

Hydrogeologic Conditions at the Niagara Falls Storage Site, New York – 14142

Bill Frederick, US Army Corps of Engineers, Buffalo District, Buffalo, NY, USA

John Busse, US Army Corps of Engineers, Buffalo District, Buffalo, NY, USA

ABSTRACT

The Niagara Falls Storage Site (NFSS) is located in the Town of Lewiston, NY and a parcel contained within the previous Lake Ontario Ordnance Works (LOOW) property. The LOOW manufactured trinitrotoluene (TNT) from 1944 to 1946, after which the Manhattan Engineering District (MED) used the land to stage, store, transfer, and contain radiologically contaminated uranium-ore residues derived from early atomic weapons manufacturing [1].

Site operations caused soil, sediment, and groundwater contamination that lead to several remedial actions, which culminated in the construction of the Interim Waste Containment Structure (IWCS) on the NFSS. The site is surrounded by Chemical Waste Management Chemical Services, LLC (CWM) to the north and Modern Landfill, Inc. (ML) to the east and south; other private commercial and public lands border the site to the west and northeast. Natural water-quality conditions, anthropogenic impacts from historic operations, and past remedial actions have produced a complex picture of groundwater conditions. Geochemical sampling, groundwater flow mapping, and contaminant-transport modeling have coalesced into a hydrogeochemical conceptual site model that guides groundwater flow and transport analyses for the NFSS and surrounding area. The groundwater data and modeling indicate that 1) uranium impacts derived from past ore-residue handling operations still exist, 2) impacts from other inorganic and organic compound exist in TNT manufacturing and support areas, 3) residual soil contamination still exists in certain areas of the site, and 4) contaminant transport from past source areas is minimal [1].

The scale of the NFSS and complexity of prior operations provide many investigatory challenges. Public interest in this legacy site is significant at many levels and site-related risks dominate stakeholder discussions.

INTRODUCTION

The NFSS is located in the Town of Lewiston, NY, approximately 30.6 kilometers (km) (19 miles) north of Buffalo, NY. The NFSS is a 77 hectare (191-acre), federally-owned property that was originally part of a 3,035-hectare (7,500-acre) World War II explosives plant called the Lake Ontario Ordnance Works (LOOW). From 1944 to 1954, the Manhattan Engineer District (MED) and the Atomic Energy Commission (AEC) (a predecessor to the U.S. Department of Energy [USDOE]) brought radioactive wastes and residues to the LOOW Site. Through the 1970s, the AEC gradually consolidated its operations and sold excess LOOW property to the public. In 1974, the AEC instituted the Formerly Utilized Sites Remedial Action Program (FUSRAP) to manage and

remediate such sites. In the 1980s, the USDOE constructed a 4-hectare (10-acre) Interim Waste Containment Structure (IWCS) on the NFSS to contain the radioactive wastes and residues remediated throughout the LOOW and NFSS (Figure 1) [1].

In October 1997, Congress transferred the management of FUSRAP from the USDOE to the U.S. Army Corps of Engineers (USACE). USACE is administering and executing cleanup at eligible FUSRAP sites pursuant to the provisions of the Energy and Water Development Appropriation Act, 1998 (Title I, Public Law 105-62, 111 Stat. 1320, 1326). Under FUSRAP, an environmental surveillance program was initiated at the NFSS in 1981 by the USDOE to ensure radioactive materials buried within the IWCS are not a threat to human health and the environment. This program has evolved with time and now includes air, water, and sediment monitoring for radiological and chemical parameters.

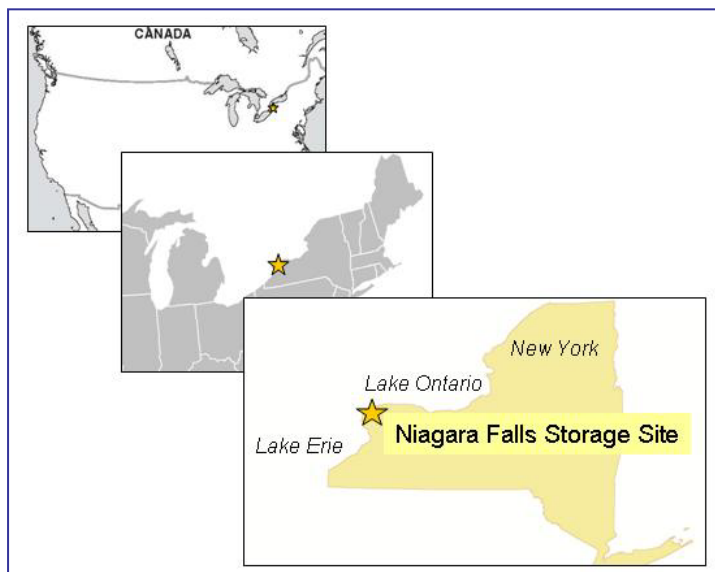


Figure 1: Location of Niagara Falls Storage Site

The USACE Buffalo District completed a Remedial Investigation Report, Remedial Investigation Report Addendum, and focused groundwater contamination studies from December 2007 to December 2013. The nature and extent of contaminants on the NFSS and potential long-term risks associated with those contaminants were assessed; the studies also determined that the IWCS is functioning properly [1, 2, 3, 4]. Hydrogeologic conditions at the NFSS do not promote radionuclide transport, however uranium appears to be the most mobile radionuclide of the site inventory.

