CHARACTERIZATION TO SUPPORT WATERSHED-SCALE DECISION MAKING FOR THE BEAR CREEK WATERSHED AT THE OAK RIDGE RESERVATION, OAK RIDGE, TENNESSEE

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ABSTRACT

The Bear Creek Watershed is located on the U.S. Department of Energy's Oak Ridge Reservation in Oak Ridge, Tennessee. The 2800-acre watershed contains numerous disposal areas previously used for waste management by the Oak Ridge Y-12 Plant. Inventory records indicate that more than 18 million-kg (44 million-lbs) of uranium were disposed at three principal waste disposal areas in the eastern third of the valley. In addition, it is estimated that nearly 3,000,000 gal of waste oils and solvents were poured into debris-filled trenches. Aside from solid wastes that remain in place, contamination occurs in groundwater in the fractured shale bedrock below the disposal areas, including dense non-aqueous phase liquids. Contamination also occurs in groundwater in the karst bedrock downstream of the waste areas and in surface water streams draining the waste areas. To address contamination following a watershed management approach, data needs were identified for likely remedial actions using a data quality objectives planning stage. A conceptual approach was adopted at the watershed scale that focuses on minimizing risk to off-site receptors and reducing the footprint of impacted land before addressing risk reduction at the waste areas. Thus, a sampling strategy was formulated for the remedial investigation (RI) that focussed on measuring the rate of release of contaminant mass from the waste areas rather than defining the extent of contamination at each site in detail. The RI concluded that, as a result of the geology and hydrology of the valley, more than 99% of contamination leaving the waste units is transported through surface water in tributaries to Bear Creek or shallow groundwater (<50 ft). Transportation pathways from the waste disposal areas converge at an integration point (IP) located immediately downstream of the westernmost waste disposal area (the Burial Grounds). Mass balance of contaminant fluxes in tributaries and the total mass flux at the IP provides for a sitewide contaminant source ranking in terms of human health risk at the IP. Uranium is the constituent that poses most of the risk at the IP (98%), and most uranium comes from the Boneyard/Burnyard (61%), followed by the S-3 Site (26%) and the Burial Grounds (13%). The IP assessment provides a decision-making tool for the watershed since it: (1) identifies the primary contaminants contributing to the risks and hazards at the IP; (2) ranks the primary waste sources in terms of their contribution of contaminant mass flux at the IP, and (3) provides a tool for assessment of the effectiveness of remedial actions.

INTRODUCTION

Site Location

Bear Creek Valley (BCV) is contained within the Department of Energy's (DOE's) Oak Ridge Reservation (ORR), which is located in East Tennessee, ~32 km northwest of Knoxville. The valley is ~16.7 km long and spans the distance from the eastern end of the Oak Ridge Y-12 Plant to the Clinch River on the west. This paper discusses the results of the BCV Remedial Investigation (RI) that deals with that portion of BCV constituting the Bear Creek watershed. This area extends from the western boundary of the Y-12 Plant near the S-3 Ponds to ~0.4 km west of Highway 95 and the remainder of the Bear Creek Watershed north of BCV (Fig. 1).

BCV is an operationally and hydrologically complex site. There are multiple individual waste units within the valley that contain various types of hazardous and radioactive wastes derived from the Y-12 Plant. Groundwater is contaminated throughout the eastern 5 km of the valley; individual plumes from separate sources have commingled to produce seemingly continuous contamination of groundwater with multiple contaminants (1).

