Appendix B. Site Geology and Hydrology

ORR is located in the East Tennessee Valley, which is part of the Valley and Ridge Province of the Appalachian Mountains. The East Tennessee Valley is bound to the west by the Cumberland Mountains of the Appalachian Plateau Province and to the east by the Smokey Mountains of the Blue Ridge Province. The defining characteristics of the Valley and Ridge Province are the southwest trending series of ridges and valleys caused by crustal folding and vaulting due to compressive tectonic forces as well as the differential weathering of the various formations underlying the area. There are ten geologic formations underlying parts of the ORR, all are of sedimentary origin. These formations range in age from early Cambrian (530 mya) to early Mississippian (354 mya). From youngest to oldest they are:

1. Fort Payne Chert (Mfp)
2. Chattanooga Shale (MDc)
3. Rockwood Formation (Sr)
4. Sequatchie Formation (Os)
5. Reedsville Shale (Or)
6. Chickamauga Group (Och)
7. Knox Group (O€k)
8. Conasuaga Group (€c)
9. Maynardville Formation (€)
10. Rome Formation (€r)

Each of these formations is described briefly in Table B-1. All of the formations consist mainly of shales, limestones and siltstones. The three major geologic formations are the Chickamauga Group, the Knox Group, and the Conasuaga Group. These formations are considered ‘major’ based on the location of the various plants (ETTP, ORNL, and Y-12), location of the contaminant plumes (see Figure 4), and proportion of ORR underlain by these three formations.