METHOD

Site Contaminants

The MED and AEC stored radioactive residues and other materials at the NFSS beginning in 1944. These residues originated from uranium-ore processing activities at the Linde Air Products facility in Tonawanda, New York (NY), the Mallinckrodt Chemical Works refinery in St. Louis, Missouri, and the Middlesex Sampling Plant in New Jersey. The original ore materials (pitchblende) contained 3.5% to 60% of tri-uranium octoxide (U_3O_8) or uranium dioxide (UO_2), along with a wide range of radium-226 (Ra-226) and thorium-230 (Th-230) concentrations. In addition to these residues, radioactive wastes from the Knolls Atomic Power Laboratory in Schenectady, NY, the University of Rochester (NY), and the Middlesex Sampling Plant in New Jersey [1, 3] were sent to NFSS for storage, transfer, or disposal.

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These residues (and other containerized materials) were stored at various locations throughout the LOOW and NFSS. Materials were eventually consolidated onto the NFSS property in differing configurations, which produced localized soil and groundwater impacts. From 1981 to 1991, the USDOE systematically remediated the NFSS and vicinity properties and placed the impacted materials into the engineered IWCS on the west side of the NFSS property (Figure 2). The inventory of high-activity radioactive residues were placed in existing reinforced concrete structures that were components of a freshwater treatment plant for the LOOW. Contaminated soil and debris from the cleanup actions were then placed atop the various residues and compacted to 90% Proctor conditions to increase stability.

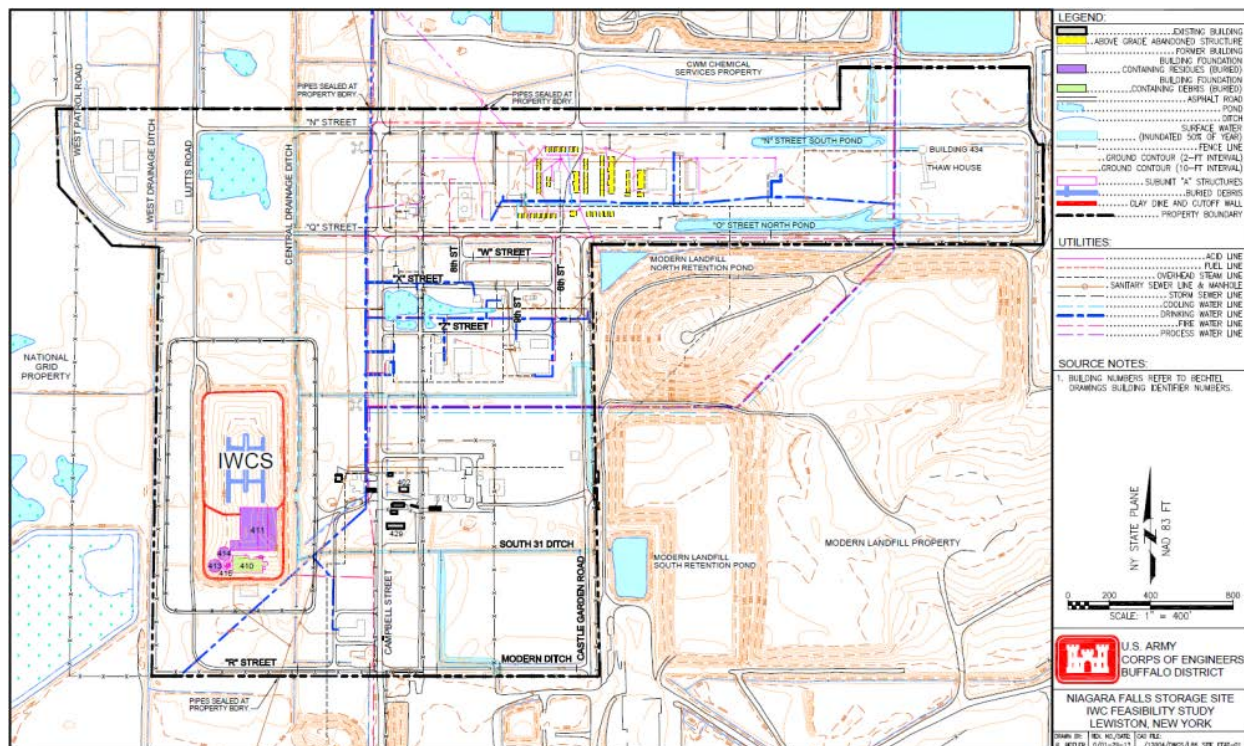


Figure 2: NFSS Site Components

The IWCS is encircled by a clay dike and subsurface cutoff wall that is tied into an underlying gray clay layer. A multi-layered cap was placed over the contents and construction details are provided the Remedial Investigation Report (USACE 2007) and the references cited therein. The USDOE determined the IWCS cap would have a projected service life of 25 to 50 years, while the clay dike and cutoff walls would have a 200- to 1,000-year lifespan [4].

Due to the nature of material handling at the NFSS, the area around the IWCS, localized areas of residue storage, select utility areas, and other operational areas all show groundwater impacts in the underlying silty clay glacial till (or brown clay till). The extent of this contamination reveals that uranium is the most transportive radionuclide at the site and thus the focus of the water-media sampling [2, 5].