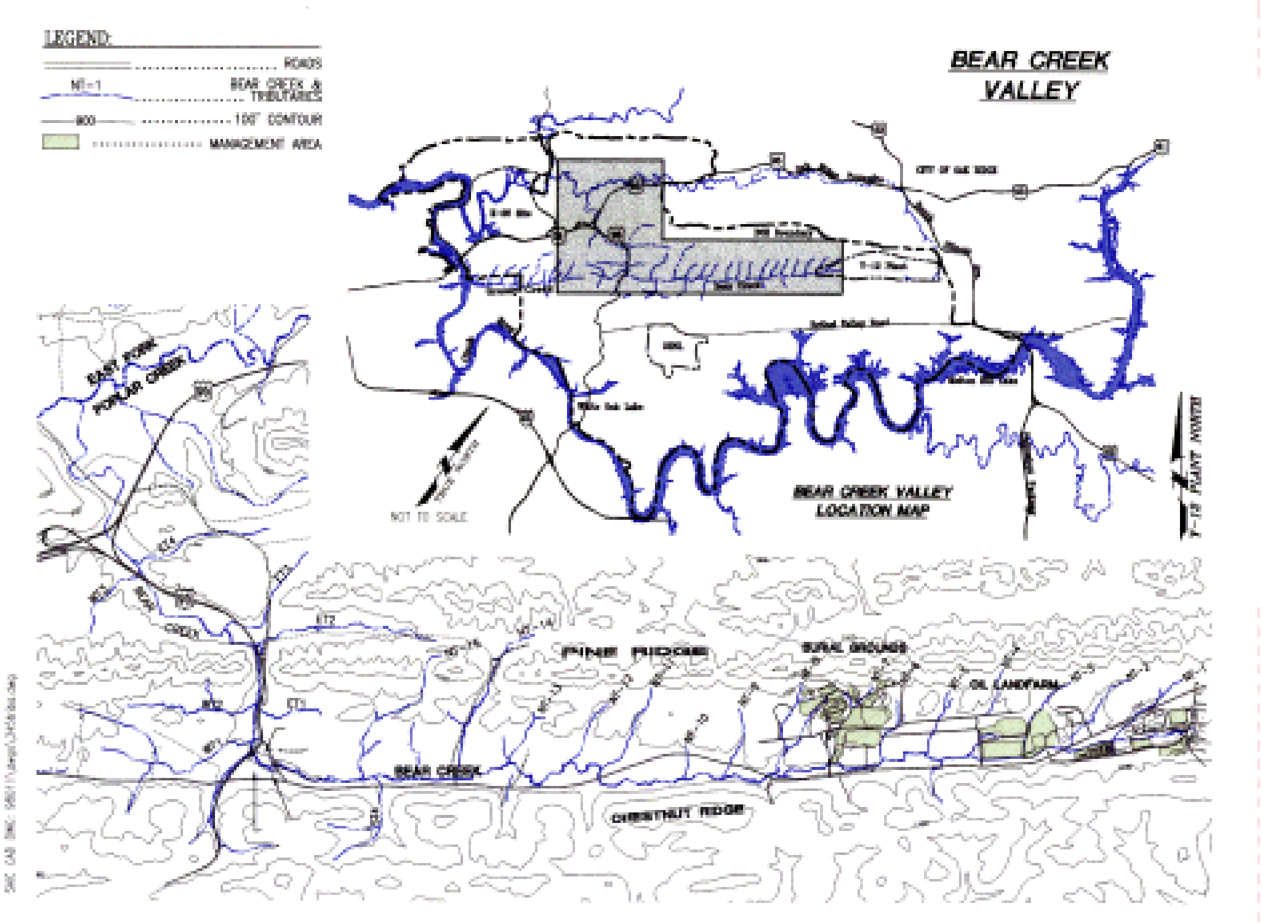


Figure 1. Location Map for Bear Creek Valley showing the main physical features of the watershed

Site History

During the operation of the Y-12 Plant since the 1940s, hazardous and radioactive materials were disposed at the various sites in BCV (2) (Table I and Fig. 2). Considerable volumes of solid hazardous and radioactive materials, including over 18 million-kg of uranium, are buried in unlined trenches at the Bear Creek Burial Grounds (BCBG) and Boneyard/Burnyard (BYBY). Hazardous liquids, including over 200 million L of uranium-contaminated nitric acid and 5 million L of waste oils and solvents, were disposed at the S-3 Ponds, Oil Landfarm (OLF), Hazardous Chemicals Disposal Area (HCDA), and BCBG. Since 1983, there have been five major site closures under the Resource Conservation and Recovery Act (RCRA) in BCV, and engineered caps cover parts of BCBG, OLF, HCDA, and the S-3 Ponds (3). With the exception of a leachate collection system at the BCBG, groundwater remediation has not been implemented. Remedial action for sites in the

BCV watershed is now governed under the Comprehensive Environmental Response, Compensation, and Recovery Act (CERCLA).

Approach to Characterization

Consistent with the Watershed Approach to remedial investigation/feasibility study (RI/FS) planning adopted by the Oak Ridge Federal Facility Agreement parties in 1994, the environmental media and waste sites in BCV were combined into a single Characterization Area encompassing the entire Bear Creek Watershed. The benefits of this approach have included:

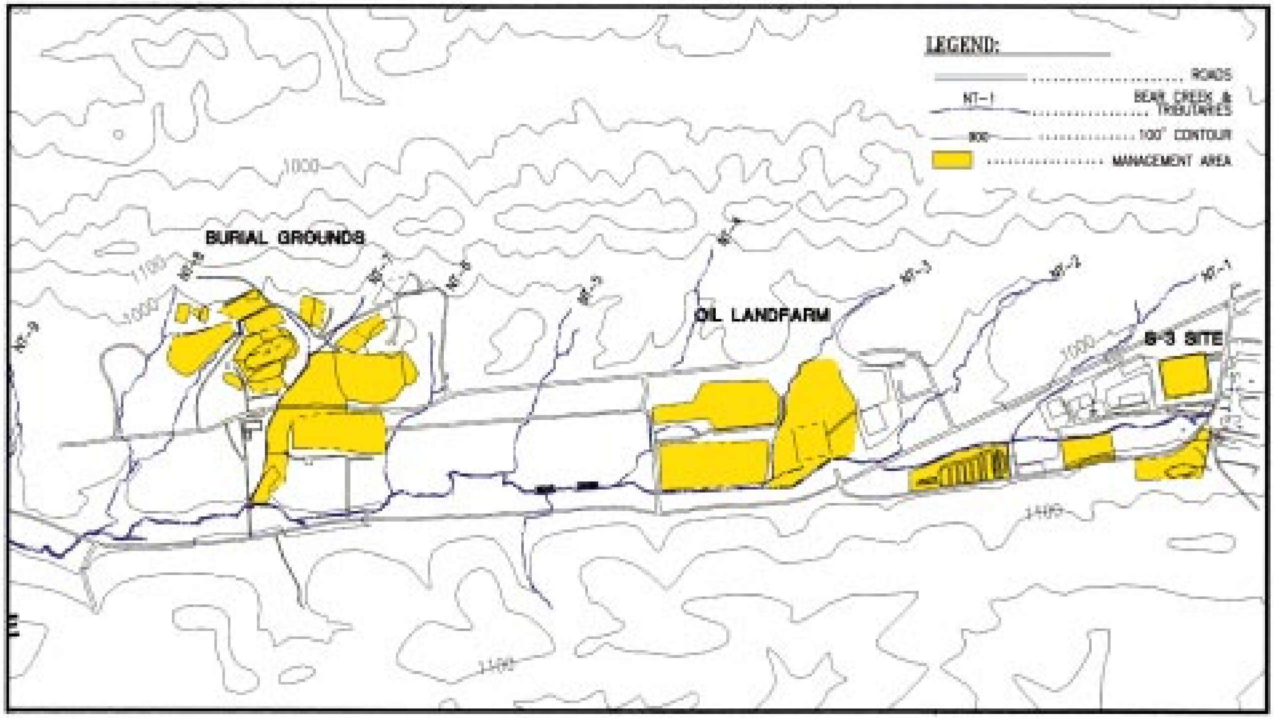


Figure 2. Location Map for the waste units in the Bear Creek Watershed

- a significantly reduced site investigation phase, with more reliance on historical data and waste inventory records as the basis for remedial action decisions;
- development of more consistent Remedial Goal Options (RGOs) across the multiple source units;
- an increased focus on development of an integrated prioritization for remedial actions, particularly for sites appropriate for near-term actions; and
- an overall reduction in cost and schedule for the RI/FS process.

The likelihood of important data gaps in the BCV RI was minimized by adherence to the data quality objective (DQO) process during the planning phase with a clear focus on the characterization needs of the decision-making process selected for the Bear Creek Watershed. Part of the DQO development was the recognition of two elements: (1) that while waste materials remain in-place, on-site risks for a potential future resident are unacceptable; and (2) that detailed, design-scale characterization of the watershed source areas was neither necessary nor practical at the RI stage. The DQOs were based on meeting the needs of the first major steps in the decision-making process, which include:

- prioritizing remedial action decisions;

- setting watershed remedial action objectives (RAOs) based on an integrated, valley-wide, future land use plan; and
- ordering implementation of highest priority remedial actions

Thus, the approach to characterization was focussed on measuring contaminant fluxes in the pathways for migration of contaminants away from the source areas. Contents of the source areas were sufficiently defined by a detailed analysis of inventory data.