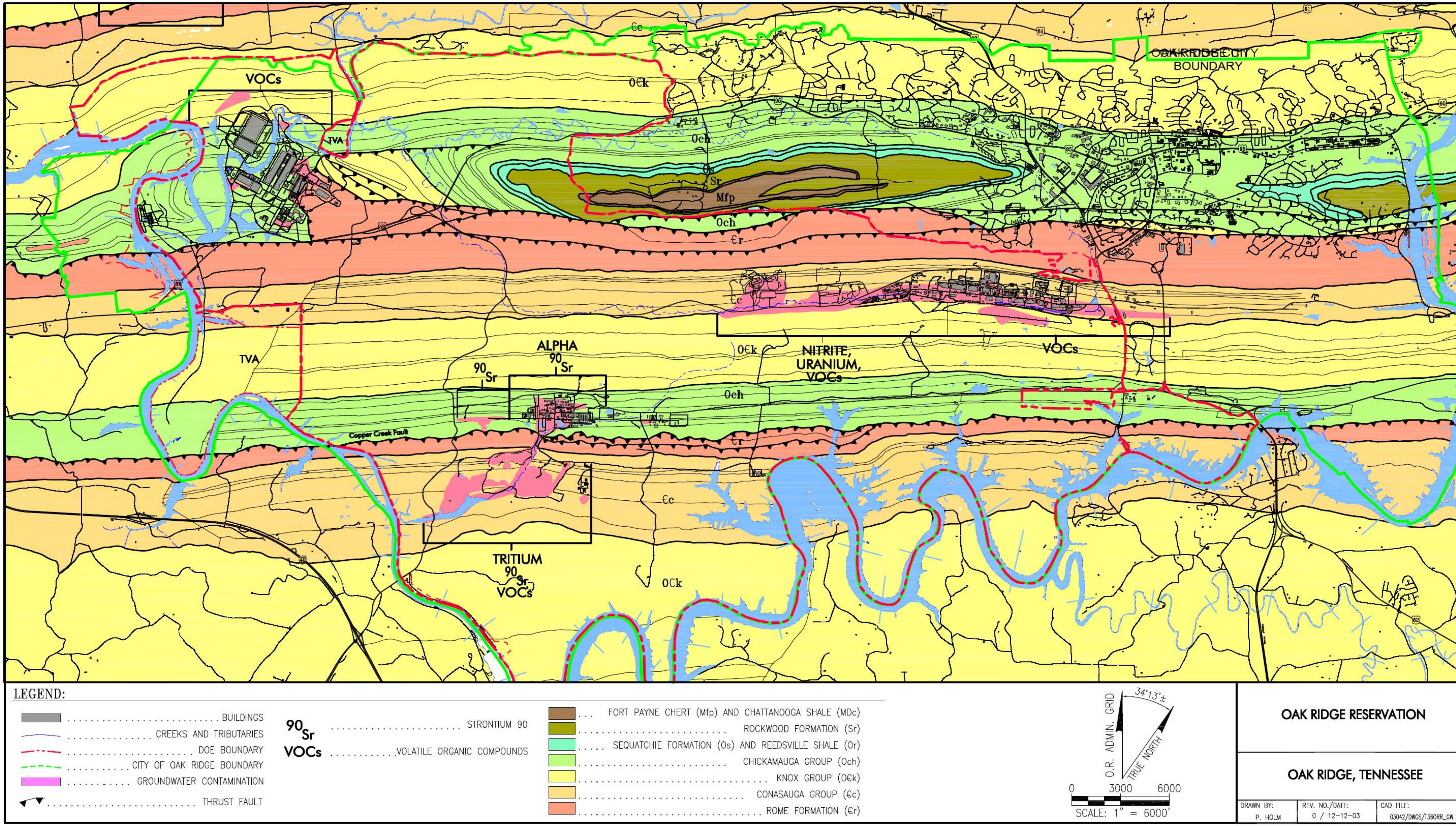

Figure B-1: Geologic Map of the ORR and Groundwater Contaminant Plumes

Table B-1: Hydrogeology of the Formations Underlying the Oak Ridge Reservation (USGS 2004)

Geologic Feature	Age	Geology	Description	Conductivity (at ORR)
Fort Payne Chert (Mfp)	Mississipian (early)	Bluish-gray Limestone	Thin outcrops at western edge of Valley and Ridge Province Average thickness 100' – 250'	Contains water in secondary openings. Yields from 0 to more than 300 gpm.
Chattanooga Shale (MDc)	Mississipian (early), Devonian (late)	Black, fissle shale	About 25 ft thick Very dark to black carbonaceous shale Overlies Rockwood Formation Underlies Fort Payne Chert	Low porosity and permeability. Yields little or no water to wells.
Rockwood Formation (Sr)	Silurian (early – middle)	Greenish to Brownish Shale, Limestone	Ranges in thickness from 150 – 1000 feet Limited outcrop results in limited recharge Some beds associated with iron ore (hematite) deposits Underlies Chattanooga Shale Overlies Sequatchie Formation	Not a good aquifer because of limited recharge. Groundwater occurs in fractures.
Sequatchie Formation (Os)	Ordovician	Shale, Limestone	Near ORR, thickness approx. 100ft. Overlies Chickamauga Group	Poor aquifer Groundwater occurs in fractures.
Reedsville Shale (Or)	Ordovician (late)	Shale	Uppermost layer of the Chickamauga Group Underlies the Sequatchie Formation Near ORR, thickness ranges from 250 – 400 feet	Poor aquifer Groundwater occurs in fractures.
Chickamauga Group (Och)	Ordovician (middle)	Limestone	ORNL (Bethel Valley) and ETTP are built on this group Approximately 2000' thick Overlies the Knox Group Underlies the Sequatchie Formation	AQUITARD - flow limiting strata Groundwater occurs in fractures Variable lithology results in varying conductivities
Knox Group (O€k)	Ordovician (early, middle), Cambrian (late)	Dolomite, Limestone	Overlies Conasauga Group (Shale) Massive calcareous unit that is the prominent formation in the Appalachian Valley ranging from 2000 – 4000 feet thick Contains fossil fuels (oil, gas) in other regions	AQUIFER Most important aquifer in the ORR area Groundwater occurs in joints and fractures Large springs are common Highly variable flow rates: from several gpm to several thousand gpm
Maynardville Formation	Cambrian (late)	Limestone, Dolomite	Off-site contamination at Y-12 occurs in this formation. Uppermost unit of the Conasauga Group Historically included in the Knox Group Relatively thin (thickness 60-250ft)	AQUIFER Generally yields several gpm up to 200 gpm
Conasauga Group (€c)	Cambrian	Shale, Limestone, Dolomite	Y-12 complex is built on this group Contains the largest waste management areas at ORR: Bear Creek Valley Melton Valley Very limited migration of contaminant plumes Most groundwater resurfaces to surface water Limestone layers retard downward migration of groundwater In some areas can be up to 2000' thick	AQUITARD – typically flow limiting strata Contains the AQUIFER subunit Maynardville Formation (limestone), which contains the only off-site contaminant plume from Y-12.
Rome Formation (€r)	Cambrian (early)	Shale, Siltstone	Underlies Conasauga Group Approximately 1500 feet thick	Groundwater occurs in fractures Upper zone is more permeable than lower zone Springs are common Wells can yield several gpm.

