Grove Pond Arsenic Investigation:

Final Report

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TABLE OF CONTENTS

List of Figures

List of Tables

List of Appendices

Appendix	Content
A	Geophysics report
B	Phase II boring logs
C	Surface water and sediment sampling report, ESAT
D	Supplemental data
E	Bedrock core analysis report (USGS)
F	Electron microprobe report (R. Hon)
G	Human-health risk assessment
H	Ecological risk assessment

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EXECUTIVE SUMMARY

In order to meet the current and projected future water demands of the Town of Ayer, Massachusetts, two water supply wells on the south shore of Grove Pond have been returned to service. Assurance that the groundwater drawn by these wells will meet certain quality standards is sought by the Town of Ayer, regulatory agencies, and the concerned public. The purpose of this investigation is to address data needs that were identified after a review of previous studies of Grove Pond. The central goal of this work is to address concerns regarding the potential for migration of inorganic contaminants, particularly arsenic, from pond sediments to the wells.

This report is a compilation of data resulting from activities that took place during two field seasons, in accordance with the tasks outlined in the Phase I and Phase II Work Plans (Gannett Fleming, 1999a; 2000). Phase I was executed between July and October, 1998, and the final sampling round was conducted in February 1999. A draft interim data report was submitted in April 1999 (Gannett Fleming, 1999b), prior to receiving the analytical results from the last round of Phase I sampling. At the conclusion of Phase I, it was apparent that this investigation was incomplete. Data obtained from the final Phase I sampling round were inconsistent with results obtained earlier in the investigation. Moreover, ambiguities in the preliminary interpretation of the Phase I data, plus the identification of some data gaps, supported the need for additional work. Accordingly, Phase II was launched in July 1999, and the last round of samples was obtained in February 2000. Results of the Phase II work, in addition to those from Phase I, indicate a radically different interpretation than that presented in the draft Phase I data report. While much of the draft Phase I data report is included in this document, the interpretations and conclusions have been substantially modified in light of the final Phase I data as well as all of the Phase II results.

Summary of Key Activities and Results, Phase I: Surface water from Grove Pond, water from the Town of Ayer wells, and groundwater from five monitoring wells surrounding the production wells were sampled during the Phase I 1998-1999 field activities. The monitoring wells are all screened within the pumping horizon, which is from 40 to 60 feet below ground surface. The pumping wells and the two closest, flanking monitoring wells were sampled immediately upon start-up of production in July 1998, several times during the first week of production, and with decreasing frequency thereafter, through the concluding Phase I sampling round in February 1999. The two supply wells typically are pumped at about 700 gallons per minute, for approximately 10 hours per day.

Arsenic was observed in the production wells at initial concentrations of 45 to 47 μg/L, dropping within the first three days of pumping to approximately 20 to 30 μg/L. Arsenic was not detected in any of the other monitoring wells at concentrations significantly above the detection limit of 1 μg/L. Surface water concentrations ranged from 3 to 10 μg/L. Historical and anecdotal evidence indicates that the pumping wells have produced arsenic at concentrations of 20 to 30 μg/L for decades, suggesting that redevelopment of the wells in July 1998 neither initiated nor exacerbated present-day arsenic levels. The absence of comparable levels of arsenic in any of the surrounding monitoring wells, screened at the production horizon, was not explained by the Phase I data. Moreover, it was apparent from the final Phase I data that Grove Pond surface water experienced large, seasonal perturbations in certain parameters (for example, chloride and temperature), and these fluctuations were not observed in a monitoring well assumed to be located on a flow path between the pond and the production well screens. At the conclusion of Phase I, the arsenic source remained unresolved, and evidence implicating or exonerating the pond sediment was inconclusive. No alternative explanation had emerged from the Phase I data, and data gaps (e.g., pond sediment sampling) remained.

Summary of Key Activities and Results, Phase II: In order to fill the data gaps remaining at the end of Phase I and to constrain better the arsenic source(s) and transport pathway(s), Phase II was begun in the fall of 1999. At the outset of Phase II, a geophysical survey confirmed that depth to bedrock beneath the production wells is approximately 110 feet below ground surface, contradicting previous estimates that were considerably shallower. Other field activities included the collection of closely spaced soil and groundwater samples along vertical profiles extending from the top of the aquifer to bedrock, during the installation of five new monitoring wells. In contrast to the monitoring wells sampled during Phase I, the new wells were screened at depths ranging from the top of the aquifer to within bedrock. A sixth borehole, located in Grove Pond offshore of the production wells, was sampled for soil and groundwater but was not completed as a monitoring well. Phase II results provided significant insight into the heterogeneous nature of the geochemical and hydraulic characteristics of the aquifer, vertically as well as horizontally. Reducing conditions were observed in the upper ~40 feet of the aquifer. Below this interval, oxidizing conditions prevailed from approximately 45 feet to 75 feet, and reducing water was again encountered near and into bedrock.

The vertical profile groundwater sampling during installation of three of the new wells showed an increase in dissolved arsenic concentration with depth through the upper ~40 feet of the aquifer, to a maximum of 189 μg/L. Below this interval, arsenic was not detected (at detection limits typically <5 to 20 μg/L) until approaching bedrock, where arsenic concentrations of ~100 μg/L were observed. Similarly, dissolved iron increased with depth in the upper part of the aquifer and was highly correlated with arsenic in the three vertical profiles throughout the reducing zone. Dissolved iron was also highly correlated with arsenic in water from the production wells for the 18-month period over which sampling took place. Major-element chemistry (calcium, sodium, magnesium, potassium, chloride, sulfate, and alkalinity) also distinguished 'upper aquifer' water (the upper ~40 ft) from the 'lower aquifer' (~75-102 ft). Graphical analysis of these two compositional populations, using Piper diagrams, suggests that production well water composition is consistent with a mixture of these two end members. Stable isotope results (δD and $\delta^{18}O$) indicate that the production-well water is similar in composition to groundwater sampled elsewhere at and below the production horizon. However, the isotopic composition of the production wells and surrounding aquifer is significantly lighter than surface water, which, in turn, is lighter than the shallowest groundwater sampled (8-13 ft bgs). Therefore, the isotope data do not indicate mixing of surface water and groundwater at the pumping wells. Phase II data also indicate that the production wells intercept water flowing from the north side of the pond, i.e. from the vicinity of the Town of Ayer. This water is characterized by high chloride and nitrate concentrations, and lower pH and alkalinity, all of which are consistent with urban impact.

Grove Pond sediments are known to have arsenic of order ~100 mg/kg. Bottom-sediment pore waters extracted during Phase II contained dissolved arsenic at concentrations up to ~100 µg/L. However, analysis of pore waters obtained from soft-sediment cores through the pond bottom showed that dissolved arsenic decreases by an order of magnitude within a foot or two of the sediment-water interface, before increasing again in the upper aquifer to a depth of approximately 40 ft below ground surface. Arsenic concentrations in pond sediment samples taken during this investigation were not quantified, due to detection limit problems experienced by the laboratory.

Limited analyses by optical petrographic microscopy and electron microprobe confirmed the presence of sulfide minerals in the bedrock immediately underlying the production wells. These sulfides, predominantly pyrite (FeS_2) and cobaltite (CoAsS), appear to represent multiple generations of mineralization and contain arsenic concentrations ranging from a few tenths to approximately 45 weight percent.

Boring logs based on continuous split-spoon sampling of the overburden aquifer material reveal over 100 feet of sand and gravel with occasional silty interbeds. Historic pumping tests performed on the two water-supply wells yielded hydraulic conductivity estimates of the order of several hundred feet per day, based on calibration of a model assuming a homogeneous aquifer. In the present investigation, slug tests carried out in monitoring wells screened within the interval of the production well screens yielded similar results. However, slug tests performed in a screened drive point within the upper ~40 feet of the aquifer resulted in notably lower conductivities, typically in the range of a few feet to a few tens of feet per day. Highly variable recovery in the drive point used in the profile sampling suggests that the shallow aquifer (i.e., less than ~40 ft bgs) exhibits heterogeneous horizontal conductivity, and, correspondingly, low vertical conductivity over the unit as a whole. Below the production horizon, slug tests again indicate conductivities of the order of tens of feet per day, with a zone of higher-conductivity sand and gravel at greater depth. These results are generally corroborated by thirteen grain-size analyses performed on selected split-spoon soil samples. The gross conductivity structure of the aquifer, then, comprises a relatively fast layer at intermediate depth, overlain by a vertically heterogeneous unit of much lower conductivity, and underlain by somewhat lower-conductivity materials, as well. The low vertical conductivity of the interbedded sands and silts comprising the upper ~40 feet of the aquifer inhibits transport of surface water from the pond downward to the pumping horizon.

Six drive-point piezometers were installed through the organic-rich layer underlying the pond and into the top of the sandy aquifer in order to obtain direct indications of vertical hydraulic gradients induced by the pumping wells. The maximum recorded drawdown across the pond-bottom sediment, 0.4 ft, was observed at the piezometer closest to Production Well #1 (about 150 feet away) and about 50 feet offshore. The minimum recorded drawdown was 0.03 ft, at the farthest piezometer, about 300 feet from the pumping wells and 200 feet offshore. These results show that there is a downward hydraulic gradient across the pond-bottom muck that decreases in magnitude with distance from the supply wells. Thus, while the upper ~40 feet of the aquifer isolates the pumping horizon to some extent, drawdown is measurable immediately beneath the pond, and some infiltration from the pond to the underlying aquifer is induced.

