

Arsenic in the Groundwater at Naval Station Mayport; Geochemical Processes or Anthropogenically Caused?

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ABSTRACT:

Arsenic (As) contamination in soil and groundwater throughout the world has resulted in significant impacts to human health. The tube wells installed in Bangladesh, initially designed to substitute groundwater for polluted surface water, ended up exposing millions of people to extremely high levels of As. Prior to the installation of the tube wells, there was no indication of As poisoning. In fact, initiating groundwater as drinking water was designed to decrease the incidence of surface water-borne diseases (Smedley and Kinniburgh 2002).

Studies have shown that worldwide in nonurban areas, the range of As concentrations in soil is from 0.1 to 40 mg kg⁻¹, while in Florida the range is from 0.01 to 61.1 mg kg⁻¹ (Chirenje, Ma et al. 2003). Although As is an element and is mobilized in the environment through weathering and biological conditions, anthropogenic sources of As include adding it to livestock and poultry feed, wood preservatives, as well as pesticide and herbicide use (Smedley and Kinniburgh 2002).

Naval Station (NS) Mayport has had a history of elevated levels of As in soil. The soil As background concentration reported in 1994 was 5.3 mg kg⁻¹, higher than the Florida residential Soil Cleanup Target Level (SCTL) of 0.8 mg kg⁻¹ at that time. Remediation was required in areas identified in the Corrective Action program. Since most of the installation had been filled with material from dredging, a study was conducted in 2008 to determine the cause of the excessively high As levels in the soil, either the dredged material or industrial releases. Results determined that the high As soil levels were from naturally occurring As in marine deposit and sediment materials, rather than industrial releases, and the background concentrations for NS Mayport were modified from the Florida industrial SCTL of 12 mg kg⁻¹ to 13.7 mg kg⁻¹. Some groundwater As levels at NS Mayport exceed Florida Groundwater Cleanup Target Level (GCTL) of 10 µg L⁻¹, including at sites without high levels of soil As. This paper discusses the possibility that some areas of elevated groundwater As are not necessarily a result of anthropogenic releases.

The data for this report were derived from regulatory sampling and analysis and existing reports, therefore some geochemical information is not available. Nevertheless, based on the historical data reviewed for this evaluation and the reductive properties of the groundwater at locations where As exceeded GCTLs, As in groundwater is concluded to be the result of geochemical changes, instead of anthropogenic contamination, at SWMUs 13 and 17 and Sites 25 and 250.

Abbreviations:

ASR - Aquifer Storage and Recovery

CERCLA - Comprehensive Environmental Response, Cleanup and Liabilities Act of 1980

DWS - Drinking water standard

EGIS - Environmental Geographical Information System

FDEP - Florida Department of Environmental Protection

GCTL - Groundwater Cleanup Target Level

LD50 - Lethal Dose 50%

MCL - Maximum Contaminant Level

MCLG - Maximum Contaminant Level Goal

NS - Naval Station

RCRA - Resource Conservation and Recovery Act

RFA - RCRA Facility Assessment

SCTL - Soil Cleanup Target Level

SWMUs - Solid Waste Management Units

Introduction

Arsenic (As) contamination in soil and groundwater throughout the world has resulted in significant impacts to human health. The tube wells installed in Bangladesh, initially designed to substitute groundwater for polluted surface water, ended up exposing millions of people to extremely high levels of As. Prior to the installation of the tube wells, there was no indication of As poisoning. In fact, the technology was embraced because using groundwater decreased the incidence of water-borne diseases. Other areas of the world such as Argentina, Chile, China, Vietnam and portions of the United States have had similar experience while trying to provide drinking water to populations (Smedley and Kinniburgh 2002).

Studies have shown that worldwide in nonurban areas, the range of As concentrations in soil is from 0.1 to 40 mg kg⁻¹, while in Florida the range is from 0.01 to 61.1 mg kg⁻¹ (Chirenje, Ma et al. 2003). Although As is an element and is mobilized in the environment through weathering and biological conditions, anthropogenic sources of As include adding it to livestock and poultry feed, wood preservatives, as well as pesticide and herbicide use (Smedley and Kinniburgh 2002).

Before 2005, the Florida Soil Cleanup Target Levels (SCTLs) were 0.8 mg kg⁻¹ for residential and 3.7 mg kg⁻¹ for industrial sites. During an update to the SCTLs in 2005, As levels were changed to 2.1 mg kg⁻¹ for residential and 12 mg kg⁻¹ for industrial sites (FDEP 2005). Since these levels are still lower than those documented in undisturbed locations, the Florida Department of Environmental Protection (FDEP) allows parties to provide alternatives to remediation using risk-based criteria.