While this approach to characterization has greatly reduced the schedule and cost of the RI, it has resulted in higher levels of uncertainty in some aspects of the remediation process; for example, remedial design. It was recognized that additional pre-design characterization would be conducted on a site-by-site basis once sites have been selected for remediation. Such a design study has recently been conducted at the BYBY that was focussed on the specific design needs of the selected remedy (4).

Table I. Summary of site characteristics and waste disposal practices for the main waste disposal areas in Bear Creek Valley

Site Characteristics	Waste Disposal Practices
S-3 Site	
The S-3 Site consisted of four unlined, 0.4-ha ponds. The site is covered with a Resource Conservation and Recovery Act (RCRA) cap	About 7.5 million L/yr. of uranium-contaminated nitric acid wastes and other liquid wastes were disposed in the ponds between 1951 and 1984.
Boneyard/Burnyard (BYBY)	
The BYBY consists of three sites: the Boneyard, the Burnyard, and the Hazardous Chemicals Disposal Area. This site was one of the earliest used waste areas in Bear Creek Valley	Uranium metal and various other wastes were disposed here in unlined trenches between 1943 and 1970. Some wastes were burned.
Oil Landfarm (OLF)	
The OLF was a 4-ha flat-lying area adjacent to BYBY. The site is now covered with an RCRA cap.	Approximately 3.8 million L of waste oils and machine coolants were treated by landfarming at the OLF between 1973 and 1982.
Bear Creek Burial Grounds (BCBG)	
The BCBG consists of several, principal waste-disposal units covering over 30 ha. These are designated as BG-A, -B, -C, -D, -E, and -J; the Walk-In Pits; the Uranium Vaults; and the Oil Retention Ponds. Each waste-disposal unit consists of a series of unlined trenches.	Solid and liquid wastes were disposed in unlined trenches between 1955 and 1989. Approximately 18 million kg of uranium metal and 1 million L of waste oils and chlorinated solvents were disposed here.

SITE ENVIRONMENTAL CONDITIONS

The geological and hydrogeological framework of BCV is complex and governs the direction and rate of transport of contaminants away from the source units. In fulfilling the DQOs for the Bear Creek Watershed, a detailed understanding of the environmental framework of the valley was established during the RI (5). Understanding this physical framework is the basis to decision making for the watershed and in selecting remedial strategies. The physical components of this system that are important in governing the movement of contaminants and which are described in the following sections include:

1. Low-permeability lithologies underlying the waste units maintain most groundwater and contaminant movement to the shallow (< 15 m depth) subsurface. Only where waste was in a dense liquid form have contaminants moved to greater depths under the waste units—dense non-aqueous phase liquids (DNAPL) at the BCBG and dense acid solutions at the S-3 Site.
2. Movement of groundwater and contaminants at the sources is directed along geological strike (almost perpendicular to the hydraulic gradient) to tributary streams. Contaminants are subsequently transported to Bear Creek via surface water.
3. Bear Creek and groundwater in the Maynardville Limestone, a karstified limestone underlying the axis of the valley, transport contaminants discharged from the tributaries along the valley and out of the watershed.

Site Geology

The geology of BCV displays an inclined layer-cake-style stratigraphy that is observed on a variety of scales: on a regional scale where limestone- and dolomite-dominated rock groups are interbedded with predominantly clastic shale groups, and on the scale of outcrops where clastic beds are interlayered with carbonate beds. This layered structure results in anisotropy of permeability and hydraulic conductivity that, especially in the predominantly clastic formations, exerts a strong influence on groundwater flow directions and contaminant migration.

BCV is underlain by rocks of three regionally important stratigraphic units: the Rome Formation, the Conasauga Group, and the Knox Group that typically dip 45° to the southeast (6). These units can be grouped into those that are mainly clastic and generally have low permeability, and those that are mainly carbonates and are generally more permeable (7). The Conasauga Group is a sequence of fractured shale, siltstone, and thin-bedded limestone that underlies all the waste units on the north side of the valley. Some formations in this group include laterally continuous limestone beds that can be several meters thick and, where karstification has enlarged fractures in limestone beds, high permeability zones may exist. The Maynardville Limestone, the uppermost member of the Conasauga Group, is a massively bedded limestone and dolomite with extensive karstification. This formation forms the floor of BCV and contains the channel of Bear Creek along most of the valley. Although this carbonate lithology has little matrix porosity, extensive karst formation has resulted in substantial secondary porosity and high permeability (8). Sinkholes are common at outcrop, and springs and seeps are common features. Overlying the bedrock on the ORR is unconsolidated material that consists mostly of weathered bedrock ranging in thickness from 3 to 15 m (9).

The primary permeability of the rocks underlying BCV is very low. However, diagenesis, fracturing, and solution weathering of bedrock have resulted in secondary porosity and increased permeability through which most fluid movement occurs (7, 10, 11). The formations are extensively fractured and, in the case of carbonate formations, extensively karstified, thereby enhancing their permeability. It is only in the Knox Group and the Maynardville Limestone that cavity systems are highly developed and extensive; however, many of the smaller limestone or dolomite beds within the predominantly clastic formations exhibit solution openings and cavities at shallow depth.

The orientations of well-connected fractures or solution conduits are predominantly parallel to geological strike and enhance the effect of anisotropy caused by layering. This results in dominance of strike-parallel groundwater flow paths. Fracture aperture width generally decreases with depth in all formations and, thus, restricts the depth of active groundwater circulation hydrology. Active (or open) fractures occur at greater depths in the Knox Group and the Maynardville Limestone than in the siliceous members of the Conasauga Group, and active groundwater circulation is deeper in these formations.

Hydrogeology

The hydrogeologic system in BCV is governed by the valley's geology: a lithology that is predominantly shale and limestone; a geologic structure characterized by tilted stratigraphy, faults, and fractures; and a geomorphology of parallel ridges and valleys. Listed below are the key geologic features that affect transmission of fluids in BCV (6, 7).