Site hydrogeology

Within 15 meters (m) (50 feet [ft]) of the ground surface, the NFSS and surrounding vicinity are underlain by two water-bearing zones separated by a plastic gray clay aquitard. The two water-bearing zones are identified as the upper water-bearing zone and the lower water-bearing zone, which are described below.

Upper Water-bearing Zone

The upper water-bearing zone (UWBZ) is composed of a surficial Brown Clay Till unit that overlies a Gray Lacustrine Clay unit (Figure 3). The Brown Clay Till is a clayey silt

and silty clay groundmass containing individual sand and gravel lenses that are distributed unevenly throughout the layer [5]. A geostatistical analysis of these coarse-grained lenses in the upper water-bearing zone suggest they vary in thickness, color, texture, extent, and saturation, and are not horizontally continuous over distances greater than 4.6 to 6.1 m (15 to 20 ft) and vertical distances of 1.2 to 1.8 m (4 to 6 ft) [1,3,6]. As a result, the occurrence of groundwater varies across the site (i.e., proximate wells may have noticeably different water levels depending on sand lens presence and Brown Clay Till saturated thickness).

The horizontal hydraulic conductivity of the Brown Clay Till reflects the fine-grained lithology, so most values vary between 1×10^{-5} to 1×10^{-7} centimeters per second (cm/s). Hydraulic conductivity values for wells screened through sand lenses typically show higher values (up to 1.3×10^{-2} cm/s). Vertical hydraulic conductivity values for the Brown Clay Till average 6×10^{-7} cm/sec [2].

Regional groundwater flow in the upper water-bearing zone follows topography to the northwest towards Lake Ontario. The average horizontal gradients typically range between 0.001 and 0.007 m/m, which reflects the flat lake plain environment surrounding the site (Figure 4). Seasonal groundwater fluctuations range up to 2.4 m (8 ft) and average 0.6 m (2.1 ft); fluctuations are most pronounced in wells with no sand lenses [1, 2].

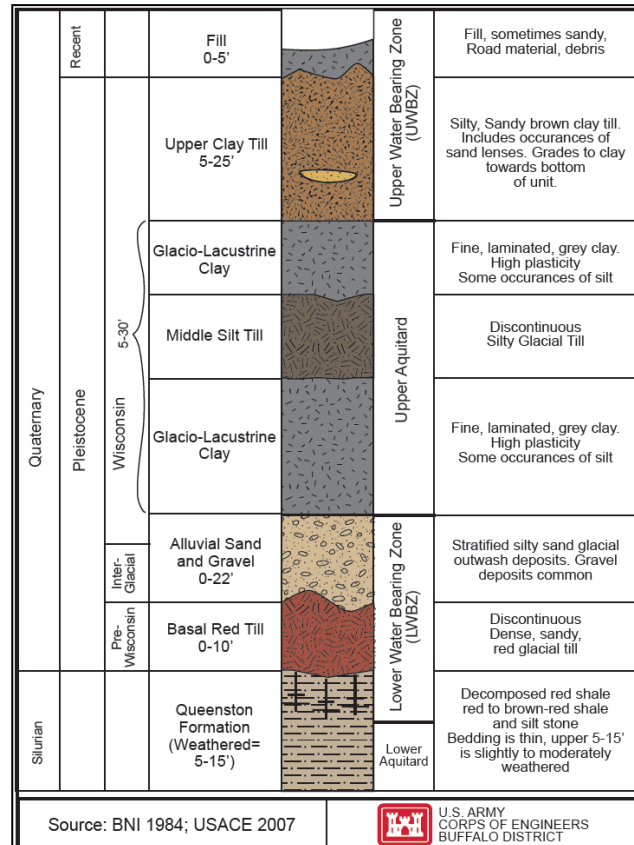


Figure 3. NFSS Hydrostratigraphy

Underlying the Brown Clay Till is the Gray Lacustrine Clay aquitard that separates the upper and the lower water-bearing zones (Figure 3). The hydraulic separation is exemplified by a seasonal hydraulic lag between the two zones. Normal high-water conditions in the UWBZ occur from late winter through spring, while the LWBZ shows high-water conditions during late summer and fall. Consequently, vertical gradients are normally downward through the aquitard in the spring and become upward in the summer and fall due to low-water conditions in the upper zone and high-water conditions in the lower zone.

Lower Water-bearing Zone

The LWBZ consists of 1) stratified sands and gravels of the Alluvial Sand and Gravel unit, 2) dense silt and sands of the Red Silt Till unit, and 3) a 4.6-m (15-ft) thick weathered and fractured zone along the top of the Queenston Formation (Figure 3). The entire lower water bearing zone varies from 3.1 to 11.7 m (10 ft to 38.5 ft) in thickness and has higher bulk permeability than the UWBZ. The Red Silt Till is not ubiquitous under the NFSS, so areas exist where the Alluvial Sand Gravel contacts the upper Queenston Formation directly [2, 5].

The horizontal hydraulic conductivity of the Alluvial Sand and Gravel Unit ranges from 1.3×10^{-3} to 9×10^{-6} cm/s. The fractured portion of the Queenston Formation exhibits hydraulic conductivities that geometrically average 2.2×10^{-5} cm/s. The potential for surface contamination to reach this lower zone or shale bedrock is inhibited by the confining Gray

Lacustrine Clay. Vertical gradients within the LWBZ are commonly upward from the bedrock to the Alluvial Sand and Gravel Unit where the Red Silt Till is absent [2].