Soil As causes health concerns due to its exposure carcinogenicity, but As in drinking water is more bioavailable and of greater health concern (Center for Environmental & Human Toxicology 2005). Significant health effects occur by ingesting high levels of inorganic As (defined as >50 µg L⁻¹) in drinking water, and are well documented in areas such as Bangladesh, China and Vietnam (Smedley and Kinniburgh 2002). Ingestion of low levels of As causes symptoms such as nausea, vomiting, and circulatory problems. Furthermore chronic, low levels of exposure can cause effects such as skin discoloration and wart-like sores (ATSDR 2010). The As LD₅₀ (lethal dose for 50% of the population exposed) is 1 to 4 mg kg⁻¹ body weight, which, for adults weighing 70 kg, translates to a range of 70 to 280 mg of As. Taking this into consideration, the US Environmental Protection Agency proposed reducing the Maximum Contaminant Level Goal (MCLG) to zero µg L⁻¹ and the Maximum Contaminant Level (MCL) from 50 to 5 µg L⁻¹ in 2000. After public comment, the MCL was finalized at 10 µg L⁻¹ (USEPA 2001). As the groundwater in Florida provides up to 90% of the drinking water supply, (Delfino 2009), in order to protect such a valuable resource, the Florida Groundwater Cleanup Target Levels (GCTLs) do not exceed MCLs, and the As GCTL was changed to 10 µg L⁻¹ to be consistent with US Environmental Protection Agency (USEPA).

While As is the third most common inorganic compound requiring remediation, it most commonly comes from geological sources in groundwater (Vance 2008). A recent chain of events has helped emphasize the As soil-water interaction. To ensure stable drinking water supplies, Aquifer Storage and Recovery (ASR) has been initiated in Florida. The concept is simple: Store treated drinking water in an unconfined aquifer meeting certain boundary criteria, then pump it for use as necessary. The technology has been embraced worldwide, and in Florida the number of wells has grown from 6 in 1998 to 26 in 2010 (Arthur, Dabous et al. 2009). The benefit is a viable source of water during times of shortages. The unintended consequence has been an unexpected leaching of metals, including As, in some of the systems (Arthur, Dabous et al. 2009). The ASR projects are placed in areas where soils do not have elevated As levels, but some systems have recovered water exceeding As MCLs. The increased levels have been identified in a number of the ASR systems in Florida, indicating geochemical processes that release As to solution during either storage or recovery, and is the subject of a number of studies (Maliva and Missimer 2008). The most consistent finding is that redox conditions seem to be mobilizing the As in water recovery in some of the ASR systems. The treated water has higher levels of dissolved O^{2+} than native water. As the dissolved O^{2+} reduces, the geochemical reactions continue through sulfate reduction and iron oxyhydroxide becomes unstable, releasing As into solution (Mirecki 2006).

Naval Station (NS) Mayport has had a history of levels of As in soil with the background soil As concentration at 5.3 mg kg^{-1} in 1994 requiring remediation in areas identified in the Corrective Action program. Since most of the installation had been filled with material from dredging, a study was conducted in 2008 to determine the cause of the excessively high As levels in the soil, either the dredged material or industrial releases (Tetra Tech NUS 2008). Results suggested that the high As soil levels were from naturally occurring As in marine deposit and sediment materials, rather than industrial releases. Some groundwater As levels at NS Mayport exceed Florida GCTLs of $10 \text{ } \mu\text{g L}^{-1}$, including at sites without high levels of soil As. This paper therefore discusses the potential for As to leach from the soil to the groundwater, not as plumes of contamination but as a result of geochemical processes in the soil.

Naval Station Mayport

In 1942, NS Mayport was initially commissioned as an airfield and a harbor. A natural bay, shown in Figure 1 as Ribault Bay, was eventually dredged and sea walls installed to construct a Turning Basin (Basin), providing a place for multiple ships to berth and sufficient space to maneuver around other berthed ships. When begun, much of NS Mayport was wetlands and low-lying areas which did not support the infrastructure necessary for a military installation. As was common at the time, dredged material was used to fill in the low lands and Figure 2 shows the

reconfiguration of dunes and placement of the dredged material throughout NS Mayport over the years.

To support an aircraft carrier, the Basin was dredged to the current depth of 40 feet in 1948. Extensive tidal action by the confluence of the St Johns River and the Atlantic Ocean continues to influence sedimentation in the Basin, and the Basin is dredged every two years to maintain the depth necessary for ship movements (ABB Environmental Services 1995). Dredged sediments are sampled for bioassay analysis and are generally disposed in the ocean dredged material disposal site at Jacksonville, permitted by USEPA and managed by the Army Corps of Engineers (Shaw Environmental 2008).

Other activities at NS Mayport include maintenance and repair of helicopters and ships. Most activities provide intermediate repair, but some activities involve fabricating new parts and major repair or refit of the aircraft or shipboard spaces, which generate industrial and hazardous waste. In addition to historical spills and releases, portions of NS Mayport had been used in the past as landfills for both domestic and industrial waste (A.T. Kearney 1989).

To comply with the Comprehensive Environmental Response, Cleanup and Liabilities Act of 1980 (CERCLA), the Navy had identified past disposal sites and those that had released hazardous substances into the environment. In 1984, Congress reauthorized the Resource Conservation and Recovery Act (RCRA), and the corrective action program began to be administered by the USEPA. To initiate the list of sites to be included, USEPA conducted a RCRA Facility Assessment (RFA) at NS Mayport, which included the sites already under investigation and identified additional potentially contaminated sites, called Solid Waste Management Units (SWMUs).

During the initial investigatory sampling in 1994, soil (depth to >2 feet), groundwater, surface water, and sediment samples were collected to provide preliminary information relative to As background concentrations in non-industrial impacted areas of NS Mayport. Results indicated that 249 soil samples (25%) exhibited As concentrations ranging from 0.4 to 138 mg kg⁻¹ (ABB Environmental Services 1995). Since the sites included in this preliminary study had not been impacted by industrial activities or solid waste disposal, the relatively high soil As concentrations were likely due to natural occurring processes. In addition, As was generally the only contaminant above regulatory levels, which further indicates that these sites likely reflect background As conditions at the NS Mayport.