Four seepage meters were deployed in the pond within about 100 feet of the shore, immediately north of the production wells. The meters were monitored over four time intervals of three to four days each. One period coincided with a shutdown of the supply wells. Measured seepage fluxes ranged from 0 to 0.034 feet per day (downward) under pumping conditions, averaged over the monitored time interval. Assuming a 300-foot-radius, half-circular area of the pond over which the pumping induces infiltration, as suggested by the piezometer data, and the maximum measured infiltration rate, the total induced volume flux from the pond to the aquifer is less than 1% of the volume flux extracted by the supply wells. Thus, the seepage meters indicate that induced infiltration contributes negligibly to the water produced at the wells, consistent with the conclusions drawn from the major-element chemistry of waters from the pond, the aquifer, and the supply wells.

A conceptual model has been developed from the geologic, hydrologic, and chemical data gathered during this investigation. This model holds that the aquifer is the source of the arsenic detected at the supply wells. The correlation with iron in three vertical profiles and in the production well water suggests that arsenic is liberated via the 'reductive dissolution' mechanism, i.e., arsenic adsorbed onto solid ferric oxyhydroxide surfaces in the aquifer matrix is released when the solid phase dissolves under reducing conditions. Furthermore, the tops of the production well screens appear to lie within the high-arsenic reducing zone in the upper part of aquifer. A detailed discourse on the glacial history of the area and diagenetic processes within the overburden, resulting in the redistribution of arsenic, iron, and other trace elements from minerals originating in the bedrock, is beyond the scope of this study. However, the evidence presented in this report suggests that the ultimate source of arsenic is the bedrock. The presence of arsenic-bearing sulfide minerals in the formation immediately underlying the Town of Ayer production wells has been confirmed by electron microprobe analysis. The chemical and mechanical weathering of bedrock mineralogy during and after glaciation and post-glacial deposition resulted in the mobilization and redistribution of arsenic, iron, manganese, and other pH- and redox-sensitive elements through the overburden. This hypothesis is supported by data from the vertical-profile soil sampling showing that iron in the solid phase is highly correlated with arsenic, and that the distribution of both elements is relatively uniform throughout the overburden. A similar correlation of iron with other metals further supports the role of iron as an effective sorbent.

The removal of arsenic from solution by sorption onto ferric oxyhydroxide surfaces, the dissolution of these surface coatings due to exposure to reducing water, and the subsequent remobilization of sorbed elements has been well documented through numerous laboratory, field, and theoretical studies described in the current geochemical literature. In the data reported here, elevated arsenic levels observed in the groundwater profile sampling are highly correlated with elevated iron and manganese. Furthermore, dissolved arsenic, iron, and manganese are consistently associated with reducing conditions, defined by low sulfate, dissolved oxygen (DO), and oxidation-reduction potential (ORP). Low-ORP groundwater conditions develop when the rate of consumption of dissolved oxygen (e.g., by oxidation of native organic matter in the aquifer) is greater than the rate at which oxygen is replenished (e.g., by recharge of well-oxygenated rain water). Such conditions have developed in the present setting due to the low hydraulic conductivity observed in the uppermost portion of the aquifer, which results in low groundwater velocity and long residence time in this subdomain. The general conclusion arising from this investigation is that the reductive dissolution of ferric oxyhydroxides, under naturally occurring low-ORP conditions, and subsequent release of sorbed trace metals is responsible for the elevated levels of arsenic in the Town of Ayer wells.

Neither the major-element results nor the stable isotope data are consistent with a substantial contribution of pond water to the production wells. While there is apparently some induced infiltration from the pond, it does not contribute a significant volumetric fraction to the production wells. A conservative estimate based on data collected from seepage meters indicates that the volume flux induced from the pond is less than 1% of the pumping rate. The downward mass flux associated with this induced infiltration is negligible. Dissolved arsenic in the shallowest aquifer is below the detection limit of 20 µg/L achieved by the analytical laboratory. If arsenic at this conservatively estimated concentration is advected downward in only 1% of the volume produced, it can contribute only 0.2 µg/L to the supply wells, far less than the observed levels of ~30 µg/L.

In conclusion, it appears that the presence of arsenic in the Town of Ayer water-supply wells is due to naturally occurring geochemical and hydrologic processes within the aquifer, and is not related to arsenic-enriched pond sediment or to any anthropogenic sources or activities.

1.0 INTRODUCTION

The purpose of this report is to:

- present results of groundwater and surface water sampling at Grove Pond, in conjunction with the startup of production from the Town of Ayer wells in July 1998 and for approximately 18 months thereafter;
- estimate flux and possible breakthrough time of induced infiltration from the pond to the production wells, using piezometer and seepage meter data;
- provide "ground-truth" for arsenic concentrations reaching the Town wells, including transient behavior observed during startup of production wells;
- use results obtained from water, soil, pond sediment, and bedrock sampling, as well as other relevant information, to constrain possible sources and transport pathways for arsenic.

1.1 Report Organization

This report consists of seven sections. In Section 1, the Introduction defines the study objectives and describes the physical setting of the site. A synopsis of the site history, with emphasis on possible sources of arsenic contamination, is provided, and a brief summary of results from previous investigations is included. Section 2 describes the activities undertaken in both Phase I and Phase II of this study. The number and location of existing and new monitoring wells are listed, and the frequency of sampling events, for groundwater and surface water, is given. The preliminary site geophysical survey and borehole logging activities are summarized. The "vertical profile" soil and groundwater sampling activities are described, along with the sampling of pond sediments, hydraulic characterization of the overburden, and coring of bedrock immediately beneath the production wells. Section 3 summarizes the physical characteristics of the study area, and includes a brief description of surface features, local meteorological conditions, surface water and groundwater hydrology, bedrock geology, and soils in the Devens area. In Section 4, the nature and extent of contamination is addressed. This section includes a summary of analytical data from Phases I and II, discussion of contaminant trends spatially and temporally, comparison of data with site-specific background groundwater concentrations and regulatory standards, and an evaluation of data quality. In addition, this section includes analytical results from the soil, pond sediment, and bedrock core samples. An assessment of induced infiltration and mixing at the production wellheads is discussed in Section 5. Conceptual models for the probable arsenic source(s) and pathway(s) to the production wells are described in Section 6, and the model that has emerged from this study is presented. This section also includes a discussion of the influence of site-specific geochemical conditions on arsenic behavior. Conclusions drawn from this investigation and a list of unresolved issues are presented in Section 7.

1.2 Study Objectives

Grove Pond, adjacent to the former Fort Devens Military Reservation, lies within an area in which a number of known or suspected contaminant sources are located (Fig. 1-1). A tannery operated near the pond's northwest corner from 1854 until 1961 and is known to have discharged waste directly into the pond. Based on previous investigations (e.g., ABB-ES, 1995a) contaminants of greatest concern are the metals lead (Pb), arsenic (As), chromium (Cr), and mercury (Hg).

Analytical results have been reported previously from Grove Pond surface water and sediments, and adjacent wells (e.g., CDM, 1993; ABB-ES, 1995a). Although high concentrations of metals (Pb, Cr, As, etc.) have been reported from Grove Pond sediments, these metals have not been detected above Maximum Contaminant Levels (MCLs) in either pond surface water or groundwater withdrawn from the Fort Devens wellfield, located approximately 1000 feet west of the Town of Ayer wells. The Town of Ayer Grove Pond wells, too, historically have produced water that meets the drinking water standards of the Massachusetts Department of Environmental Protection (MADEP), with the exception of elevated levels of iron and manganese. Prior to this study, arsenic had been detected persistently in untreated Grove Pond well water at up to 30 μg/L (e.g., MADEP Inorganics Report, July 24, 1997), below the historic MCL of 50 μg/L but above the current standard of 10 μg/L. Thus, arsenic has been identified as a contaminant of particular concern. It is a goal of this investigation to assess the likelihood that current and future levels will remain below present and projected MCLs. It should be noted that treatment at the on-site plant successfully removes arsenic to below detection limits (usually 4 μg/L or lower) before the water enters the Ayer distribution system.

The issue of induced infiltration, defined here as the extent to which pond water contributes to the total production at the wellhead, is also addressed in this investigation. If any contaminants originate in pond-bottom sediments, then the volumetric contribution of pond water to the production wells is a critical parameter in assessing the impact of this source on the water supply. Previous estimates of induced infiltration cover a broad range, depending upon the assumptions made, and are inferred principally from model calculations. Little direct, field evidence was available previously to quantify induced infiltration. A major goal of this investigation is to quantify induced infiltration using data from seepage meters deployed in the pond as well as chemical indicators of mixing of pond water and groundwater (major-element chemistry and stable isotopes).

Specific objectives of Phase I (Gannett Fleming, 1999a) were:

1. Measure the concentration of arsenic arriving at the production wells. This information is critical to a general assessment of the potential impact of Grove Pond sediment contamination on the water quality at the well head. In addition, these data supplement those collected by the Town of Ayer to evaluate the efficiency of the

treatment plant, by comparison to analyses performed on the output stream of the plant.

2. Assess the elevation (if any) of arsenic above relevant measures of "background" concentrations for groundwater, particularly that arriving from the upgradient area to the south of the production wells. The definition of a background level of groundwater arsenic was not specifically identified as a goal in the Phase I Work Plan; however, as will be discussed later in this report, the data produced during this work point to a need to reevaluate "background" – both the general definition and the absolute concentration – for this particular site.

3. Measure the concentration of arsenic and other metals in Grove Pond surface water, and compare to background groundwater and water at the wellheads.

4. Determine the fraction of the well production that is drawn from the pond. Major-element chemistry and possibly other natural chemical tracers may provide a direct, quantitative indication of the mixing of groundwater with water added to the aquifer from the pond via induced infiltration.

5. Determine the time scale for transport of chemical species from the pond to the production wells based on the transient "breakthrough" of water bearing the chemical characteristics of the pond, if identifiable.

6. Assess alternatives for potential sources and transport pathways for arsenic and other inorganic constituents observed at the Town of Ayer wells.

