundwater velocities in silicate aquifers, from 49 tracer tests over distances >100 m (see Table S2 in online supplementary data for details).

The rapid tracer test velocities from both carbonate and silicate aquifers are much faster than would be calculated under intergranular flow conditions. For instance, Barker et al. (1998) noted that such velocities would have been about 1 m/d for a sandstone tracer test in England, whereas measured velocities were up to 140 m/d. The rapid measured velocities are suggestive of flow through connected pathways such as fractures or channels with apertures >1 mm. It is possible that weathering and self-organization have played a major role in forming these connected pathways.

In addition to the rapid preferential flow described above, there is also much slower intergranular flow through the matrix of bedrock aquifers, as well as diffusion of solutes from fractures into the matrix. Environmental tracers yield average groundwater velocities derived from a combination of the slow matrix flow (typically <<10 m/d) and more rapid fracture and channel flow (typically >10 m/d). Where both artificial tracer tests and environmental tracers have been used, the latter yield groundwater ages that are usually two to three orders of magnitude higher than the ages from artificial tracer tests (Worthington, 2015b). These contrasts demonstrate how bedrock aquifers often behave as dual-porosity or dual-permeability aquifers.

5.3. Incidence of microbes in wells

Microbes give an indication of the recent fraction of groundwater in wells because they are derived from the surface and their abundance in groundwater rapidly decreases over time (John and Rose, 2005). Consequently, large data sets of microbe concentrations in wells can be used to infer relative residence times in the different lithologies. If weathering has been effective in creating interconnected channel networks that provide pathways for rapid groundwater flow, then the more soluble lithologies should have better-developed channel networks and so be more susceptible to bacterial contamination than less soluble rocks. They should also be more susceptible to contamination than intergranular flow aquifers, where the high effective porosities give rise to slow groundwater velocities.

Total coliform and fecal coliform (or *Escherichia coli*) are commonly tested for in water-supply wells and so there are large data sets that can be evaluated for the presence of recently-recharged groundwater (Macler and Merkle, 2000; Embrey and Runkle, 2006). To compare results for the different lithologies, we used the three largest compilations that we found where bacterial occurrence in wells was linked to lithology. A study in New Jersey (USA) analyzed data from 25,574 domestic wells in unlithified sediments and 25,226 domestic wells in bedrock (Atherholt et al., 2013). The second study analyzed data from 854 wells with a range of uses that were chosen by the U.S. Geological Survey to be representative of major aquifers across the USA (Embrey and Runkle, 2006). The third study assessed the presence of bacteria in 262 domestic wells in Ireland (Hynds et al., 2012).

Defects in well construction or maintenance may allow microbial contamination of wells. Hynds et al. (2012) found that contamination was higher in dug wells than in drilled wells, and other significant factors included proximity to septic tanks, overburden type and thickness, antecedent precipitation, and lithology. Consequently, microbial contamination of wells is clearly associated with multiple factors.

Despite the possible confounding factors, all three studies do show consistent differences between the various lithologies, with bacterial contamination being more common in the more soluble and more permeable rocks (Fig. 8). Furthermore, bacteria are more commonly found in siliciclastic rocks than in siliciclastic sediments. These results provide further support for the hypotheses that preferential flow along fractures is common in bedrock aquifers, and that weathering enhances permeability by enlarging the apertures of preferential flow pathways.

In summarizing the susceptibility of groundwater in the USA to waterborne pathogens, the Environmental Protection Agency (2006, p. 65595) state: “Sensitive aquifers (e.g., karst, fractured bedrock, or gravel) can have fast (kilometers per day) and direct ground water flow through large interconnected openings. Ground water flow in non-sensitive aquifers (such as a sand aquifer) tends to be very slow (feet per day)”. This finding is largely similar to the evidence presented in Section 5.2, suggesting that the common occurrence of microbes in bedrock wells points to fast groundwater velocities along connected fractures.

5.4. Large springs

Dissolution in bedrock aquifers produces self-organized, preferential-flow networks that discharge to the surface at springs (Section 3.1). This suggests that better-developed self-organized networks with larger springs should occur in the more soluble lithologies. This hypothesis was investigated by compiling spring data by lithology from three extensive spring inventories; these are the most comprehensive data that we found in the literature. The Spanish data are from an area covering 62% of Spain, where the geology was determined for 2851 bedrock springs with flows >1 L/s (Sanz Pérez, 1996). The West Virginia data cover the whole state, and comprise 393 springs with flows >1 L/s that discharge from bedrock (McColloch, 1986). The data from the USA represent all springs in the country that have discharges >2832 L/s (100 ft^2/s; Meinzer, 1927).

In the Spanish data set, all 47 bedrock springs with flows >500 L/s discharge from carbonates, with springs in conglomerate and sandstone being next in importance (Fig. 9a). There are similar relationships with springs in West Virginia (Fig. 9b), and with the 65 largest springs in the USA, although the latter data set also have large springs issuing from basalt (Fig. 9c). All three figures show that large springs occur more commonly in the more soluble and more permeable rocks, implying that these lithologies have the best-developed channel networks. In the case of carbonate and basalt aquifers, this inference is also supported by measured kilometer-per-day groundwater velocities (Section 5.2).

5.5. Summary

The data sets analyzed in the four previous sections give some important insights into groundwater flow. The flowmeter data show that fracture flow is common, and that flow is usually focused on just a few fractures in all five major lithologies (Fig. 6). Calculations of the apertures of the fractures with the greatest flow indicate hydraulic apertures <1 mm, with velocities in some situations being >100 m/d (Tables 4 and 5). This assumes that fractures have smooth walls, which is not the case, and major flowing apertures visible in wells are somewhat larger, being in the mm–cm range. The tracer data confirm the rapid velocities, and show that rapid velocities over distances >100 m do occur in all five lithologies (Fig. 7). This provides an explanation for more frequent detection of bacteria in bedrock wells than in wells in unconsolidated sediments (Fig. 8). The spring data show that the more permeable lithologies are much more likely to have large springs (Fig. 9). Differences in weathering between the different lithologies provide a logical explanation for all these contrasts, suggesting that the more soluble and more permeable rocks have better-developed and more extensive channel networks, which are integrated though the process of self-organization. Consequently, they have more rapid flow and hence more microbial contamination, and they channel more flow towards focused discharge locations at springs.

6. Discussion and conclusions

6.1. Enhancement of permeability by fracturing

The matrix of most bedrock aquifers has low permeability, and fracturing substantially increases the permeability. This is demonstrated by the flowmeter data (Section 5.1), with most of the flow into wells often being transmitted by just a few fractures (Fig. 6). Tracer test results in

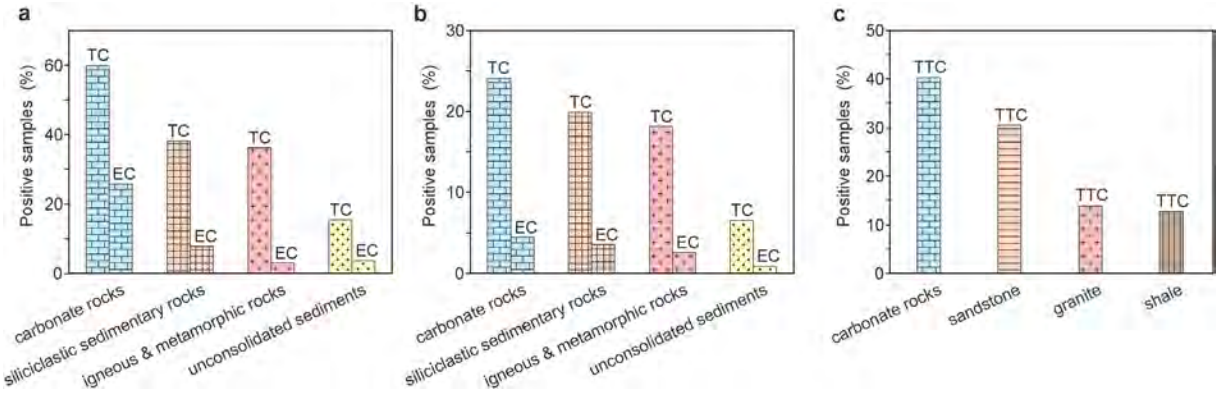

Fig. 8. Percentage of water samples from wells that were positive for total coliform (TC), for fecal coliform or *Escherichia coli* (EC), and for thermotolerant coliform (TTC) in (a) the USA, (b) New Jersey, USA, and (c) Ireland (based on data from Embrey and Runkle (2006), Atherholt et al. (2013), and Hynds et al. (2012)).

bedrock show high groundwater velocities, confirming that there must be flow through connected open fractures and not just through the pores of the rock (Section 5.2). Depositional structures such as bedding planes and channel deposits in sedimentary rocks and interflow zones or lava tubes in basalt offer the potential for continuous open pathways over distances of many kilometers, and these may be associated with much of the preferential flow in these rocks.

Fracturing clearly enhances permeability in most bedrock aquifers, giving a direct relationship between permeability and fracturing. Consequently, it might be expected that aquifers with close fracture spacing would have higher permeability than aquifers with widely-spaced fractures. However, the data from flowmeter measurements does not support this hypothesis, because just a few fractures account for most of the flow in most bedrock wells in all lithologies, despite their substantial permeability contrasts (Fig. 6).

An alternative hypothesis is that there is an inverse relationship between the number of fractures and permeability. This is supported by the evidence for siliciclastic sedimentary rocks that bed thickness increases with grain size, that joint spacing is proportional to bed thickness, and that the aperture of opening-mode fractures is proportional to fracture length (Pettijohn, 1975; Narr and Suppe, 1991; Bai et al., 2000). This may explain why shales are likely to be thin-bedded, have closely-spaced joints that are short and so have small apertures, and this may help explain their observed low permeability. However, limestone and basalt typically have smaller grain sizes than sandstone and granite, yet their permeability is higher. Thus, in the case of grain size differences, there seems to be a weak relationship between permeability and fracturing. A further consideration is that the fundamental physical properties of tensile strength and compressive strength are similar in limestone, basalt and granite (Pollard and Fletcher, 2005), yet the three lithologies have strongly contrasting permeabilities (Table 1). These contrasting relationships illustrate the complicated relationship between permeability and the physical properties of the different lithologies, and the lack of any single physical property that might explain the observed permeability contrasts between the five major lithologies.

6.2. Enhancement of permeability by weathering

The rapid groundwater velocities from tracer tests demonstrate the presence of connected open fractures in many aquifers. Fracture networks have low specific surface areas, allowing the deep penetration of weathering along fractures (Fig. 4c and d). The evidence from dissolution experiments and modeling efforts (Sections 2 and 3), and from case studies (Section 4) shows that weathering occurs in all major lithologies and can enhance permeability. There are positive correlations between permeability and both solute concentrations in the five major lithologies and dissolution rate of a rock's constituent minerals (Figs. 1 and 3, respectively). This suggests that dissolution does play a substantial role in enhancing permeability, and the following scenario may be postulated.

Physical processes such as tectonics and unloading create fracture networks that enhance permeability in comparison with unfractured rocks. Fracture networks provide preferential flow pathways, and then the positive feedback between flow and weathering proceeds to enhance the permeability, resulting in integrated channel networks that discharge at springs.

Tracer test results show that groundwater velocities >100 m/d occur in all five major lithologies, suggesting networks of connected open fractures. This provides an explanation for the distribution of bacteria in bedrock aquifers, which have more frequent bacterial contamination than aquifers in unconsolidated deposits. The more soluble rocks have higher permeability, better-developed fracture networks, faster groundwater flow, and consequently more frequent bacterial contamination than less soluble rocks. Our analysis shows that there is no simple division of bedrock aquifers between those with weathering-enhanced

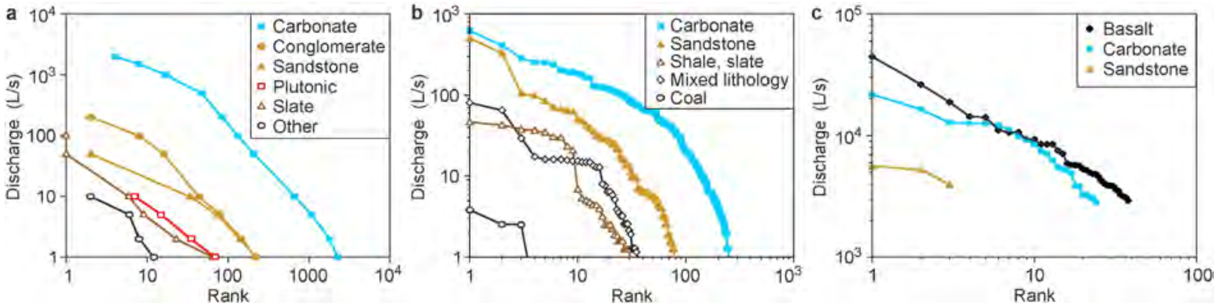

Fig. 9. Rank and discharge of the largest bedrock springs by lithology; (a) in Spain, for springs where lithology was identified; (b) in West Virginia; (c) in the USA for springs with flows >2832 L/s. Data from (a) Sanz Pérez (1996); (b) McColloch (1986); (c) Meinzer (1927).

permeability and those that can be treated as inert. Instead, the evidence suggests that weathering plays an important role in permeability enhancement in most bedrock aquifers.

The principal uncertainty in the above scenario concerns the fate of the clay minerals and iron oxides that are produced as a result of the incongruent dissolution of silicate minerals. Several studies of wells and tunnels have examined fracture fills in crystalline rocks (Banks et al., 1992), sandstone (Wealthall et al., 2001), and basalt (Kocbay and Kilic, 2006), and found that most fractures in these rocks contain fills, with sand predominating in the sandstone fractures and secondary clay being common in the igneous rocks. The filling of fractures lowers their permeability, resulting in the focusing of flow in the less-filled and thus more permeable fractures. Presumably, the focusing of flow on the more permeable connected fracture pathways will result in higher velocities, and it is possible that this could result in the erosion of clay minerals that are produced by weathering and also enlarge the apertures by weathering along those preferential flow paths. However, hydrogeological studies of fracture fills are relatively rare, and more studies are needed to investigate the putative processes described above.

6.3. Emergent properties of weathered bedrock aquifers

Weathering results in self-organization of flow paths in bedrock aquifers, which become drained by integrated channel networks that discharge to the surface at springs (Section 3.1). These channel networks exhibit a number of emergent properties (Holland, 1998). These are properties that were not originally present in the bedrock, but that emerged as a result of feedbacks between flow and weathering processes. The properties provide diagnostic tools for differentiating aquifers with these networks from intergranular-flow aquifers. Emergent properties include the presence of springs that may have large discharges, networks of solution channels that discharge at the springs, turbulent flow in the larger channels, troughs in the potentiometric surface, increasing permeability in a downgradient direction, and decreasing hydraulic gradients in a downgradient direction (Worthington, 2015b).

The traditional approach to conceptualizing groundwater flow is reductionist, assuming that permeability varies randomly in space, that processes are linear, and that the framework of aquifers is inert (Hubbert, 1940; Freeze, 1975; Bear, 1979; Kitanidis, 2015). However, the aquifers described in this review have very different properties, but this may only become clear when diagnostic tests such as long-distance tracer tests are carried out (Section 5.2).

Weathering in bedrock aquifers can produce channel networks that exhibit a number of similarities to river networks. These include fractal permeability structures, non-linear processes, and multiple feedbacks (Baker, 1973; Curl, 1986; Dreybrodt, 1990; Rodríguez-Iturbe and Rinaldo, 1997; Hergarten et al., 2014; Worthington, 2015a). It is not known how commonly such channel networks do occur. There are numerous examples that show that they are common in carbonate rocks, especially where the aquifers have high permeability. The evidence examined in this paper suggests that they may also be common in silicate rocks.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.earscirev.2016.07.002.