Since this health assessment is focused solely on groundwater in and around the ORR, it is necessary to first establish a basic understanding of general groundwater principles, particularly as they relate to the specific geology of the ORR. An important feature of the hydrology of the ORR is the interaction of groundwater with surface water. Depth to bedrock in the ORR is typically very shallow. In this physiographic region, groundwater flow tends to be localized (within a relatively small area such as a watershed), as opposed to regional (larger area such as the Oak Ridge Reservation or perhaps an even larger area), and flow-paths to surface water are short (USGS 1986b). So, a discussion on how groundwater and surface water interact is warranted.

In general, a stream can be described in three ways based upon it's interaction with groundwater. A stream can either be a *gaining stream*, a *losing stream*, (Figure 8) or a combination of both (Figure 14). In order to have a *gaining stream* system, the water table altitude must be higher than that of the stream (USGS 1998). The reverse is true for a *losing stream* system. Because the bedrock is very close to the ground surface in and around the ORR, and in many cases, occurs as outcrops, the streams are gaining. This is a very common situation in East Tennessee because of the topography of the area. The water table and the groundwater flow path typically mirror the undulations of the overlying land. Since surface water occurs at the low areas, groundwater often flows toward surface water. Therefore, the altitude of the water table is higher than that of the surface water. Recharge of groundwater around the ORR is spatially distributed (occurs over a large area as opposed to small outcrops or ridgelines), but discharge areas are at local springs, seeps as well as diffuse discharge into surface waters (MMES 1986, USGS 1986b, SAIC 2004). Indeed, groundwater constitutes much of the baseflow of many streams and tributaries in the area, including East Fork Poplar Creek (EFPC) (USGS 1989, SAIC2004).

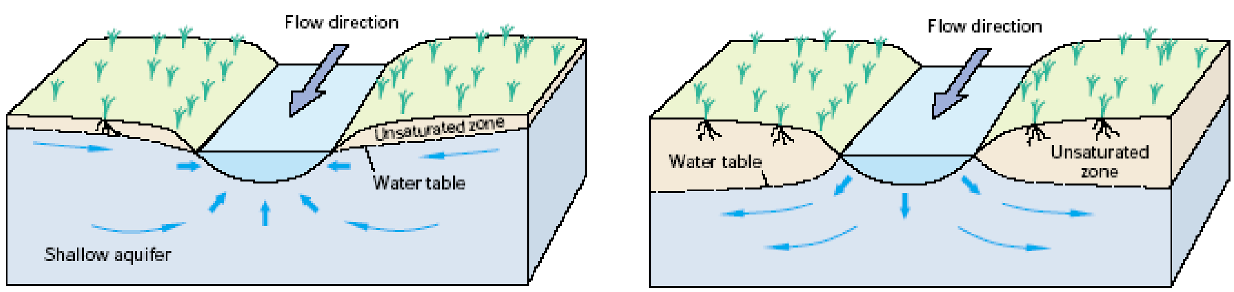

Figure B-2: Gaining (Left) and Losing (Right) Streams and Associated Groundwater Flow Direction