One of the main points raised by the conceptual model is that although the largest mass of water (and, consequently, the largest mass of contaminants) exits Bear Creek Valley via surface water in Bear Creek and its tributaries, groundwater is the principal pathway for water entering the tributaries. This is one observation that forms the building block of the integration point assessment and the prioritization model for the watershed.

For a 10-month monitoring period of BCV RI, it was estimated that 97% of water available for flow moved through Bear Creek (Table II). In addition, of water available for flow in the predominantly clastic formations outcropping on Pine Ridge, 94% drained off the ridge via surface water in tributaries. Flow in pathways on the flank of Pine Ridge (overland flow, soil interflow, and groundwater flow) have not been quantified; however, hydraulic monitoring data show that overland flow and soil interflow are only important during storm events, and recharge followed by groundwater flow to tributaries constitutes the main water flux pathway.

Table II. Water balance model for Bear Creek Valley above BCK 9.47 during the 10-month period from April 1994 – January 1995

Water Balance Component	10-Month Water Volume (L)	Reference/Method of Calulation
Precipitation (P)	4.8×10^{9}	National Oceanic and Atmospheric Administration
Evapotranspiration (ET)	2.8×10^{9}	Unknown parameter in water balance equation
Available water	2.0×10^{9}	P-ET
Gauged surface water flow	1.6×10^{9}	Gauged flow at BCK 9.47
Gauged subsurface flow	0.32×10^{9}	Gauged flow at SS-5
Ungauged subsurface flow	0.06×10^{9}	Groundwater flow model for BCV

Hydrogeology differs significantly between the formations of the Conesauga Group and mainly carbonate formations (such as the Maynardville Limestone) that outcrop in the center of the valley.

Hydrogeology of the Clastic Formations

Groundwater movement in the predominantly clastic formations is mainly by way of fracture flow (7, 12), and more than 95% of flow occurs through the shallow intervals of the formations, principally in the water table interval at the bedrock - residuum interface. In this interval of the groundwater regime, flow rates can be very rapid (up to 40 m/d) (13, 14) and may be even greater during transient storm events. The transient response of surface water streams to precipitation shows that both interflow through soils and groundwater flow through the water table interval are probably major components of the total flow during storm events.

Most flow in clastic formations occurs in the shallow interval. This interval includes the water table interval that usually occurs close to the bedrock/residuum interface. Most flow in the shallow interval is probably through high-conductivity zones that may exist at the bedrock/residuum interface (7) or through other preferential flow pathways in the bedrock. Flow in the shallow interval is oriented predominantly along geological strike, with discharge occurring at the tributaries to Bear Creek.

An upward hydraulic gradient occurs almost everywhere in the bedrock of the clastic formations that crop out on the southern flank of Pine Ridge. This upward hydraulic gradient is a function of the anisotropy of the geological formations and the average 45° dip of the beds. Transmissivity along bedding planes may be on order of magnitude greater than that across bedding planes. Groundwater in deep formations is hydraulically connected along the bedding planes to recharge areas located up dip at higher elevations up on Pine Ridge. As a result, deeper formations tend to have recharge zones farther up-slope than shallow formations; therefore, the hydraulic head in successively deeper formations generally increases.

Hydrogeology of the Carbonate Formations

Groundwater movement in the carbonate dominant formations has components of both fracture flow and flow through solution-enlarged cavities and conduits (10). Although most flow in the carbonate dominant formations probably occurs in the shallow intervals (< 30 m depth), a component of groundwater flow occurs in deeper intervals (> 30 m depth) (7). The shallowest intervals of the Maynardville Limestone in BCV are dominated by a maze-like system of interconnected cavities and solution-enlarged fracture. Bear Creek can be considered as one of the primary conduits for flow in this cavity system. The Maynardville Limestone crops out along the southern side of the BCV floor. This formation and Copper Ridge Dolomite act as a hydraulic drain for the valley. Flow in these formations is predominantly along strike and parallel to the maximum hydraulic gradient.

The shallow interval includes groundwater to ~30 m depth. Flow in this interval occurs through a maze of interconnected fractures and solution conduits and cavities and is closely associated with flow in Bear Creek. The channel of Bear Creek can be considered conceptually as one of the main hydraulic conduits in this conduit system. In this interval, groundwater flow is relatively rapid and, during storm events, recharge to this interval occurs as a quickflow. Contaminants are easily flushed through this interval, and dilution effects that arise from rainfall/recharge and quickflow mean that contaminant concentrations attenuate rapidly along strike.

Bear Creek displays losing and gaining reaches where groundwater is recharged and discharged to the surface, respectively. Major gaining reaches along strike are associated with large springs in the floodplain of Bear Creek (SS-2, -5, -6, -7, and -8 on Fig. 1), which may be sites of upwelling groundwater from deep flowpaths in the Maynardville Limestone and Knox Group. The locations of these springs may be controlled by large-scale geologic structure, such as across-strike faults, or thinning of the Maynardville Limestone due to stratigraphic changes or faulting.

Hydraulic Variability

The dynamic nature of the hydrology of BCV is extremely important, both for clastic- and carbonate-dominated formations. The nature, rate, and direction of groundwater flow are transient and vary based on the climatological conditions. Variations occur on different scales: an annual cyclic variation resulting from seasonal climate changes and short-term variation resulting from the response to individual storm events. Piezometric head in groundwater wells and baseflow in streams relate both to the amount of precipitation and the rate of evapotranspiration. In general, flow in streams, as well as groundwater elevations, peaks during late winter and early spring because annual precipitation is greatest during this time period, and moisture demand from plants is at a minimum. Conversely, during the summer and fall, precipitation is usually relatively low and evapotranspiration is high. During this time, flow in most tributaries to Bear Creek ceases and groundwater elevations fall to a minimum.

CONTAMINATION IN BCV

Groundwater and surface water throughout the upper third of BCV is contaminated with multiple contaminants: uranium, volatile organic compounds (VOCs), nitrate, and metals. Contamination in groundwater and surface water extends away from the sources on the Nolichucky Shale to the karstified Maynardville Limestone in the axis of the valley, which acts as the principle pathway for contaminants moving along the valley. The highest concentrations of water contamination occur at the sources. Soils outside the waste units are sporadically contaminated; however, there is little evidence for secondary soil contamination.