Results from Phase I suggested that arsenic may be transported from the direction of the pond to the production wells along flow lines that either over- or underflow the screen of the monitoring well located between the pond and the pumping wells. Prior to the initiation of Phase II, it was assumed from all available information that the ultimate source of arsenic in the system was, at least originally, sulfide mineralization in the underlying bedrock. Accordingly, in Phase II the focus of attention was shifted to sampling the deep aquifer and vertical-profile sampling of the overburden in selected locations to determine arsenic source, direction of transport, and magnitude in various portions of the aquifer / bedrock system.

Phase II activities targeted the uppermost and deepest portions of the aquifer, as well as the underlying bedrock, and included:

1. Geophysical characterization of the study area, to delineate depth to bedrock and distinct stratigraphic horizons, particularly in the immediate vicinity of the production wells.

2. Closely-spaced sampling of aquifer material and groundwater during installation of new monitoring wells, to obtain detailed vertical profiles of sedimentary characteristics and groundwater chemistry through the overburden and into bedrock.

3. Pond sediment and pore water sampling, to characterize arsenic distribution in the pond.

4. Coring through pond sediment into the top of the aquifer, for evaluation of arsenic distribution in solid phase and pore water.

5. Hydraulic characterization of aquifer (e.g., slug test data at discrete points along vertical profiles; piezometers in pond; conductivities of core samples from pond-bottom sediments), in order to ascertain variability in hydraulic conductivity and to obtain realistic values for flow modeling.

6. Assessment of communication between the pond and the production wells, and between bedrock and the monitoring wells adjacent to the supply wells.

7. Bedrock coring for lithology and mineralogy, especially for presence or absence of arsenic-bearing phases and identification of such phases, if present.

In addition to these site-specific objectives, it is noted that arsenic in drinking water has emerged recently as a national issue of some prominence (e.g., NRC, 1999a). Under a Congressional mandate, the USEPA recently reassessed the federal Maximum Contaminant Level (MCL) of 50 µg/L for arsenic in drinking water. In 1999, the National Research Council released a study (NRC, 1999b) concluding that the standard should be made more stringent, based on human-health effects. A new standard, 10 µg/L, was adopted by the USEPA on October 31, 2001.

1.3 Site Background

1.3.1 Site Description

Grove Pond is roughly triangular in shape and covers about 60 acres adjacent to the northeast corner of the former Fort Devens Main Post (Fig. 1-1). It is shallow, with maximum water depth approximately 5 to 6 feet, and the water is frequently eutrophic. The pond bottom consists largely of a thick mat of decomposing vegetation. It is the fifth in a string of six ponds (in the downgradient direction: Long Pond, Sandy Pond, Flannagan Pond, Balch Pond, Grove Pond, Plow Shop Pond) that were formed by a series of dams installed in the 19th century. During that time, Grove Pond was periodically "flowed" or flooded during the winter months to provide a source of ice, and drained during the spring and summer for grazing livestock. Prior to the existence of the ponds, the area that is now submerged was occupied by meadows underlain by peat bogs. An internal MADEP memorandum (H. R. Cutting to L. Chappell, MADEP, 9/8/92) refers to the October 1905 Title Report of Edward Woodward, which states that 'the Worcester Peat Company bought extensively in the area' in 1856.

Grove Pond receives drainage from Balch Pond, as well as from Cold Spring Brook and Bowers Brook, and discharges through a culvert on the western edge of the pond into Plow Shop Pond. Discharge from Plow Shop Pond, at a dam in the northwest corner, forms Nonacoicus Brook and its associated wetlands, which in turn flows northwest to the Nashua River.

1.3.2 Site History

A tannery, located on the northwest corner of the pond, operated intermittently from 1854 until 1961. Prior to 1953, tannery wastes were discharged directly into pond with little or no treatment. In addition, a landfill was formerly located between the tannery and Grove Pond. Its location is suggested by aerial photographs that show gradual infilling of an embayment in the northwest corner of Grove Pond.

Other potential sources of contamination to the pond are: stormwater runoff from the Boston and Maine railroad yard on the southern shore; historical infilling of portions of the pond's perimeter; inflow from Cold Spring Brook and Balch Pond; and runoff from Fort Devens and the Town of Ayer. Extensive apple orchards lie within the drainage for the pond, and historical application of arsenic-containing pesticides has been suggested as a potential contaminant source. The contribution of arsenic and other metals to pond-bottom sediments by discharging groundwater may be significant.

The wells that are of immediate concern were installed by the Town of Ayer originally as backup to the Town's Spectacle Pond well field. The first, Grove Pond No. 1 (herein, PW-1), was installed in 1943 (60 ft deep; rated capacity 694 gpm), and Grove Pond No. 2 (PW-2) was constructed in 1952 (60.5 ft deep; rated capacity 780 gpm) 120 ft west of the first well. Both are within 150 ft of Grove Pond. The original, hand-sketched construction diagrams for these wells, as well as the drillers' log for Grove Pond No. 2, are reproduced in Appendix A of the 1999 Phase I Interim Data Report (Gannett Fleming, 1999b).

1.3.3 Previous Investigations

In December 1992 and January 1993, ABB-ES collected five sediment samples and five surface water samples from Grove Pond in conjunction with the U. S. Army's Fort Devens Remedial Investigation (ABB-ES, 1993). None of the surface water samples exceeded the Ambient Water Quality Criteria (AWQC) of 190 µg/L for arsenic. Highest concentrations of the inorganics, including arsenic, cadmium, chromium, copper, lead, manganese, mercury, nickel, and zinc, were found in sediments along the pond's northwest shoreline, south of the former tannery site and adjacent to the railroad causeway.

In October 1992, MADEP collected six sediment samples from the western shore of Grove Pond. Similar to the ABB-ES data, the highest concentrations of arsenic, chromium, lead, and mercury were reported from the northwest corner of the pond.

In December 1993, Boston and Maine Corp. collected four surface water and four sediment samples. Of the reported inorganics in the water samples, aluminum slightly exceeded the AWQC for fresh water aquatic life (110 µg/L versus 87 µg/L). Inorganics exceeding MADEP S-1/S-2 reportable concentrations for surface water were arsenic, chromium, cadmium, cobalt, copper, and lead; elevated levels of these metals were found in sediment samples from the northwest and western edges of the pond.

In 1994 the Plastic Distributing Corporation (a current occupant of the tannery site) installed four monitoring wells between the filled-in cove and the former tannery site, and collected five subsurface soil samples from borings in the same area. Arsenic (up to 78 µg/L), barium (up to 348 µg/L), chromium (up to 588 µg/L), and mercury (up to 6.0 µg/L) were reported in all of the filtered groundwater samples. Arsenic, barium, chromium, lead, and mercury were found in all of the soil samples. Additional soil samples were taken in the filled area, although concentrations of metals in those samples were within ranges judged to be naturally-occurring. It was concluded that these samples were probably taken in clean soil overlying the fill material.

In April 1995, additional sediment, surface soil, and surface water analyses were obtained from Grove Pond by the Army in accordance with the Grove Pond Site Investigation Work Plan (ABB-ES, 1995a). Shallow sediment samples (0-6 in) were collected at 48 locations; at ten of these locations, deep (up to several feet below the sediment surface) samples were also taken. Six surface water samples, co-located with six of the sediment samples, were taken just below the water surface. Five of the six surface water samples showed non-detectable arsenic (< 2.54 µg/L); arsenic in one sample was measured at 3.94 µg/L. (Note, for reference, that the drinking-water maximum contaminant level (MCL) for arsenic at the time was 50 µg/L and currently is 10 µg/L). Results obtained from the shallow sediment samples confirmed the presence of high levels of a suite of inorganics. These elements, and maximum concentrations detected, included: arsenic (340 µg/g; 1300 µg/g at a depth of 3 ft), barium (470 µg/g), cadmium (110 µg/g), chromium (49800 µg/g), copper (240 µg/g), iron (42800 µg/g), lead (1760 µg/g), manganese (1730 µg/g), mercury (220 µg/g), vanadium (111 µg/g), and zinc (755 µg/g). The distribution patterns of arsenic (Fig.1-2), barium, chromium, copper, lead, manganese, mercury, and vanadium suggest that the former tannery may have been the source of at least some of these elements. However, the transport processes that led to the observed distributions throughout the pond are not well understood at this time..

The focus of the 1995 sediment investigation (ABB-ES, 1995a) was principally on the northwest cove, where the highest concentrations of metals were reported. A few samples were taken to characterize the broader distribution of contaminants across the pond, but coverage is rather sparse in the vicinity of the Ayer wells. Contour plots of key metals (e.g., Fig. 1-2) show extreme peaks offshore of the production wells that are probably a consequence of the low data density. Phase II of this investigation included pond sediment sampling in order to fill these data gaps.

During the summer and fall of 1999, a limited investigation of the former tannery site was performed by Environmental Compliance Services, Inc. (ECS, 2000) for the

Massachusetts Department of Environmental Protection (MADEP). Field activities included five soil borings, all of which were completed as groundwater monitoring wells, and the collection of two surface water samples. In one soil boring, the highest concentrations of arsenic (494 mg/kg), chromium (63,800 mg/kg), antimony (1,770 mg/kg), and mercury (525 mg/kg) were found at a depth of 9-11 ft below grade. In groundwater, all metals were below the MCP GW-3 standards, with the exception of zinc. Maximum concentrations of soluble chromium and arsenic in groundwater were 69 μg/L and 168 μg/L, respectively. For reference, the MCP GW-3 standards for chromium and arsenic are 2000 μg/L (total Cr) and 400 μg/L, respectively.

1.3.4 Historical Occurrence of Arsenic in Town of Ayer and Nearby Wells

Town of Ayer wells: Arsenic at concentrations of approximately 20 μg/L to 30 μg/L has been reported, anecdotally, from the Ayer wells for several decades. Unfortunately, many of the Town's records are no longer available. Table D-1, Appendix D, and Figure 1-3 summarizes data that show arsenic concentrations from the early 1990s that are of the same order as the results reported for this study.