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Appendix A: Supplementary data

Table S1. Compilation of total dissolved solids (TDS) data from the UK and US

Table S1A. Calculation of median TDS values

Aquifer	Period	Median Ca (mg/L)	Median Mg (mg/L)	Median Na (mg/L)	Median K (mg/L)	Median Cl (mg/L)	Median SO4 (mg/L)	Median HCO3 (mg/L)	Median Si (mg/L)	Number of samples*	Median TDS (mg/L)	Reference
UK DATA												
Limestone												
Dorset Chalk	Cretaceous	105	3	11	2	21	13	269	5	30	429	Edmunds et al., 2002
North Downs Chalk - reducing conditions	Cretaceous	98	22	182	11	179	107	345	6	10	950	Smedley et al., 2003
North Downs Chalk - oxidising conditions	Cretaceous	150	7	53	5	78	69	338	11	36	711	
Lee / Colne Chalk - unconfined	Cretaceous	125	2	12	2	23	22	329	7	12	522	Shand et al., 2003a
Lee / Colne Chalk - confined	Cretaceous	93	24	83	9	40	102	323	9	21	683	
Yorkshire Chalk - oxidising conditions	Cretaceous	108	3	10	1	17	18	240	3	97	400	Smedley et al., 2004a
Yorkshire Chalk - reducing conditions	Cretaceous	108	45	290	9	300	120	400	5	19	1277	
Great Ouse Chalk	Cretaceous	128	3	14	3	30	34	277	7	77	496	Ander et al., 2004
North Norfolk Chalk	Cretaceous	124	13	63	6	110	93	295	9	96	713	Ander et al., 2006
Berkshire and Chilterns Chalk - unconfined	Cretaceous	110	2	9	2	17	13	289	7	18	449	Edmunds and Brewerton, 1997
Berkshire and Chilterns Chalk - confined	Cretaceous	57	19	36	7	30	33	303	8	24	493	
Lincolnshire Chalk - unconfined	Cretaceous	115	6	15	2	35	51	252	3	41	479	Smedley and Brewerton, 1997a
Lincolnshire Chalk - confined	Cretaceous	82	15	34	4	46	32	304	6	52	523	
Hampshire Chalk	Cretaceous	105	2	9	1	18	12	286	6	36	439	Stuart and Smedley, 2009
South Downs Chalk - Chichester Block	Cretaceous	91	2	10	1	21	8	290	4	12	427	Smedley and Brewerton, 1997b
South Downs Chalk - Worthing Block	Cretaceous	99	3	18	1	34	17	275	4	153	451	
South Downs Chalk - Brighton Block	Cretaceous	92	2	14	1	28	17	238	3	165	395	
Cotswold Oolite	Jurassic	97	5	7	1	16	33	242	2	50	403	Neumann et al., 2003
Oxfordshire and Wiltshire Corallian	Jurassic	103	8	22	4	34	62	342	6	32	581	Cobbing et al., 2004
Yorkshire Corallian	Jurassic	108	7	11	2	30	47	221	4	25	430	Bearcock et al., 2015
Magnesian Limestone	Permian	92	43	28	3	38	89	351	4	110	648	Bearcock and Smedley, 2009

Aquifer	**Period**	**Median Ca (mg/L)**	**Median Mg (mg/L)**	**Median Na (mg/L)**	**Median K (mg/L)**	**Median Cl (mg/L)**	**Median SO4 (mg/L)**	**Median HCO3 (mg/L)**	**Median Si (mg/L)**	**Number of samples***	**Median TDS (mg/L)**	**Reference**
UK DATA												
Limestone												
Dorset Chalk	Cretaceous	105	3	11	2	21	13	269	5	30	429	Edmunds et al., 2002
North Downs Chalk - reducing conditions	Cretaceous	98	22	182	11	179	107	345	6	10	950	Smedley et al., 2003
Carboniferous Limestone - northern England	Mississippian	69	11	12	2	13	20	280	3	158	410	Abessar et al., 2005b
Carboniferous Limestone - Derbyshire	Mississippian	104	8	12	1	22	28	268	3	57	446	Abessar and Smedley, 2008
Lincolnshire Limestone	Jurassic	145	7	24	2	57	110	288	3	32	636	Griffiths et al., 2006
Number of samples										**1363**		
Median TDS											**486**	
Aquifer	**Period**	**Median Ca (mg/L)**	**Median Mg (mg/L)**	**Median Na (mg/L)**	**Median K (mg/L)**	**Median Cl (mg/L)**	**Median SO4 (mg/L)**	**Median HCO3 (mg/L)**	**Median Si (mg/L)**	**Number of samples***	**Median TDS (mg/L)**	**Reference**
Granite - southwest England	Carboniferous/ Permian	12	3	16	3	27	14	11	3	**195**	**89**	Smedley et al., 2004b
Shale												
Shale - Severn	Ordovician and Silurian	4	2	6	0	7	8	20	3	23	50	Shand et al., 2005
Shale - Wye		6	2	5	0	5	9	17	2	19	46	
Shale - Teifi		18	4	12	1	21	12	27	3	48	98	
Shale - Rheidol		9	3	9	1	14	14	21	3	15	74	
Number of samples										**105**		
Median TDS											**62**	
Sandstone												
Vale of York sandstones	Triassic	140	35	36	4	37	170	333	7	43	762	Shand et al, 2002
West Cheshire and Wirral sandstone	Permo-Triassic	74	21	30	4	49	48	226	5	238	457	Griffiths et al., 2002
S.Staffordshire and N. Worcestershire sandstones	Permo-Triassic	68	9	14	4	31	50	177	6	72	359	Tyler-Whittle et al., 2002

Aquifer	Period	Median Ca (mg/L)	Median Mg (mg/L)	Median Na (mg/L)	Median K (mg/L)	Median Cl (mg/L)	Median SO4 (mg/L)	Median HCO3 (mg/L)	Median Si (mg/L)	Number of samples*	Median TDS (mg/L)	Reference
UK DATA												
Limestone												
Dorset Chalk	Cretaceous	105	3	11	2	21	13	269	5	30	429	Edmunds et al., 2002
North Downs Chalk - reducing conditions	Cretaceous	98	22	182	11	179	107	345	6	10	950	Smedley et al., 2003
Manchester and East Cheshire sandstone	Permo-Triassic	78	25	25	4	29	54	298	6	89	519	Griffiths et al., 2003
Liverpool and Rufford sandstone	Permo-Triassic	87	34	27	4	41	104	265	8	59	570	Griffiths et al., 2005
Shropshire sandstones	Permo-Triassic	76	11	13	3	29	37	207	5	95	381	Smedley et al., 2005
Devon and Somerset Sherwood Sandstone	Triassic	140	35	36	4	37	170	333	7	28	379	Bearcock and Smedley, 2012
Lower Greensand - southern England	Cretaceous	52	3	10	3	20	22	148	7	81	265	Shand et al., 2003b
Bridport Sand	Jurassic	116	5	16	2	26	44	300	5	52	514	Shand et al., 2004
Devonian sandstone - S. Wales/Hertfordshire	Devonian	77	8	13	2	21	20	241	4	50	386	Moreau et al., 2004
Millstone Grit	Pennsylvanian	34	7	11	2	13	15	163	5	183	250	Abessar et al., 2005a
Number of samples										**990**		
Median TDS											**386**	
Aquifer	**Period**	**Median Ca (mg/L)**	**Median Mg (mg/L)**	**Median Na (mg/L)**	**Median K (mg/L)**	**Median Cl (mg/L)**	**Median SO4 (mg/L)**	**Median HCO3 (mg/L)**	**Median Si (mg/L)**	**Number of samples***	**Median TDS (mg/L)**	**Reference**
US DATA												
Limestone												
Domestic wells (DeSimone, 2008)	-									215	252	DeSimone, 2008
Public supply wells (Toccalino et al., 2010)	-									81	292	Toccalino et al., 2010

Aquifer	**Period**	**Median Ca (mg/L)**	**Median Mg (mg/L)**	**Median Na (mg/L)**	**Median K (mg/L)**	**Median Cl (mg/L)**	**Median SO4 (mg/L)**	**Median HCO3 (mg/L)**	**Median Si (mg/L)**	**Number of samples***	**Median TDS (mg/L)**	**Reference**
UK DATA												
Limestone												
Dorset Chalk	Cretaceous	105	3	11	2	21	13	269	5	30	429	Edmunds et al., 2002
North Downs Chalk - reducing conditions	Cretaceous	98	22	182	11	179	107	345	6	10	950	Smedley et al., 2003
Number of samples										**296**		
Median TDS											**271**	
Sandstone												
Domestic wells										263	240	DeSimone, 2008
Public supply wells										93	415	Toccalino et al., 2010
Number of samples										**356**		
Median TDS											**328**	
Crystalline												
Domestic wells										240	121	DeSimone, 2008
Public supply wells										2	115	Toccalino et al., 2010
Number of samples										**242**		
Median TDS											**118**	
Volcanic												
Domestic wells										-	-	
Public supply wells										**43**	**280**	Toccalino et al., 2010

Notes:
* In some cases, there are different number of analyses for different ions. In these cases, the number of samples listed above is given for the ion with the highest concentration (usually bicarbonate).

Table S1B. Calculation of upper and lower quartiles.

Area	Electrical condictivity lower quartile	Electrical condictivity median	Electrical condictivity upper quartile	TDS median	TDS lower quartile	TDS upper quartile
UK limestone (from Shand et al., 2007)						
Dorset	520	570	610	429	391	459
Kent	550	600	660	763	699	839
Lee Colne	520	550	600	625	591	682
Yorks	490	600	720	544	444	653
Gt Ouse	610	680	810	496	445	591
E Norfolk	710	800	1200	713	633	1070
Cotswold	430	630	680	403	275	435
Corallian	620	760	860	581	474	657
Carb Lst	390	460	610	410	348	544
Lincs Lst	810	870	1010	636	592	738
Median				**563**	**459**	**655**
UK Sandstone (from Shand et al., 2007)						
York	750	1010	2100	762	566	1584
Cheshire	490	650	950	457	345	668
S Staffs	400	530	640	359	271	434
Manchester	550	680	1040	519	420	794
Liverpool	570	750	920	570	433	699
Shropshire	480	550	640	381	333	443
L Greensand	250	430	550	265	154	339
Bridport	570	680	740	514	431	559
Devonian	460	580	690	386	306	459
Millstone grit	250	450	550	250	139	306
Median				**422**	**339**	**509**

Note: TDS lower quartile = TDS median * EC lower quartile / EC median
TDS upper quartile = TDS median * EC upper quartile / EC median
Median TDS values are from Table S1A

Area	Electrical condictivity lower quartile	Electrical condictivity median	Electrical condictivity upper quartile	TDS median	TDS lower quartile	TDS upper quartile
Limestone						
US Domestic wells (DeSimone, 2008)					180	337
US Public supply wells (Toccalino et al., 2010)					220	375
US Median					200	356
UK median					459	655
Overall median					330	506
Median corrected for just weathering					240	371
Sandstone						
US Domestic wells					160	340
US Public supply wells					310	715
US Median					235	528
UK median					339	509
Overall median					287	518
Median corrected for just weathering					208	372
Crystalline						
US domestic wells					80	160
UK median					64	116
Overall median					72	138
Median corrected for just weathering					31	64

Volcanic						
US Public supply wells					175	375
Median corrected for just weathering					83	183
Shale (Shand et al., 2005)						
Uncorrected value					37	163
corrected for just weathering					14	77

Note: Corrections for just weathering are y=(x-10)*0.75 for sandstone and limestone and y=(x-10)*0.5 for the other rocks, where x is the uncorrected value, y is the corrected value, 10 (mg/L) is the correction for atmosphe-derived TDS, and 0.75 and 0.5 are corrections for atmosphere-derived CO_2. See text for details.

Table S2. Tracer tests >100 m in silicate rocks

Injection location	Lithology	Sample location	Distance (m)	Velocity of tracer arrival m/d	Tracer velocitity of peak concentration m/d	Reference
Siliciclastic sedimentary rocks						
well	Triassic sandstone, England	Liverpool Loop Line Tunnel, B	278	139†	139‡	Barker et al., 1998
		Liverpool Loop Line Tunnel, H*	272	136	68	
sinkhole	Precambrian sandstone, Minnesota, USA	residential well MW 23	500	>128	-	Alexander et al., 2005
Ahrensfeld Creek Sink 1	Cambrian St. Lawrence Formation (fine-grained siliciclastics with minor carbonates), MN, USA	Ehlenfeldt Spring	2200	>150	-	Green et al., 2008
Ahrensfeld Creek Sink 2		Wolfram Spring	3350	670	260	MDNR, 2013, Green et al., 2012
Kiefer Valley		Little Green Spring	1500	>123	-	Ustipak et al, 2013
Crystal Springs SW		Crystal Springs #2	860	>41	-	
Daley Creek Sink		Elit Spring	1040	>150	-	MDNR, 2009; Green et al., 2012
Sullivan Creek		Eleven Springs NE	1890	>48		Green et al., 2009, Green et al., 2012
Stockton Vicinity 1		Haase Spring	1014	>127		Barry and Green, 2015
Sullivan Creek		Sullivan Headwater Spring	1700	>35	-	Green et al., 2009
Borson Northeast Sink		Borston Spring	3450	>75	-	MDNR, 2013
Gilbert Creek		Hinck Spring	1400	>137		Green, 2015
Indian Springs		Connif Outcrop Spring	2300	>287		
Bridge Creek Sink 1	Cambrian St. Lawrence Formation (fine-grained siliciclastics with minor carbonates) and Tunnel City Group (sandstone), MN, US	Rostvold Spring	4100	>146	-	Bridge Creek, 2014a
Bridge Creek Sink 2		Rostvold Spring	4720	314	131	
Campbell Valley		Power Spring	1775	>214	-	Barry et al, 2015

Injection location	Lithology	Sample location	Distance (m)	Velocity of tracer arrival m/d	Tracer velocitity of peak concentration m/d	Reference
Stockton Vicinity 2		Butenhoff Spring	2591	37	-	Barry & Green, 2015
Girl Scout Camp Creek Sink		Peterson Spring	2150	>154		Barry & Green, 2014b
Diaterna stream (tracer test 1)	Oligocene - Miocene siliciclastic turbidites, Italy	Raticosa Tunnel, xR22SXm*	127	9.1	2.4	Vincenzi et al., 2014
		Raticosa Tunnel, R23SX	307	12†	5.8‡	
Veccione stream (tracer test 2)		Firenzuola Tunnel, 20DXmv	133	133†	67‡	
		Firenzuola Tunnel, OSTDX*	91	23	5.4	
Rampolli stream (tracer test 3)	Oligocene - Miocene siliciclastic turbidites, Italy	Firenzuola Tunnel, 4DX	1140	63†	20‡	Vincenzi et al., 2014
MW05, Woodland Park	Pennsylvanian sandstone, siltstone, shale, CO, USA	Trout Creek Spring	3100	119	109	Davies, 1999
		Widdick Well (GW17)	1350	45	45	
		Widdick Well (GW16)	1360	90	30	
		Lucky Lady Well #4 (GW35)	2400	120	96	
		Lucky Lady Well #1 (GW34)	2500	125	62	
Igneous rocks						
well	gneiss, Norway	Romeriksporten Tunnel	200	>960	190	Kitterød et al., 2000
BF101 well	granodiorite, Sweden	BF102 well, Finnsjön	168	183	115	Guimerà and Carrera, 2000.
BF101well		BF102 well, Finnsjön	168	202	115	
KF106 well		BF102 well, Finnsjön	189	567	284	
KF111 well		BF102 well, Finnsjön	155	744	465	
b77e well	granite, Germany	b20e well, Lindau	346	554	198	
well (tt-5)	Lac du Bonet granite, Canada	well	102	38	8.6	
well (tt-6)		well	108	22	2.8	
Hopper well	basalt, Idaho, USA	Riddle well	805	402	89	Farmer and Blew, 2011

Injection location	Lithology	Sample location	Distance (m)	Velocity of tracer arrival m/d	Tracer velocitity of peak concentration m/d	Reference
		Malad Springs, MG1 to MG5	1673	608	289	
Park picnic well		Malad Springs, MG6 to MG10	335	1730#	620#	Farmer et al., 2014
Riddle well		Malad Springs, MG1 to MG7	873	749	256	
Meyer well		Malad Springs, MG7 to MG13	3627	334§	161§	
Conklin well		Malad Springs, MG7 to MG11.7	1113	876	324	
Victor well		Malad Springs, MG4 to MG19	4984	172	65	
		Turner well	1680	112	76	
		Clinton Palmer well	2859	150	62	
		Umek well	3035	138	58	
Ashmead well		Clear Springs	661	925#	496#	
Strickland well		Briggs Spring	5640	235	171	

Notes: * Sampling location with greatest tracer recovery
† Sampling location with greatest groundwater velocity, based on time to tracer arrival at sampling point
‡ Sampling location with greatest groundwater velocity, based on time to tracer peak concentration at sampling point
# Mean value from three tracer tests
§ Mean value from two tracer tests

Table S3. Flowmeter data from boreholes in bedrock

Carbonate rocks

Well	Logged depth	Test type*	Percentage of flow per fracture 1	2	3	4	5	Lithology	Reference
CE-DT-4, Las Vegas, NV, USA	88	P	47	22	14	-	-	Mississippian limestone	Morin et al., 1988
limestone, Arizona, USA	195	P	41	15	13	12	11	limestone	Paillet, 1998
SM1, dolomite, Waupun, WI, USA	60	N	31	25	13	11	9	dolomite	Paillet, 1998
SM2, dolomite, Waupun, WI, USA	60	N	39	25	20	8	8	dolomite	Paillet, 1998
SM3, dolomite, Waupun, WI, USA	60	N	40	22	17	12	4	dolomite	Paillet, 1998
Victoria Gardens, Brighton, UK	107	P	55	15	10	10	-	Cretaceous chalk	Jones and Robins, 1999
SW Kentucky, USA	25	P	50	25	25	-	-	dolomite	Paillet, 2000
Faribault, MN, USA	54	P/N	36	31	15	14	2	Ordovician dolomite	Paillet et al., 2000
Rochester, MN, USA	38	P/N	68	28	2	2	-	Ordovician dolomite	Paillet et al., 2000
Austin, MN, USA	10	P/N	93	7	-	-	-	Devonian carbonate	Paillet et al., 2000
FC-29, KY, USA	34	P	77	23	-	-	-	Mississippian limestone	Wilson et al., 2001
FC-15, TN, USA	22	P	50	45	5	-	-	Mississippian limestone	Wilson et al., 2001
FC-16, KY, USA	32	P	100	-	-	-	-	Mississippian limestone	Wilson et al., 2001
BB1, Berkshire, UK	70	P	16	9	5	-	-	Cretaceous chalk	Schürch and Buckley, 2002
BB2, Berkshire, UK	70	P	66	20	7	7	-	Cretaceous chalk	Schürch and Buckley, 2002
PL10A, Berkshire, UK	73	PA	38	17	16	13	-	Cretaceous chalk	Butler et al., 2009
6, Walkerton, ON, Canada	61	P	50	25	5	5	5	Silurian-Devonian carbonates	Worthington et al., 2012
1-86, Walkerton, ON, Canada	59	AA	55	25	15	5	-	Silurian-Devonian carbonates	Worthington et al., 2012