Burial Grounds

Groundwater and surface water at the Burial Grounds are extensively contaminated with VOCs, principally tetrachloroethene (PCE), trichloroethene (TCE), and 1,2-Dichloroethene (1,2-DCE). Contamination extends to over 150 m depth in the Nolichucky Shale, and the concentration of total VOCs exceeds 1,000 μg/L in numerous wells (up to 16% of solubility of the chemicals in some cases). DNAPL has been sampled in two wells at over 85 m depth, and ganglia of free product are probably distributed throughout the subsurface below the waste units (15, 16). Radiological contamination in groundwater is sporadically detected. The mean gross alpha activity detected at the BCBG is 7.1 pCi/L, and only three wells out of 52 wells detected radiological contamination more than once between 1991 and 1994 (overall 41 detects of 418 samples). Surface water is contaminated with VOCs but also contains uranium (mean of 68 pCi/L in NT-8) and sporadic metal contamination.

Considering that over 18 million kg of uranium are buried in unlined trenches at the BCBG, radiological contamination of groundwater is conspicuous by its apparent virtual absence. This highlights the control that the form of the waste material has on the resulting distribution of groundwater and surface water contamination in BCV (Fig. 3). Where wastes were dense liquids and the mechanism for release is infiltration of the waste liquid (as is the case for the S-3 Site and the solvents at BCBG), contamination occurs in groundwater below the shallow zone (<15 m). Where contamination is in solid form and the mechanism for release is chemical leaching (as is the case for BYBY and uranium at the BCBG), contamination of groundwater is restricted to the shallowest flow paths that discharge into tributaries (Fig. 3). Thus, for the BCBG, where most wells are located across strike from the trenches and screened below 15 m depth, groundwater contamination is not detected but can be inferred from surface water contamination.

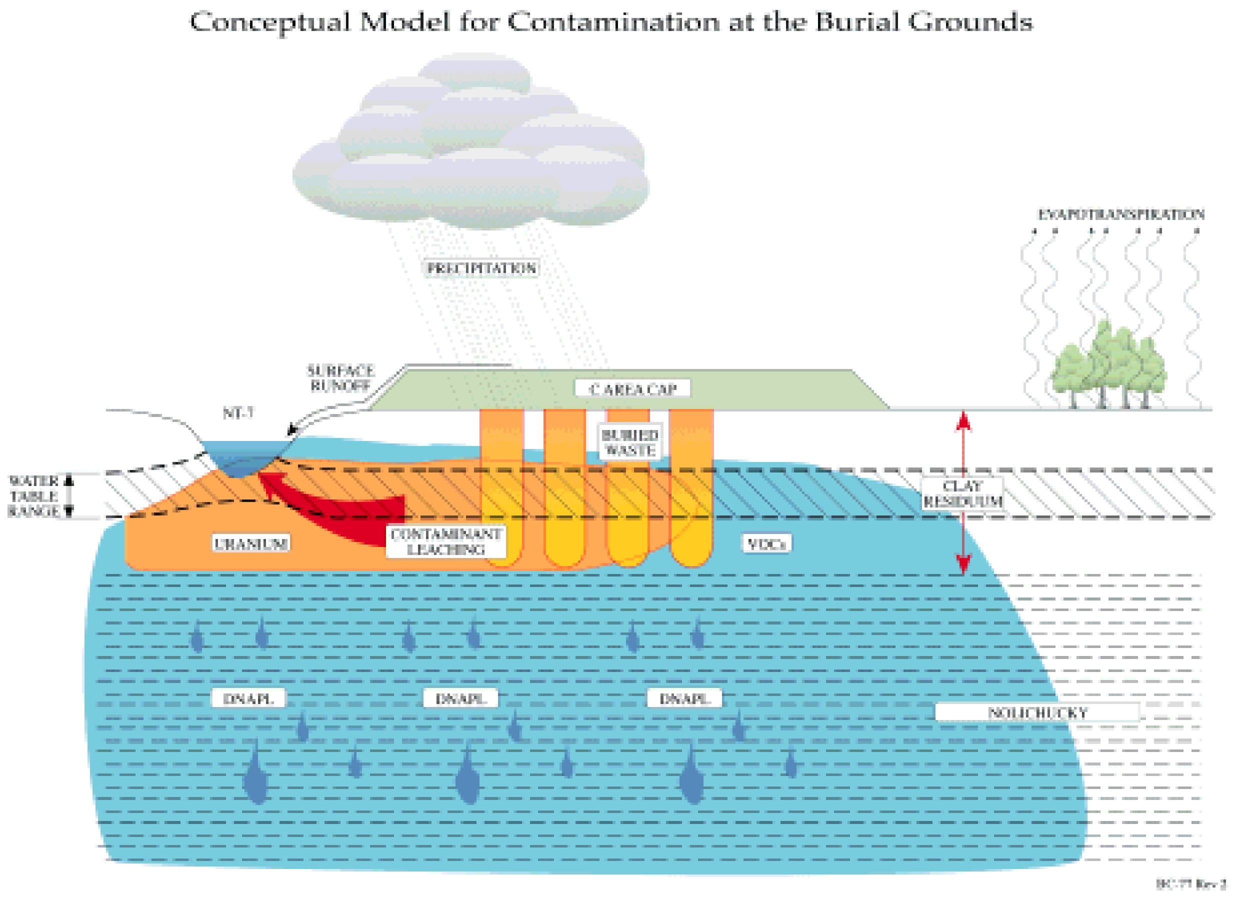


Figure 3. Conceptual model for contamination at the Bear Creek Burial Grounds

OLF Area

Of the three sites at the OLF area, BYBY poses the greatest threat to off-site migration of contaminants. Groundwater at BYBY is contaminated with uranium, mercury, and VOCs, and surface water in the tributary draining from this site (NT-3) contains the highest concentrations of uranium found in surface water in the Bear Creek Watershed (up to 1 mg/L). A pre-design study conducted at this site has identified 150,000 m^3 of uranium-contaminated fill material that had been bulldozed into the low area that formed the former floodplain of NT-3. Of this material, over 27,000 m^3 contained residue from burning of waste uranium metal, and this is the primary source of the groundwater and surface water contamination associated with this site. Concentrations of uranium in unfiltered samples of groundwater in this follow-up study ranged from 0.14 to 161 mg/L. Groundwater contamination is restricted to a shallow perched groundwater table that saturated most of the burned waste material.