Raw water pumped from the production wells was sampled frequently between July 1998 and June 1999 at the treatment plant for both the Town of Ayer and the Massachusetts Department of Environmental Protection (MADEP). Within the first few days following startup of the wells in July 1998, arsenic was observed at concentrations around 20 μg/L, and remained consistently at this level, with occasional excursions (Table D-2). The data obtained by treatment plant personnel are in good agreement with arsenic levels obtained independently (this study). Arsenic in the treated water is consistently below the MDL of 5 μg/L. Comparison of present arsenic concentrations to analyses prior to the startup of the wells in 1998 indicates that the well development activities did not initiate or exacerbate arsenic levels.

Ft. Devens Grove Pond well field: The Ft. Devens Grove Pond wells are located approximately 1000 feet to the west of the Town of Ayer wells. The general hydrogeologic setting of this well field is similar to the Town of Ayer wells, i.e., the wells are screened in the overburden aquifer in proximity to Grove Pond. In samples taken on April 16, 1997, arsenic was reported as non-detectable (<2.5 μg/L) (MADEP Inorganics Report, May 5, 1997). These 12 wells have 8-inch diameter casings and 10 ft screens centered at depths of 35 ft to 43 ft below ground surface (bgs). The wells have been pumped at relatively low rates since activities on the Base decreased in recent years (e.g., 550--680 gpm total production for several days per month, at the time of this report). Chemical data from the Devens Grove Pond wells, although limited, suggest that these wells are producing oxygenated water. The analytical data from 4/16/97 reported sulfate at 20.8 mg/L, while an analysis performed on 5/28/98 reported non-detectable iron (<0.05 mg/L). Differences between the hydrogeochemical setting of the Devens wellfield and the Town of Ayer wells are discussed in more detail in Section 6.3.

Massachusetts National Guard wells: In 1993, two monitoring wells on property belonging to the Massachusetts National Guard (MNG-6 and MNG-7) were sampled as part of the Well-Head Protection Monitoring Network program (ENSR, 1993). Arsenic values of 34 µg/L, 51 µg/L, and 22 µg/L were reported for the unspiked grab water sample, matrix spike grab water sample and the duplicate matrix spike grab water sample, respectively, from MNG-7. In addition, 84 µg/L arsenic was reported from MNG-6. Recent analyses (this study) from MNG-7, using the low-flow sampling technique, consistently showed arsenic at levels near or at the MDL of 1 µg/L, suggesting that the 1993 samples may have been taken with a bailer and/or were unfiltered, so that the earlier analyses reflected the presence of particulates and sorbed arsenic. Construction details and drillers' logs for these wells are in Appendix A. of the Phase I Interim Data Report (Gannett Fleming,1999b).

Randolph and Baldwin wells: In the early 1940s, the US Army constructed two production wells at the northwest corner of Grove Pond, on the former tannery site. These wells have extensive, engineered, gravel packs that minimize drawdown even under maximum pumping conditions (~600 gpm). One of these wells is located on a point of land adjacent to the sampling location at which pond sediment arsenic concentration was the highest detected (340 µg/g at the sediment surface; 1300 µg/g at 3 ft depth; ABB-ES, 1995a). The wells are screened at bedrock, around 87 ft, and data provided by Randolph and Baldwin (a current site occupant) show <5 µg/L arsenic in untreated water. It is not known whether the absence of detectable arsenic in these wells is due to a local hydrogeochemical condition, the unusual well construction, or some other influence.

Unnamed commercial well: Another production well, located approximately 0.7 mile to the east of the Grove Pond wells, is screened at bedrock at a subsurface depth of 97 feet. Maximum production from this well is 512,000 gpd (~350 gpm, assuming constant, 24-hr/day pumping). Analyses of metals from a sample from this well (Table D-3, Appendix D) show ~20 µg/L arsenic, but no detectable iron (MDL = 0.01 mg/L) and ~0.160 mg/L manganese. Water from this well is treated prior to entering a commercial production stream.

2.0 STUDY AREA INVESTIGATION

2.1 Phase I: Groundwater and Surface Water Investigation

During Phase I of this investigation, groundwater was sampled at the two production wells, designated PW-1 and PW-2, and at two nearby monitoring wells, designated 92-1 and 92-3 (Fig. 2-1), at a frequency designed to capture transient effects associated with the onset of pumping. In addition, three monitoring wells farther upgradient to the south, designated MNG-7, MNG-3, and 92-4, were sampled twice, and a single well on the north side of Grove Pond, designated 92-5, was sampled once. Well locations, elevations, and screen intervals are summarized in Tables 2-1 and 2-2. Well construction diagrams and boring logs for all wells sampled in this program are reproduced in Appendix A in the Phase I Interim Data Report (Gannett Fleming, 1999b). The rationale for the sampling schedule is given in this subsection.

Preliminary examination of data from previous investigations (CDM, 1993; ABB-ES, 1995a) indicated that Grove Pond surface water and water from the aquifer could be distinguished by their major-element chemical compositions. The sampling schedule (Table 2-3) was designed to yield sufficient data to characterize the transient response of the groundwater chemistry to the startup of the production wells. Particular emphasis was placed on attempting to resolve the breakthrough of water originating in Grove Pond. It was anticipated that recharge from the pond to the underlying aquifer would be induced by the head drop due to pumping. Chemical indicators of the arrival of pond water at the production wells were sought to confirm this scenario, to estimate the magnitude of the induced infiltration, and to characterize the time scale for transport along this pathway.

The schedule included sampling at the production wells and the nearest monitoring wells, 92-1 and 92-3, twice per day for the first three days, based on the estimated minimum breakthrough time. The minimum travel time for water from the pond to the pumping wells would obtain for a homogeneous aquifer, open at its top to the pond. The estimate was based on a simple, kinematic argument. For steady, radial flow to a fully penetrating well, the travel time from a point a distance R_2 from the well is given by

$$t_b = \frac{\pi bn}{Q}\left(R_2^2 - R_1^2\right)$$

where b is the saturated thickness of the aquifer, n is the porosity, Q is the volume flow rate at the well, and R_1 is the radius of the well. The two wells, each pumping continuously at 700 gallons per minute, yield a total flow rate of $Q = 2.7 \times 10^5$ cubic feet per day. For a saturated thickness of 80 feet (the best estimate available at the time of development of the sampling plan), porosity of 0.3, and well radius of 1 foot, the above expression gives a breakthrough time of about three days for water originating 100 feet away, the approximate distance from the wells to the shore of the pond. This simple calculation guided the focus on the first three days of pumping at the production wells. However, it should be noted that this estimate represents the first arrival of water drawn along the shortest flow path from the pond. The area from which induced infiltration is drawn very likely extends well into the pond. The above expression shows that the travel time increases with the square of the distance from the well, R_2^2, so that arrivals along flowlines originating farther out in the pond will require weeks to months. Thus, it can be anticipated that breakthrough of pond water may be stretched out over a broad period of time. In addition, this idealization neglects possible influence of lower-conductivity material that may lie between the pond bottom and the screened interval of the previously existing monitoring wells and the production wells. Such material, if present, may significantly increase the travel time of water from the pond to the pumping wells.

It should be noted that the water-supply wells underwent a complex history of redevelopment, starting on June 2, 1998. In addition to sporadic pumping to test equipment, the wells were "shocked" with hydrochloric acid and sodium hypochlorite in order to eliminate possible fouling. In the course of this process, the wells were surged and subsequently pumped to remove debris as well as the treatment chemicals. These activities were completed by Friday, July 24, 1998. The system was not subjected to pumping stress again until the full production startup on Monday, July 27. The development activities, however, may have induced infiltration from Grove Pond to the underlying aquifer, and drawn pond water toward the production wells to an undetermined extent prior to the sampling activities associated with this investigation.

The following subsections itemize locations for groundwater samples (Fig. 2-1), and provide the sampling schedule for each location. Sampling procedures followed the USEPA Region I low-flow sampling methodology (USEPA Region I SOP #GW0001, Low Stress (Low Flow) Revision 2, July 30, 1996). This procedure minimizes water-level drawdown through low pumping rates, in order to minimize chemical perturbation of the sample.

An exception to this approach was the sampling of the production wells, which were sampled from taps at the wellheads, with the wells flowing at the full production level. All water samples were analyzed for major element chemistry, Project Analyte List (PAL) metals, and water quality parameters (see Phase I Work Plan, Gannett Fleming, 1999a). The Work Plan also lists analytical methods, method detection limits for the analytes, total numbers of samples, bottle requirements, sample preservation requirements, maximum sample holding times, and the frequency of Quality Control (QC) sampling.

In addition to the analytes listed in the Work Plan, water samples were collected during this study for analysis of oxygen and hydrogen isotopes (^{18}O and ^{2}H). The motivation for obtaining isotope data was to provide further constraints on the mixing ratio of pond water and upgradient aquifer water, in the event that other chemical signatures did not quantify induced infiltration unambiguously.

2.1.1 Production wells PW-1 and PW-2

Prior to startup of production at the end of July 1998, the Town of Ayer wells were treated with hydrochloric acid (HCl), sodium hexametaphosphate, and sodium hypochlorite. During a typical well rehabilitation, these chemicals are pumped into the well screen area and the well is repeatedly surged and pumped (G. Volpicelli, Tata & Howard, personal communication, 1999). The rehabilitation of PW-2 was initiated on May 19 and completed on May 28, 1998. The cleaning of PW-1 was begun on June 2, 1998, but it is noted in the drillers' log that on June 3, the pump began producing sediment. Subsequently, a video inspection of the well revealed severe deterioration of the old well screen. A new stainless steel screen was inserted into PW-1, while the original, silicon bronze screen was retained in PW-2. Cleaning of PW-1 was completed on July 11, 1998. Details of the well rehabilitation activities are included in Appendix D, of the Phase I Interim Data Report (GF, 1999b).