* test type: P = pumping at the tested well; N = no pumping during the test; D = no pumping, flow from well during air-rotary drilling; PA = pumping in adjacent well; AO = artestian flow in tested well; AA = artesian overflow in adjacent well

Table S3 (continued) Volcanic rocks

Well	Logged depth	Test type*	Percentage of flow per fracture 1	2	3	4	5	Lithology	Reference
BH2, Portree,UK	101	P	50	23	17	-	-	Paleogene basalt	Buckley, 2000
Kaimuki, Hawaii, USA	180	P	31	18	18	15	15	basalt	Paillet et al., 2002
OB A, Waipahu, Hawaii, USA	62	N	52	25	13	7	3	basalt	Paillet and Hess, 1995
OB B, Waipahu, Hawaii, USA	73	N	26	18	17	13	11	basalt	Paillet and Hess, 1995
OB C, Waipahu, Hawaii, USA	75	N	50	24	10	9	7	basalt	Paillet and Hess, 1995
OB D, Waipahu, Hawaii, USA	70	N	27	21	19	10	8	basalt	Paillet and Hess, 1995
OB E, Waipahu, Hawaii, USA	73	N	35	20	13	11	8	basalt	Paillet and Hess, 1995
OB F, Waipahu, Hawaii, USA	66	N	38	26	12	8	7	basalt	Paillet and Hess, 1995
OB H, Waipahu, Hawaii, USA	64	N	24	22	9	9	8	basalt	Paillet and Hess, 1995

Coarse-grained siliciclastic sedimentary rocks

Well	Logged depth	Test type*	Percentage of flow per fracture 1	2	3	4	5	Lithology	Reference
Cargen, UK	101	P	50	23	17	-	-	Permian sandstone/breccia	Buckley, 2000
Terregles P1, UK	106	P	41	29	15	5	-	Permian sandstone	Buckley, 2000
Terregles P2, UK	90	P	38	35	10	10	7	Permian sandstone	Buckley, 2000
Terregles P3, UK	86	P	56	23	10	-	-	Permian sandstone	Buckley, 2000
Moffat Trial, UK	104	P	48	30	7	5	5	Permian breccia	Buckley, 2000
Moffat SS1, UK	63	P	21	8	8	-	-	Permian breccia	Buckley, 2000
Moffat SS2, UK	96	P	33	31	20	-	-	Permian breccia	Buckley, 2000
Arran 1C, UK	140	P	18	15	15	13	7	Triassic sandstone	Buckley, 2000

* test type: P = pumping at the tested well; N = no pumping during the test; D = no pumping, flow from well during air-rotary drilling; PA = pumping in adjacent well; AO = artestian flow in tested well; AA = artesian overflow in adjacent well

Table S3 (continued) Crystalline rocks

Well	Logged depth	Test type*	Percentage of flow per fracture 1	2	3	4	5	Lithology	Reference
H7 Oracle, AZ, USA	33	PA	100	-	-	-	-	granite	Paillet et al., 1987
WRA4, Manitoba, Canada	80	N	50	34	16	-	-	granite	Paillet, 1989
URL14, Manitoba, Canada	350	P	70	30	-	-	-	granite	Paillet, 1989
URL15, Manitoba, Canada	350	P	100	-	-	-	-	granite	Paillet, 1989
Siblingen, Switzerland	1031	P	54	25	12	1	1	granite	Paillet et al., 1990
HA, Ashford, CT, USA	27	P	100	-	-	-	-	gneiss, schist	Paillet et al., 1992
WO, Ashford, CT, USA	55	P	100	-	-	-	-	gneiss, schist	Paillet et al., 1992
WI, Ashford, CT, USA	36	P	67	33	-	-	-	gneiss, schist	Paillet et al., 1992
CZ, Ashford, CT, USA	37	P	53	37	10		-	gneiss, schist	Paillet et al., 1992
XM, Ashford, CT, USA	79	P	54	46	-	-	-	gneiss, schist	Paillet et al., 1992
RQ6, Raymond, CA, USA	68	PA	80	10	10	-	-	granite	Paillet and Duncanson, 1994
KR-2, Millville, MA, USA	111	N	35	31	19	15	-	gneiss, amphibolite	Paillet and Ollila, 1994
KR-3, Millville, MA, USA	137	N	59	41	-	-	-	gneiss, amphibolite	Paillet and Ollila, 1994
KR-15A, Millville, MA, USA	140	P	48	35	16	-	-	gneiss, amphibolite	Paillet and Ollila, 1994
KR-29, Millville, MA, USA	76	N	50	28	22	-	-	gneiss, amphibolite	Paillet and Ollila, 1994
KR-30, Millville, MA, USA	42	P	100	-	-	-	-	gneiss, amphibolite	Paillet and Ollila, 1994
KR-508, Millville, MA, USA	87	P	61	39	-	-	-	gneiss, amphibolite	Paillet and Ollila, 1994
Calaveras, CA, USA	50	P	84	8	4	3	1	metamorphic	Paillet, 1995
CO-1, Mirror Lake, NH, USA	41	P	100	-	-	-	-	granite, schist	Paillet, 1995
CO-2, Mirror Lake, NH, USA	41	PA	40	27	16	16	-	granite, schist	Paillet, 1995
CO-3, Mirror Lake, NH, USA	41	PA	52	44	4	-	-	granite, schist	Paillet, 1995
CO-4, Mirror Lake, NH, USA	41	PA	68	27	5	-	-	granite, schist	Paillet, 1995
FSE-5, Mirror Lake, NH, USA	30	PA	30	49	32	19	-	granite, schist	Paillet, 1993
FSE-6, Mirror Lake, NH, USA	48	P	51	25	22	2	-	granite, schist	Paillet, 1998
FSE-8, Mirror Lake, NH, USA	53	P	85	15	-	-	-	granite, schist	Paillet, 1998
North Carolina, USA	95	P	37	28	22	13	-	granite	Paillet, 2004
F28, Brittany, France	62	P	49	35	8	8	-	granite, mica schist	Le Borge et al., 2006

* test type: P = pumping at the tested well; N = no pumping during the test; D = no pumping, flow from well during air-rotary drilling; PA = pumping in adjacent well; AO = artestian flow in tested well; AA = artesian overflow in adjacent well

Table S3 (continued) Fine-grained siliciclastic sedimentary rocks

Well	**Logged depth**	**Test type***	**Percentage of flow per fracture**					**Lithology**	**Reference**
			1	**2**	**3**	**4**	**5**		
LS6, Plynlimon, UK	38	P	80	15	5	-	-	Silurian mudstone	Neal et al., 1997
VB3, Plynlimon, UK	41	P	48	20	17	10	5	Silurian mudstone	Neal et al., 1997
MW25, Raritan, NJ, USA	81	D	40	31	8	8	7	Triassic-Jurassic siltstone shale, sandstone	Michalski and Britton, 1997
1, Hopewell, NJ, USA	42	P	40	18	11	6	4	Triassic-Jurassic siltstone, shale, sandstone	Morin et al., 1997
3, Hopewell, NJ, USA	43	P	44	20	14	5	4	Triassic-Jurassic siltstone, shale, sandstone	Morin et al., 1997
4, Hopewell, NJ, USA	38	P	41	40	2	-	-	Triassic-Jurassic siltstone, shale, sandstone	Morin et al., 1997
10, Hopewell, NJ, USA	45	P	36	12	9	6	-	Triassic-Jurassic siltstone, shale, sandstone	Morin et al., 1997
164, Lansdale, PA, USA	110	P	36	28	12	12	6	Triassic-Jurassic siltstone, shale, sandstone	Morin et al., 2000
618, Lansdale, PA, USA	189	P	44	39	6	4	3	Triassic-Jurassic siltstone, shale, sandstone	Morin et al., 2000
64, Lansdale, PA, USA	315	P	32	17	17	16	10	Triassic-Jurassic siltstone, shale, sandstone	Morin et al., 2000
TA5, Plynlimon , UK	38	P	52	19	13	8	8	Ordovician mudstone	Buckley, 2000
65, Watervliet, NY, USA	43	P	43	31	24	1	1	Ordovician shale	Williams and Paillet, 2002
68, Watervliet, NY, USA	18	P	66	34	-	-	-	Ordovician shale	Williams and Paillet, 2002
71, Watervliet, NY, USA	29	P	80	20	-	-	-	Ordovician shale	Williams and Paillet, 2002
65, Watervliet, NY, USA	35	P	89	11	-	-	-	Ordovician shale	Williams and Paillet, 2002

* test type: P = pumping at the tested well; N = no pumping during the test; D = no pumping, flow from well during air-rotary drilling; PA = pumping in adjacent well; AO = artestian flow in tested well; AA = artesian overflow in adjacent well

Table S3 (continued)
Wells where flowmeter results indicate substantial intergranular flow or zones with multiple fractures, vugs, or channels

Well	**Logged depth**	**Test type***	**Percentage of flow per fracture**					**Lithology**	**Reference**
			1	**2**	**3**	**4**	**5**		
JPG-1, IN, USA	48	P	all inflow from vuggy zone 4 -7 m thick in dolomite bed or from minor bedding planes					Silurian dolostone	Wilson et al., 2001
JPG-2, IN, USA	48	P							
JPG-5, IN, USA	49	P							
dolostone, Kuwait	170	N	About 50% from intergranular flow and 50% from fractures					dolostone	Paillet, 2004
M03, Poitiers, France	80	P	Most flow is on networks of karst channels in three stratigraphic zones up to 10 m thick. Some flow is from productive fractures.					Jurassic limestone	Audouin et al., 2008 Chatelier et al., 2011
M07, Poitiers, France	65	P							
M21, Poitiers, France	65	P							
M22, Poitiers, France	80	P/PA							
P1, Poitiers, France	85	P							
MP7, Poitiers, France	75	P/PA							
M5, Poitiers, France	75	P/PA							
M20, Poitiers, France	75	PA							
Benningholme, Yorkshire, UK	63	P	Flow from combination of individual fractures and zones with multiple fractures					Cretaceous chalk	Parker et al., 2010
North End, Yorkshire, UK	16	P						Cretaceous chalk	Parker et al., 2010
Carnaby, Yorkshire, UK	86	P						Cretaceous chalk	Parker et al., 2010
IW512, WI, USA	200	AO/N	intergranular flow in Cambrian sandstone is about 50% of flow. Remainder of flow from fractures					Cambrian-Ordovician sandstone, siltstone, dolostone	Leaf et al., 2012
Savage, MN, USA	49	P/N	82-100% from intergranular flow					Cambrian sandstone	Paillet et al., 2000
H2, Oracle, AZ, USA	85	PA	flow from multiple fractures					granite	Paillet et al., 1987
H6, Oracle, AZ, USA	65	PA	flow from multiple fractures					granite	Paillet et al., 1987

* test type: P = pumping at the tested well; N = no pumping during the test; D = no pumping, flow from well during air-rotary drilling; PA = pumping in adjacent well; AO = artestian flow in tested well; AA = artesian overflow in adjacent well

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STATE OF TENNESSEE
DEPARTMENT OF ENVIRONMENT AND CONSERVATION
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May 16, 2016

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Dear Mr. Japp

TDEC Comment Letter
Remedial Investigation/Feasibility Study for Comprehensive Environmental Response, Compensation, and Liability Act Oak Ridge Reservation Waste Disposal, Oak Ridge, TN
DOE/OR/01-2535&D4
March 2016

The Tennessee Department of Environment and Conservation (TDEC), Division of Remediation has reviewed the above referenced document pursuant to the Federal Facility Agreement (FFA) for the Oak Ridge Reservation (ORR). Based on that review, significant issues remain to be resolved. Some of the issues of greatest concern are summarized below. A complete list of comments with more specific detail is attached. Given these concerns, TDEC cannot approve the D4 RI/FS at this time and places the document in informal dispute.

At this juncture, TDEC sees no benefit in Department of Energy (DOE) submitting a proposed plan for Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) waste disposal prior to agreement of FFA parties on the associated issues. Given that remedial operations at ORR will continue into the foreseeable future, TDEC recommends DOE increase its waste minimization and segregation efforts in order to conserve capacity at the existing CERCLA disposal facility, the Environmental Management Waste Management Facility (EMWMF).

Summary of Concerns

1. Lack of consensus regarding which laws are applicable and/or relevant and appropriate (ARARs)
   Previously DOE has contended that TDEC 0400-20-11, *Licensing Requirements for Land Disposal of Radioactive Waste* were not ARARs. DOE's position has shifted to allow these rules as ARARs, with the exception of 0400-20-11-.17(1)(h), which states that the hydrologic

unit used for disposal shall not discharge ground water to the surface within the disposal site. TDEC believes this rule is appropriate and should be an ARAR.

2. Site characteristics

   The candidate sites being considered in this version of RI/FS require the use of an underdrain to suppress groundwater. Underdrains are engineered pathways for future release of hazardous substances, pollutants, and contaminants from the landfill. TDEC's position is that unless and until an acceptable evaluation is performed that demonstrates that an underdrain, releasing water and potentially leachate from under the EMDF, will be protective of human health and environment over the long-term, a design with an underdrain that would produce flowing water once the liner had been fully constructed is unacceptable.

   As TDEC commented on 8/6/15, releases and future releases from all sources into Bear Creek Valley, including EMDF, EMWMF, and the Bear Creek Burial Grounds should be evaluated together for cumulative impact.

3. Weaknesses in the model used as the basis for assessment of risk and preliminary Waste Acceptance Criteria (PreWAC)

   Although the risk assessment has been somewhat improved, the methodology has changed little through the various CERCLA documents that have been provided. The models remain too limited to predict accurate travel times for water or contaminants. It still includes just one scenario, three pathways, and addresses water resource protection ARARs for a finite time only – 1,000 years.

   The draft whitepaper DOE presented concerning the Low-level Waste Disposal Facility Federal Review Group (LFRG) and RI/FS coordination allows the RI/FS to serve as the technical basis for the preliminary disposal authorization statement (DAS) in place of performance assessment and/or composite analysis. There remains a lack of consensus on model input parameters in the RI/FS, some of which affect timing and magnitude of release. It is TDEC's position that DOE perform performance assessment and composite analysis pursuant to DOE orders without influence from the RI/FS. Therefore, TDEC's position remains that an approved preliminary DAS is needed prior to RI/FS approval.

   Given the importance of waste acceptance limits to protect human health and the environment, there remains a need to address outstanding programmatic issues with WAC attainment. For example, the WAC should be easy to audit; and responsible parties for WAC attainment and operation of the landfill should be independent from the demolition contractor.

4. PreWAC limits call cost justification into question

   It appears that the proposed EMDF PreWAC limits for uranium (52 mg/kg) and technetium 99 (45 pCi/g) may be protective of human health and the environment. However the majority of waste currently disposed in EMWMF would not be accepted at EMDF, given those limits. This calls into question the volume of waste that can be accepted for disposal at EMDF; and subsequently the cost justification for a project of this magnitude.

5. Mercury

   TDEC continues to have concerns regarding mercury disposal in the proposed landfill. Since mercury does not degrade over time and bio-accumulates in aquatic species, it presents a long term hazard. TDEC expects a full evaluation of mercury treatment and disposal options with the FFA parties before mercury waste is introduced to EMDF.

6. CERCLA Risk Range and ARARs for CERCLA waste in the EMDF.

   The RI/FS recognizes ARARs for the 1000 year compliance period and the CERCLA carcinogenic risk range for constituents that are modeled in the RI/FS to peak within 2000 years. It is TDEC's position that the CERCLA carcinogenic risk range, CERCLA protection for non-carcinogenic health threats, CERCLA protection of the environment, and ARARs apply for as long as CERCLA waste remains onsite in the EMDF.

Questions or comments regarding the contents of this letter should be directed to Howard Crabtree at the above address or by phone at (865) 220-6571.

Sincerely

Randy Young
FFA Manager

Enclosure

xc Shari Meghreblian, TDEC
Patricia Halsey, DOE
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Tennessee Department of Environment and Conservation Comments on: *Remedial Investigation/Feasibility Study for Comprehensive Environmental Response, Compensation, and Liability Act Oak Ridge Reservation Waste Disposal Oak Ridge, Tennessee Operations Plan, Oak Ridge, Tennessee* (DOE/OR/01-2535&D4)

Background

In *Remedial Investigation/Feasibility Study* [RI/FS] *for Comprehensive Environmental Response, Compensation, and Liability Act* [CERCLA] *Oak Ridge Reservation* [ORR] *Waste Disposal, Oak Ridge, Tennessee* (DOE/OR/01-2535&D1), the Department of Energy (DOE) proposed a second on-site waste disposal facility for the disposal of CERCLA waste on the ORR. As proposed, the Environmental Management Disposal Facility (EMDF) would primarily be a Low Level Radioactive Waste (LLRW) Disposal Facility, but also authorized under CERCLA to dispose of hazardous and chemical wastes regulated under the Resource Conservation and Recovery Act (RCRA) and the Toxic Substances Control Act (TSCA). The Tennessee Department of Environment and Conservation (TDEC) and the U.S. Environmental Protection Agency (EPA) submitted comments on the D1 RI/FS in early 2013 that were not resolved in the D2 revision and that document was elevated to informal dispute. By agreement of parties to the Federal Facility Agreement (FFA), a D3 RI/FS (to be treated as D2) was to be submitted by DOE addressing associated issues.