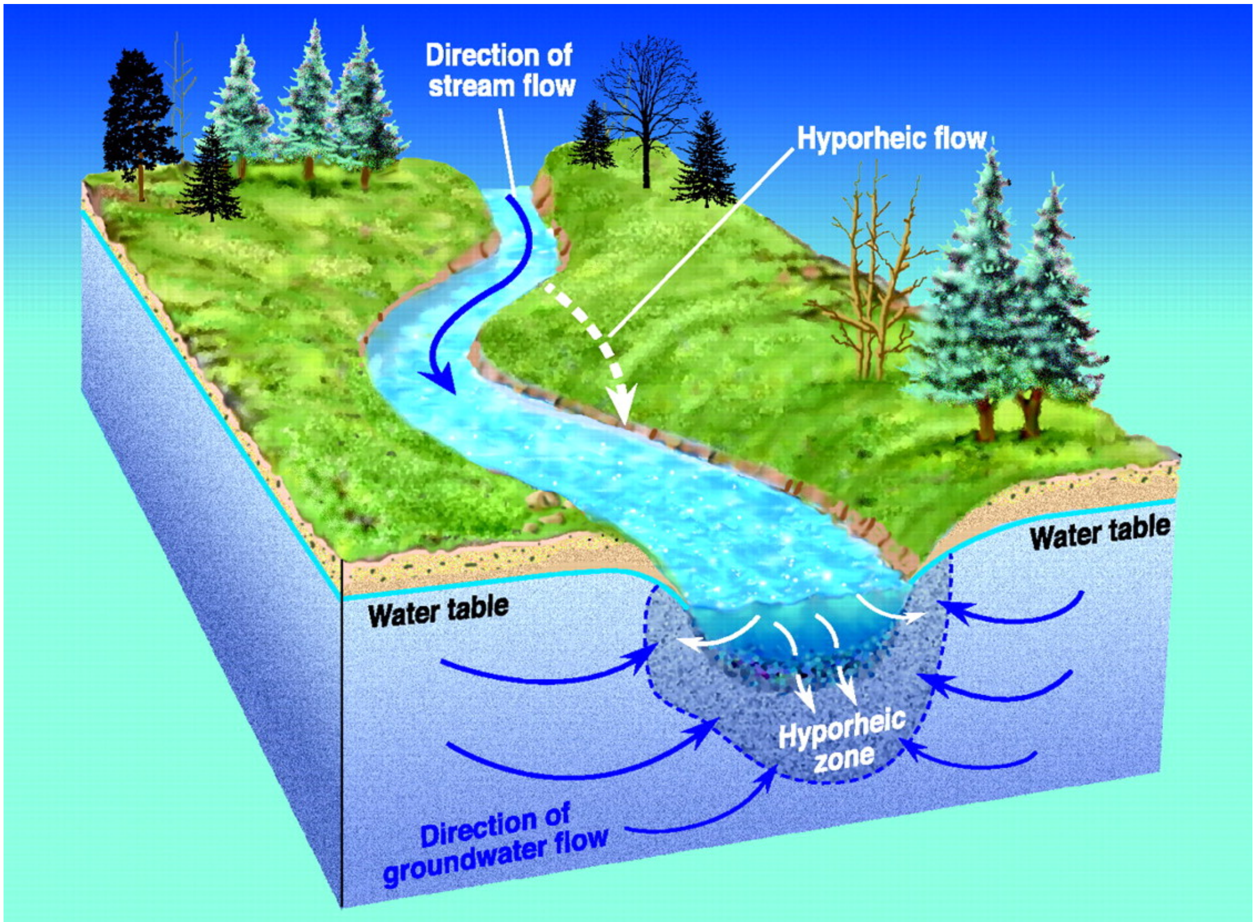

Figure B-3: Groundwater System Involving the Hyporheic Zones (Alley et. al 2002)

In the Bear Creek Valley watershed there are both gaining and losing reaches of Bear Creek. This illustrates the third groundwater-surface water system where there groundwater enters and exits the surface water at different sections of the stream. In this case the concept of hyporheic flow becomes relevant (Figure B-3). Hyporheic flow, or the hyporheic zone, refers to the areas beneath and adjacent to the stream where surface water and groundwater mix. In systems such as this, surface water contamination can percolate through the sediments and contaminate the groundwater (Alley et al. 2002).

Groundwater flow in this area (ORR) is influenced largely on the extent of fractures in the bedrock which create preferential flow paths. In the regional aquifers of East Tennessee, including those underlying the ORR, fractures in bedrock are typically limited to the upper extents of the bedrock formations and significantly decrease with depth (MMES 1986, USGS 1986b, USGS 1988, USGS 1989, SAIC 2004). The karst geology of the ORR makes accurate predictions of groundwater flow rate and direction problematic, particularly in the carbonate formations such as the Knox Group and the Maynardville Limestone. Most groundwater flow in these carbonate formations occurs in the shallow interval (<100 feet) through fracture flow and through solution-enlarged cavities. For example, there are several large solution cavities beneath Bear Creek which (along certain reaches) serve as a hydraulic drain to the Maynardville

Limestone (Lemiski 1994, SAIC 1996b). Groundwater will flow along bedding planes and along strike, especially in areas where carbonate units have well-developed conduit systems (ORNL 1982, USGS 1997). This is the case in the UEFPC Watershed where VOC contamination has migrated off-site from the Y-12 Complex and is migrating along strike in the Maynardville Limestone (ORNL 1982, SAIC 2004).