A request was made to the Town of Ayer to allow the maximum practical "rest" period for the wells before startup, in order to ensure that the initial samples were as close as possible to ambient aquifer conditions. Well development activities were completed on the afternoon of Friday, July 24, the system was at rest over the weekend, and production pumping was initiated at approximately 1:00 p.m. on Monday, July 27. The two production wells were sampled once on the afternoon of startup (within an hour of the time the pumps were started), twice a day for the next three days, once a week for the next three weeks, and once two months later. An additional round of sampling was completed in February 1999 in order to verify the stability of the groundwater chemistry.

During preliminary well development, pumping of the wells almost certainly resulted in perturbation of the system by drawing in water from the overburden surrounding the production well screens. The lines were cleared immediately prior to startup of the wells by pumping water through the hydrant adjacent to the PW-1 well house into the pond. Personnel on site at that time detected a strong smell of chlorine as far away as the treatment plant; subsequently, a bright orange-brown coating was noted on trees and other vegetation in the path of the spray from the hydrant. It is assumed that the well rehabilitation activities may have resulted in the oxidation of dissolved ferrous iron, which was then ejected as ferric oxyhdroxide when the lines were cleared. Alternatively, some of the iron oxide may have come from corrosion of the well system.

2.1.2 Monitoring Wells

Town of Ayer Grove Pond monitoring wells 92-1 and 92-3

Grove Pond monitoring wells 92-1 (located approximately 50 feet south of the production wells) and 92-3 (located between the production wells and the pond) were sampled a few hours prior to startup of the production wells, and subsequently on the same schedule as the production-well sampling. Well 92-l was expected to sample water on flowlines originating hydraulically upgradient in the aquifer to the south. Well 92-3 was believed to be located on a flowline originating from the direction of the pond and the aquifer to the north of the pond. In the absence of any additional information available at the outset of the Phase I activities, water on such a flowline was expected to have the maximum fraction of water derived from induced infiltration from the pond, at the depth of the production-well screens.

Massachusetts National Guard monitoring wells and Town of Ayer monitoring well 92-4

Two existing Massachusetts National Guard (MNG) monitoring wells (MNG-3 and MNG-7, both directly upgradient of the production wells) and one existing Town of Ayer monitoring well (92-4, approximately 200 feet south of the production wells) were sampled in order to establish representative aquifer conditions for the period during which the production wells were sampled. The purpose of sampling these wells was to define chemical characteristics of a potential groundwater "end member" coming to the production wells.

MNG-3, MNG-7, and 92-4 were sampled three times during the program, in August and October 1998, and February 1999. It was expected that these wells would be relatively unaffected by the pumping of the production wells. The purpose of the second and third sampling rounds at MNG-3, MNG-7, and 92-4 was to test the reproducibility of analyses at these locations.

Town of Ayer Grove Pond monitoring well 92-5

Monitoring well 92-5 is located approximately 1000 feet northwest of the production wells, on the opposite shore of the pond. This well was sampled once, in month 3 of the program, to characterize groundwater in the aquifer as it flows beneath the pond from the north. This well was not resampled in the February 1999 round because the water level had dropped below an obstruction in the well.

2.1.3 *Surface Water Investigation*

Initially, surface water samples were taken at six locations in the pond (Fig. 2-2). Pond water represents one possible "end member" of the mixture that may be reaching the production wells. All samples were analyzed for major element chemistry, Project Analyte List (PAL) metals, and water quality parameters (see Phase I Work Plan, Gannett Fleming, 1999a). Sample locations were marked by buoys at the time of the surface water sampling. Water samples were collected from a boat by means of a submersible pump, with the inlet placed approximately six inches above the sediment-water interface (pond bottom). Vegetation in the pond was extremely thick at the time of sampling, so determination of depth to the sediment-water interface may not have been accurate to within more than six inches. The sample was taken near the bottom in order to obtain water that would be drawn most immediately into the sediment due to induced infiltration. If any vertical variation in metals concentration is present in the water column, it is expected that the maximum will lie near the sediment-water interface due to diffusion from the underlying pond-bottom pore water. The pumping rate was sufficiently low to minimize turbidity of the samples caused by entrainment of bottom sediment, and samples were collected only when the pumped water appeared to be clear.

The surface water samples were taken once, during week 5 of the Phase I program (Table 2-3). Review of results raised a concern for possible seasonal variations in chemical composition of the surface water, particularly because the pond is shallow and subject to eutrophication as well as evaporation. For this reason, an additional surface-water sample was taken in conjunction with the February 1999 groundwater sampling round.

2.2 Phase II: Geophysical Investigation

2.2.1 Seismic Refraction Survey

In 1992, a seismic refraction survey was conducted in preparation for the Zone II aquifer characterization (CDM, 1993). This survey was performed with ten-geophone arrays along four traverses. Because the traverse adjacent to Grove Pond consisted of two disconnected seismic lines that intersected in the vicinity of the production wells, bedrock in the study area could not be located with certainty. Best estimates, based on the results of this survey, suggested that bedrock and/or dense till lay somewhere between 60 and 100 ft below ground surface (bgs). The upper limit of this depth estimate was consistent with the bottom of the production well screens, so it was speculated prior to the Phase II investigation that the wells were simply drilled to refusal at bedrock at the time of installation.

Immediately prior to initiation of Phase II of this investigation, another seismic refraction survey of the study area was conducted, in order to determine depth to bedrock more accurately in the candidate locations of the new monitoring wells. The seismic traverses are shown schematically in Appendix A (Fig. 1). Results of this survey estimated depth to dense till and/or bedrock at approximately 115 ft and 120 ft (plus or minus ~10 ft) beneath GF-1 and GF-2, respectively. Beneath GF-3, bedrock was thought to lie around 80 ft bgs, although this estimate carried some uncertainty due to the presence of a velocity inversion (slower wave speed underlying faster) that was observed on that seismic line. Because GF-4 was located at the end of Line 2 (App. A, Fig. 1), where the number of arrivals was limited, bedrock was located by manual depth calculations and was therefore subject to significant uncertainty. Overburden was characterized by velocities between 5000 and 6000 ft/sec, suggesting a possible mix of silt, sand, and gravel.

2.2.2 Resistivity Survey

A one-dimensional resistivity survey was performed with a Wenner array aligned roughly coincident with seismic refraction Line 4 (App. A, Fig. 1). The purpose of the resistivity measurements was to evaluate the method for its ability to discriminate any finer-grained strata that might influence the hydraulics of the groundwater / surface water interaction.

2.3 Phase II: Groundwater and Surface Water Investigation

2.3.1 Production Wells PW-1 and PW-2

The production wells were sampled only once during Phase II, as part of the confirmatory sampling round that was conducted in February 2000. Because these wells were the focus of Phase I sampling, these data have been added to those collected during Phase I and are included in Tables 4-1 and 4-2 (unfiltered and filtered metals, respectively), 4-3 (anions and alkalinity), and 4-4 (field water quality parameters).

2.3.2 Monitoring Wells (existing)

Existing monitoring wells 92-1 and 92-3 were sampled only once during Phase II, as part of the confirmatory sampling round that was conducted in February 2000. These wells were also part of the Phase I program, and the February 2000 results are also included in the Phase I data: Tables 4-2 (filtered metals), 4-3 (anions and alkalinity), and 4-4 (field water quality parameters).

2.3.3 Monitoring Wells (new)

Locations of new monitoring wells and borings installed in Phase II are shown on Figure 2-3, and listed in Table 2-1. Screen elevations are summarized in Table 2-2. All of the new boreholes were drilled by the drive-and-wash method. Groundwater samples were taken, using a submersible pump, through a drive point with a 2-foot screen driven ahead of the 4-inch steel casing. At intervals where running sands precluded use of the drive point, pea gravel was placed in the boring, the steel casing was withdrawn approximately one foot, and a water sample was taken using the submersible pump, with the gravel acting as a screen. Continuous soil sampling, using a 2-inch diameter split-spoon sampler, was used to construct the lithologic logs (Appendix B). Permanent monitoring wells were cased with 2-inch diameter, Schedule 40 PVC with 5-foot well screens at depths noted below. Bedrock well GF-2 was installed with a 7-foot screen.

GF-1: Drilling of GF-1 began on October 14, 1999. The first groundwater sample was taken just below the top of the water table, with the drive-point well screen positioned at 8.5-10.5 ft bgs. A soil sample was collected immediately below this depth. Split-spoon sampling was continued to 100 ft bgs; soil and water samples were collected at 98-100 ft. The split-spoon samples from 104-106 ft and 106-108 ft bgs contained dense, gray, clayey till. The bedrock surface was intercepted at a subsurface depth of 110 ft bgs. The casing was driven into the top of rock, and the boring was advanced using a 3.25-inch roller bit to 111 ft, at which point the response of the bit indicated competent rock. A water sample was taken from the open hole from 110-111 feet, interpreted to represent weathered top-of-rock. At this point, a 2.5-inch ID rock coring bit was inserted and the hole was advanced from 111 ft to 121 ft. Following the recovery of ten feet of bedrock core, a five-foot well screen was set in the interval from 116-121 ft, with a two-foot sand pack and a two-foot bentonite seal above the well screen. Bedrock groundwater was sampled upon completion of the well and again during the confirmatory sampling round in February 2000.