TDEC received the D3 RI/FS on April 2, 2015. However, major issues identified in comments on the previous versions of the document and discussed in subsequent technical sessions remained unresolved. Contrary to the previous versions of the RI/FS, DOE took the position in the D3 RI/FS that state regulations governing the disposal of LLRW (TDEC 0400-20-11) were not relevant and appropriate to the disposal of DOE radioactive wastes; therefore, the state rules should not be considered Applicable or Relevant and Appropriate Requirements (ARARs) for the proposed facility. It was also DOE's position that DOE Orders regulating LLRW should not be cited as requirements or to be considered guidance (TBC) in Records of Decision and other CERCLA agreements. As a consequence, TDEC rules regulating LLRW were removed as ARARS from the D3 RI/FS, as were DOE Orders listed as TBC. DOE also proposed that TDEC and EPA waive provisions of 40 CFR 268 to allow treatment of mercury contaminated demolition debris within the EMDF disposal cells.

TDEC comments on the D3 RI/FS were submitted to DOE on August 6, 2015. The D4 revision of the document was received by TDEC March 17, 2016 and TDEC comments on the document submitted to DOE on 05/16/2016.

General Comments

1. The D4 version of the RI/FS was significantly modified from the D3 version in response to regulatory concerns. The changes provide partial resolution to several issues that have prevented TDEC approval of previous drafts. The inclusion of additional ARARs, particularly those specific to radioactive waste management, has strengthened the legal foundation for

authorization of the disposal facility. Additional alternatives were added, including disposal facilities at on-site locations thought to potentially be more compatible with State of Tennessee criteria for siting radioactive waste disposal facilities. An alternative that incorporated more aggressive volume reduction strategies and more off-site disposal was evaluated.

Changes to risk assessment methodology were relatively few but had significant consequences for certain important contaminants of concern. The establishment of waste acceptance limits at any on-site disposal facility that would be protective of water resources has been a consistent and significant regulatory concern. While the risk assessment methodology may still not properly address contaminants of concern for which travel time to the receiving stream or aquifer is critical to the risk evaluations, the risk assessment for contaminants that will be limited predominantly by release mechanisms at the source and dilution in the receiving waters has been significantly strengthened. The waste acceptance limits that would be imposed by the PreWAC given on page 77 and on pages 81-83 of Appendix H for relatively mobile contaminants that are assumed to undergo little radioactive decay or reaction throughout the compliance period are arguably within a range that would protect water resources.

2. The last paragraph of page ES-4 of the D4 version of the RI/FS states "Based on these results, it can be concluded that most future CERCLA waste to be generated after EMWMF reaches maximum capacity would be able to be disposed at the proposed EMDF." This conclusion is repeated in slightly different but equivalent form throughout the document, including on page 1-8, in section 2.1.3 on page 2-5, in section 2.3, and in Appendix H. However, there is little evidence to back up this assertion in the document.

To the extent that time and resources have been available, TDEC has been able to verify that PreWAC limits for uranium and technetium presented in this RI/FS may fall within a reasonable range of waste acceptance limits that should protect health and environment from risks generated by a 2.2 million cubic yard radioactive waste disposal facility sited in Bear Creek Valley. Based on our current knowledge of contamination levels in future CERCLA waste, the limits suggested by the PreWAC would also preclude much of the projected CERCLA waste from the on-site disposal facility. At EMWMF, waste acceptance has been largely controlled by the levels of uranium and technetium isotopes in the waste. The majority of the waste disposed at EMWMF could not have been accepted under limits similar to those proposed in this PreWAC, 52 mg/kg for uranium and 45 pCi/g for technetium 99.

If the claim that the PreWAC demonstrates that majority of CERCLA generated waste can be disposed safely on-site should prove valid, then it follows that much of the CERCLA waste could also meet disposal limits established for the permitted Y-12 landfill or other permitted solid waste disposal facilities. This can be inferred from a comparison between the waste acceptance limits at the Y-12 permitted landfill and the PreWAC for the proposed facility.

The limits imposed on any waste contaminated with depleted uranium (U 234 and U235 below the naturally occurring isotopic abundance) would be more stringent at the proposed facility than at the Y-12 landfill. The technetium 99 limit at the Y-12 landfill is only 5 pico-Curies per gram higher at the proposed facility than at the Y-12 landfill. Much of the projected waste from Y-12, including debris from buildings in the West End Mercury Area, is likely to be contaminated with depleted uranium. Birchfield and Albrecht (2012) report uranium concentrations at the 90 percent upper confidence level for Alpha 5 building structure at approximately 500 mg/kg, an order of magnitude greater than the PreWAC for uranium.

As stated on page G-12 (Appendix G, 4.1.1) of the RI/FS, PCB wastes with a PCB concentration greater than 50 ppm are not anticipated to contribute significantly to the quantity of CERCLA waste generated on the Oak Ridge Reservation. Page 2-4 states that RCRA F listed waste will not be disposed in the proposed CERCLA landfill, and characteristic waste must comply with the treatment standards of 40 CFR 268. Most RCRA and TSCA mixed waste, as well as low level radioactive waste which could be disposed in a future CERCLA disposal facility with PreWAC limits similar to those given in Appendix H, could be disposed in the ORR landfills.

This significant inconsistency between the numbers generated by risk assessment and the conclusions in the text effectively invalidates any cost comparison between the various alternatives set forth in the document. The limits on uranium and technetium, which generally match TDEC's attempts thus far to assess risks imposed by on-site disposal, show that rather severe limitations on waste acceptance will be necessary to ensure protection of human health and the environment at a radioactive waste disposal facility of this size and at these locations. Despite significant changes that address a number of regulator concerns, the D4 version of this document still fails to provide a sufficiently thorough risk assessment and enough additional information on candidate waste streams to form the basis for an informed decision concerning the value added by the proposed disposal facility to the overall remediation goals for the Oak Ridge Reservation.

3. CERCLA Section 121(d)(1) requires that "*Remedial actions selected under this section or otherwise required or agreed to by the President under this Act shall attain a degree of cleanup of hazardous substances, pollutants, and contaminants released into the environment and control of further release at a minimum which assures protection of human health and the environment. Such remedial actions shall be relevant and appropriate under the circumstances presented by the release or threatened release of such substance, pollutant, or contaminant.*"

TDEC D3 RI/FS comment TDEC.S.099 in the *CERCLA D3 RI/FS Comment and Response Summary* identified concerns with risk posed from an underdrain. TDEC's comment stated that the proposed EBCV site underdrains, like the underdrain at the EMWMF, would presumably be able to supply several gallons per minute of water continuously even during drought conditions, and might be a usable water supply even when individual wells were dry. The D4

RI/FS did not identify the underdrain as a potential exposure pathway in either Appendix H Section 2.2 *Conceptual Model and Exposure Pathways* or Section 2.3 *Hypothetical Receptor*. Further, potential risk posed by an underdrain was neither quantified in the D4 RI/FS nor used in PreWAC development.

Underdrains are engineered pathways for future release of hazardous substances, pollutants, and contaminants from the landfill. Over time, the underdrains would contain constituents released from the landfill directly overlying the underdrain, as well as from other areas of the landfill where constituents are released to groundwater and the contaminated groundwater subsequently discharges to an underdrain.

Page 7-51 of the RI/FS also states that while underdrain networks are necessary and effective in isolating wastes from the underlying saturated zone, they do provide avenues for localized and relatively rapid transport of contaminants in groundwater that could be released below the footprint and discharge at underdrain outfall locations. Figure H-16 shows the underdrain may have concentrations in the range of 0.1 to 0.9 of the leaching source in areas where underdrains may discharge to surface near the edge of the landfill. Once again, an underdrain that would presumably be able to supply several gallons per minute of water continuously even during drought conditions might be a usable water supply. Further, with the low flow in Bear Creek in the vicinity of the EBCV site, it is conceivable that a future farmer could impound flow from an underdrain to develop a farm pond for livestock watering or irrigation. Fish are common in farm ponds and risk from consuming fish from an underdrain fed farm pond was not evaluated.

Underdrains provide a direct conduit to surface water with potentially minimal sorption or other attenuation of constituents. Bear Creek is classified for recreational use, and impact on surface water resources including consumption of fish from Bear Creek was not evaluated.

These exposure pathways associated with a flowing underdrain should be added to the maximally exposed individual (MEI) evaluation to verify whether a site with a flowing underdrain meets the CERCLA Section 121(d)(1) threshold requirement for control of further release at a minimum which assures protection of human health and the environment. Further, these exposure pathways should be added to waste acceptance criteria (WAC) development to assure future waste disposed does not pose an unacceptable risk due to a flowing underdrain.

TDEC's position is that unless and until an acceptable evaluation is performed that demonstrates that an underdrain, releasing water and potentially leachate from under the EMDF, will be protective of human health and environment over the long-term, a design with an underdrain that would produce flowing water once the liner had been fully constructed is unacceptable.

4. TDEC believes that compliance with siting criteria and developing a WAC protective of human health and environment are necessary for long term protection of human health and the environment.

Page 7-19, Section 7.2.2.3 Long-term Effectiveness and Permanence (On-site), Engineering and Institutional Controls, second paragraph states the leachate collection system and removal system above the primary liner and the leak detection and removal system below the primary liner would be effective for the period of active institutional controls. The period of active institutional controls is not known, but is assumed for design purposes to extend for at least 100 years. Subsequently, the final cover system, secondary liner, and geologic buffer would provide long-term control of leachate release since these engineered features would last minimally for 500 years.

Page 7-31 Cost discusses a "Perpetual Care Trust Fund" and states said fund is intended to cover certain costs for 1,000 years following closure of the landfill.

Page 7-51, Section 7.3.3 states "Off-site disposal of waste at Energy Solutions, WCS, and NNSS in the long-term may be more reliable at preventing exposure than on-site disposal at the ORR, as they are located in arid environments that reduce the likelihood of contaminant migration or exposure via groundwater or surface water pathways. Fewer receptors exist in the vicinity of Energy Solutions, WCS, and NNSS than on the ORR." **Page 7-51 also states that while underdrain networks are necessary and effective in isolating wastes from the underlying saturated zone, they do provide avenues for localized and relatively rapid transport of contaminants in groundwater that could be released below the footprint and discharge at underdrain outfall locations.**

Page 7-52 states that "The extent of the underdrain networks vary among the proposed sites. Assuming some degree of greater mobility is associated with the areal extent of the underdrain, the Hybrid Site 6 has the least underdrain network area (27,000 ft^2) and the EBCV Site has the most area (297,000 ft^2) with the Dual Site 7a/6b Option (132,000 ft^2) and the WBCV Site (259,000 ft^2) of intermediate area." Page 7-52 goes on to state that "while the cover system remains in place, migration of contaminants into groundwater and surface water is the only credible pathway of exposure," implying uncertainty as to whether and how long the cover system will remain in place.

5. TDEC does not agree that the risk assessment presented in Appendix H provides reasonable assurance that the proposed facility will be protective of human health and the environment, a threshold criterion for actions authorized under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). The risk assessment in this RI/FS is based on the same general approach and the same set of software packages used for modeling risk at the EMWMF nearly two decades ago. TDEC has made numerous comments, both written and verbal, expressing both lack of confidence in the approach to risk assessment and concerns with the applicability of the models over the past five years. However, the methodology has changed little through the various documents that have been written to initiate the process to authorize a new disposal facility for radioactive, hazardous and toxic waste.

As DOE has not suitably addressed these comments, some of which were first given informally to DOE in 2012 after the submission of the Focused Feasibility Study for Comprehensive Environmental Response, Compensation, and Liability Act Oak Ridge Reservation Waste Disposal, Oak Ridge, Tennessee (DOE/OR/01-2535&D0), it will be incumbent upon TDEC to ensure that independent verification of the risk assessment is performed and to confirm that CERCLA waste can be compliantly and cost effectively disposed on the Oak Ridge Reservation. Whether this is carried out by a group chosen by the FFA parties, an independent contractor answering directly to TDEC, or TDEC staff, this will require independent re-calculation of the PreWAC using a substantially different approach to that used in this and in the previous versions of this RI/FS.

Proper verification of the risk assessment will require that sufficient scenarios and pathways be evaluated to substantiate that the threshold criteria of CERCLA can be met while allowing acceptance of sufficient candidate waste to render the proposed facility viable. Some of the additional scenarios and exposure pathways that should be considered, at least at the screening level, include:

- Ecological and recreational risks in Bear Creek due to bioaccumulative hazardous substances, including radionuclides
- Radon flux through the facility cap to demonstrate compliance with 40 CFR 61.192, listed as an applicable requirement in Appendix G
- Air dispersion modeling to demonstrate compliance with 40 CFR 61.92, listed as an applicable requirement in Appendix G
- Direct exposure pathways

For exposure pathways where multiple sources may impact a receptor, such as radionuclide emissions to ambient air or recreational use of Bear Creek below BCK 9.2, cumulative risk from EMWMF and any proposed disposal facility should be evaluated.

A resident farmer scenario similar to that reported in this RI/FS, along with the remedial action objectives that require compliance with maximum contaminant limits (MCLs) in groundwater and ambient water quality criteria (AWQC) in surface water, could be used to ensure protection of water resources. However, other methods would need to be used to predict many key components of contaminant fate and transport. The software used in this RI/FS, with reasonable assumptions for key parameters, might yield a credible hydrologic balance, including estimates of release rates from the proposed facility and dilution factors in groundwater and in Bear Creek. Unfortunately, the models are too limited to predict accurate travel times for water or contaminants.

The HELP model cannot account for the effect of a sloping landfill base, which will lead to ponding and a distribution of travel times through even a uniform liner. The flow field through the liner would not be uniform even if the water pooled above it were of uniform depth, since flow through the geomembrane is controlled by orifice flow through discrete holes or tears, usually with an equivalent radius not greater than a few millimeters (Rowe, 2012). Several studies, including that of Giroud and Bonaparte (1989), showed that the greatest hydraulic resistance to leakage through composite liners is generally at the interface between the geomembrane and underlying clay liner. Until the geomembrane deteriorates considerably, which, as noted in the RI/FS, may take decades or even centuries, leakage rates depend primarily on such unpredictable variables as the care taken to prevent holes and wrinkles during installation of the barrier (Rowe, 2012).

As TDEC has expressed on numerous occasions, deterministic prediction of contaminant travel times in fractured media on the ORR, such as the bedrock in Bear Creek Valley, and, to a lesser extent, the saprolite and weathered residuum, does not seem viable. Tracing results in the bedrock and residuum of the Conasauga group yield travel times that are highly variable and clearly dependent on the specific location and design of the test (c.f. Spalding, 1987). A realistic prediction of travel times for contaminants is probably not feasible, and estimating travel times using consistently conservative assumptions may limit waste acceptance unnecessarily, perhaps to the point of indicating that the facility is not cost effective. It would seem that a stochastic approach to contaminant fate and transport prediction might provide a better basis for risk assessment.

6. As stated in General Comment 2, Uranium risk-based PreWAC values may be limiting factors as to what may be placed in a future EMDF. Please see the table below.

Isotope	**Non-carcinogenic Table H-12 (Page H-81) HI=3 (mg/kg)**	**Carcinogenic Calculated 10^{-4} ELCR (pCi/g)**
U-233	60.5	57
U-234	57.6	55.1
U-235	52.2	50.7
U-236	52.3	53.1
U-238	52.2	55.2

PreWAC carcinogenic limits for Uranium-238 calculated using the risk-based approach included in the D4 RI/FS and a 10^{-4} ELCR will be on the order of 50 to 60 pCi/g. Table H-12 includes a non-carcinogenic PreWAC for uranium-238 of 52.2 mg/kg. The amount of future waste that meets uranium risk-based PreWAC limits should be evaluated to refine estimates of additional onsite landfill capacity needed. Risk based limits used for this evaluation must be consistent with CERCLA required carcinogenic risk range (i.e. 10^{-4} to 10^{-6}) and non-carcinogenic (e.g. HI of 1 to 3) risk.

7. The waste volume estimates in Chapter 2 and Appendix A include both wastes that may be suitable for disposal at the Y-12 industrial and construction and demolition landfills (ORR landfills), as discussed on pages 1 and 2 of Chapter 6, and an added 25 percent of the projected waste volume to account for uncertainty. Inclusion of landfill waste into the overall waste inventory inflates the quantity of waste requiring disposal in a CERCLA facility by an undetermined amount, as well as the differential cost between the on-site and off-site alternatives. The U.S. Department of Energy Office of Inspector General performed an audit in 2013 that identified 140,000 cubic yards of material disposed in EMWMF that could have been disposed at the ORR landfills.

Based on the candidate waste streams listed in Appendix A, TDEC might expect between 25 and 40 percent of the waste to be acceptable at the ORR landfills, depending on the level of waste segregation used. No characterization data is available to better define this range, which we acknowledge to be not much better than a guess. An effort to better estimate the probable quantity of waste suitable for disposal in the ORR landfills should have been made, identified separately in Appendix A, and subtracted from the total volume needed for disposal of waste in a CERCLA landfill.

In the past, DOE has indicated that radioactive waste disposal under the authority of the Atomic Energy Act as implemented by DOE Orders was impractical due to the anticipated quantities of mixed low level radioactive and TSCA or RCRA waste. As stated elsewhere in these comments, the D4 version of the RI/FS states that DOE has no plans to dispose of significant quantities of either TSCA waste (> 50 ppm PCBs) or hazardous waste that exhibits a prohibited characteristic at the point of land disposal. In this case, additional on-site disposal alternatives might include disposal under DOE authority rather than through CERCLA. Also, since risk assessment of on-site disposal in the D4 indicates that some key contaminants of concern may have waste acceptance limits similar to those on the ORR landfill, an expansion of current permitted solid waste disposal capacity might prove to be just as feasible as disposal authorized under CERCLA.