The lower water-bearing zone generally shows a westerly to northwesterly flow with more uniform gradients that typically vary between 0.002 to 0.004 m/m (Figure 5).

Groundwater fluctuations average ~0.3 m (~1.0 ft), which further indicates the hydraulic separation of the LWBZ from the UWBZ. By comparing historical potentiometry to current

data, the local landfill operations (e.g., Modern and

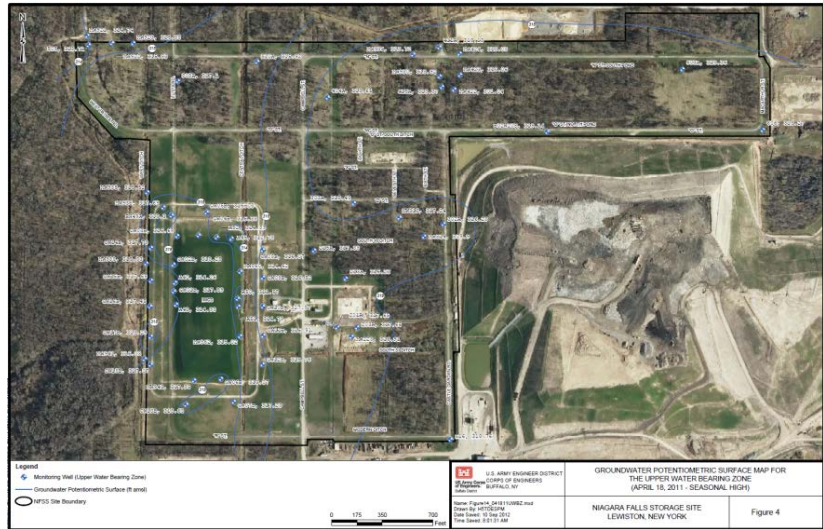


Figure 4. Upper Water Bearing Zone Potentiometry

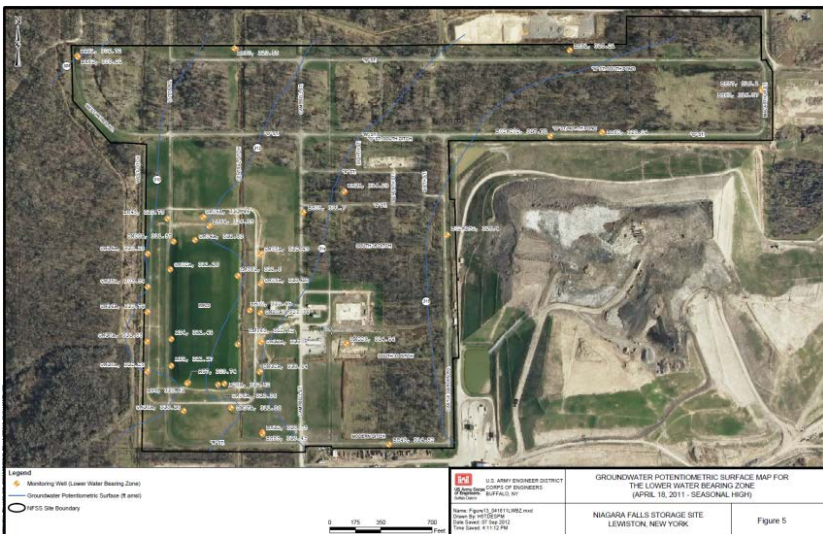


Figure 5. Lower Water Bearing Zone Potentiometry

Chemical Waste Management) are in equilibrium with the hydrogeology and not transiently affecting flow patterns in the lower water-bearing zone under the NFSS [1, 2].

Surface-water Drainage

Natural site drainage has been modified to route surface water to a series of linear ditches that coalesce into a 2.4- to 3.1-m (8- to 10-ft) deep Central Drainage Ditch that runs centrally through the site (Figure 2). The Central Drainage Ditch enters into Four Mile Creek approximately 4.8 km (3 miles) northwest of the NFSS. A ditch along the western site boundary (West Drainage Ditch) is similarly configured. These two ditches were deepened by 3 m (10 ft) during site remediation and now contain up to 1.5 m (5 ft) of sediment and organic matter.

The phreatophyte vegetation that grows in and along the ditches during the growing season (May through November) increases evapotranspiration that lowers groundwater elevations in wells proximal to the ditches (i.e., the wetland vegetation in and along the ditch creates a significant moisture deficit in the surrounding soils). This condition, in conjunction with low observed baseflow, together indicate that groundwater does not significantly discharge into the ditches (i.e., surface drainage is the main contributor to flow). Consequently, the presence of these hydraulic breaks in the groundwater flow system limits the pathways for groundwater transport across and from the site in the UWBZ [1].

Groundwater Quality

Groundwater quality was assessed on and around the NFSS during the RI and is routinely sampled at 39 on-site monitoring wells (Figure 6). Water levels are measured on a quarterly basis in 101 wells to identify groundwater flow paths (Figures 4 and 5).