GF-2: This borehole was drilled on the north side of the PW-2 well house, 125 ft west of GF-1, also by the drive-and-wash method. The groundwater sampling scheme was similar to that for GF-1, using the drive-point method and sampling beneath the water table, in the interval 8.5-10.5 ft bgs; deep in the aquifer, at 106 ft bgs; and in the weathered top of bedrock at 110-111 ft. Running sands were encountered beginning around 85 ft bgs. The top of competent bedrock was encountered at a subsurface depth of 111 ft. Again, ten feet of bedrock core were recovered. A seven-foot well screen was set in bedrock in the interval from 114 ft to 121 ft bgs, with a sand pack to 113 ft and a bentonite seal from 111 to 113 ft. The dense, gray, clayey till that was penetrated by GF-1 was reported in GF-2 as a very thin layer, from 110.5 to 110.7 ft bgs, and mixed with black, hard, weathered rock fragments. The split spoon in the preceding interval, 106--108 ft bgs, contained only homogeneous gray sand. These observations indicate that the dense till layer overlying bedrock beneath GF-2 is considerably thinner than at the GF-1 location.

GF-3A: This well was installed approximately 15 ft south of the existing monitoring well 92-3, but screened in the lower part of the overburden, in order to monitor deep-aquifer water. Another objective of this hole was to confirm the presence or absence of the gray silty layer that was reportedly encountered at 34-47 ft during the installation of monitoring well 92-3 (CDM, 1993). In addition, the hole afforded an opportunity to characterize the vertical variation of water chemistry through the entire overburden. Neither the lithologic description (App. B) nor the geophysical log (Appendix A of the geophysics report, attached as Appendix A) contained any features that are consistent with the presence of a discrete, silty layer at the depth reported in 92-3. Running sands were encountered at depth, beginning around 70 ft bgs. Nineteen groundwater samples were collected throughout the aquifer, at approximately five-foot intervals, beginning immediately beneath the water table with the drive-point well screen in the interval 3-5 ft bgs. The deepest aquifer sample was recovered at 98-100 ft bgs. No clay was noted in the split-spoon sample from 103 ft, suggesting that the till layer lying above bedrock at GF-1 is absent at the GF-3A location. The drillers encountered refusal at 104 ft, and drilled 3 feet into bedrock at that point with a 3.25-inch roller bit. The borehole was screened from 97 ft to 102 ft bgs. The well was sampled on completion and again during the February 2000 confirmatory round.

GF-3B: This well was installed 5 feet south of GF-3A. The primary objective of this hole was to install a permanent monitoring well screen that would likely intercept shallow flow in the aquifer. It was anticipated that samples from GF-3B would either support or eliminate a scenario holding that high-arsenic water, possibly from the pond, was reaching the production wells by flowing above the top of the 92-3 well screen. Monitoring well GF-3B is screened from 8 to 13 ft bgs. Due to the proximity of this well to GF-3A, GF-3B was only sampled upon completion of the well and again during the February 2000 confirmatory sampling round.

GF-4: This well is located approximately 175 ft west of, and in line with, GF-1 and GF-2. It was intended that GF-4 represent "background conditions," i.e., away from the influence of the pumping wells, but adjacent to the pond. Bedrock was encountered around 85 ft bgs in GF-4, much shallower than anticipated. However, the original estimate of depth to bedrock was based on the poorly-constrained seismic refraction survey. When bedrock was encountered at GF-4, drill cuttings consisted of fine-grained, white to light gray particles that were tentatively identified as indicators of a granitic bedrock. The possibility that the drill had encountered a large boulder cannot be discounted, but no boulders or other large rock fragments were observed in any of the other boreholes. The appearance of the GF-4 cuttings was entirely different from the black, phyllitic and graphitic bedrock beneath GF-1 and GF-2, suggesting the presence of a lithologic contact between GF-2 and GF-4. Running sands were encountered during drilling of GF-4 and the well was sometimes pumped dry during purging prior to collection of groundwater samples. Therefore, stability of the field water quality parameters was not always strictly in accordance with the low-flow sampling protocol, but compromise between approximately stable conditions and drilling stand-by time was necessary. The well screen was set at a depth of 79-84 ft bgs, with two feet of sand above the screen and a two-foot bentonite seal above the sand.

BH-1 (in-pond borehole): This borehole was drilled from a barge and extended through the pond-bottom sediments into the aquifer immediately beneath the pond. The purpose of this borehole was to obtain a water chemistry profile extending from pond surface water, through the silty, organic-rich, pond-bottom sediments, and into the sandy aquifer. Running sands were also encountered in the drilling of BH-1, beginning at 21-23 ft below the pond surface (bps). The drillers advanced the casing to a depth of 73 ft and sampling was terminated at 68 ft bps due to slow progess and associated high cost, as well as the onset of freezing of the pond. A total of 11 groundwater samples was taken at approximately five-foot intervals, beginning with the end of the drive point 8 ft below the pond surface. Following collection of the last water sample from the interval 66-68 ft bps, the casing was cut off close to the sediment-water.interface in the pond and the hole was grouted to the top.

2.3.4 Borehole Geophysics

Geophysical logs were obtained in each of the newly-installed borings. Monitoring wells GF-1, GF-2, GF-3A, and GF-4 extend through the full thickness of the overburden, and are cased with 2-inch, schedule 40 PVC. The in-pond boring, BH-1, did not reach refusal; depth to bedrock at this location is unknown. The boring was temporarily cased with 2-inch PVC in order to accommodate the geophysical logging, and was subsequently abandoned. A suite of geophysical measurements was collected in each of these PVC-cased wells: fluid temperature, fluid resistivity, spontaneous potential (SP), natural gamma, and electromagnetic (EM) conductivity. The natural gamma tool was also used to log the older, steel-cased wells, 92-1 and 92-4, south of the production wells. The principal objective of the geophysical logging was to characterize stratigraphic variations. Note that some of these methods (e.g., natural gamma, EM conductivity) are sensitive to the presence of clay minerals. Results are shown graphically in the report from Geophysical Applications, Inc., included as Appendix A, and are discussed further in Section 4.8.2.

2.4 Phase II: Soil Sampling

2.4.1 Monitoring Well (new) Profiles

During installation of the new monitoring wells, a two-inch diameter, split-spoon sampler was driven in front of the casing to obtain relatively undisturbed samples of the overburden. The purpose of these samples was to provide material for visual description of the aquifer material, bulk-sediment chemical analyses, and grain size analyses. Lithologic logs (Appendix B) were constructed from the on-site geologists' descriptions.

2.4.2 "In-pond" Borehole

Two soil samples were scheduled for collection in the in-pond borehole, BH-1. One was collected from the interval 48-50 ft below pond surface and submitted for analysis of PAL metals. The second sample was omitted because the boring was terminated at a depth of 68 ft below the pond surface due to time and budget limitations; drilling progress was very slow because of running sands and the limitations of the relatively light, barge-mounted drilling rig. The primary purposes of the "in-pond" borehole were: to quantify the thickness of pond-bottom sediments in the immediate off-shore vicinity of the production wells; to characterize the unconsolidated materials immediately beneath the pond sediments (including verification of the lateral extent of the silty layer reported during the installation of well 92-3); and to sample the overburden and groundwater along a vertical profile beneath the pond.

2.5 Phase II: Pond Sampling

2.5.1 Surficial Pond Sediments

In August 1999, ten sediment samples were collected from the bottom of Grove Pond, in cooperation with EPA ESAT personnel (Appendix C). These samples were obtained with an Ekman dredge from the uppermost foot of pond sediment. Every effort was made to exclude the layer of rotting vegetation covering the pond bottom, in order to sample primarily inorganic matter. Locations of surficial pond sediment sampling are shown on Figure 2-4. The purpose of this sampling was to analyze pond sediments in the area offshore of the production wells for the PAL metals. In addition, the Work Plan specified the extraction of pore waters from these samples by centrifugation for the same PAL metals, in order to quantify partitioning of arsenic and other elements between the solid phase and pore water.

2.5.2 Sediment Pore Waters

The pore waters were extracted from the surficial pond sediment samples by centrifugation according to EPA Method 200.15 (Methods for the Determination of Metals in Environmental Samples, Supplement I (EPA 600/R-94/111)) and analyzed for PAL metals. Analytical results are presented in Tables 4-13 (unfiltered) and 4-14 (filtered), and discussed in sections 4.5.2 and 4.5.3.

2.5.3 Soft-Sediment Cores

Three soft-sediment cores were collected through the pond-bottom muck (Fig. 2-5). The purpose of the cores was to provide constraints on the chemistry and hydraulic properties at the interface between groundwater and surface water. In particular, the cores were sub-sampled for analyses for bulk-sediment chemistry, pore-water chemistry, grain-size analysis, and vertical hydraulic conductivity.

The cores were located offshore, within the area occupied by the other sampling activities (i.e., the in-pond boring, surficial sediment and surface water samples, seepage meters, piezometers), and potentially subject to the influence of the supply wells. The cores were taken within approximately 100 ft of the shoreline. The barge constructed for installing boring BH-1 was moved successively to each core location, casing was set approximately 1 foot into the pond bottom, and a core barrel lined with a 2.375-inch (inside diameter) plastic sleeve was hammered into the sediment in two-foot increments. Water depths were approximately 3 feet at all locations. Following recovery of 2 to 5 feet of material, relatively clean sands were encountered, which were not recoverable in the core barrel, and which flowed into the hole, precluding further coring. About 5 feet of core were recovered from SC-1, and approximately 2.5 feet were recovered from SC-2 and SC-3.

The cores were sub-sampled for various analyses. The top-most recovered material (from 0 to 0.3 or 0.4 ft) was collected for bulk sediment chemical analysis. The next interval, approximately 0.3 to 0.4 ft in length, was collected for pore-water extraction and analysis. The third segment down (typically to about 1 ft below the top of the recovered material) was sampled for laboratory determination of vertical hydraulic conductivity. Further sub-samples were taken toward the bottom of the cores for the same analyses in order to obtain some control on vertical variations in chemistry and hydrology. Descriptive core logs showing the sampled intervals are provided in Table 2-4.