The numerous springs and seeps in the area support the notion of a very active shallow groundwater system in the ORR. Open cavities at bedrock outcrops in the ORR area range in size from small drains to easily enterable caves. These areas serve as rapid recharge areas and result in rapid flow rates through the interconnected fractures and solution cavities and can contribute to significant hydraulic head pressure changes during heavy rainfall events (SAIC 1996, Lemiszki 1994). The intermediate interval (100 feet – 300 feet) of the Maynardville Limestone is known to have high flow rates but does not receive the dilution effect that is seen in the shallow interval (SAIC 1996b), and therefore, is seen as an important interval with respect to contaminant transport. While fracture flow remains the dominant mode of groundwater movement at depth (below 300 feet), solution cavities and fractures are limited and decrease significantly beyond 300 feet.

While mapping springs and seeps in the ORR area, Lemiszki (1994) noted that most occurred along the banks of the Clinch River. For most of the year, these seeps and springs were underwater, but winter is when the Clinch River is in low stage and these karst features can be seen. There was a wide variety in flow rates observed. Some springs were mere trickles of water from bedrock outcrops while others were large volume springs (up to 25 gal/min) actively filling potholes along the river flats. This observation supports the notion that the incised meander (see Appendix A) of the Clinch River serves as an effective hydraulic barrier for groundwater flow.

An **incised meander** is formed when a stream's ancestral floodplain is uplifted causing intense downward erosion by the current stream. In East Tennessee, this uplifting caused the formation of many of the ridges in the area such as Black Oak Ridge, Pine Ridge, Chestnut Ridge, and Haw Ridge. The incised meander of the Clinch River cuts through these uplifted ridges creating "gaps". This deep, relatively rapid erosion of the bedrock creates exposed bedrock on the river banks. Groundwater is discharged to surface water where bedrock is exposed. Because of this deep erosion through bedrock, the Clinch River serves as an effective barrier to groundwater flow.

Groundwater flow in predominantly aquitard formations occurs mostly in the shallow interval (<100 feet) at the bedrock/residuum interface or in other preferential flow paths, such as fractures. In times of heavy precipitation, the elevation of the water table typically rises rapidly and discharge to streams increases. Groundwater flow through porous media in predominantly aquitard formations near the ORR is minimal.

Karst groundwater systems form through the chemical weathering of predominantly carbonate formations (Prothero and Schwab 1996). In the vicinity of the ORR, calcium carbonate ($CaCO_3$) limestones and calcium magnesium carbonate [$CaMg(CO_3)_2$] dolomites are eroded as rainwater (H_2O) combines with carbon dioxide (CO_2) to form carbonic acid (H_2CO_3). This weak acid solution dissolves limestone and dolomite according to the following reaction:

$$CaCO_3 \text{ (limestone)} + H_2CO_3 \text{ (carbonic acid)} \rightarrow Ca^{2+} \text{ (dissolved calcium)} + 2HCO_3^- \text{ (dissolved bicarbonate)}$$

SAIC (1996b) cites studies that show distinct groundwater geochemical facies in the Bear Creek Valley. In the shallow zone (<100 ft), the geochemical profile is similar to that of the equation above. This facies type indicates that there is a shallow water table and a short residence time, meaning that groundwater is quickly replaces by recharge as it is discharged to surface water. There is a gradual, but noticeable change in groundwater composition from Ca/Mg HCO_3 to a sodium bicarbonate (Na-HCO_3) at depth. This implies longer residence times at depth where groundwater mixes with older, less active brines. However, because of the interconnected karst networks in the area, Ca/Mg HCO_3 type groundwater occurs at many depths, but in the deepest wells Na-Cl groundwater dominates (SAIC 1996b).

Depending on the geology of the area, flow times from points of recharge to points of discharge can range from days to millennia (Figure 15). As is the case at the ORR, shallow surface water has short flow paths with relatively quick travel times. However, the limestones and dolomites of the Valley and Ridge Province often contain cracks, fissures, fractures, and solution cavities that can make groundwater flow direction and speed unpredictable (USGS 1997).