Through 2012, groundwater was analyzed for a suite of radionuclides, including cesium-137, plutonium-238, plutonium-239/240, strontium-90, technetium-99, tritium, radium-226, radium-228, isotopic thorium, isotopic uranium, target analyte list (TAL) metals, volatile organic compounds (VOCs), and water quality parameters (such as

alkalinity and total dissolved solids).



Figure 6. NFSS Monitoring Well Inventory

The groundwater samples obtained during the Remedial Investigation (RI) confirms that groundwater in the NFSS area is naturally poor in quality due to high salinity and mineralization [5, 7, 8]. The water quality in the UWBZ is indicative of a low-recharge, hydraulically slow flow system that produces poor-quality groundwater containing high total dissolved solids (TDS) and calcium/magnesium sulfates derived from the glacial sediments. The LWBZ is highly mineralized and exhibits high total dissolved solids, sulfate species, and several metals without drinking water standards (e.g., calcium, magnesium, potassium, sodium).

The TDS values range from 410 milligrams per liter (mg/L) to 4,800 mg/L and produce average values for sodium, magnesium, calcium, potassium, iron, boron, and manganese that summarily reach ~1.0 gram per liter of water. Several UWBZ and LWBZ wells naturally exceed these average concentrations. This condition is significant in the LWBZ because primary recharge occurs along the base of the Niagara Escarpment approximately 3.2 km (2 miles) to the south. Groundwater then flows northerly at 0.82 meters per year (2.7 feet per year) towards the site and is not significantly diluted by vertical flow from the UWBZ while in transit [1, 2, 3, 4]. This long residence time and minor dilution indicates that the geochemistry of the LWBZ is in equilibrium with natural inorganic species within the glacial sediments.

Other inorganic species that naturally exceed drinking water standards throughout the site and at background locations include:

- Arsenic at multiple locations in the LWBZ and limited locations in the UWBZ;
- Boron at multiple locations in the LWBZ and limited locations in the UWBZ;
- Iron at approximately one quarter of the wells both in the UWBZ and LWBZ;
- Magnesium at nearly all sample locations in the UWBZ and LWBZ;
- Manganese at multiple locations in the UWBZ and LWBZ; and
- Sodium at nearly all sample locations in the UWBZ and LWBZ [1].

The elevated arsenic, iron, and manganese are indicative of the low oxygen-reduction potentials (redox) and the residence time of groundwater in the LWBZ. Conversely, periods of low redox conditions in the UWBZ and LWBZ (especially the LWBZ) can suppress uranium solubility and seasonally lower uranium concentrations in monitoring wells, as discussed below [2].

Site Contamination

The long-term handling and storage of radioactive materials at the NFSS produced soil contamination and associated uranium impacts in the shallow groundwater (UWBZ). Although remedial actions throughout the 1970s and 1980s mitigated the vast majority surface contamination on the NFSS, some operational areas still exhibit residual contamination in NFSS soils. These areas pose both an exposure risk and a potential risk to groundwater due to continued leaching for surface soils [1]. These soil areas have been characterized according to exposure units (EU) and are undergoing additional sampling to bound impacted areas. Soil-based constituents of concern identified during the Baseline Risk Assessment (BRA) [9], include select radionuclides

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from the uranium-238 (U-238) and uranium-235 (U-235) series, arsenic, boron, cadmium, antimony metals and methylene chloride. The widest impacts to groundwater appear from U-238 (or a total uranium equivalent), thus the majority of groundwater monitoring is focused on U-238 or total uranium species.

Uranium contamination at the site is typically present as U_3O_8 in soils [10]. The original ore also contained UO_2 , which is a reduced tetravalent (U^{4+}) species that has exceedingly low solubility in water (approximately 1×10^{-26} microgram per liter [$\mu\text{g/L}$] at pH 7) [11]. Uranium in the U_3O_8 state contains both U^{4+} and oxidized U^{6+} ions that are stochastically represented by $(2U^{6+})U^{4+}O_8$. This compound has low solubility in water and is sensitive to redox conditions and associated soluble species (e.g., iron and manganese), pH, and the presence of calcium, carbonates, and humic substances. Aqueous chemistry variations can increase the solubility of U^{6+} species and produce uranium concentrations in groundwater that exceed the U.S. Environmental Protection Agency (USEPA) maximum contaminant level (MCL) of $30 \mu\text{g/L}$ [12].

The UWBZ exhibits the following geochemical signatures derived from 16 years of annual monitoring:

- Average pH of 7.2,
- Average specific conductance of 1,920 microSiemens per centimeter (uS/cm),
- Average oxygen reduction potential of 170 millivolts (mV), and
- Sulfate and bicarbonate dominate speciation, with chloride as a tertiary anion.

The LWBZ exhibits the following geochemical signatures derived from 6 years of annual monitoring:

- Average pH of 7.9,
- Average specific conductance of 1,910 uS/cm,
- Average oxygen reduction potential (redox) of -38 mV, and
- Sulfate and bicarbonate dominate speciation, with chloride as a tertiary anion.

The pH and specific conductance vary slightly with seasonality. However, the redox values in both upper and lower water-bearing zones vary over 200 mV in some wells. In the UWBZ, redox is greatest (most positive values) during the spring recharge period after the ground thaws and before vegetation grows. However, redox then lowers into negative values as summer evapotranspiration lowers groundwater levels. In the LWBZ, the seasonal fluctuation varies by well, yet the average redox is lower in the fall than spring (e.g., the average redox of 61 mV in April 2012 lowered to -89 mV in October 2012).