When the SCTLs were initiated in 1999 by the Florida Department of Environmental Protection (FDEP), the residential level for As was 0.8 mg kg⁻¹ which, as a known carcinogen, was very near the instrument detection limit (FDEP 1999). Multiple studies determined that bioavailability of As from soil is significantly less than from water, resulting in the residential As SCTL changing to 2.1 mg kg⁻¹ and the industrial

As SCTL becoming 12 mg kg^{-1} in 2005 (Center for Environmental & Human Toxicology 2005).

In 2001, NS Mayport initiated documentation required to dredge an additional section to the existing Basin. As currently required by the USEPA permit for the ocean dredged material disposal site at Jacksonville, the sediments were analyzed beforehand to determine proper disposal/placement. Since Florida had no sediment standards at the time, the samples were compared to SCTLs. The As levels in seven of the 14 sediment samples ranged from 0.32 to 15.8 mg kg^{-1} at 38- to 50-foot depths (Ecology and Environment 2000).

Since the levels of As in the sediments exceeded the pre-2005 industrial SCTLs of 2.3 mg kg^{-1} and exceeded the land disposal standards in the hazardous waste regulations, disposal options were limited (40 CFR 268.48). The cost of hazardous waste disposal in a lined landfill would have been prohibitive. As an alternative, the FDEP allowed NS Mayport to place the dredged material in an area near the runway, cover it with 2 feet of clean soil, and document it in the RCRA Corrective Action program as Area of Concern (AOC) D with Land Use Controls. Additional sampling of the dredged material was conducted in 2007 after placement to determine if the AOC-D required additional remediation. The As results of the placed material ranged from below 2.1 to 6.3 mg kg^{-1} , which still exceeded residential standards.

The high As sediments excavated in 2001 emphasized the probability that the soil levels at the NS Mayport were likely due to the dredged material rather than anthropogenic sources. During various sampling events, it was noted that other sites also exceeded As SCTLs, and in many cases it was shown that As was the only contaminant of concern. In 2008, a new study was conducted by TetraTech NUS, Inc. to determine if As in the soil was naturally occurring background concentrations or the result of industrial releases of contaminants.

Approximately 800 soil samples were collected from sites that had suspected contamination. Additional soil samples were also collected from areas that were either native soil or in areas not previously sampled. The results of this study stated there was no evidence that an As spill or discharge to the environment had occurred that would warrant cleanup. FDEP concurred, changing the As background concentration for NS Mayport to 13.70 mg kg^{-1} .

A question remained regarding the As levels in the groundwater and whether the groundwater levels could be correlated to the soil levels. The obvious way to determine any correlation was to compare the soil As samples exceeding SCTLs (Figure 3) with the groundwater samples exceeding the As GCTLs (Figure 4). Figure 3 shows the soil samples with As levels that exceed 2.1 mg kg^{-1} and Figure 4 shows the groundwater samples with As levels greater than $10 \text{ } \mu\text{g L}^{-1}$. The majority of the sites with elevated groundwater As levels appear to be correlated with the elevated soil As levels, with a few exceptions. The three areas to be discussed

further are SWMU 15, SWMU 13, and the grouping of sites identified on the figures as SWMU 17, Sites 25 & 250.

To begin the evaluation, soil sampling data from 1992 through 2005 were compiled from the NS Mayport Environmental Geographical Information System (EGIS). The criteria for inclusion in this evaluation were that the samples (1) exceeded FDEP residential SCTL of 2.1 mg kg^{-1} , (2) were not associated with pesticide usage, which is frequently a source of As contamination, and (3) do not have laboratory quality control qualifiers associated with the sample as identified in 62-160.700 Florida Administrative Code. Qualifiers are used by laboratories to report information regarding the sample results. In addition to reporting that samples were not detected above the method detection limit or what the dilution factor for the sample was, qualifiers also identify samples that do not meet quality control criteria (FDEP 2008). Of the 994 soil samples analyzed for As between 1992 and 2007, 181 were not detected above the method detection limits and 552 samples had levels less than the contract required quantitation limit, but above method detection limits. All samples met the laboratory quality control requirements. From the remaining samples, 75 had As levels more than the FDEP residential SCTL, minus 3 that were associated with SWMU 15, leaving 72 samples for evaluation. Another 12 soil samples taken for the Arsenic Background Study in 2008 were added to the remaining 72 samples for a total of 84 soil samples exceeding As SCTLs at NS Mayport.

The surficial aquifer is 100 feet or less, so shallow monitoring wells at NS Mayport are screened at approximately 5 to 15 feet below land surface (bls) for shallow wells, and 15 to 30 feet bls for intermediate wells. (ABB Environmental Services 1995) To evaluate groundwater, it was determined that more than 700 samples from the surficial aquifer were analyzed for groundwater As throughout NS Mayport during the period from 1992 through 2007. The criteria for groundwater samples being included were similar to soil in that the samples (1) exceeded FDEP GCTL of $10 \mu\text{g L}^{-1}$, (2) were not associated with pesticide usage, and (3) do not have laboratory quality control qualifiers associated with the sample as identified in 62-160.700 Florida Administrative Code. The groundwater sample results meeting these criteria totaled 148 samples.