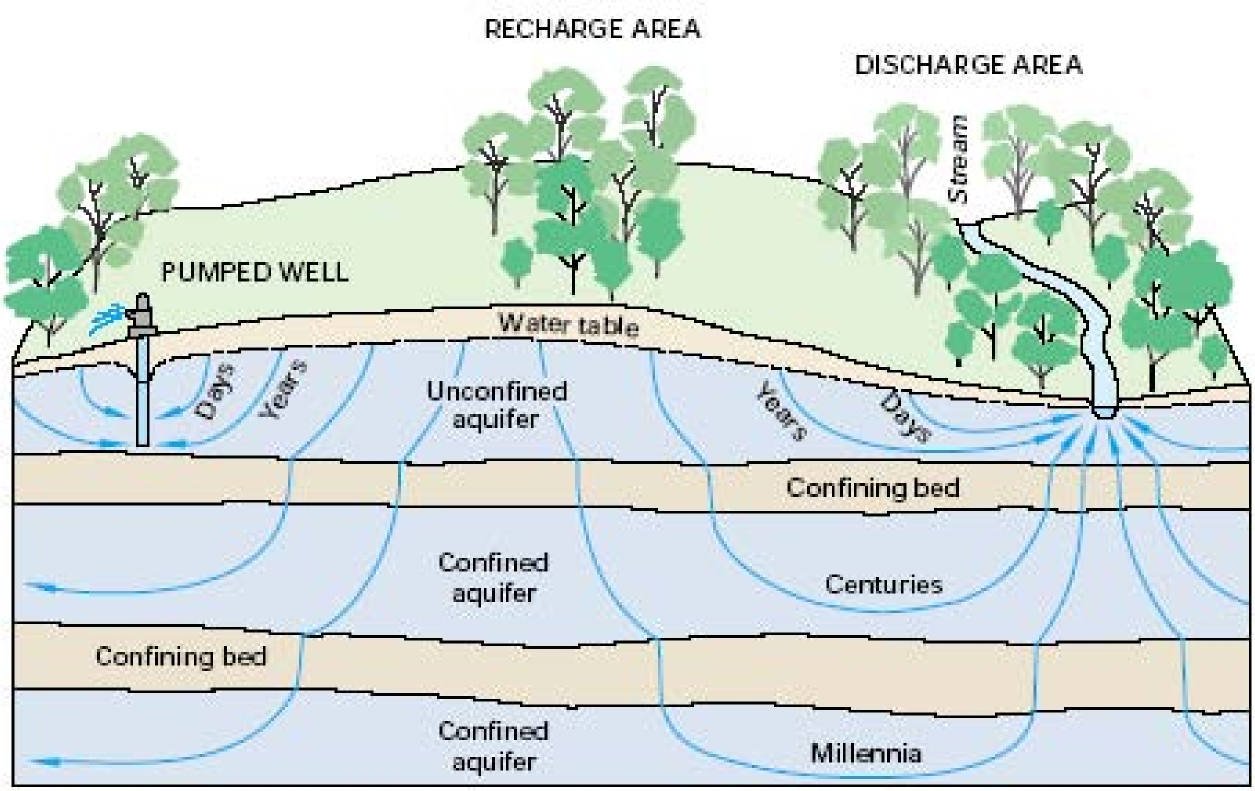

Figure B-4: Groundwater Flow Times

It is unlikely that contaminated groundwater at the ORR will flow beneath, and continue to flow away from, streams and rivers that surround the site. The vast majority of information available concerning the geology and hydrogeology of the site indicates that groundwater occurs as shallow flow with short flow paths to surface water (ORNL 1982, MMES 1986, USGS 1986b, USGS 1988, USGS 1989, SAIC 2004). The fractures and solution cavities present in the bedrock occur in shallow (0'-100' deep) bedrock and significantly decrease at depth. There is also evidence that beneath the alluvium at the bottom of the stream beds there is a silty-clay glei horizon that likely further impedes downward groundwater movement (USGS 1989). The incised meander (see Appendix A) of the Clinch River in bedrock represents a major topographic feature that prevents groundwater from passing beneath the river (ORNL 1982). The extensive interconnection between groundwater and surface water coupled with the fact that groundwater contamination sources at the ORR are in the shallow subsurface (with the exception of deep-well injection conducted at ORNL, which will be discussed in the Melton Valley Watershed section of this document), leads ATSDR scientist to conclude that on-site contaminated groundwater does not likely migrate beneath and away from streams and rivers either as slug-flow or in fractures, solution channels, or other conduits in the bedrock.

It is important for the reader to understand that ATSDR scientists acknowledge the fact that karst systems are notoriously difficult to fully characterize with respect to groundwater flow direction and rate. We have based our conclusions on currently available data concerning groundwater flow and specific contaminant fate and transport from well monitoring data. There are large solution cavities beneath ORR and the surrounding area which are often interconnected and have high flow rates. Some have been encountered in various well drilling activities or by casual observation, and some have yet to be discovered. It is our intention to assess the currently available data, and to arrive at a conclusion of whether the community has had (or is currently having) an exposure to contaminants in off-site groundwater.