8. The Remedial Action Objectives (RAOs) on page 4-1 and *goals* used to determine PreWAC concentrations on page 4-2 are inconsistent. RAOs on page 4-1 appear applicable as long as CERCLA waste is managed, disposed or entombed at the landfill and do not include a time limit. However, page 4-2 *goals* include a 1,000 year compliance period. Additional discussion of water resource protection on page H-75 references the goal language, not the RAOs, and implies that water resource protection is only accomplished within the 1,000 year compliance period. Similarly, the response to TDEC comment TDEC.S.100 references protection of water resources and ecological receptors within the 1,000 year compliance period, implying that protection of water quality and the environment after 1,000 years is not necessary. TDEC reads the RAOs on page 4-1 to include protection of water resources as long as CERCLA waste is in the landfill, a time period which presumably extends beyond 1,000 years. Remedial Action Objectives need to be consistent and consistently applied.

9. Disregarding the Remedial Action Objectives, the risk methodology specified in the RI/FS, and the CERCLA 10^{-4} to 10^{-6} risk range in proposing carcinogenic PreWAC limits for radionuclides is unacceptable.

   The Remedial Action Objectives (RAOs) specify:

   > **<u>Page 4-1:</u>** "*1. Prevent exposure of human receptors to CERCLA waste (or contaminants released from the waste into the environment) that exceeds a human health risk of 10^{-4} to 10^{-6} Excess Lifetime Cancer Risk (ELCR) or hazard Index of 1.*"
   >
   > **<u>Page 4-2:</u>** "*These PreWAC waste concentration limits are determined based on demonstrating the following goals are met during the 1,000 year compliance period:10^{-5} ELCR and HI of 1 ... for the compliance period (to 1,000 years) using a resident farmer scenario, and 10^{-4} ELCR and HI of 3 at times exceeding 1,000 year compliance period.*"
   >
   > However, on **<u>Page H-75:</u>** "*A ratio is set up to scale this assumed concentration and corresponding risk to the appropriate carcinogenic risk goal (set as 10^{-5} for contaminants that peak <1,000 years post closure, and as 10^{-4} for those COPCs predicted to peak between 1,000 and 2,000 years, see Table H-1), which allows calculation of the PreWAC limit for each radionuclide COPC. For radioisotopes predicted to peak after 2,000-years post closure, preliminary administrative limits based on modeling exposures at 100 m have been assigned...*"
   >
   > The methodology to <u>assign</u> PreWAC limits in the D4 RI/FS is a significant change from the D3 version. The D3 version calculated the PreWAC for carcinogenic radionuclides based on formulas in the RI/FS for all constituents that peak after 1,000 years utilizing a 10^{-4} ELCR, similar to the approach the D4 utilizes for the time period 1,000 to 2,000 after closure. The D4 RI/FS disregards Remedial Action Objectives and the CERCLA 10^{-4} to 10^{-6} risk range for constituents that, according to the D4 RI/FS, peak after 2,000 years. There are no analyses that demonstrate risk is within the CERCLA risk range where preliminary administrative limits are assigned for constituents that peak after 2,000 years.
   >
   > For example, using the equations and approach specified in the D4 RI/FS, a carcinogenic PreWAC on the order of 55 pCi/g may be calculated for U-238 utilizing a 10^{-4} ELCR. The D4 RI/FS includes 3,170 (3.17E+03) pCi/g as the carcinogenic PreWAC limit for U-238 in Table H-10 (not an Adjusted PreWAC). Table H-10 includes no reference to preliminary administrative limits. A value of 3,170 pCi/g equates to about a 5.75E-03 (5.75 per thousand) ELCR. PreWAC limits for only four carcinogenic radionuclides (i.e. C 14, Cl-36, H-3, and Tc-99), highlighted in bold in the table below, were determined by the risk-based methodology specified in the D4 RI/FS. PreWAC limits for the remaining 28 carcinogenic radionuclides (i.e. Am-241, Am-243, Cf-249, Cf-251, Cm-245, Cm-246, Cm-247, Cm-248, I-129, K-40, Nb-94, Ni-59, Np-237, Pa-231, Pu-239, Pu-240, Pu-242, Pu-244, Re-187, Se-79, Si-32, Sn-126, U-233, U-234, U-235, U-236, U-238, and Zr-93) are

> presumably set using preliminary administrative limits. The process and rationale for modifying each carcinogenic radionuclide PreWAC with the administrative limit is not transparent and is not discussed in Appendix H. Risks for these 28 radionuclide PreWAC limits (modified by the administrative limits) range from approximately 2.6E-02 (2.6 per hundred) to 9.8E-04 (9.8 per ten thousand) ELCR, based on the limited resident farmer scenario.

The table below estimates risk-based PreWAC concentrations for radionuclide carcinogenic risk and compares the risk numbers to the D4 RI/FS PreWAC Table H-10 and Table H-13 limits. The calculated ELCR for the D4 Proposed EMDF PreWAC limits are also included.

Table 1

Radionuclide	**Appendix H, Attachment B, Table 1: PR_{eff}**	**Target Risk Level using D4 proposed methodology**	**Calculated PreWAC (pCi/g) Based on Target Risk Level**	**Proposed Carcinogenic EMDF PreWAC Table H-13 (page H-91)**	**Calculated ELCR of D4 Proposed EMDF Carcinogenic PreWAC Limit**
Am-241	9.031E-13	1.00E-04	6.92E+13	1.46E+15	2.11E-03
Am-243	2.777E-01	1.00E-04	2.25E+02	4.74E+03	2.11E-03
C-14	**9.068E-01**	**1.00E-04**	**6.89E+01**	**6.89E+01**	**1.00E-04**
Cf-249	2.774E-15	1.00E-04	2.25E+16	3.30E+17	1.46E-03
Cf-251	1.281E-06	1.00E-04	4.88E+07	7.21E+08	1.48E-03
Cl-36	**1.793E+00**	**1.00E-05**	**3.49E+00**	**3.49E+00**	**1.00E-05**
Cm-245	3.641E-01	1.00E-04	1.72E+02	3.48E+03	2.03E-03
Cm-246	9.401E-02	1.00E-04	6.65E+02	1.32E+04	1.99E-03
Cm-247	2.194E+00	1.00E-04	2.85E+01	6.05E+02	2.12E-03
Cm-248	9.479E+00	1.00E-04	6.59E+00	1.58E+02	2.40E-03
H-3	**1.643E-19**	**1.00E-05**	**3.80E+19**	**3.80E+19**	**1.00E-05**
I-129	3.173E+01	1.00E-04	1.97E+00	1.10E+02	5.58E-03
K-40	7.358E-01	1.00E-04	8.49E+01	1.37E+04	1.61E-02
Nb-94	1.013E-02	1.00E-04	6.17E+03	1.14E+06	1.85E-02
Ni-59	1.490E-08	1.00E-04	4.19E+09	7.34E+11	1.75E-02
Np-237	1.361E+00	1.00E-04	4.59E+01	1.05E+03	2.29E-03
Pa-231	4.670E-03	1.00E-04	1.34E+04	1.31E+05	9.79E-04
Pu-239	1.476E+00	1.00E-04	4.23E+01	9.27E+02	2.19E-03
Pu-240	2.809E-01	1.00E-04	2.22E+02	4.87E+03	2.19E-03
Pu-242	2.682E+00	1.00E-04	2.33E+01	5.04E+02	2.16E-03
Pu-244	3.179E+00	1.00E-04	1.97E+01	4.78E+02	2.43E-03
Re-187	1.910E-03	1.00E-04	3.27E+04	8.61E+06	2.63E-02

Table 1. Continued

Radionuclide	Appendix H, Attachment B, Table 1: PR_{eff}	Target Risk Level using D4 proposed methodology	Calculated PreWAC (pCi/g) Based on Target Risk Level	Proposed Carcinogenic EMDF PreWAC Table H-13 (page H-91)	Calculated ELCR of D4 Proposed EMDF Carcinogenic PreWAC Limit
Se-79	3.384E-03	1.00E-04	1.85E+04	1.79E+06	9.69E-03
Si-32	6.108E-11	1.00E-04	1.02E+12	2.64E+14	2.58E-02
Sn-126	1.483E-01	1.00E-04	4.21E+02	9.37E+04	2.22E-02
Tc-99	**1.370E+00**	**1.00E-04**	**4.56E+01**	**4.56E+01**	**1.00E-04**
U-233	1.096E+00	1.00E-04	5.70E+01	3.25E+03	5.70E-03
U-234	1.134E+00	1.00E-04	5.51E+01	3.23E+03	5.86E-03
U-235	1.232E+00	1.00E-04	5.07E+01	3.04E+03	5.99E-03
U-236	1.177E+00	1.00E-04	5.31E+01	3.05E+03	5.74E-03
U-238	1.133E+00	1.00E-04	5.52E+01	3.17E+03	5.75E-03
Zr-93	1.879E-02	1.00E-04	3.33E+03	1.32E+05	3.97E-03

10. During Site Management Team (SMT) discussions between the D3 RI/FS and D4 RI/FS, DOE stated that all sites being considered for the possible waste management facility required underdrains. TDEC suggested that DOE evaluate the extent of underdrain(s) needed for each site and whether any site may require only "minimal underdrains." TDEC offered that "minimal underdrain" refers to siting and constructing a landfill facility over small spring(s) or seep(s) that will dry up, due to capping or cutting off the recharge area, so that the resulting facility will not require a continually functioning underdrain once the facility is constructed. It is believed that a minimal underdrain poses a significantly reduced threat compared to an extensive or flowing underdrain.

Both the East Bear Creek Valley (EBCV) site and the West Bear Creek Valley (WBCV) site have groundwater fed creeks flowing through the proposed landfill sites that will require extensive underdrains to convey the water from under proposed future landfills. The D4 RI/FS states (page 6-40) that the EBCV site requires an extensive underdrain system (Figure 6-12). Page 6-41 states that the individual pieces of the WBCV site underdrain system are similar to the EBCV option because the natural drainage ways extend across most of the WBCV site, but fewer areas of underdrain appear to be required than at the EBCV site. The RI/FS also states (page 6-41) that the conceptual underdrain proposed for Site 7a in the Dual Site Option is similar to that for the WBCV site (Figure 6 15).

Based on TDEC review of the RI/FS, Site 6b has the smallest underdrain system and is likely to require only minimal underdrains. The D4 RI/FS (page 6-41) states "Site 6b was selected as the onsite location for the Hybrid Alternative based on a conceptual design that requires the least expansive underdrain system. It is likely that these seeps would not produce any water once the liner had been fully constructed for this site. The locations would no longer have available recharge." (Figure 6-14).

11. TDEC personnel walked the periphery of sites 7a and 7b to evaluate the need for underdrains and potential for minimal underdrains. Based on TDEC observations, it appears possible that either site 7a, 7b, or both sites 7a and 7b may be configured without extensive underdrains. This would require changing the Site 7a conceptual design to avoid the underdrain. Suitability of sites 7a and 7b would need to be verified by site-specific hydrogeologic assessment. We agree with the D4 RI/FS text on page E-181 that states *"new site specific hydrogeological and geotechnical data will be required to establish key relationships between the base cell elevations and the underlying water table and bedrock configuration, as well as other data required for detailed design, modeling, etc."*

12. Calculations for the PreWAC values require clarification and verification. For example, the equation for calculating the peak creek dose (PD'eff) for non-carcinogenic constituents is given on page H-66. Multiple DFcreek and DFwell values are given on pages H-58 and H-64 and it is unclear which dilution factors are used for which calculations. Further, while trying to duplicate the non-carcinogenic PD'eff for uranium in Appendix H, Attachment B, Table 2 and the uranium Adjusted PreWAC in Tables H-12 and H-13, it appeared that a scaled dilution factor for DFcreek may have been used in the D4 RI/FS. This effort was further confused by the acrylonitrile example given on page H-80. The PD'eff for acrylonitrile referenced on page H-80 does not agree with the PD'eff for acrylonitrile in Attachment B, Table 2; utilizing the formula on page H-66 subsequently yielded a third PD'eff value for acrylonitrile. This may be dilution factor uncertainty again. Further, the acrylonitrile example on page H-80 specified dividing by the reference dose and instead of using the reference dose from Attachment A, Table 3-2, the value for the slope factor was used in the example.

13. **<u>Page H-75 of the RI/FS specifies</u>** "...water resource protection is accomplished within the 1,000 year compliance period as specified in the RAOs.......These PreWAC waste concentration limits are determined based on demonstrating the following goals are met during the *1,000 year compliance period*: Appropriate AWQC for chemicals (risk-based discharge levels for radionuclides in Bear Creek and tributary surface water are per the *Integrated Water Management Focused Feasibility Study* [UCOR, 2016].)" (*emphasis added*).

TDEC comments to the *Integrated Water Management Focused Feasibility Study* (UCOR, 2016) are incorporated into these RI/FS comments by reference.

14. The conceptual site model assumes a surface water pathway where a future farmer utilizes surface water at BCK 11.54 for irrigating vegetation and watering livestock. In the D4 RI/FS modeling analysis, one input parameter required for PATHRAE is the river flow rate (the annual flow in Bear Creek). An annual flow of 736,000 cubic meters was input into the PATHRAE model in the D4 RI/FS to calculate the concentration of pollutants in surface water, while an annual flow of 491,000 cubic meters was used in the D3 RI/FS. Use of a total annual flow rate appears to underestimate the risk.

Evaluating streamflow data for BCK 11.54, TDEC calculated average median flows for June 1 through November 30 and December 1 through May 31 as 155 L/minute and 1160 L/minute respectively. Converting median flow in L/minute to total flow in cubic meters yielded an average of 40,845 cubic meters for the period of June 1 through November 30 and 304,012 cubic meters from December 1 through May 31; this results in an average annual cumulative median flow on the order of 344,858 cubic meters.

Similarly, plotting BCK 11.54 on USGS StreamStats[1] shows BCK 11.54 has a drainage area of about 0.6 square miles. Evaluation of DOE flow data for BCK 11.54 shows that, over the five year period analyzed, 37% to 53% (average of 45%) of the total annual flow occurred over a 25 day period each year. The sensitivity analysis table on page H-71 shows there is a linear relationship between stream flow rate and peak concentration – if the flow is reduced in half, the calculated peak stream concentration doubles.

In conclusion, peak stream concentrations reported in the D4 RI/FS are low by about a factor of about 2. Doubling the peak steam concentration will double the peak effective risk for the carcinogenic pathway (see equations on page H-65 and H-66) and will double the peak effective dose for the non-carcinogenic pathway (see equations on page H-66.)

15. Utilizing C'_{Creek} calculated from PATHRAE and the annual river flow rate input into PATHRAE, the peak flux/load per year and peak average flux/load per day to Bear Creek can be calculated. This flux may be used to evaluate EBCV site impact on capture and subsequent consumption of fish downstream of BCK 11.54. For example, utilizing assumptions in PATHRAE for U-238, including a basis of 1 kg/m^3 in the waste, PATHRAE yields a peak concentration in Bear Creek of 5.97E-2 mg/L. Utilizing an annual flow of 7.36E+5 m^3/yr, an annual peak load/flux of 4.39E+7 (43,900,000) mg/yr or 1.2E+5 (120,000) mg/day or 83.6 mg/min can be calculated. For U-238 with a specific activity of 3.36E-7, 83.6 mg/min equates to about 28,089 pCi/min. Adding this flux/load to calculated flux provided in TDEC comments on the *Integrated Water Management Focused Feasibility Study* (UCOR, 2016) shows concentrations exceed recreational use calculated risk standards based on capture and consumption of fish in Bear Creek at BCK9.2 without additional future release from EMWMF. (It is assumed that by the time EMDF is releasing constituents to Bear Creek, EMWMF will also be releasing constituents to Bear Creek.) This analysis should be redone using the PreWAC concentrations to evaluate loading/flux resulting from the landfill and whether the landfill WAC would potentially impact downstream water resources.

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[1] USGS StreamStats is found at http://streamstatsags.cr.usgs.gov/v3_beta/viewer.htm?stabbr=TN.

16. PreWAC development for constituents that peak after 200 years after maintenance of a dense fescue groundcover is discontinued or 4,000 years in the future, whichever is earlier, should be recalculated using infiltration rates consistent with a cover where the four foot vegetation layer and sand from the underlying one foot sand/gravel layer have been totally removed by erosion, evapotranspiration is negligible, and the amended clay layer and underlying compacted clay layer are compromised.

TDEC utilized the Revised Universal Soil Loss Equation 2 (RUSLE2) to evaluate soil loss on the East Bear Creek Valley (EBCV) Site. Soil loss may be used to estimate future erosion in tons per acre of the engineered cover. Erosion of the cover affects infiltration through the cover and performance of remaining cover components. The model was run utilizing 5% slope for the first 100 feet, and 25% slope for the next 635 feet for a total of 735 feet with grade channels at 265 feet, 475 feet and 735 feet.

Management of activities and vegetation on the cover and erosion of the cover are important considerations in long term effectiveness of the cover. Page H-24 discusses the importance of the upper part of the cover to support root systems for evapotranspiration, drain away water to remove chances of deeper root penetration, create a barrier for deep root development, prevent long term erosion and protect the underlying clay barrier from degrading effects of desiccation and the freeze thaw cycle.