One area without apparent correlation between groundwater and soil As levels is a pesticide mixing area, SWMU 15 shown in Figure 5. The groundwater As samples analyzed at this site ranged from 0.01 to $640 \mu\text{g L}^{-1}$, but since many pesticides historically contain As as an active ingredient, the 67 groundwater samples SWMU 15 were removed from this evaluation.

Solid Waste Management Unit 13

One of the areas identified for further evaluation was SWMU 13, shown in Figure 6. Used for firefighting training between 1973 and 1982, SWMU 13 was identified in the RFA as three areas where waste oil and solvents were placed in an "earthen-

bermed pit” and lit to allow personnel to practice extinguishing the fire. The solvents that had not burned would have leached into the soil and groundwater. Buildings and parking lots were constructed on the site after 1982 and before 1989. During the course of the investigation of this site, no organic compounds were detected above regulatory levels, although high concentrations of metals were found.

The data evaluated for SWMU 13 included 49 soil samples taken in 1992 and 2000 and 572 groundwater samples taken between 1992 and 2003. The soil samples were analyzed for As, Ca, Fe, Mg and Mn, and of the 49 soil samples, none exceeded Florida SCTLs for As, Fe or Mn. Although not contaminants, the concentrations of five samples analyzed for Ca ranged from 28,100 to 100,000 mg kg⁻¹, Mg concentrations in nine samples ranged from 144 to 1100 mg kg⁻¹ and the Cation Exchange Capacity in this area ranged from 0.7 to 1.8 meq 100g⁻¹, indicative of inorganic soils.

The groundwater data were more extensive. A total of 573 groundwater samples were taken and analyzed for metals and “miscellaneous parameters” such as total suspended solids and total organic compounds. Of those samples, GCTLs for As, Fe, Mn and V were exceeded as shown in Table 1. Chloride and total dissolved solids exceeded Florida GCTLs, but not background samples taken in 1992 (ABB Environmental Services 1995). One sample exceeded groundwater As GCTL at 11.3 µg L⁻¹ (Table 1) just slightly above the GCTL, preventing this site from having a No Further Action determination. Interestingly enough, of the data reviewed, only one other sample identified As at 0.6 µg L⁻¹, but the laboratory qualifier associated with the sample indicated that the result was reported at the laboratory method detection limit (FDEP 2008).

As was previously stated, redox is an important factor in arsenic mobilization in groundwater, and the elevated levels of iron and manganese indicate that reducing conditions were evident in groundwater at SWMU 13. Two arsenic compounds most frequently found in nature are arsenate (As⁵⁺) and arsenite (As³⁺), the exact speciation is determined by reduction-oxidation (redox) reactions, pH and methylation (Masscheleyn, Delaune et al. 1991). Soil samples collected adjacent to the monitoring well in 1994 showed pH ranging from 8.19 to 9.11, normally not considered a range for As solubility but speciation studies have shown otherwise. Figure 7 shows that as the groundwater becomes more reductive, As⁵⁺ can be reduced to As³⁺, and Fe³⁺ reduces to Fe²⁺ (Vance 2008). Masscheleyn, on the other hand, experimented with the different As species, and determined that at pH 8, the predominate species in solution is As⁵⁺ (Masscheleyn, Delaune et al. 1991).

Arsenic is one of the few elements that can be released into solution in both oxic and reduced environments, depending upon the oxidation state (Smedley and Kinniburgh 2002). Although speciation was not conducted for any of the samples at NS Mayport, the elevated sample of As at SWMU 13 is consistent with As⁵⁺ in a reduced environment. Essington explains that As (as As³⁺) is absorbed by manganese oxides, and the resulting compound (As⁵⁺) is released to soil solution

(Essington 2004). In addition, flat and low-lying areas tend to enhance reductive processes at pH levels that might not be excessively high (defined as greater than 8.5). This environment leads to high Fe^{2+} and manganese oxide release to solution, with resulting As release (Smedley and Kinniburgh 2002).

Site 25, Site 250, and SWMU 17

Three sites at NS Mayport that are in relatively close proximity to each other also have groundwater As impacts with no apparent correlative soil impact. Site 25 is one of the sites where the soil did not exceed Florida SCTLs for metals, but groundwater samples exceeded Florida GCTLs for As. The 1989 RFA noted that Site 25 was the Public Works Department Service Station (A.T. Kearney 1989). According to the RFA, there was stained concrete at the time of the assessment and petroleum contamination was found in the soil and groundwater in 1991 (ACOE 1992). In addition to As, one monitoring well had two Pb samples of 24 and 27 $\mu\text{g L}^{-1}$, which exceeded the Florida GCTL of 15 $\mu\text{g L}^{-1}$. The Pb results are not included in this evaluation since Pb is commonly associated with leaded gasoline, which was used at this site.

One of the other sites close to Site 25 is Site 250 had a leaking diesel underground storage tank, which was remediated with the exception of a small amount of soil remaining under the storm sewer. Since petroleum contamination was left in place, land use is restricted to non-residential uses (WRS 2006). The third site is SWMU 17, which was a carbonaceous fuel boiler that began operation in 1979 and continued operations until 1994. Trash collected throughout NAVSTA Mayport was burned in the boiler, and at various times the fly ash generated from the burning was found to have levels of Cd, Cr, and Pb that exceeded hazardous waste limits (A.T. Kearney 1989).