This seasonal variation in redox conditions, coupled with the de-saturation of the UWBZ during the summer and fall months, lessens the overall uranium mobility in the UWBZ. Redox conditions below zero (0) mV have been shown to suppress uranium mobility by reducing U^{6+} to U^{4+} [13]. These seasonal oxic to anoxic (or mixed) variations are influenced by the carbonate and sulfate in the glacial sediments and groundwater at the NFSS. Carbonate and sulfate ions can form complexes with uranium and increase its solubility and mobility [14]. A geochemical modeling analysis using MINTEQA2 and

groundwater data from well OW4B calculated a maximum uranium solubility of U^{6+} species at 312 mg/L [1]. The solubility limiting uranium mineral schoepite $((UO_2)_8O_2(OH)_{12} \cdot 12(H_2O))$, although other interim minerals are possible.

The LWBZ did not have a separate solubility calculation performed, yet pH and Eh conditions (with Eh being the equivalent of ORP +199 mV) can be bounded on a Pourbaix diagram to evaluate potential uranium speciation in the LWBZ [13]. Figure 7 shows that the uranium species in the UWBZ and LWBZ include both hexavalent and tetravalent uranium, thus a different solubility in each zone. Uranium in the UWBZ will form more soluble species (as noted above), although uranium in the LWBZ likely occurs in low-solubility U_3O_8 and U_4O_9 species that have combined U^{4+} and U^{6+} valence states (e.g., $(2U^{6+})U^{4+}O_8$ and $(4U^{4+})U^{6+}O_9$ respectively), with lesser amounts of the more soluble, pure hexavalent species $(UO_2(OH)_2 \cdot H_2O)$.

Literature values for the solubility of the two dominant mixed-valence species are not prevalent (most note simply as “insoluble” [11, 14]) and background values for total uranium in the LWBZ range

between 0.24 ug/L and 16.1 ug/L, with an average of 3.6 ug/L [3]. The upper range of background data (16.1 ug/L) may represent a solubility limit for naturally occurring uranium in the LWBZ soils. The USEPA Soil Screening Guidance (1996) enumerates a process to estimate a soil saturation concentration using site-specific data, such as:

- Solubility limit for uranium (trial and error input),
- Soil-water partitioning coefficient (Kd) (uranium Kd is 122 milliliters per gram, mL/g),
- Dry bulk soil density (1.7 grams per cubic centimeter, g/cc), and
- Saturated porosity (0.3 for the LWBZ) [15].

The natural soil concentrations for uranium in the LWBZ average 2.4 milligram per kilogram (mg/kg) and are considered in equilibrium with the upper range for natural groundwater. The soil and water data were input to the USEPA soil screening limit method that estimated a solubility of 19.7 ug/L is needed for total uranium to achieve the observed background groundwater values [15]. Since groundwater in the LWBZ naturally flows at 2.7 feet per year, natural uranium concentrations should elevate along the 3.2-km flowpath in the LWBZ, yet do not show gross increases in the large array of wells in and around the site. Consequently, a potential solubility limit of 20 ug/L for total uranium is possible in the LWBZ, which will be verified with additional geochemical modeling.

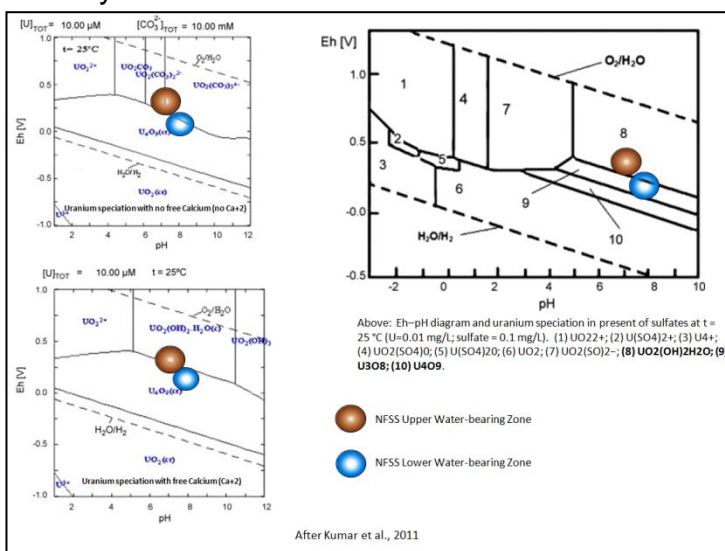


Figure 7. Uranium Speciation at NFSS

This estimated solubility and the competence of the GLC aquitard is supported by routine sampling results that show impacts in the UWBZ are not seen in the LWBZ. Uranium concentrations above the USEPA MCL (30 µg/L) in the UWBZ range up to 7,080 µg/L. Wells with elevated uranium results are near historic residue storage