Groundwater contamination at OLF and SL-1, the other two sites in the cluster of sources at the Oil Landfarm Area, is of lesser concern. Groundwater at OLF is contaminated with VOCs in the shallow zone (<15 m depth). No contaminants were identified in the surface water body that drains OLF–NT-4.

S-3 Site

Liquid wastes that remained in the former S-3 Ponds were neutralized and treated during the RCRA closure activities. The remaining sludges may leach uranium, ^{99}Tc, and metals to shallow groundwater. Most contamination moving to Bear Creek from this site is derived from the plume of uranium- and nitrate-contaminated groundwater that extends almost 1000 m along strike from the ponds in the Nolichucky Shale. This plume formed during operations at the former S-3 Ponds by direct infiltration of uranium-contaminated nitric acid wastes to groundwater. Concentrations of nitrate exceed 10,000 mg/L in the center of the plume indicating little or no dilution of the original acid solutions. These acid wastes were dense compared to groundwater, and contamination extends to over 100 m depth.

The plume is chemically stratified due to chemical reactions with bedrock that have retarded migration of uranium and some metal contaminants to the shallow (< 15 m) groundwater. Directly below the former ponds, the highest concentrations of nitrate that exceed 10,000 mg/L occur below 30 m depth but contain no detectable uranium. Conversely, activity concentrations of uranium in shallow groundwater (< 30 m depth) below the ponds have exceeded 10,000 pCi/L. This has resulted in variable contaminant suites at the multiple discharge points for the plume. In upper Bear Creek groundwater discharging to the creek contains 1 to 3 mg/L uranium but < 10 mg/L nitrate. In the tributaries along strike, NT-1 and NT-2, groundwater discharging to seeps contains over 2,000 mg/L but less than 0.05 mg/L uranium.

Bear Creek and the Maynardville Limestone

Bear Creek and the Maynardville Limestone represent the downgradient pathways and receptors of contaminants migrating away from the sources on the Nolichucky Shale. The primary sources of contaminant input to Bear Creek and the Maynardville Limestone from the source sites are the source areas previously discussed:

- S-3 Site: Nitrate and radionuclides via discharge from NT-1 and NT-2, shallow groundwater discharges to Bear Creek, and shallow groundwater discharges directly to the Maynardville Limestone.
- BYBY: Uranium via discharge from NT-3 and direct runoff to the Floodplain, and uranium and VOCs by shallow groundwater discharge into the Maynardville Limestone.
- BCBG: VOCs and uranium via discharge from NT-7 and NT-8.
- Past releases of TCE and 1,2-DCE from an unknown site or Rust Spoil Area.

Nitrate, uranium, and ^{99}Tc contamination occurs close to the S-3 Site and continues west as far as BCK 9.47 and Picket A (Fig. 4). Nitrate contamination in groundwater occurs further (2590 m) west, but uranium and ^{99}Tc have not reached this far west. TCE- and 1,2-DCE-contaminated groundwater occurs in groundwater wells at the Spoil Area 1 and Rust Spoil Area. Concentrations of TCE and 1,2-DCE in groundwater increase downgradient of the Rust Spoil Area at Picket C and adjacent to BYBY.

At monitoring points downgradient of BYBY (groundwater and surface water), the plumes from the S-3 Site and BYBY source areas are completely commingled. It is only possible to identify BYBY as a contributor to the inorganic and organic Maynardville Limestone contaminant plumes because of the relative concentrations of contaminant in groundwater, surface water, and springs. Progressive changes in relative concentrations of contaminants in groundwater along the valley reflect the inputs to the Bear Creek/Maynardville Limestone system and suggest that, after entering Bear Creek, contaminants can migrate downward into the Maynardville Limestone.

Surface water in Bear Creek and shallow groundwater in the Maynardville Limestone are closely interrelated and constitute 96% of water flowing along the valley. Contaminants in these media pathways are quickly diluted by rapid recharge of rainwater and inputs from noncontaminated tributaries. Concentrations of contaminants in the intermediate and deep groundwater pathways (30 to 90 m depth) are not attenuated as rapidly as those in shallow groundwater because this interval is somewhat isolated from inputs from recharge and tributaries. Plumes of groundwater contaminated above maximum contaminant levels in the 30 to 90 m depth interval are more continuous and extend further along the valley.

Migration Pathways

Based on the understanding of the physical and chemical processes in BCV, a conceptual model was developed that depicts the migration of contaminants in the valley (Fig. 5). Contaminants migrate away from the waste disposal units using the following pathways:

- Contaminated shallow groundwater at sources on the Nolichucky Shale migrates through fractures along geological strike and discharges to tributaries, or directly to Bear Creek, causing the tributaries and Bear Creek to become contaminated.
- Contaminants in deep groundwater in the Nolichucky Shale also migrate through fractures along strike and discharge to tributaries. However, contaminant pathways in the deep groundwater can underflow proximal tributaries and/or springs and be a source of contamination in neighboring tributary subwatersheds.
- After entering tributaries, contaminants migrate in surface water directly to Bear Creek. Bear Creek intermittently loses and gains water from groundwater in the Maynardville Limestone throughout the length of the valley.
- Losing reaches of Bear Creek cause groundwater contamination in the Maynardville Limestone. Gaining reaches of Bear Creek are associated with large springs at the base of Chestnut Ridge, some of which have contaminated discharge (SS-1, -4, -5, and -6) (Fig. 2).
- Surface water in Bear Creek and shallow groundwater in the Maynardville Limestone constitute 96% of water flowing along the valley. Contaminants in these media pathways are quickly diluted by rapid recharge of rainwater and inputs from noncontaminated tributaries.
- Deep groundwater in the Maynardville Limestone (30 to 90 m depth) constitutes <4% of water flowing along the valley. Concentrations of contaminants in this and in the deep groundwater pathway are not attenuated as rapidly as those in shallow groundwater; this pathway is an important source of long-distance groundwater transport along the valley.
- Contaminant concentrations in shallow groundwater in the Nolichucky Shale and the Maynardville Limestone and in surface water are diluted by recharge during storm events, and show seasonal trends of lower concentrations during periods of high rainfall.