Approximately 250 soil samples from sites 25, 250 and SWMU 17 were collected and analyzed only for volatile organic compounds and semi-volatile organic compounds. Site 25 and SWMU 17 had 119 soil samples analyzed for As, Ca, Fe, Mg and Mn. Since Site 250 did not have any soil samples analyzed for inorganic compounds, only soil samples from Site 25 and SWMU 17 were used for this evaluation. Of the 119 soil samples, 62 samples contained laboratory quality control qualifiers that disqualified them from this evaluation. Of the remaining 57 samples, Fe and Mn were detected but did not exceed Florida SCTLs of 53,000 mg kg^{-1} and 3500 mg kg^{-1} respectively. Mg was detected in four samples ranging from 1120 to 1850 mg kg^{-1} , and Ca was detected in 22 samples ranging from 4220 to 281,000 mg kg^{-1} .

Between 1995 and 2000, 219 groundwater samples were collected and analyzed for inorganic and miscellaneous parameters (Table 2). The groundwater sample locations for Sites 25, 250 and SWMU 17 are shown in Figure 8.

Table 3 provides an easy snapshot of redox conditions in groundwater. Evaluating the data in Table 2, the groundwater in this location shows indications of being strongly reducing. At the range of 266 - 453 mg/L⁻¹, this area exceeds the typical alkalinity value of <100 mg/L⁻¹ (Smedley and Kinniburgh 2002). The progression of oxygen reduction is that once oxygen is depleted, elements reduce progressively in this order: Nitrogen, manganese, iron, sulfur, carbon, and finally nitrogen gas to ammonia (Smedley and Kinniburgh 2002). The groundwater parameters in the Site 25 area indicate that reduction is occurring, and the presence of sulfate seems to indicate that the environment is anoxic. With the understanding that most of the soils in this area are actually sediment material, Smedley and Kinniburgh (2002) identified studies conducted with sediments that showed “[As] release has long been associated with Fe oxide dissolution.”

To summarize, several studies have been conducted regarding the behavior of As in redox environments. The practice of placing dredged material throughout NS Mayport as fill material for wetlands has provided a significantly reducing environment for As to solubilize in groundwater. The revised background concentrations of As at NS Mayport exceed industrial SCTLs. At the sites investigated in this paper, the groundwater has reducing conditions with elevated dissolved Fe and Mn. While additional investigation is necessary to determine if these conditions exist at other areas of elevated groundwater As, there is significant evidence that the groundwater at SWMUs 13, 17, Sites 25 and 250 have natural dissolution of As in a reductive groundwater at NS Mayport. Additional studies should include sampling for soil characteristics to better understand the geochemical reactions occurring at NS Mayport.

APPENDIX A Figures

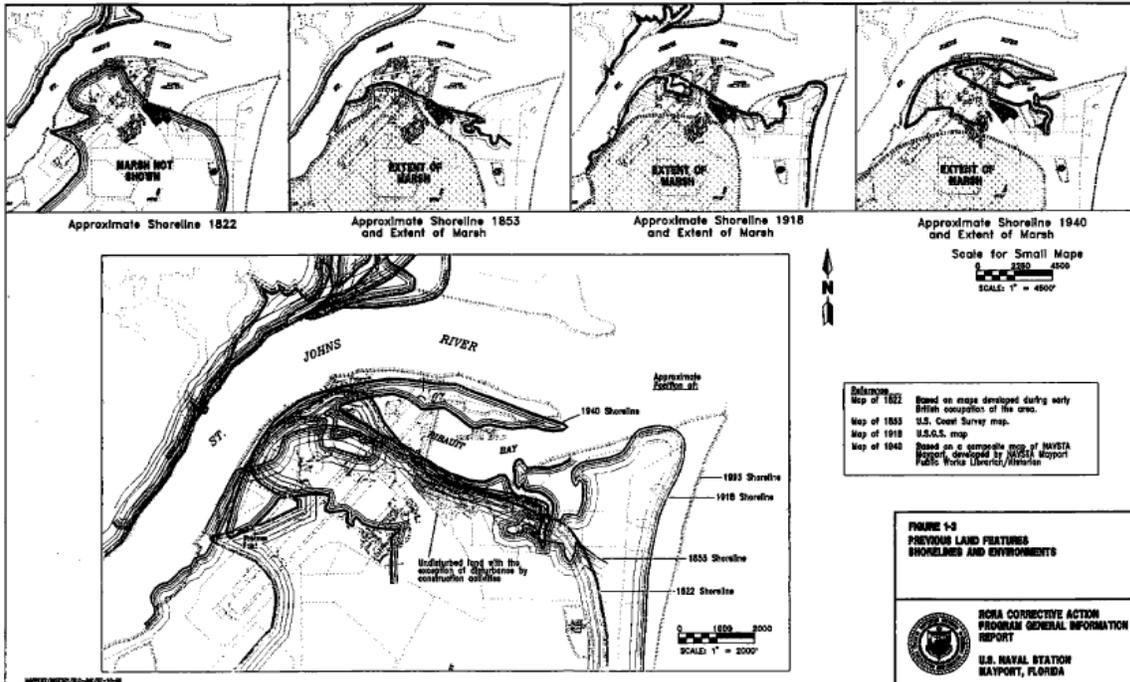


Figure 1 - Changing shoreline due to dredge and fill operations at NS Mayport (ABB Environmental Services 1995)