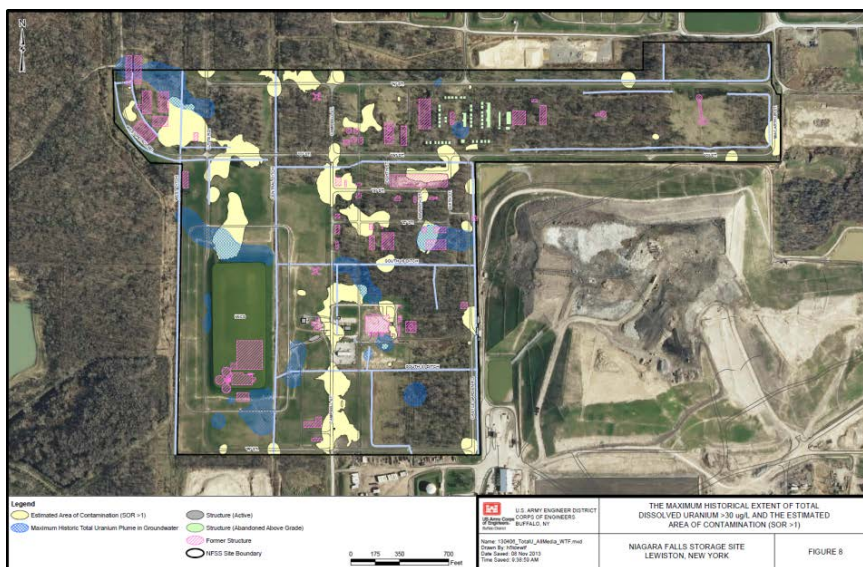


Figure 8. Uranium Distribution in UWBZ and Legacy Soil Impacts

areas, operational corridors, and impacted utilities (Figure 8); several of these areas are under continued investigation. Uranium concentrations in the LWBZ range from non-detect to 13.04 µg/L, which fall below the estimated solubility limit of 20 µg/L for uranium.

RESULTS

Uranium transport in groundwater

To assess the transportive and attenuative processes in site groundwater, uranium results from 1997 through 2012 were subjected to the Mann-Kendall test [16] to determine if any surveillance well shows a statistically significant upward (or downward) trend in concentration. Temporal data plots were inspected to identify seasonality, or predictable increases or decreases in concentration within a time cycle. The data, collected primarily in the spring and fall, do not indicate a consistent repeating pattern and, as such, did not support the use of the seasonal Kendall test [16]. This may be due to weather variations at the time of sampling, as sampling efforts do not rely on antecedent conditions, and/or the small seasonal dataset that is still developing.

The results of the trend evaluation (spring and fall data from 1997 to 2012) were evaluated based upon sample size that reflects the statistical power of the test. Wells with sample sizes greater than 10 were treated differently than those with sample sizes less than or equal to 10. The evaluation indicates that no increasing or decreasing trends in total uranium concentrations were identified in 34 of 39 wells used for analysis (i.e., uranium concentrations are in dynamic equilibrium with background uranium, low-concentration legacy soil sources, or minimally transported uranium stored in the pore spaces). Decreasing uranium trends were identified at four UWBZ wells, while an increasing trend was identified at one UWBZ well; one high concentration well showed an increasing trend and now shows a neutral trend due to investigations (trenching) in

the area (Figure 9). No trends were evident in LWBZ wells, thus indicating the competence of the glacial lacustrine clay aquitard and uranium-solubility inhibiting geochemistry of the lower zone.

To predict the potential for long-term uranium transport in this low-flux hydrogeologic regime, the USACE employed numerical modeling that included the leaching of contaminant from current soil and IWCS sources. These input were coalesced in a three-dimensional numerical groundwater flow and contaminant-transport model of the hydrostratigraphy (UWBZ and LWBZ components) to predict site conditions at different timescales and potential risks to groundwater resources [1, 2, 3].

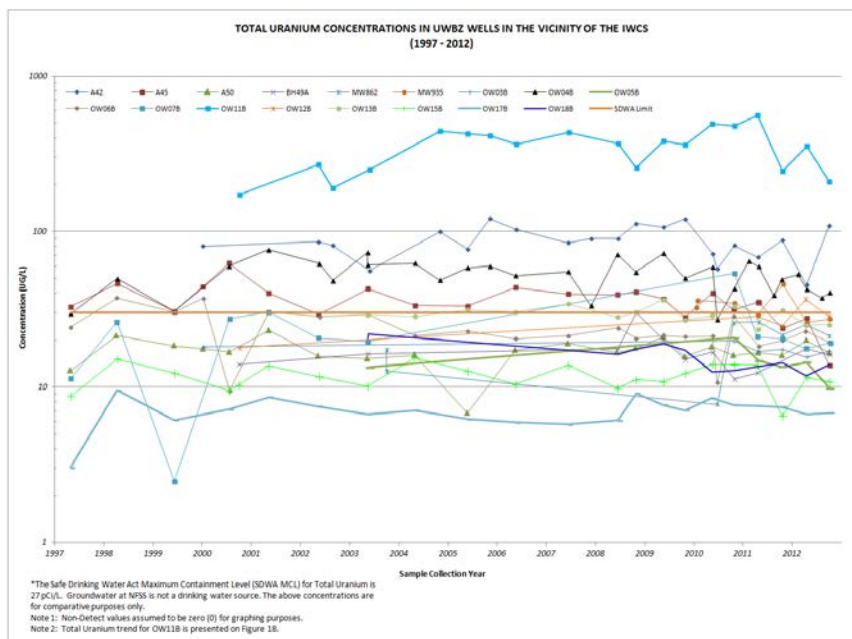


Figure 9. Uranium Trends in UWBZ Monitoring Wells

The modeling results for a 1,000-year period under steady-state flow predict that the uranium minimally transports horizontally in the UWBZ and vertically to the LWBZ, where predicted impacts are below 0.2 ug/L (Figure 10) [2, 3]. By 10,000 years, uranium concentrations entering the LWBZ are 366 ug/L, yet do not migrate beyond the IWCS area above 2 ug/L, which indicates the natural system adds to the