RUSLE2 modeling indicated that maintaining a dense fescue grass cover is needed to prevent substantial erosion of the portion of the cover with the 25% slope. It was estimated that within 200 years after maintenance of a dense fescue groundcover is discontinued or 4,000 years in the future, whichever is earlier, the four feet thick vegetative cover and sand from the underlying one foot sand/gravel layer could be removed through erosion.

This increased infiltration will significantly change leachate volume, leachate concentrations, peak concentrations in surface water, groundwater well dilution rates and other factors. Summary of PATHRAE Model sensitivity analyses in Table H-9 on page H-71 shows that if the infiltration rate increases by a factor of 3, the peak concentration in surface water will increase by a factor of three or higher and the time to reach the peak concentration decreases by a 40 to 65%. Similarly, if the infiltration rate increases by a factor of 8.2, the peak concentration in surface water increases by a factor of 8 to 10 or higher and the time to peak concentration decreases by 65 to 85%.

17. Bear Creek is classified for recreational use. Human health risk from the capture and consumption of fish living in water polluted by site constituents and decay products (such as Po-210) is needed. Polonium-210 (Po-210) is in the decay chain for U-238, is highly toxic, and bioaccumulates in fish.

18. **Page 7-17** states that "One siting requirement, TDEC 0400-20-11-.17(1)(h), has been determined to be relevant but not appropriate. See Appendix G Section 4.3 for a discussion." TDEC disagrees and determined siting requirement TDEC 0400-20-11-.17(1)(h) is both relevant and appropriate.

TDEC 0400-20-11-.17(1)(h) states "The hydrogeologic unit used for disposal shall not discharge groundwater to the surface within the disposal site."

The discussion in Appendix G Section 4.3 on page G-17 and G-18 distinguishes between

> (1) "shallow land disposal" where packaged waste is placed in excavated trenches and the filled trenches are backfilled with soil, capped, and mounded to facilitate runoff and
>
> (2) an engineered disposal facility that incorporates an engineered earthen cover, liner system, and geologic buffer. Further the engineered disposal facility is built above existing grade and utilizes underdrains to mitigate the effects of shallow groundwater.

Page G-18 states that "Based on this analysis, the siting requirements appear to regulate a structure/facility that is vastly different from the proposed EMDF....while it may be relevant in that it applies to LLW disposal, is not appropriate due to the differences in the types of facilities..."

Tennessee is an NRC state, and TDEC 0400-20-11-.17(1)(h) is identical to 10 CFR 61.50(a)(8) which states "The hydrogeologic unit used for disposal shall not discharge groundwater to the surface within the disposal site."

10 CFR 61.50(a) includes criteria for determining whether a disposal site is suitable for near surface disposal. As defined in 10 CFR 61.2:

> *Near-surface disposal facility* means a land disposal facility in which radioactive waste is disposed of in or within the upper 30 meters of the earth's surface.
>
> *Land disposal facility* means the land, building, and structures, and equipment which are intended to be used for the disposal of radioactive wastes.

10 CFR 61.7 Concepts recognizes in (a)(2) that, for near surface disposal, the disposal unit is usually a trench. However, near surface disposal facility is not limited to disposal in trenches as 10 CFR 61.7 (a)(1) states "Part 61 is intended to apply to land disposal of radioactive waste and not to other methods such as sea or extraterrestrial disposal. Part 61 contains procedural requirements and performance objectives applicable to any method of land disposal. It contains specific technical requirements for near-surface disposal of radioactive waste, a subset of land disposal, which involves disposal in the uppermost portion of the earth, approximately 30 meters. **Near-surface disposal includes disposal in engineered**

facilities which may be built totally or partially above-grade provided that such facilities have protective earthen covers. Near-surface disposal does not include disposal facilities which are partially or fully above-grade with no protective earthen cover, which are referred to as 'above-ground disposal.'" (emphasis added)

TDEC further considered that EMDF is proposed for disposal of long half-life radionuclides, such as, Tc-99 (i.e. half-life 2.13E+5 years) and various uranium isotopes (U-234 with a half-life of 2.45E+05 years, U-235 with a half-life of 7.04E+08 years, U-236 with a half-life of 2.34E+07 years, and U-238 with a half-life of 4.47E+09 years) that will remain in the disposal facility long after engineering components fail.

To further clarify 10 CFR 61.50(a)(8) and the identical state requirement, TDEC evaluated NUREG-0902 which deals with Site Suitability, Selection and Characterization and gives background on the purpose for the siting requirement. It states this requirement should provide sufficient space within the buffer zone to implement remedial measures, if needed, to control releases of radionuclides before discharge to the ground surface or migration from the disposal site. It further states the staff prefers long flow paths from the disposal site to the point of groundwater discharge in order to increase the amount of decay of radionuclides, increase the hydrodynamic dispersion within the aquifer, and increase the likelihood of retardation of radionuclides in the aquifer.

TDEC rules are consistent with the NRC purpose for this requirement, as disposal means the *isolation of radioactive waste from the biosphere inhabited by man and containing his food chains* by emplacement in a land disposal facility (*emphasis added*).

Underdrains (either under or adjacent to the disposal area and that will not dry up due to covering the recharge area) discharge groundwater and any pollution to ground surface. Underdrains may further provide concentrated pathways for conveyance of pollution from under the disposal site to onsite ditches or conveyances to surface water. The effect of extensive or flowing underdrains conflicts with the purpose for this relevant and appropriate requirement. EBCV site (Site 5), WBCV site (Site 14), and Site 7a contain underdrains that conflict with the purpose of this requirement. The effect of this requirement on Sites 6b and 7b with anticipated flow along strike to natural tributaries is not determined.

19. **<u>Page 7-17</u>** states that the facility design would also incorporate TSCA requirements for a chemical landfill to accommodate waste containing PCBs at concentrations > 50 ppm. The discussion on page 7-17 further states that this will require waivers of two TSCA technical requirements. The first waiver is required for: "There shall be no hydraulic connection between the site and standing or flowing surface water...The bottom of the landfill liner system or natural in-place soil barrier shall be at least fifty feet from the historical high water table." It further states that Appendix G Chapter 4 provides evidence and rationale in the following three categories to support this waiver:

(a) PCB management and disposal practices on the ORR;
(b) Equivalent or superior effectiveness of site soils and engineered features on the EMDF; and
(c) Results of risk assessment and related fate and transport modeling for PCBs.

One basis for this waiver in Appendix G assumes PCBs will be disposed only in bulk waste at concentrations of < 50 ppm. It is unclear that justification for a waiver based on disposing bulk PCB waste with concentrations <50 ppm applies to granting a waiver for disposing PCB>50 ppm.

a. PCB management and disposal practices on the ORR discussion: PCB management and practices are described on pages G-12 and G-13. Third paragraph on G-13 states that as a result of these in-place procedures on the ORR, disposal of PCB waste in the existing EMWMF has been limited to bulk PCB waste disposal (<50 ppm), and has been confirmed in Waste Lot acceptance documents to date. It further states that it is expected that these procedures will continue in effect throughout operation of a future on-site disposal facility as well, thereby limiting all on-site disposal of PCB waste to <50 ppm.

b. Equivalent or superior effectiveness of site soils and engineered features on the EMDF: Discussion on pages G-13 and G-14 demonstrate that the liner system proposed for EMDF should be superior to TSCA liner requirements. On page G-14 it also states that "In conjunction with the limitations imposed on the quantities and volume of PCBs allowed for EMDF disposal, these features limit the possibility of PCB releases that would present an "unreasonable risk of injury to health or environment" (emphasis added). The EMDF also relies on an underdrain network to lower the pre-existing water table. Underdrains are engineered pathways for future release of hazardous substances, pollutants, and contaminants from the landfill. Over time, the underdrains would contain constituents that release from the landfill directly above the underdrain and from other areas of the landfill where constituents are release to groundwater and said contaminated groundwater discharges to an underdrain. Underdrains may provide a diluted leachate discharge to surface that may flow in a ditch or tributary to surface water with potentially minimal sorption or other attenuation of constituents. The ditch or tributary may also provide for sediment erosion to Bear Creek. Bear Creek is classified for recreational use. Creation of extensive or flowing underdrains conflicts with the TSCA requirement that "There shall be no hydraulic connection between the site and standing or flowing surface water."

c. Results of risk assessment and related fate and transport modeling for PCBs: Pages G-14 and G-15 describe results of risk assessment and modeling. This analysis did not evaluate the effect of an underdrain on PCB risk and transport of PCB contamination to surface water and Bear Creek. Fish downstream in Bear Creek already have PCBs in their tissue. The discussion once more assumes that PCBs are disposed in the future EMDF only in the solid phase and in relatively low bulk concentrations. It also assumes "significantly reduced infiltration rates within the landfill footprint."

20. **Page 7-18**, first paragraph, the second TSCA requirement requiring a waiver is needed for EBCV (Site 5) only and requires "The landfill site shall be located in an area of low to moderate relief to minimize erosion and to help prevent landslides or slumping. The discussion on page G-16, Section 4.2.2. states that the majority of the EMDF footprint (about three-fourths of the footprint area) lies on existing slopes of 30% steepness or less, while only about one-fourth of the footprint is developed on steeper slopes of Pine Ridge. Page G-15, Section 4.2.1 states that PCB limiting procedures are expected to continue thereby *limiting all on-site disposal of PCBs waste to <50 ppm*. This information was given as evidence the proposed facility will not pose an unreasonable risk of injury to health or the environment from PCBs when the requirement is not met. The basis for this waiver in Appendix G assumes PCBs will be disposed only in bulk waste at concentrations of < 50 ppm. It is unclear that justification for a waiver based on disposing bulk PCB waste with concentrations <50 ppm applies to granting a waiver for disposing PCBs>50 ppm.

21. Consensus has not been reached on input parameters to the modeling. These parameters control the calculated amount of leachate, the calculated leaching rate, and time to peak concentration in surface water.

22. The Remedial Action Objectives (RAO) on page 4-1 references several RAOs which define protectiveness of the remedy including:

a. Prevent exposure of humans receptors to CERCLA waste (or contaminants released from the waste into the environment) that exceeds a human health risk of 10^{-4} to 10^{-6} Excess Lifetime Cancer Risk (ELCR) or Hazard Index of (HI) 1.

b. Prevent adverse impacts to water resources or unacceptable exposure to ecological receptors from CERCLA waste contaminants through meeting chemical-, location-, and action specific ARARs, including RCRA waste disposal and management requirements, Clean Water Act (CWA) Ambient Water Quality Criteria (AWQC) for surface water in Bear Creek, and Safe Drinking Water Act (SDWA) MCLs in waters that are a current or potential source of drinking water.

Other goals are identified on page 4-2 that page 4-1 states do <u>not</u> define protectiveness. Page 4-2 states that "PreWAC waste concentration limits are determined based on demonstrating the following goals are met *during the 1,000 year compliance period*" (emphasis added).

- 10^{-5} ELCR and HI of 1 based on a human receptor's (direct) ingestion of groundwater from a drinking water well and (indirect) uptake of surface water for the compliance period (to 1,000 years) using a resident farmer scenario, and 10^{-4} ELCR and HI of 3 at times exceeding 1,000 year compliance period

- Appropriate AWQC for chemicals (risk-based discharge levels for radionuclides in Bear Creek and tributary surface water are per the *Integrated Water Focused Feasibility Study* (UCOR, 2016)

- MCLs in groundwater present in drinking water well of the resident farmer scenario.

Therefore, the PreWAC as identified in the D4 RI/FS should be consistent with RAOs during the 1,000 compliance period, *but not necessarily thereafter*.

CERCLA 121(d)(1) requires the remedial action "shall attain a degree of cleanup of hazardous substances, pollutants, and contaminants released into the environment and of control of further release at a minimum which assures protection of human health and the environment." RAOs should also include protection of environmental receptors allowing for environmental risk assessment or screening. We found no timeframe in either CERCLA or the NCP that specifies that after a specified number of years it is no longer necessary to assure protection of human health and the environment under CERCLA. CERCLA 121(d)(2) discussed ARARs for any hazardous substance, pollutant, or contaminant that will remain onsite. We found no timeframe in either CERCLA or the NCP that says that ARARs are no longer applicable or relevant and appropriate after a specified timeframe. CERCLA utilizes a review process every 5 years to determine whether remedial actions remain protective.

As a follow-up for the May 3rd meeting discussing changes from the D3 to D4 RI/FS DOE's contractor sent TDEC and EPA the following:

> *"For the EMDF D4 RIFS, PreWAC for radionuclides predicted to peak after 2,000 years were based on a risk-informed, 500 mrem/yr radiological dose criterion. The flow and transport model predictions and receptor exposure assumptions utilized were the same as for the risk-based PreWAC, but rather than estimating ELCR with a carcinogenic slope factor (for comparison to a specific target risk level), the peak annual radiological dose was calculated using water ingestion dose conversion factors for each radionuclide. This predicted peak dose corresponding to the assumed unit waste concentration (1 Ci/m3) was then used to estimate the waste concentration limit (PreWAC) corresponding to the 500 mrem/yr criterion. The assumptions underlying this calculation are exactly the same as those made for calculating risk-based PreWAC."*
>
> This methodology developed PreWAC limits for 28 radionuclide with excess lifetime cancer risk (ELCR) in the range from about 2.6E-02 (2.6 per hundred) to 9.8E-4 (9.8 per

ten thousand) based on the limited resident farmer scenario. Much of this risk results from drinking from the residential water well. The ELCR may be higher if additional pathways of exposure are considered.

CERCLA and the RAOs reference SDWA MCLs. SDWA MCLs are identified in the RAOs for waters that are a current or potential source of drinking water. The future farmer scenario assumes drinking from a residential water well in the exposure risk scenario and development of the PreWAC. Potential use of groundwater for a drinking water supply does not end at the end of the 1,000 year compliance period and may increase farther out in the future. MCLs for radionuclides include beta/photon emitters (4 mrem/yr), gross alpha particle (15 pCi/L), Radium-226 and Radium-228 (5 pCi/L) and Uranium (30 μg/L). The MCL for uranium limits toxicity of uranium as a heavy metal in addition to effects as a radionuclide. It should be verified that PreWAC limits will result in groundwater concentrations at the residential water well that are less than or equal to the appropriate MCLs irrespective of how far in the future modeling predicts a peak concentration in surface water.

23. Of note is the fact that, for the different proposed disposal sites, there are different lithological and formation contact areas for different sites. This may be more significant than initially appears, particularly when there are formations that contain more carbonate. If the streams on the sites are walked and water quality parameters are measured along them, it is apparent that when, for example, a stream crosses a carbonate unit, say the Dismal Gap Formation (formerly Maryville Limestone), there is a measurable change in electrical conductivity of the water. This means that a higher dissolved load is in the water, which means that channels or conduits are developing in the subsurface.

24. The general groundwater situation in this part of Bear Creek Valley needs to be described in a clearer way. The document is written such that a "pick and choose" method is used to obtain supporting materials to justify the position. Sometimes references are quoted out of context, and previous comments were made about this, but have not been rectified.

Specific Comments

1. **Page 4-1, RAO 2:** The RAO to protect ecological receptors includes ARARs that may not include radionuclides. Protection of ecological receptors from radionuclides should also be established through ecological risk assessment.

2. **Page 6-9, 2nd paragraph:** *"No known federal- or state-listed T&E species have been identified in the EBCV site area (Option 5), except for Northern long-eared bats, which are listed as threatened. An acoustic bat survey conducted by ORNL personnel in August 2013 at and near Site 5 prior to timber recovery did not detect any Gray or Indiana bats that are listed as endangered species, but did identify Northern long-eared bats (See Appendix E for details)."*

Did DOE previously notify the U.S. Fish and Wildlife Service regarding timber recovery at this site? Given the threatened Northern Long-eared bat was detected onsite, has DOE been in Section 7 consultations with the USFWS regarding the EBCV site (Option 5)?

Under Section 7 of the Endangered Species Act, Federal agencies must consult with the U.S. Fish and Wildlife Service when any action the agency carries out, funds, or authorizes (such as through a permit) *may affect* a listed endangered or threatened species. This process usually begins as informal consultation. A Federal agency, in the early stages of project planning, approaches the Service and requests informal consultation. Discussions between the two agencies may include what types of listed species may occur in the proposed action area, and what effect the proposed action may have on those species.

3. **Page 6-14, last paragraph titled: Ecological/cultural resources:** *"No recent site-specific surveys to identify T&E species have been completed for Site 14. Ecological conditions for the WBCV area were reported in an environmental impact statement data package for the LLWDDD program published in 1988.*

   This study is outdated for the purpose of establishing current T&E species status. TDEC agrees that detailed assessments to evaluate potential impacts to wetlands and to identify T&E species would be warranted at Site 14 if the site is selected for construction, as stated on page 6-15. Furthermore, as NEPA values are to be incorporated into CERCLA, TDEC expects a thorough evaluation of ecological and cultural resources at any candidate site before approval of an alternative that would authorize construction of a disposal facility on the site.