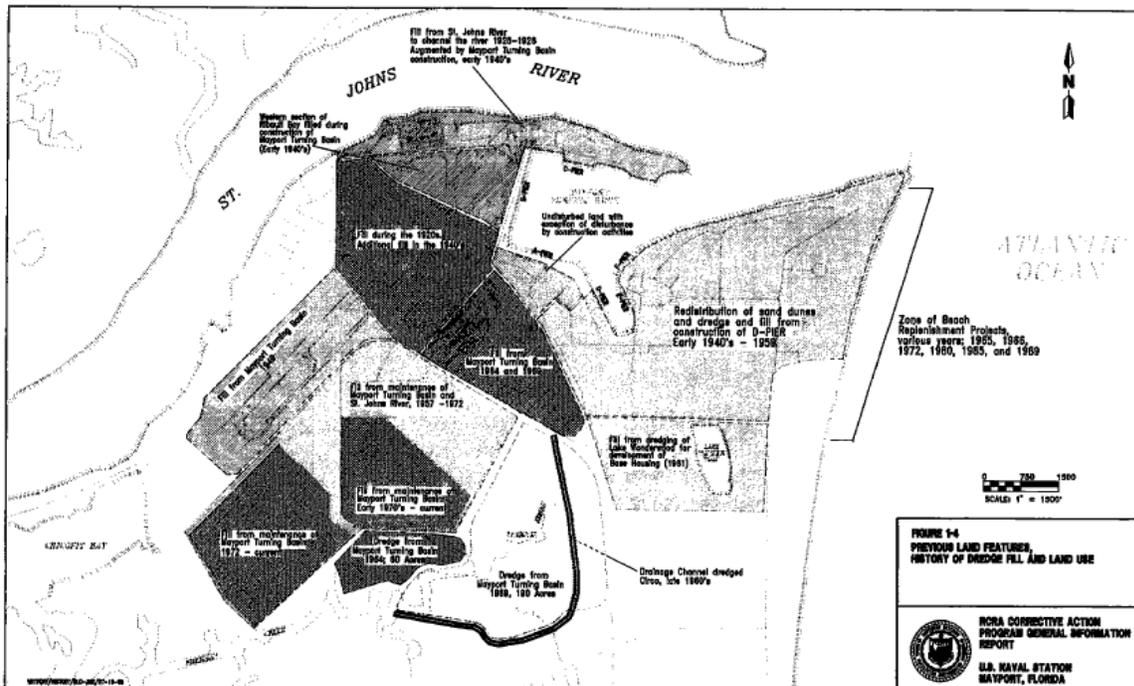


Figure 2 - Changing shoreline due to dredge and fill operations at NS Mayport (ABB Environmental Services 1995)

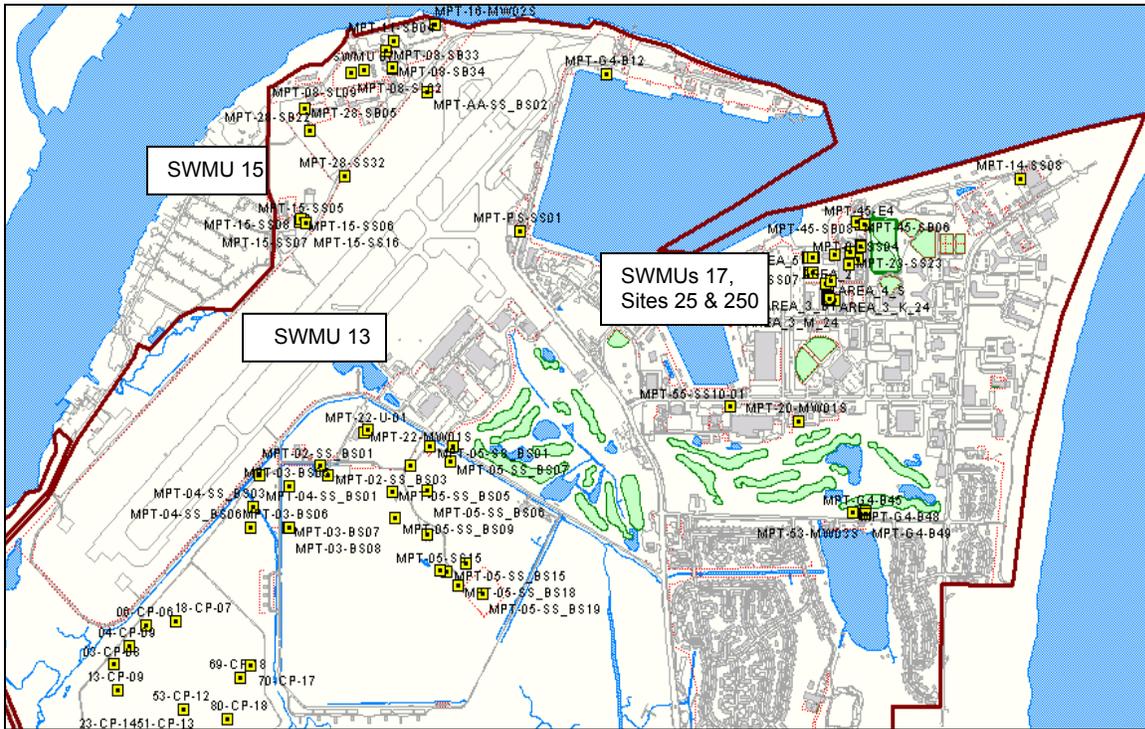


Figure 3 - NS Mayport soil sample locations showing As levels exceeding 2.1 mg kg^{-1} residential SCTL. (Tetra Tech NUS 2007)