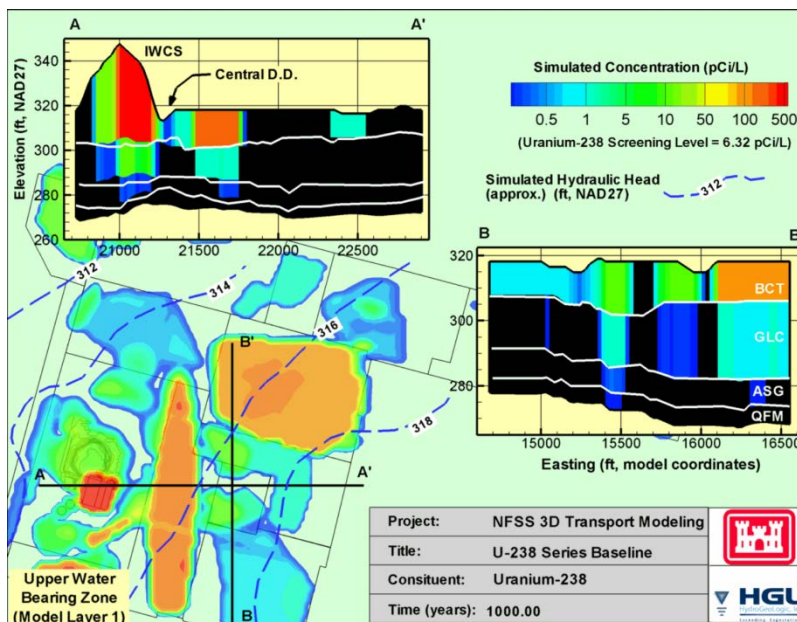


Figure 10. 1,000-year Predicted Uranium-238 at NFSS

protectiveness of the IWCS. However, select non-IWCS impacts in the UWBZ are predicted to discharge to the site ditches at concentrations that may pose off-site risk due to transmission down the Central Drainage Ditch. The

long-term sources of these plumes are legacy soil contamination that is under investigation and may be remediated under FUSRAP, if required by CERCLA protocols.

CONCLUSION

Natural groundwater conditions and site-related contamination, specifically uranium as the most mobile radionuclide at NFSS, have been investigated multiple times under specific actions (i.e., source-term investigations). The natural condition of groundwater in the UWBZ is slightly to moderately saline, exhibits high TDS and sulfates, and does not yield appreciable quantities to monitoring wells due to low to moderate hydraulic conductivities, thus not a viable drinking water source. To achieve drinkability (negate the deleterious effects of high salinity [pulmonary stress] and sulfate [digestive stress]), the groundwater would require treatment, which also would remove any residual uranium impacts. Consequently, the need for legacy uranium plume remediation is debatable for the UWBZ.

The natural condition of the LWBZ is moderately to highly saline from high (to very high) TDS, sulfates, carbonates, and chlorides, and has a hydraulic conductivity that can yield domestic-use quantities to wells. The LWBZ groundwater meets New York State Class "GSA" classification standards (saline and potable with treatment); GSA water does not have designated maximum contaminant levels (MCLs) [16]. Human consumption of LWBZ groundwater also would require treatment to negate the deleterious effects of high salinity and sulfate, which would then remove potential uranium impacts that are not expected to occur.

Uranium contamination in the UWBZ exceeds the MCL of 30 ug/L in several residue handling areas. Many locations exceed the MCL by very little, yet the concentrations are recalcitrant due to the very slow migration, low dilution, and seasonal redox conditions. Select locations that show very high uranium concentrations are collocated with contaminated utilities, foundations from demolished structures, and elevated uranium concentrations in UWBZ soil. The seasonal variations in geochemistry in the both the UWBZ and LWBZ, along with seasonal saturation, both lessen the transport of uranium in site groundwater and limit the impacts from historic activities.

Groundwater flow and contaminant-transport modeling indicate that uranium will not migrate advectively, but rather dispersively in the UWBZ and underlying aquitard due to very shallow gradients and low bulk hydraulic conductivities. Potential uranium sources in the UWBZ were predicted to migrate into the LWBZ at concentrations up to 0.2 ug/L in 1,000 years and up to 366 ug/L in 10,000 years. However, such concentrations attenuate to 1.3 ug/L in the LWBZ below the IWCS, which is a level indistinguishable from background. Once in the reducing environment of the LWBZ, uranium solubility may be reduced further and limit the potential for migration. This combined effect provides an inherent level protection of human health and the environment.

Additional geochemical modeling of the LWBZ will be completed as a decision-making tool for the groundwater operable unit at the NFSS. If either the UWBZ or LWBZ

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groundwater were tapped as domestic water source, potability treatments to negate the naturally poor water quality would also remove any residual uranium (e.g., reverse osmosis), so the overall potential for human exposure to residual uranium in groundwater is minimal.

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