INTEGRATOR POINT/PLANE ASSESSMENT

To determine the contribution of each contaminant source to the valley-wide contaminant flux migrating offsite from BCV, an integrator point/plane (IP) assessment was completed. Contaminants migrating from the waste sites in BCV converge at BCK-9.47/SS-5 (the IP for BCV). More than 99% of available water from the upper portion of the valley passes through this location as either surface water or groundwater. Using a mass balance calculation, 69% of uranium measured at BCK-9.47 and SS-5 was measured at monitoring stations in tributaries to Bear Creek (gauged flux) (Table III). The remaining 31% was not measured in the RI (ungauged flux) but is expected to be derived from migration of uranium directly to Bear Creek and the Maynardville Limestone via shallow groundwater at the BYBY and S-3 Site sources.

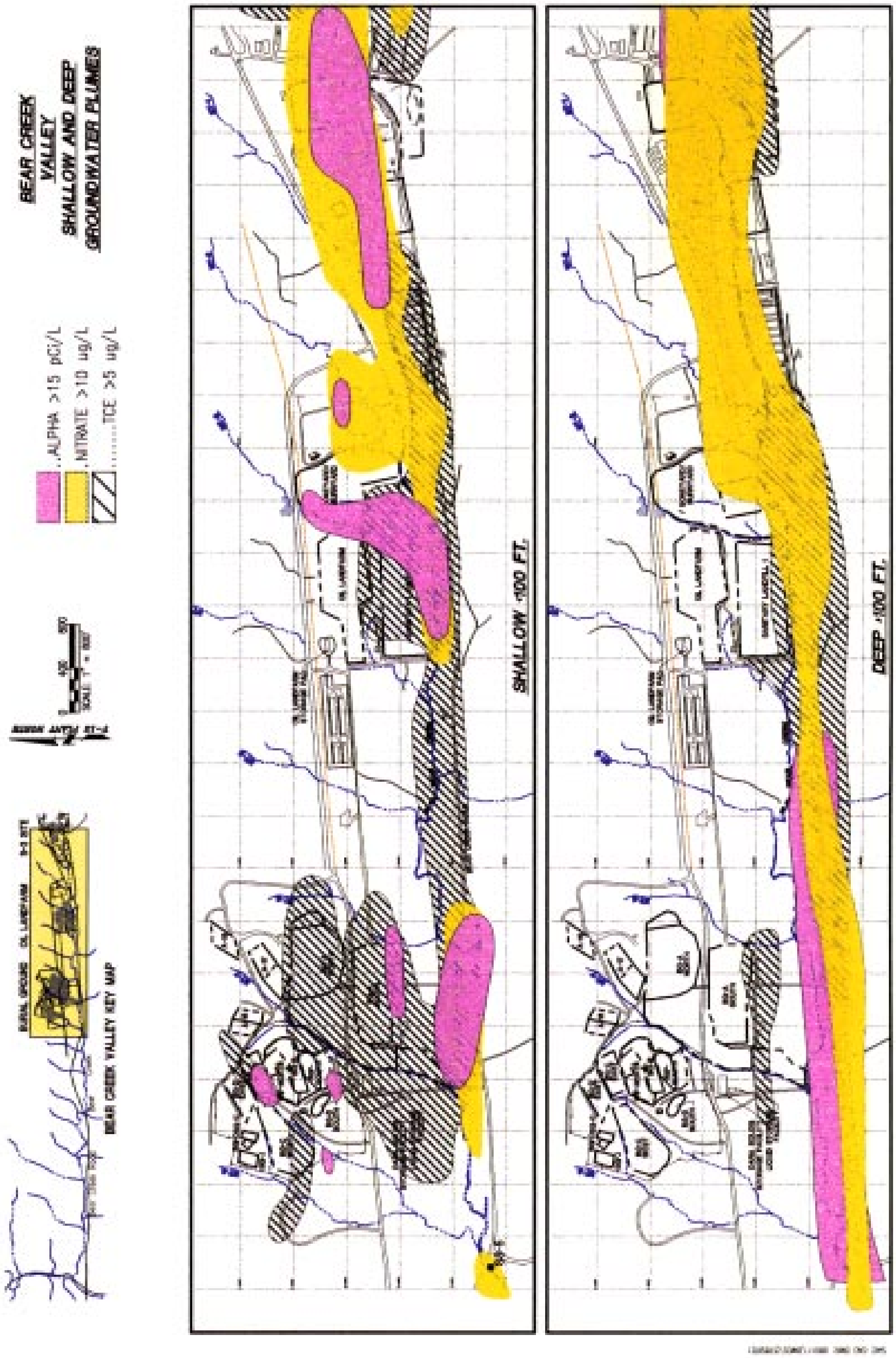


Figure 4. Extent of groundwater contamination in Bear Creek Valley

Assuming a similar distribution of the ungaged flux as the gauged flux, then ~ 61% of the uranium found in surface water and groundwater at the IP is derived from BYBY. The S-3 Site is the second major contributor of uranium (26%), and this site contributes approximately 94% of the nitrate contamination at the IP. Approximately 13% of the uranium is derived from the Burial Grounds. VOCs at the IP are mainly derived from BCBG; however, most VOCs (82%) discharged to surface water at source areas volatilize before reaching BCK-9.47. Boron was not measured in tributaries in the RI but is probably mostly derived from the BCBG, where it was reported to be a contaminant in waste liquids that accompanied uranium tailings disposal and is found in the current leachate collected in BCBG.

Table III. Mass balance of fluxes for uranium and nitrate for the 10-month period from April 1994 - January 1995