4. **Page 6-20, 3rd paragraph titled: Ecological/cultural resources:** *"Two separate surveys to identify T&E species of vascular plants and fish were completed in 1998 for the EMWMF that included the Site 6b area (see Appendix E for details). Neither survey identified T&E species in the Site 6b area, although recommendations were made to preserve habitats and implement best management practices to protect the Tennessee Dace in downstream areas. ORR ecological surveys mapped a "natural area 28" across and adjacent to the Site 6b area (See Appendix E) that includes wetlands delineated east and west of the site. Wetlands on the east and west sides of Site 6b along the NT-5 and NT-6 tributaries were delineated by Rosensteel and Trettin (1993) that could be impacted by EMDF construction (See maps and details in Appendix E). Surveys to evaluate potential impacts to wetlands and other T&E species may be warranted at Site 6b if the site is selected for EMDF construction."*

   As discussed in comment 3 above, the documents cited in this paragraph are outdated for the purposes of establishing the current status of T&E species. Given that the Northern Long-eared bat was detected in an acoustic survey in Bear Creek Valley as recently as 2013, bat survey data for any candidate site should be collected prior to approval of an alternative that would allow a facility to be constructed on the site.

5. **Page 6-81:** The PreWAC values listed in Table 6-5 do not include the non-carcinogenic PreWAC for uranium of 52.2 mg/kg identified in Table H-12 (page H-81). Presumably, uranium non-carcinogenic PreWAC limits were calculated based on a Hazard Index (HI) of 3. The non-carcinogenic pathway for uranium metal is based on a reference dose of 0.003 mg/kg-day. Since this reference dose is the same for all isotopes of uranium, the PreWAC for the non-carcinogenic threat from uranium metal should be determined by EPA approved analytical methods and reported as total uranium in units of mg/kg instead of speciation into the various uranium isotopes.

6. **Page 6-51, Section 2.2.4.8, Longevity of Engineered Features Cover/Liner Systems:** *Geomembrane liners of the landfill liner system at all sites would control releases of leachate to ground water for their design life reported to extend from 500 to 1000 years or more (Koerner, et al. 2011, Rowe, et al. 2009a, Benson 2014, EPA 2000). Both cap and liner systems contain geomembranes to prevent water infiltration into the waste, reduce contact of water and waste, and minimize leachate production and migration. As described by Bonaparte et al. (2016), it appears that HDPE geomembranes of the type being used in some MLLW disposal facilities are relatively unaffected at total alpha doses of 5 megarad (Mrad), or more. These geomembranes are also reportedly unaffected by radiation from gamma and/or beta sources until total doses reach on the order of 1 to 10 Mrad, which is much higher than what would be expected to be disposed in the EMDF.*

   TDEC agrees that properly designed and installed geocomposite barriers may control leachate releases to groundwater for many decades or even centuries. However, the difference between a service life of a few hundred years and a thousand years might be critical for isolation of an isotope like strontium 90, which would require 30 to 40 half-lives, or about 1000 years to decay from the proposed limit set by the administrative waste acceptance criteria to levels that would be innocuous in leachate.

   TDEC also agrees that disposal of waste that could produce a total dose of 1 megarad to the geomembrane in either cap or liner is unlikely, due in part to the small amount of waste that is likely to be generated with high concentrations of beta/gamma emitters and in part to shielding by clay and drainage layers. However, as the proposed administrative WAC would allow 4600 Curies per cubic meter of Cesium 137 and places no limits on Cobalt 60, it is not clear to TDEC that localized liner damage due to radiation fields would be completely impossible without dose calculations and possibly further WAC restrictions.

7. **Page 7-10, Section 7.2.2.2.3 Action-specific ARAR, first bullet, TDEC 0400-20-11-.17(1)(b) Disposal site shall be capable of being characterized, modeled, analyzed and monitored:** *"All sites selected for consideration meet this ARAR. All sites under consideration in this RI/FS as locations for an on-site disposal facility – EBCV Site, WBCV Site, Dual Site (Site 6b and Site 7a) – are located in BCV, which has been extensively characterized over the last 40-50 years. More than 1,000 groundwater wells have been installed and monitored many of which continue*

to be monitored, multiple characterization events have been executed and documented, and over 900 acres of the valley are incorporated in the BCV model (see Appendix E and Appendix H). Additionally, an effort is underway within OREM to develop a more detailed groundwater model of BCV outside of this RI/FS. ***The current BCV model, a porous media model, has been questioned in terms of its ability to adequately predict groundwater movement in Bear Creek. Discrete fracture flow models have been suggested to be more applicable for this area. However, development of a fracture-based flow model would take a large amount of capital and time, without any guarantee of producing a successful accurate model. The scale of fractures compared to the scale of the current porous flow model grid is such that this approximation is appropriate, and modeling calibration efforts and results support that conclusion. See further discussions in Appendix H.***"

The approach cited above assumes a porous medium. In other parts of the document the equivalent porous medium approach is promoted.

A porous medium has: areal recharge (no losing or sinking streams), parallel flow lines, with laminar flow, (no convergent flow, no turbulent flow, no troughs, valley or ridges in the potentiometric surface), discharge across the entire downgradient face of the aquifer (no springs or seeps) and a convex profile to the water table (in cross section), or a steepening hydraulic gradient towards the discharge.

So, do any of the proposed sites deviate from any of the ideal criteria? If so, the porous medium assumption is invalid. ASTM (1995) state in fractured rocks the porous medium is poorly approximated, and should be avoided.

It appears that the settings proposed fail for most if not all of these fundamental porous medium test criteria.

An equivalent porous medium is: "a homogeneous setting with parameters chosen to be characteristic of the fissured rock" (Barker, 1993) – essentially an ideal porous medium with the chosen parameters assumed if they are not measured.

The term equivalent porous medium appears quite straightforward. However, further in Barker (1993) there is a discussion and it is such that there are different scenarios to choose from, that involve various characteristics about the transport mechanisms in the rock matrix and the fissures, for example, whether transport is diffusive or advective, whether there is flow in the matrix and fissures or only in the fissures, but still diffusive exchange between the two. When the time scale is small with respect to the diffusion across the fissures and the effects of matrix porosity can be ignored, (conditions he suggests are probably restricted to the laboratory) an equivalent porous medium model might work, using just the fissure porosity. This might also work if diffusive equilibrium exists, with the time scale small, the setting behaving like a homogeneous medium and using the total porosity, with alternatively a double porosity approach (flow in only the fissures). If there is a wide distribution of timescales, then only diffusive double permeability approaches can be envisioned (flow in both the fissures and the matrix and diffusive exchange).

This discussion hopefully shows the complex interactions that have to be determined when using what appears to be a relatively simple: "equivalent porous medium" approach. In reality it involves choosing a complex and interwoven set of assumed conditions, of which most are impossible to validate, unless they are measured directly.

It is often suggested that large scale can allow a better fit to such approaches. This may be the case with general parameters to determine mass balance, but when tested with methods not buried in the same assumptions details emerge that usually result in a model more closely approximating a discrete situation that defies equivalence with anything but reality. There are numerous traces in fractured non-carbonate/clastic rocks that have been done kilometers in length with velocities of > 100 m/day (Worthington et al., 2016 [in review]). When the proportions of flow in different porosity elements (matrix, fissure and channel/conduit) are included, it is obvious that the concept of any type of porous medium is much less likely.

It is overly simplistic to assume that fissured rock can be modeled as a porous medium. One alternative is to use parameters determined directly by groundwater tracing, although tracing is likely to prove that rock is not a porous medium. Another alternative is to apply parameters derived by tracing in similar settings on the ORR (e.g., Gwo et al., 2005) and to assume those values are representative.

Convergent flow to major fissures must be considered and thus the inclusion of channeling must be included in the thought process. Channeling will obviously result in more rapid velocities, which will result in any dissolved solutes or contaminants reaching users more rapidly and in higher concentrations.

8. **Page 7-13, TDEC 0400-20-11-.17(1)(f):** *"All proposed sites are situated such that upland drainage areas are minimized by locating the footprints as far upslope as possible."*

   TDEC is not sure this statement is true since several of the sites are proposed to be located on knobs separated from Pine Ridge.

9. **Page 7-18, Section 7.2.2.3 Long-term Effectiveness and Permanence (On-site):** The Residual Risk discussion is limited to the 1,000 year compliance period. Residual risk beyond 1,000 years is not considered in the Long-term Effectiveness and Permanence discussion.

10. **Page E-16, Figure E-1, BCV Phase I ROD land use zones...:** Symbols displayed on the map are missing from the legend. Please provide a complete legend that describes all map symbology, including existing streams, roads, and gray polygons west of Site 6B.

11. **Page E-18, Figure E-2, Existing contaminant source areas...:** A) Symbols displayed on the map are missing from the legend. Please provide a complete legend that describes all map symbology, including existing streams. B) Acronyms on the map (e.g., HCDA) are not defined on the figure or in the Appendix E acronym list. Please define all acronyms.

12. **Page E-24, Figure E-7, Potential EMDF sites in BCV with respect to the northern DOE site boundary and nearest Oak Ridge residents:** The map is annotated to portray distances between potential disposal sites and existing (current) residences. For protectiveness of future residents, it would be more appropriate to show the distance to the DOE site boundary. Please revise the figure accordingly (and any calculations or estimates based on these distances). At a minimum, revise the figure title to accurately reflect that the map only addresses *current* residents.

13. **Page E-26, Paragraph 2:** "*... the proposed sites (Option 5) and physically and hydrologically separated from this community by Pine Ridge.*" Freeze and Cherry (1979) and Fetter (1980) show the effect of topography and geology/hydrogeology on groundwater flow nets. Without tracer test information, it cannot be stated or claimed in this type of topographic setting in fractured rocks that the site is hydrologically separated from the (scarp side of the ridge) i.e., Scarboro community side of the ridge. Tracer testing from both sides of the ridge must be done to prove that there is a groundwater divide. This would be considered a common practice in carbonate settings and would be prudent in clastic and other similar settings also (Worthington et al., 2016 [in review]). Note: the higher up in the dip slope of the ridge the proposed site is increases the probability that the assumption that no groundwater will pass beneath the ridge is more likely to be incorrect.

14. **Page E-30, 2.8.1 Hydrogeological Conceptual Model for Bear Creek Valley:** The concepts of the hydrogeology of fractured rock settings used in this document have not moved with the progress made within the discipline and throughout the profession in general across the globe through the decades. For example, it is now acknowledged that it is not possible to assume that carbonate or fractured rocks behave as a porous medium (ASTM, 1995). Many papers through several decades have been written that describe rapid flow of recharge, groundwater flow and discharge in non-carbonate clastic rocks. They assume the characteristics of carbonate rocks, because there are obviously preferential flow paths, i.e., channels, the only difference being that the diameters of the channels in clastic rocks are probably less than those in carbonate rocks, because the dissolution rates are less (Worthington et al., 2016 [in review]).

    Fractured rocks have relatively long groundwater flowpaths and relatively deep flowpaths because the specific surface area contacted by water and other dissolved solutes is low as compared to the specific surface area of a well-sorted sand or gravel. This means that fractures tend to alter (or weather) along their length. With a positive feedback loop where in an open fracture within which water moves, if it becomes widened, it will take more water and thus will widen more and so on. This is one of the few reasonable explanations for deep contamination of classic rock settings. In addition the mineral assemblages of sandstones and shales dissolve incongruently, where a relatively insoluble clay mineral is formed after, e.g., feldspar minerals dissolve, which is different that when a carbonate rock dissolves and almost all the existing rock is transported away in solution. These scenarios in clastic rocks cause miscalculations in groundwater velocity, underestimations in contaminant transport, and other potentially problematic modeled predictions.

At the end of the first paragraph therein (Section 2.8.1) a differentiation is made between karst and clastic rocks, evaluate the comments here and that statement, and in particular with regards to Worthington et al. (2016 [in review]).

15. **Page E-32, Section 2.8.2, Hydrogeological Conceptual Models for EMDF Sites in Bear Creek Valley:** *"Groundwater and surface water flow paths along and adjacent to the NT valleys adjoining the proposed sites ultimately lead downgradient toward the base level elevations imposed by Bear Creek which drains the entire valley toward the southwest."*

    As shown on Figure E-3 and other diagrams, the karstic Maynardville Limestone outcrops and dips steeply to the southeast along both sides of Bear Creek. As noted on page E-76:

    > Stratigraphically and physically above the Maynardville, the Copper Ridge Dolomite dips to the southeast under the north flank and crest of Chestnut Ridge. Cavities in the Copper Ridge are generally larger than those in the Maynardville.... Uncontaminated groundwater from the cavity/fracture network below Chestnut Ridge drains northward and discharges to Bear Creek and probably commingles with groundwater in the Maynardville karst.

    In karst settings such as this, groundwater has been demonstrated to flow beneath surface streams, and surface streams may have losing reaches, as Figure E-32 shows for Bear Creek. If the intent is to communicate that Bear Creek is a hydrogeologic boundary to groundwater flow, please include supporting evidence or cite a document where this is documented.

16. **Page E-33, 2.8.2 Hydrogeological Conceptual Models for EMDF Sites in Bear Creek Valley:** *"As shown in Figure E.11, Solomon et al (1992) defined hydrologic subsystems for areas underlain by predominantly clastic (non carbonate) rocks referred to on the ORR as aquitards. ...The subsystems include...an aquiclude at great depth where minimal water flux is presumed to occur."*

    Given that 1) releases of radioactive constituents from EMDF have the potential to impact human health and the environment for thousands of years and 2) groundwater flow is one of the most significant potential transport pathways, reliance on general statements made more than a quarter century ago should be supported with site-specific data from a thorough hydrogeological investigation of the candidate sites. It is not sufficiently protective to refer to predominantly clastic rocks as aquitards or to presume minimal groundwater flux at depth.

In a region with a significantly more stable tectonic history than the ORR, Anthony Runkel, Chief Geologist of the Minnesota Geological Survey, has demonstrated that conceptual hydrogeologic models used for decades are indefensible (Bradbury and Runkel, 2011; Runkel, 2010). In particular, he finds little support for historical assumptions that groundwater flow in siliciclastic strata is primarily intergranular and that "aquitards" have uniformly low conductivity. Specifically, he finds that discrete intervals of exceptionally high conductivity, commonly bedding-plane fractures and fractures perpendicular to bedding, can dominate the hydraulics of siliciclastic strata previously presumed to be aquitards. If intervals of high conductivity dominate groundwater flow in the relatively undeformed strata of Minnesota, such intervals are more likely to influence flow in the highly deformed bedrock of Bear Creek Valley.

17. **Page E-33, 2.8.2 Hydrogeological Conceptual Models for EMDF Sites in Bear Creek Valley:** *"Detailed water budget research on ORR watersheds that are similar to those of the EMDF sites..."*

    Please cite the reference(s) supporting similarity between the candidate EMDF sites and watersheds where detailed water budgets were developed. As written, the paragraph containing the quoted statement is confusing, as it presents different findings from two studies and then speculates about groundwater flow conditions at various depths and future impacts of landfill construction on groundwater flow.

18. **Page E-43, Figure E-18, Key changes to surface and groundwater hydrology from pre-construction through EMDF construction, capping, and closure:** It is not clear how the relatively shallow upslope diversion channel will divert upgradient groundwater around the landfill. The diagram does not indicate how groundwater flow will be prevented from crossgradient (along-strike) areas into the area beneath the landfill, where the water table is predicted to be lowered.

19. **Page E-46 and Figure E-19, Water table contour map for Site 5 representing the highest groundwater levels for the winter/spring 2015 wet season:** *"Of the proposed EMDF sites, the hourly water level data from the Phase I monitoring at Site 5 provides the only complete record of water table fluctuations over a full year of record. Figure E-19 illustrates the Site 5 seasonal high water table measured on April 21, 2015, reflecting the annual wet season peaks observed each year during periods of relatively heavy winter/spring precipitation (see Attachments A and B for details)."*

A single year of water level data cannot adequately represent the potentiometric surface range over 1,000+ years. Describe any adjustments or safety factors that were applied to address this discrepancy.

20. **<u>Pages E-46 and E-52:</u>** "*If Site 5 is selected for the EMDF, additional hydrogeological data will be needed to more completely establish baseline conditions for groundwater in, adjacent to, and upgradient of the Site 5 footprint....*" and "*Additional site characterization and water table monitoring at Site 5 in conjunction with more detailed engineering analysis are envisioned to resolve whether the conceptual base elevations would need to be raised in this area or whether dewatering before or during construction would be required.*"

    Such fundamental baseline groundwater conditions should be characterized before selecting candidate sites and developing conceptual designs.

21. **<u>Pages E-72 and E-76:</u>** "*Geologic structures provide the fundamental pathways for groundwater flow and contaminant transport. Structures most relevant to the site conceptual model and fate and transport modeling include...macropores and relict fractures within saprolite....*"

    "*Descriptions and detailed systematic analyses of fracture sets are generally not provided in site investigation reports or in boring log or test pit descriptions, so that the nature of fracture systems and the detailed geometry of fracture networks remain nebulus [sic] and undefined at most sites. This is true for the EMWMF and for the proposed EMDF sites.... These uncertainties and limitations are necessarily reflected in fate and transport simulations in fractured media on the ORR.*"

    If geological structures provide the fundamental pathways for groundwater flow, understanding of those fracture systems should be defined to a higher standard than "nebulous" to reduce uncertainties and limitations of the fate and transport modeling.

22. **<u>Page E-72, Section 2.12.3.2 Bedrock Fractures in Predominantly Clastic Formations of the Conasauga Group:</u>** It should be recognized that the flowmeter readings are from boreholes that may not be connected to macrofeatures, as is often the case, simply because there is a low probability of these zones being intersected by chance (Benson and LaFountain, 1984). The only way to reliably demonstrate that hydrogeology from boreholes correctly represents a site is to test the conceptual model with tracers.