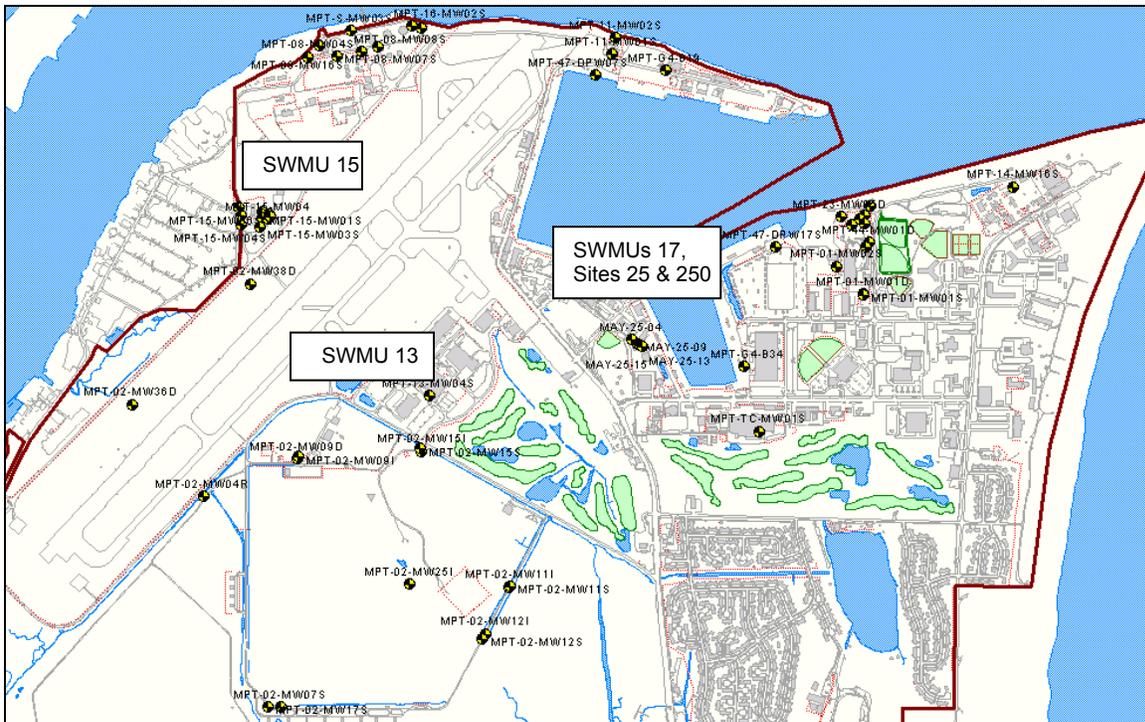


Figure 4 - NS Mayport groundwater sample locations showing As levels exceeding 10 µg L^{-1} GCTL. (Tetra Tech NUS 2007)

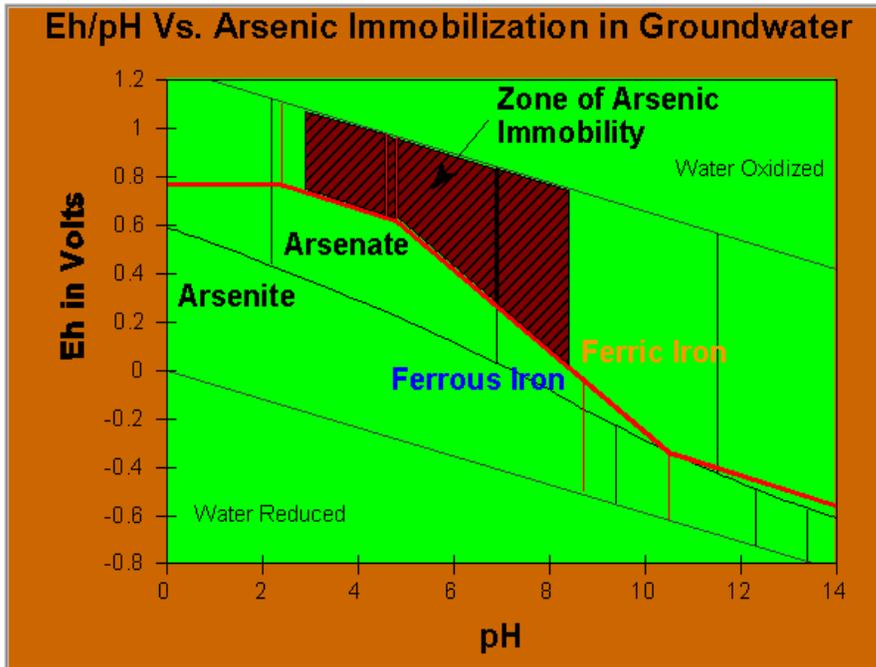


Figure 4. Arsenic Mobility in Groundwater as Controlled by the Effect of Eh/pH Conditions on the Speciation of Arsenic and Iron