2.6 Phase II: Bedrock Drilling

2.6.1 GF-1 Core Description

Coring at the bottom of GF-1 recovered approximately four feet of intact rock (111-115 ft bgs) overlying approximately six feet of highly fragmented material (115-121 ft bgs). In the more intact section, bedrock appears to consist of a dark gray, highly metamorphosed conglomerate, with quartz veining (determined in the field by application of dilute hydrochloric acid) in a predominantly fine-grained matrix. Fractures were noted at 115-116 ft and 117-119 ft bgs. The more highly fractured remainder of the core was phyllitic in appearance and contained abundant graphite. Fracture surfaces were covered with an amorphous, bright fluorescent green material that turned yellow to yellow-green when the core had dried (Fig. 2-6). No sulfide minerals were observed with hand lenses, but abundant patches and vug fillings of orange-brown material, tentatively identified as goethite, were noted in the dark gray, fine-grained matrix.

2.6.2 GF-2 Core Description

Bedrock core from GF-2 was similar in appearance and structure to that from GF-1. The upper, more competent portion of the GF-2 core was broken approximately 1.5 ft from the top of the core (111 ft bgs), and three more cracks, ~0.5 ft apart, were noted. A half-inch-wide fracture at three ft from the top of the core was filled with gray clay. Bedrock appears to be the same as at GF-1, consisting of a dark gray, metamorphosed conglomerate with abundant quartz veining. The remainder of the core was fragmented, as at GF-1, and also contained graphite.

2.7 Phase II: Hydraulic Characterization

2.7.1 Grain-Size Analyses

Thirteen grain-size analyses were performed on soil samples from borings GF-1, GF-3A, GF-4, and BH-1, and from soft-sediment core SC-1. The purpose was to quantify variability in different stratigraphic horizons, as well as to collect information that would permit calculation of hydraulic conductivities in zones where slug tests were not performed. The first three samples were analyzed by ASTM Method D422-63 using sieves numbered 4, 10, 40, and 200, which correspond to apertures of 4.75 mm, 2 mm, 0.425 mm, and 0.075 mm, respectively. After inspection of results, it was decided that greater resolution in the finer size fraction was desirable, so the remaining ten samples were analyzed with sieves numbered 10, 20, 40, 60, and 140 (corresponding to apertures of 2, 0.850, 0.425, 0.250, and 0.106 mm). Results are discussed in Section 4.8.3.

2.7.2 Slug Tests

Slugs were made from PVC pipe filled with sand and sealed with end caps. A nylon rope was tied through a screw-eye bolt at one end. Twenty-two rising-head and 25 falling-head slug tests were performed at randomly-selected depth intervals during the installation of the new monitoring wells and in the in-pond borehole, as well as in the permanent monitoring wells. A total of 19 overburden locations, 3 weathered top-of-rock intervals, and one (screened) bedrock location were tested. Results are summarized in Section 4.8.3.

2.7.3 Seepage Meters

Four seepage meters were deployed in Grove Pond, in the offshore area adjacent to the water-supply wells. Each seepage meter consisted of half of a polyethylene drum 23 inches in diameter; a length of 0.5-inch (I.D.) PVC pipe was inserted as an air vent. The fluid reservoir was a flexible, rubber, hot-water bottle connected to the drum by a short piece of Tygon tubing in which a brass shut-off valve and quick-connect coupling were inserted. The seepage meters were installed manually in the pond at the locations shown on Figure 2-7.

The rim of each seepage meter was seated as firmly as possible in the pond-bottom muck. Each meter was then allowed to stand undisturbed for approximately one hour. One liter of water was placed in each reservoir bag at the beginning of each measurement period, the air space in the bag was eliminated, and the valve was closed. The assembly was then attached to the seepage meter by the quick-connect coupler, and the valve was opened. After a suitable period of time, the valve was closed, the bag was disconnected, and the volume of water in the bag was measured with a 1-liter graduated cylinder. A decrease in volume indicates a downward flux from the pond to the underlying groundwater. Conversely, an increase in volume indicates an upward flux (i.e., groundwater discharging to the surface). The seepage meters were deployed for 4 periods of 3 to 4 days each. The third period spanned a 3-day shutdown of the water-supply wells. The purpose of the seepage meters was to quantify infiltration rates, and to identify differences in infiltration rates under pumping and non-pumping conditions.

2.7.4 Piezometers

Piezometers were installed to provide direct measurements of the hydraulic head difference across the pond-bottom sediment layer. Six piezometers, consisting of 1-inch (I.D.) galvanized steel pipe were hammered through the pond-bottom sediment and into the top of the sandy aquifer at locations shown on Figure 2-8. Each piezometer was 10 feet in total length, with a 1-foot stainless steel screen and drive point. A typical installation left approximately 2 feet of "stick-up" above the pond surface, went through about 3 feet of pond water, crossed about 2 to 3 feet of muck, and penetrated 2 to 3 feet into the underlying sand. Water levels were measured 4 times during Phase II of this investigation. The distance from the top of the piezometer to the pond surface (outside the stick-up) and the depth to water inside the stick-up were measured. The difference represents the head drop across the sediment layer. Because the supply wells were pumped on an irregular schedule, no attempt was made to coordinate piezometer readings with the pumping. The piezometer data are therefore likely to reflect both pumping and non-pumping conditions.

2.7.5 Vertical Hydraulic Conductivity

The three soft-sediment cores (Fig. 2-4) were sub-sectioned for various analyses. Four core sections were retained for laboratory determination of vertical hydraulic conductivity, two from SC-1 and one each from SC-2 and SC-3. The core sections chosen for this purpose were 0.3 to 0.4 feet long, and stored as collected in the original 2.375-inch-diameter plastic core liners.

Conductivities were measured in a constant-head permeameter. All measurements were performed on upward flows in order to minimize effects of trapped air. Cumulative volume was measured as a function of time at constant head drop. Ten to twenty measurements of volume as a function of time were recorded for each run in order to verify steady flow. Data were acquired at three or four different head differentials for each sample, in order to verify linearity of the volume flow rate as a function of head drop. Results are detailed in Section 4.8.6.

2.7.6 Pressure Transducers

Pressure transducers were installed in several monitoring wells in order to collect additional hydraulic data to support the conceptual model for groundwater flow and arsenic transport at the site. This activity was not detailed in the Work Plan (Gannett Fleming, 1999a); rather, it was added subsequent to review and interpretation of the hydrological and geochemical data obtained in earlier stages of the program. The transducer data were collected to quantify the response of the aquifer at various locations and depths to pumping of the water-supply wells.

Transducers and digital data loggers were deployed in monitoring wells 92-1, GF-1, GF-3B, GF-3A, and 92-3 for up to 11 days during the period October 20 through November 3, 2000. These wells, all located within approximately 100 feet of the pumping wells, represent a variety of settings within the aquifer. Wells 92-1 and 92-3 are screened within the same horizon as the production wells; well 92-1 is about 50 feet to the south and well 92-3 is approximately 100 feet to the north, adjacent to the pond. These wells are expected to indicate the hydraulic response of the pumping horizon. Well GF-1 is immediately adjacent to the PW-1 pumphouse, and is screened in bedrock, some 56 to 61 feet below the bottom of the extraction screen. Data from this well are expected to provide a measure of the hydraulic connection between overburden and bedrock in the vicinity of the supply well. Wells GF-3A and GF-3B complete a well cluster near 92-3; GF-3A is screened at the bottom of the overburden (117 to 122 ft bgs), while GF-3B is screened in the shallow aquifer (8 to 13 ft bgs). The cluster is expected to yield data characterizing the vertical gradients induced by the pumping well, as well as to reflect the influence of the nearby pond.

Five transducers and associated data loggers were used. Each transducer was calibrated *in situ* by recording its response as it was lowered beneath the water surface in a monitoring well in which the water level was stable. Depth to the water surface and the depths of successive intervals were measured with an electronic depth-to-water indicator and tape marked in increments of 0.01 foot, and referenced to the top of the well casing. Each transducer was lowered in five-foot increments in order to determine its operable depth range, and to acquire data for the calibration. Calibrations were obtained for each transducer via linear regression on the data collected at known depths below the water surface. All of the transducers exhibited a highly linear response.

One transducer showed a "noisy" signal; i.e., repeated measurements at a fixed depth yielded readings with large variability. The standard deviation among four to six measurements at a fixed depth for this transducer ranged up to 0.4 ft. However, averaged values from this transducer resulted in a good calibration. The unstable transducer was installed in well 92-3 because this monitoring point was expected to be in good hydraulic connection with the pumping wells, and the qualitative response could be anticipated. A better-functioning transducer was installed in monitoring well 92-1, where the response was expected to be similar to that at 92-3. Stable transducers were also installed in the new wells, GF-1, GF-3A, and GF-3B, in order to monitor the response of the bedrock, deep overburden, and shallow overburden, portions of the aquifer that were uncharacterized previously.

With the cooperation of the Town of Ayer, a shutdown of the water-supply wells was arranged in conjunction with the water-level monitoring. Pumping was halted at approximately 15:00 EDT on Friday, October 27, 2000, and resumed at approximately 08:00 EDT on Monday, October 30, 2000. As detailed in the foregoing, water levels were recorded in five monitoring wells throughout this event and for five days following the restart. Thus, these data effectively represent a crude pumping test, in which the transient recovery and drawdown in response to the shutdown and restart were recorded. It should be noted, however, that the production wells are typically operated on a rather irregular schedule, dictated by local water demand, system maintenance, availability of personnel, etc. For this reason, a true steady-state condition was not established prior to the shutdown. Furthermore, groundwater levels had not recovered fully when the wells were restarted 65 hours later. Thus, neither the recovery from shutdown nor the drawdown following restart constitutes an ideal pumping test because the initial conditions were not stable. Finally, it is noted that the exact pumping history for the production wells is not available; extraction rates are not recorded continuously. Each well, when on, was typically pumped in the range 600 to 700 gallons per minute at the time of the water-level monitoring event.