23. **<u>Page E-73, Section 2.12.3.2 Bedrock Fractures in Predominantly Clastic Formations of the Conasauga Group:</u>** First paragraph, last sentence: How do you corroborate a notion? It is more logical to rationalize that, since the water table has not been in the same place, it settles in the zone of maximum porosity and permeability. It is also likely that there is more flow parallel or aslant the strike as in other locations that have been tested with injected tracers. The remaining and previous discussion about groundwater flow should consider that there will be convergent flow in larger fractures simply because of a positive feedback

loop that develops. This could easily lead to small diameter channeling (a few mm to cm) that can be missed by boreholes, but that carry leachate or groundwater + dissolved solutes related to the waste cell to impact users probably many kilometers (miles) away.

24. **Page E-74:** The text cites Lutz and Dreier (1988). Please list the associated reference in Chapter 7, along with any others that are missing.

25. **Page E-76, Section 2.12.3.3. Karst Hydrology in the Maynardville Limestone and Copper Ridge Dolomite:** There is a discussion about karst, karstification, etc., which segregates karstification into only these two formations. A modern approach to this should be considered. Worthington et al., (2016 [in review]) show that dissolution actually occurs in non-carbonate rocks, because of geological time, almost as commonly as it does in carbonates. They cite many examples of tracer tests that show rapid velocities (>150 m/day [~500 ft/day]) and long pathways (> 3 km [~2 miles]) e.g., in arkosic sandstones (quartz, feldspar and some mica minerals). Other examples they cite show similar parameters and suggest that at the scale of contaminant groundwater and migration (dissolved solutes and colloids) in narrow channels that can permit turbulent flow at 0.001 m/s (about 90 m/day [~300 ft/day]) (Quinlan et al., 1996) there is comparability between clastic and carbonate rocks. Lowe and Waters (2014) state that there are lithological conditions that promote development of subsurface channels, conduits and karst. These are: shale beds, faults and unconformities. The first of these is because sulfide minerals are often present in shales and thus can be oxidized after being in contact with meteoric waters to produce a groundwater that contains sulphuric acid, which can significantly enhance dissolution. Faults and unconformities always have some sort of void spaces formed along them, and thus can allow groundwater or formation water and thereafter meteoric water to penetrate. This can have the effect of pre-conditioning the setting so that when it is subjected to uplift and subaerial exposure and attacked by meteoric water, dissolution processes can proceed at higher rates. Degrees of karstification are hard to quantify. Quinlan et al., (1996) provide the only numerical basis for describing the minimum size for conduits (a few mm [a few fractions of an inch] in diameter).

26. **Page E-78:** *"The maximum thickness of this unsaturated zone between the top of the waste and the post closure water table is in the range of 100-150 ft thick at Site 5 (See conceptual design cross sections in Chapter 6 of the EMDF RI/FS Report)"*.

    Please rephrase this sentence to state the minimum predicted thickness of the unsaturated zone between the bottom of the waste and the post-closure water table, which is the relevant thickness.

27. **Pages E-80 and E-81:** *"The hydraulic characteristics of unsaturated (and saturated) in-situ materials can be currently estimated based on available data at and near the proposed EMDF sites but most field investigations have not involved any direct measurements of unsaturated zone hydraulic parameters."*

"If unsaturated zone characteristics are required to support modeling, engineering design, or other project needs, they can be addressed in future work plans for site characterization."

If most investigations have not involved direct measurement, does this mean that some direct measurement data are available? If so, how are those data factored into the evaluation? If not, collection of such data is warranted to support a defensible evaluation of site suitability even before it is needed for detailed engineering design.

28. **Page E-94, Hydraulic Conductivity in Relation to Equivalent Porous Media Modeling, Third Paragraph, 9th line:** A reference by Worthington (2003) is incompletely used in the D4. The reference is also missing from the references list (note the corrected reference is included below). The original reference that should be used is Worthington (1999) below. In that paper the discussion by Worthington (1999) as used in the D4 is only partially represented and does not advocate assuming that the setting can be assumed to be an equivalent porous medium and can be modeled as such. It is part of a discussion of several techniques typically used.

29. **Page E-102, Section 2.13.4 Groundwater Geochemical Zones, Fourth complete paragraph:** TDEC comment TDEC.S.066 discusses deep groundwater circulation on the ORR and points out that Nativ et al. (1998) reply to the rebuttal of their original paper by Moline et al. (1998). The D4 version still does not quote the reply by the original author to the rebuttal. In rocks that have been faulted such as those on the ORR, TDEC would not presume, as stated in the RI/FS, that a finite number of borehole tests would be adequate to determine that permeable fractures at depth were absent or of minimal consequence.

30. **Page E-103, Section 2.13.4 Tracer Tests, First paragraph, 10th line, "informal unpublished document":** The results of tracer tests done in Bear Creek Valley are included in the TDEC Environmental Monitoring Report (2001).

31. **Appendix E, Attachment A, page 1:** *"The conceptual design for the EMDF includes the installation of underdrain systems beneath the landfill to ensure surface water and groundwater diversion, drainage, and lowering of the water table below the waste cells. The results of the Phase I site characterization are presented in relation to the existing site topography and proposed conceptual design for the landfill and underdrain system. The results support the concept that the water table can be effectively managed and lowered during and after construction to ensure that the water table does not encroach on the geologic buffer or waste materials placed above the buffer and liner systems."*

    The document should indicate any lessons learned from the failure of groundwater modeling to predict post-construction groundwater levels at the EMWMF with an acceptable level of certainty, as well as how any such lessons are incorporated in the EMDF conceptual design to ensure that the water table does not encroach on the geologic buffer or waste materials.

32. **Appendix E, Attachment A, Figure 1, Phase I Monitoring Locations at the Proposed EMDF Site:** The Rome formation symbol defined in the legend does not match the symbol shown on the map. Please correct the legend or map for accuracy and consistency. This discrepancy should be resolved on other figures throughout the RI/FS report components (e.g., Appendix E, Attachment B, Plates 5 and 6).

33. **Appendix E, Attachment B, Cut/Fill Thickness Map:** Symbols displayed on the map are missing from the legend. Please provide a complete legend that describes all map symbology, including existing streams and roads.

34. **Page G-13:** Part of the discussion to justify a waiver of TSCA requirements is that all onsite disposal of PCB waste at EMWMF and future EMDF is limited to < 50 ppm. A PCB limit of 50 ppm should be established in the WAC for the future EMDF.

35. **Page F-20, Chapter 3. NATURAL PHENOMENA HAZARDS:** *"Two natural hazards, tornados and earthquakes, are considered in this evaluation, since these are the most likely potential natural phenomena that could affect the EMDF."*

    DOE is to be commended for evaluating an air dispersion scenario. However, the source is modeled as being equivalent to waste disposed in EMWMF. While this might be reassuring that risks will be low if waste inventory in a future disposal facility is similar to EMWMF waste, it does not provide a basis for setting limits on concentrations of radionuclides that might contribute to either on-site or off-site risk during a tornado.

36. **Page H-24, Paragraph 3, Second Bullet:** *"...composite barrier layer that consists of a 40 mil thick high density polyethylene (HDPE) geomembrane layer..."* **and Page H-26, Item 8, First Bullet** *"... proposed geomembrane (40 mil) ..."* **and Page H-28, Table H 2, column 'Layer' (#5) and column 'Thickness'** (*80 mil*).

    The specified thickness of the composite barrier layer is inconsistent between the text and the table, with the text indicating 40 mil and the table indicating 80 mil. This needs to be corrected. Further, the barrier thickness in the cover layer should normally be the same as that in the liner (as indicated by the thickness of 80 mil shown for Layers 5, 12 and 15 in Table H-2; it is not clear if that is the case here.

37. **Page H-30, Table H-3, Amended Clay Hydraulic Conductivity, Stage 4:**

    The basis for adjusting the hydraulic conductivity of the amended clay layer by a factor of 2 should be provided.

38. **Page H-32, Section 4.2.1.2 Model Boundary Conditions:** *"The UBCV Model has a no-flow boundary at the top of Pine Ridge to the north of the proposed facility..."* **and Page H-38, Figure H-9:**

    The no-flow boundary assigned north of the proposed facility in the MODFLOW model appears to be only a few hundred feet away from the unit. Assigned boundary conditions should be tested to demonstrate that the boundary assignment does not have a significant influence on the calculated water levels – especially when the model boundary is in relatively close proximity to the area of interest in the model. This is particularly important since the model is used to estimate post-construction water level declines at the EMDF for comparison to the base of the landfill liner system. A no-flow boundary can enhance calculated declines by inhibiting flux into the model area. The assumption of a no-flow boundary underlying the ridge is a theoretical guideline, but field data has not been presented to support the boundary definition.

39. **Page H-43, Section 4.2.1.4 Model Calibration:**

    Since the numerical model is used as the basis for establishing pre-design components of the landfill facility as well as PreWAC values, knowledge of specific calibration results is warranted to gage the suitability of the model for the applications. Calibration details, however, are not presented in this RI/FS. Information normally required includes the distribution of calibrated heads, minimum/maximum residuals, calibration statistics (such as root mean square error, absolute error, mean error) and the spatial distribution of the head residuals. It is not clear if any of this information, specific to this model for the proposed EMDF, is presented in other reports; nonetheless, some of the basic calibration information should be included in the RI/FS to allow confirmation that the model calibration is adequate for this application.

40. **Page H-50, Section 4.3.2 MT3D Model Assumptions:**

    The MT3D model setup includes withdrawal of water from Layers 3-6 – presumably with one well node assigned in each of the 4 model layers representing the pumping of a water supply well. However, the summary of MODFLOW parameters for the Future Condition scenario (Table H-4, page H-41) lists 8 well nodes used in the model. Please clarify the representation of the pumping and number of well nodes assigned.

41. **Page H-64, second complete paragraph:** *"...dilution factors for the creek (surface water source) and residential well (see Section 4.3.3) were used for scaling the constituent concentrations in the creek to corresponding well concentrations."*

    The surface water concentrations and the residential well (groundwater) concentrations used in the scaling calculations have each been developed using different modeling approaches and assumptions (the surface water concentrations are developed using PATHRAE with consideration of advection, dispersion, and sorption, while the groundwater concentrations are developed based on advection only). The comparability of the modeled values for use in scaling calculations is questionable.

42. **Page H-69, Table H-7:**

    Response to TDEC comment TDEC.S.106 stated that differential settling is assumed post-1,000 years and is accounted for by clogging the drainage layer of the cap (decrease in hydraulic conductivity of 100). HELP model sensitivity analysis presented in Table H-7 includes a 2 order of magnitude reduction of hydraulic conductivity in the lateral drainage layer post-1000 years. TDEC does not understand the technical basis for postponing differential settling to greater than 1,000 years after closure.

43. **Appendix H, Attachment B, Table 1:** Some of the Peak Effective Risk, PR_{eff}, (ELCR) included in Table 1 appear to be PR_{well} instead of PR_{eff}. In other words, some of the PR_{eff} in Table 1 was derived from drinking from the groundwater well only and does not appear to include the risk from livestock watering and consumption of meat and produce grown on the farm.

44. **Appendix H – Attachment B, Page 7, Section 2.1.3 General Design and Evaporative Zone Data:**

    The SCS runoff curve number of 49.3 seems low when compared to curve numbers presented for Pasture, grassland, meadow or brush in Table 2-2c of the US Department of Agriculture Technical Release 55 (Natural Resources Conservation Service, *Urban Hydrology for Small Watersheds*, 210 VI TR-55, June 1986). In that document, the majority of the runoff curve numbers are greater than 60, with values less than 50 associated with good hydrologic conditions in generally sandy soils.

    Additionally, the assumption of 100% runoff for the 'Fraction of Area Allowing Runoff' in the HELP model seems optimistically (and non-conservatively) high.

45. **Appendix H – Attachment B, Page 7, Section 2.2 HELP Model Output, Paragraph 1:**

    The text indicates HELP model results for the long-term scenario are presented in Section 2.2.2; however, no Section 2.2.2 is provided in Appendix H – Attachment B. Further, output data for at least one run should be provided for some confirmation of the HELP model output.

46. **Response to Comment TDEC.S.001:** TDEC should clarify that the purpose of TDEC comment S.001 was to identify problems with the current disposal facility that have not been resolved to TDEC's satisfaction. The comment response focuses on debating or denying the significance of these problems, and the D4 does not incorporate any major changes that reflect progress on outstanding EMWMF issues. During the five previous years since the FFS was scoped with the regulators, little consideration has been given to issues at

EMWMF. DOE has only recently initiated discussions on the problems of elevated groundwater discussed in the comment and there has been little discussion on modifications to the approach to waste acceptance.
To address the response to this comment, TDEC first notes that unregulated discharges of radioactive wastewater to Bear Creek occurred very early in EMWMF operations prior to facility expansion. The problems resulted primarily from excessive runoff from a large working face and water ponding on a low permeability protective layer in cell 1 of EMWMF rather than the inability of the leachate collection system to convey water.

With regard to the second individual comment response, it is true that releases occurring during waste generation and transportation are not directly the results of on-site disposal. However, these releases, such as the contamination of Highway 95 and the contamination of sewage sludge at the Rarity Ridge wastewater treatment plant, were, in part, the result of having abundant on-site disposal capacity and flexibility in the approach to waste characterization, which favored en masse removal actions rather than a more surgical approach to risk reduction.

With regard to the groundwater intrusion into the EMWMF buffer and liner, TDEC's concerns were never strictly based on the pneumatic piezometer readings, as DOE has surmised, but on the apparent intrusion of groundwater into the liner prior to underdrain construction and persistent elevated water levels around the northeast end of EMWMF. The hypothesis that elevated piezometer readings resulted primarily from the increase in pore pressure due to the overburden weight of added waste is not consistent with the data that was presented in the referenced UCOR report, or with data collected subsequent to its publication. Pressure in pores under confined conditions increases almost instantaneously (at the speed of sound in water) and decays as consolidation occurs. In clay barriers, this decay may require months or years. The piezometer readings below cell 3 did not rise quickly during the time when cell 3 was most rapidly loaded, and the pressure recorded in the years since loading shows seasonal changes rather than decay.

Finally, while the karst system in the Maynardville Limestone in Bear Creek Valley was documented in the BCV RI, as DOE states in the response to comment, no travel times were available except an arrival time for the short trace reported by Geraghty and Miller (1989). The Bear Creek RI does not reference the several tracer studies in west Bear Creek Valley after 1995 or tracing done in similar rocks in Melton Valley, many of which are now summarized in Appendix E of the D4 version of this RI/FS. These studies did provide insight concerning the range of first-arrival times and center-of-mass travel times in Conasauga Group rocks such as those underlying the proposed sites. Changes to the fate and transport modeling made in the D4 are seen by TDEC as positive and significant, but still don't necessarily provide a conservative assessment of risks to water resources from all contaminants of concern that are of interest. TDEC anticipates working to expand the scope of the risk assessment and ensure that on-site waste disposal can be done compliantly and cost effectively and welcomes the opportunity to work with DOE on improving the analysis of water pathway risk in the D4.

As DOE states in the response, TDEC approval of and comments on the work plan (TDEC letter dated November 27, 2013) for the investigation of site 5 did not indicate that the site would be rejected on the basis of its location across the upper NT-3 valley or make any recommendations for avoiding Site 5 on the basis of its footprint across a "blue line" stream. However, TDEC believes that both discussions with DOE and the content of the approval letter made it clear that the site investigation would be made at risk.

The letter states, on page 2, "*We appreciate DOE's cooperation with TDEC's request to perform this screening evaluation prior to the proposed plan and it should be understood that TDEC's acceptance of this Limited Phase 1 Site Characterization Plan for the Proposed Environmental Management Disposal Facility Site does not constitute an endorsement of the proposed EMDF location. It should also be understood that where the screening level evaluation should assist in understanding the hydrogeology and characteristics of the site, there are also other concerns that will have to be resolved prior to TDEC acceptance of the RI/FS.*"

TDEC regrets any miscommunication and has discouraged DOE from further characterization at this site and at other proposed sites until more progress can be made on resolving outstanding issues at EMWMF and agreement reached on issues concerning characterization and acceptance of waste at any future on-site facility.

Editorial Comments

1. Page E-32, Paragraph 2 (first full paragraph), Line 11: *South* is misspelled.

2. Page E-76, Paragraph 1, Line 3: *Nebulous* is misspelled.

3. Page E-81, Section 2.13.1.4, Line 12: It appears the word *and* should be removed from "*remolding and of bulk soil materials*".

4. E-124, Paragraph 1, Line 4: *Taxa* is the plural of *taxon*. Where an individual species is spoken about, *taxon* should be used (e.g., "*one taxa*" should be *one taxon*).

5. Page E-131, Paragraph 2, Line2: The genus name for ovenbird should be *Seiurus* instead of "*Seirus*".

6. Page E-135, Paragraph 4, Lines 1-4: *Quercus prinus* is included twice in this sentence.

7. Page H-4, List of Figures: Figure H-3 is omitted from the list of figures.

8. <u>Page H-10, Line 1, partial sentence:</u> *Ridg* should be *Ridge*.

9. <u>Page H-13, Line 6, middle of partial paragraph:</u> Extra period – "*...NT-2 and NT-3 at the EBCV site.. The modeling and PreWAC development ...*"

10. <u>Page H-17, Table H-1 Title:</u> "*Risk and DoseHI-based*"

11. <u>Page H-17, Last sentence:</u> "*Detailed description of thess methods ...*"

12. <u>Page H-53, Figure H-17:</u> "*...Model Layers 53-86...*"

<u>References</u>

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