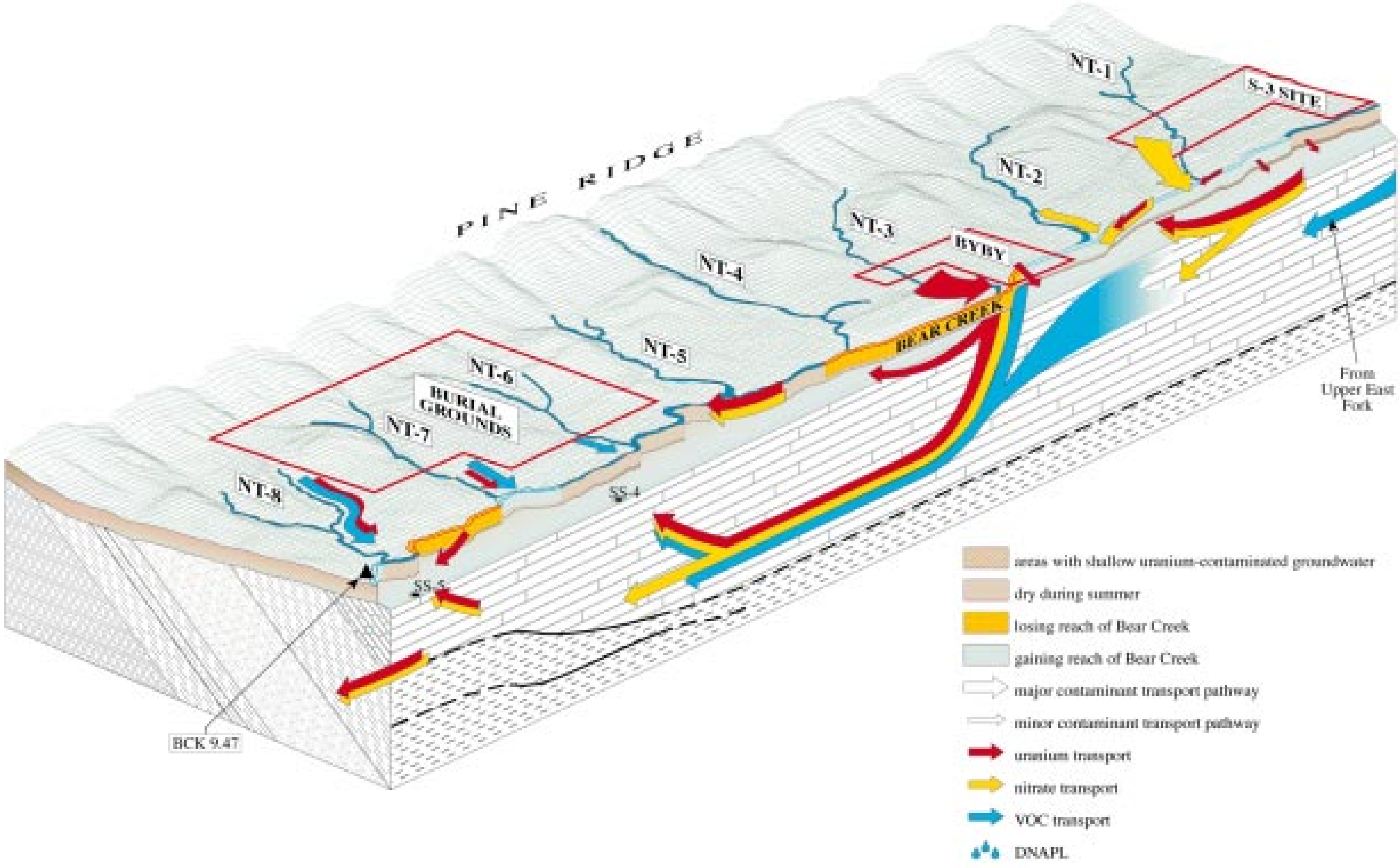
Subwatershed	Sources	Uranium Flux (kg)	Uranium Flux (%)	Nitrate Flux (kg)	Nitrate Flux (%)
Upper Bear Creek and NT-1	S-3 Site	18.65	17	11450	128
NT-2	S-3 Site	-	-	1500	17
NT-3	Boneyard/Burnyard	42.9	39	-	-
NT-4	Oil Landfarm	-	-	-	-
NT-5	-	0.22	<1	785	9
NT-6	Bear Creek Burial Grounds	1.04	1	18.3	<1
NT-7	Bear Creek Burial Grounds	2.98	3	48.1	<1
NT-8	Bear Creek Burial Grounds	9.72	9	46.7	<1
Ungaged flux[1]	Boneyard/Burnyard and the S-3 Site	33.7	31	-4920	55
IP	All	109	100	8940	100

[1] Negative ungaged flux for nitrate indicates a net sink for nitrate that is not accounted for in the model. This sink for nitrate is attributed to ungauged groundwater flux, denitrification, and plant uptake.

CONCLUSIONS

CERCLA decision making for the BCV watershed will be based on risk. Using fluxes for all chemicals measured at the IP, the relative contributions of each waste unit to human health risk at the IP were calculated (Table IV). This provides DOE with a tool to prioritize remedial action in the watershed based on risk, by identifying the sites that cause the most risk to potential future off-site receptors. BYBY contributes most to the human health risk to BCK 9.47 (38.5%) followed by BCBG (23.0%) and the S-3 Site (17.4%). Ungauged uranium fluxes contribute 20.7% of risk at BCK 9.47. It is believed that most of the ungauged uranium flux originates in the BYBY and the S-3 Site. These two sites also contribute the largest percentage of total toxic effects at BCK 9.47.

The IP assessment is the culmination of analysis, tens of thousands of data points, and is based on the comprehensive understanding of the physical and chemical environmental conditions in BCV that are manifested in the site conceptual model. This assessment meets the needs of decision makers that were defined in the DQOs for the RI. It provides a prioritization of source areas based on the relative contribution to downgradient contamination. Using the IP as a basis for prioritizing actions the first two remedial actions, selected for the Bear Creek watershed are BYBY and the S-3 te.



CONCEPTUAL MODEL FOR CONTAMINANT MIGRATION IN BEAR CREEK VALLEY.

Figure 5. Conceptual model for contaminant migration in Bear Creek Valley

Table IV. Results of the Integrator Point (IP) assessment

Subwatershed	Sources	Cancer Effects		Toxic Effects	
		Relative Risk	**Contaminats**	**Relative Risk**	**Contaminats**
Upper Bear Creek and NT-1	S-3 Site	17.4	Uranium	26.5	Uranium, nitrate
NT-2	S-3 Site	<0.1	-	1.7	Nitrate
NT-3	Boneyard/Burnyard	38.5	Uranium	27.7	Uranium
NT-4	Oil Landfarm	<0.1	-	0.2	-
NT-5	-	0.45	-	1.7	-
NT-6	Bear Creek Burial Grounds	0.93	-	0.6	-
NT-7	Bear Creek Burial Grounds	9.1	Uranium, PCE, TCE.	5.1	Uranium, vanadium
NT-8	Bear Creek Burial Grounds	13.0	Uranium, PCE, TCE.	7.1	Uranium
Ungaged	Boneyard/Burnyard and the S-3 Site	20.7	Uranium	29.4	Uranium
IP	All	100	Uranium, PCE, TCE	100	Uranium, nitrate, vanadium

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