Figure 7 - (Vance 2008)

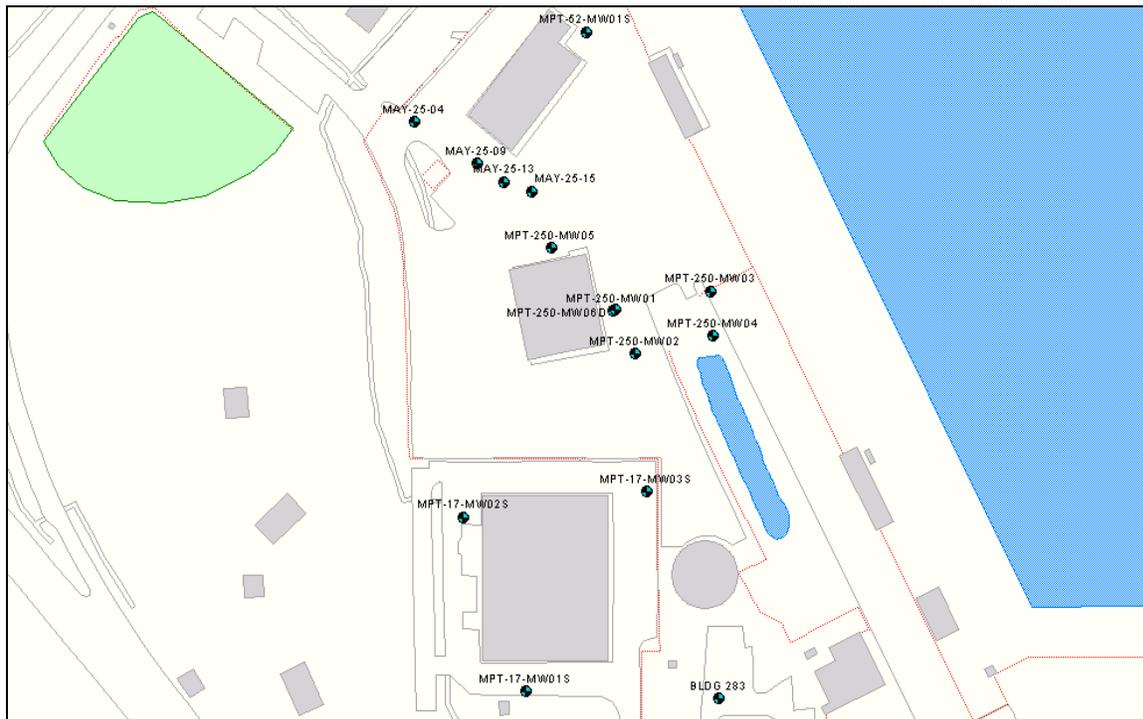


Figure 8 - Site 25, Site 250 and SWMU 17 groundwater sample locations.(Tetra Tech NUS 2007)

Table 2 - Groundwater inorganic, and miscellaneous parameters for Sites 25 and 250 and SWMU 17 (Tetra Tech NUS 2007). Data represent the range of each parameter across 117 samples collected between 1995 and 2005.

Parameter	Range	Unit	FL GCTL/ MCL	Background
Alkalinity	266 - 453	mg L ⁻¹	ND	ND
Ammonia	0.4 - 1.5	mg L ⁻¹	2.8	ND
Arsenic	14.1-22.5	µg L ⁻¹	10	5.3
Calcium	98.7 - 162.5	mg L ⁻¹	ND	226
Iron	223 - 4000	µg L ⁻¹	300	494
Magnesium	6.01 - 21.2	mg L ⁻¹	ND	184
Manganese	45.2 - 294.5	µg L ⁻¹	50	141
Phosphorus (Elemental)	0.13 - 1.5	mg L ⁻¹	0.1	ND
Selenium	2.5	µg L ⁻¹	50	ND
Sodium	15 - 25.4	mg L ⁻¹	160	1524
Sulfate	6.5 - 76.9	mg L ⁻¹	250	514
Sulfide	4	mg L ⁻¹	ND	ND
Total Kjeldahl Nitrogen	0.7 - 12	mg L ⁻¹	ND	ND

NOTES:

ND - No Data

FL GCTL/MCL - Florida Groundwater Cleanup Target Levels/Maximum Contaminant Level

Background from Technical Memo, Background Characterization Activities (ABB Environmental Services 1994)

Table 3 - Concentrations of water-quality constituents used to classify redox conditions of samples from the glacial aquifer system of the Northern United States. (Thomas 2007)

Redox classification	Oxygen (mg L ⁻¹)	Nitrate-N (mg L ⁻¹)	Manganese (µg L ⁻¹)	Iron (µg L ⁻¹)	Sulfate (mg L ⁻¹)
Oxygen reducing	≥0.5	-	<50	<100	-
Nitrate reducing	<.5	≥0.5	<50	<100	-
Manganese reducing	<.5	<.5	≥50	<100	-
Iron or sulfate reducing ₁	<.5	<.5	-	≥100	≥4
Methanogenic ₁	<.5	<.5	-	≥100	<4

NOTES:

₁These classifications are collectively referred to as “strongly reducing.”

“-“ constituent concentration not specified

[Modified from Thomas]

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