Additional water-level data were collected in wells GF-1 and GF-3B over the seven days prior to the shutdown. This is a period characterized by the rather erratic extraction pattern of normal operation of the wellfield and treatment plant, with one or both wells cycling on and off up to several times each day.

In recognition that the water-level data collected in monitoring well 92-3 over the shutdown and restart were noisy due to an unstable transducer, a brief period of monitoring was carried out in the 92-3, GF-3A, GF-3B well cluster on the afternoon of November 3, 2000. The additional data were collected in order to obtain better constraints on vertical head differences across the overburden under pumping conditions. The unstable transducer in 92-3 was replaced for this period, and stable results were obtained. The pumping wells were operated sporadically during the day; both were off immediately before starting the data loggers. Both pumping wells were restarted at approximately 14:05 EST, and PW-1 was shut down at about 15:20 EST, while PW-2 remained on.

Data were downloaded from the loggers, and the calibrations were applied to the data in order to calculate changes in head. Water levels were then calculated by reference to the elevations recorded by hand at the time of installation of the transducers.

3.0 PHYSICAL CHARACTERISTICS OF THE STUDY AREA

3.1 Surface Features

Grove Pond is a shallow, 60-acre body of water located in the northeast corner of the Main Post of the former Fort Devens (Fig. 1-1). The pond is roughly triangular in shape, with the apex toward the northwest. A railroad causeway forms the western boundary of the pond. A stone culvert under this causeway connects Grove Pond with Plow Shop Pond, which lies immediately to the northwest. The northern shore of Grove Pond, bordering the Town of Ayer, is surrounded by residential properties, a recreational area owned by the Town (Pirone Park), and former industrial properties. The southern shore abuts property owned by Fort Devens, the Massachusetts National Guard, and the Town of Ayer.

A tannery was located on the land east of the railroad causeway, at the northwest corner of Grove Pond, from 1854 through 1961. The tannery operated intermittently between 1900 and 1944. From December 1944 until its destruction by a fire in 1961, the facility was a cattle-hide tannery that produced chrome-tanned hides. The tannery has been the focus of much interest because of its historical waste-disposal practices and its potential as a source of contaminants, especially arsenic, chromium, lead, and mercury[1]. Process wastewater from the tannery was discharged directly into Grove Pond prior to 1953, with little or no treatment. A landfill was also located on tannery property between the facility and Grove Pond. Aerial photographs taken in 1943, 1952, and 1965 show gradual infilling of an embayment in the northwest corner of Grove Pond, suggesting that that area might have been the location of the landfill. In addition, the aerial photographs suggest that filling may also have occurred in the present-day northwest cove during a period of low water. By 1944, both the Town of Ayer and the Commonwealth of Massachusetts registered concern regarding potential contamination of the pond by the tannery. In 1949 the Town began borrowing funds to connect the tannery to the local wastewater treatment plant, and in 1953 the connection was completed (ABB-ES, 1993).

The tannery site is separated from Pirone Park by a wetland area. Portions of this area appear to be fill material, and landfilling may have occurred in the past. Residential areas occupy the land to the east of Pirone Park.

The southwestern shore of Grove Pond borders the Hill Yard, an active railroad yard operated by the Boston and Maine Railroad (B&MRR). The railroad facilities do not extend to the pond's shore, but stormwater runoff from the railyard may enter the pond, and there may have been historical fill activities in the vicinity. The Fort Devens Grove Pond well field and a water treatment building are located in the southern shore, west of the Town of Ayer wells. Other potential sources of contaminants are inflow from Cold Spring Brook, Balch Pond, and runoff from Fort Devens (MNG property) and the Town of Ayer (ABB-ES, 1993).

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[1] With the exception of chromium, there is no recorded use of other metals by the tannery; however, dyes that may have been associated with tannery operations may have contained mercury, cadmium, nickel, and other elements found at elevated levels near the tannery site.

Spring Brook, Balch Pond, and runoff from Fort Devens (MNG property) and the Town of Ayer (ABB-ES, 1993).

3.2 Meteorology

The Fort Devens climate is typical of the northeastern United States, with long, cold winters and short, hot summers. At Worcester (MA) Municipal Airport, approximately 25 miles to the southwest of the site, climatic records from1895 through August 2001 report an average annual rainfall of 42.57 inches (Table 3-1). Average monthly rainfall over the same period at Worcester is quite uniform, ranging from a low of 3.11 inches in February to a maximum 3.90 inches in November. January is the coldest month, with mean daily minimum temperatures of 17 °F (-8.3 °C) and a mean monthly temperature of 24.7 °F (-4.0 °C). July is the hottest month, with mean daily maximum temperature of 83 °F (28.3 °C) and monthly average of 71 °F (21.6 °C). Average annual snowfall is 65 inches. Most of the snowfall occurs between December and March, although snow has been reported for the months of September through May. Wind speed averages 5 miles per hour (mph). The highest monthly average is 7 mph (March and April), and the lowest monthly average is 4 mph (September). Average daytime relative humidities range from 71 percent (January) to 91 percent (August). Average nighttime relative humidities vary between 46 percent (April) to 60 percent (January).

Prior to startup of the Town of Ayer wells, rainfall in the area appears to have been higher than normal (Table 3-1). Meteorological data from the Worcester airport confirm that June 1998 was unusually wet. During this month, three rainfall events of 1.0 inch or more occurred, one of which registered 2.83 inches. Total precipitation for June was 10.3 inches, the second highest rainfall in June over the 106-year database for Worcester. October 1998 was also wet, with precipitation totaling 5.48 inches. One period of heavy rain, during which 2.2 inches were reported, took place approximately ten days prior to the October 1998 sampling round. Another anomalous period of precipitation that bears on the interpretation of data from the present investigation occurred in March 2001, when 9.02 inches of precipitation (largely in the form of snow) were recorded. This compares to the 100-year average of 3.76 inches for March.

3.3 Surface Water Hydrology

Grove Pond is shallow, with maximum water depth approximately 5-6 ft, and frequently eutrophic. The pond bottom consists largely of decomposing vegetation. It is the fifth in a string of six ponds (in the downgradient direction: Long Pond, Sandy Pond, Flannagan Pond, Balch Pond, Grove Pond, Plow Shop Pond). Grove Pond receives drainage from Balch Pond, as well as from Cold Spring Brook and Bowers Brook, and discharges through a culvert on the western edge of the pond into Plow Shop Pond. The water level in Plow Shop Pond is controlled by a dam in the northwest corner, where the discharge forms Nonacoicus Brook (and its associated wetlands), which in turn flows northwest to the Nashua River.

3.4 Geology

Site geology has been described in detail elsewhere (e.g., ABB-ES, Vol. I, 1993; CDM, 1993). Bedrock outcrops in some locations within the Fort Devens reservation, and in other areas is buried by glacial deposits to depths of 200 ft or more. Primary post-glacial deposits are peaty swamp deposits found mostly along streams and surface water bodies; and artificial fill. Seismic refraction lines parallel to the south shore of Grove Pond indicate that depth to consolidated till and/or bedrock is approximately 110-120 ft below grade in the general study area. Unconsolidated, surficial material in the area consists of stratified glacial outwash (kame plain and kame terrace) deposits, primarily coarse sand and gravel. Logs from borings along the south side of Grove Pond, close to the Town of Ayer wells, report fine to coarse brown sands and angular gravel. A gray silty layer, approximately 10 ft thick, was reportedly encountered at a depth of about 34 - 47 ft below grade in one well at the edge of Grove Pond (well 92-3; CDM, 1993). The lateral extent of this layer was unknown, but inferred to be continuous beneath the pond based on the response of well 92-3 in the pump tests (CDM, 1993). Lithologic profiles constructed from continuous split-spoon sampling during the installation of new monitoring well GF-3A, adjacent to 92-3, did not confirm the presence of a discrete silt layer in this subsurface interval. However, further characterization performed in this investigation indicates that the upper 40 ft of the overburden, above the top of the supply-well screens, is a fining-upward sequence, representing a depositional environment of decreasing energy. A more detailed discussion of the findings of this study is provided in Section 4.8.

3.4.1 Bedrock Geology

Bedrock underlying Fort Devens consists mainly of low-grade metasedimentary rocks, gneisses, and granites. These rocks range in age from Late Ordovician to Early Devonian (approximately 450 million to 370 million years old). A generalized summary map (Fig. 3-3 in Vol. I of the 1993 Remedial Investigation report; ABB-ES, 1993) identifies bedrock immediately to the south of Grove Pond as the Berwick Formation, and the Devens-Long Pond facies of the Ayer Granite is immediately to the west. It is noted in the Remedial Investigation that formation boundaries are approximate because bedrock exposures in this area are limited. However, this map indicates that in the vicinity of Grove Pond, the contact between the Berwick Formation and the Devens-Long Pond facies appears to strike in a northerly direction, passing between the western shore of Grove Pond and the eastern edge of Plow Shop Pond, approximately under the railroad causeway.

The Berwick Formation is described as primarily calcareous and biotitic metasiltstones and metasandstone (Robinson and Goldsmith, 1991). Two localized zones of mica schists and phyllites containing pyrite (FeS_2) and pyrrhotite ($Fe_{1-x}S$) have been identified within the Berwick Formation. Both of these zones are thin, elongate bodies oriented in a northeast-southwest direction. The western sequence lies between Townsend and Chelmsford, directly north of Ayer. This sequence is described as a quartz-rich pyrrhotitic schist containing aggregates of biotite. Cores of the Berwick Formation, taken from bedrock underlying nearby portions of former Fort Devens, have been studied extensively (ABB-ES, 1995b). From these cores, the metasiltstone is described as calcareous, with secondary quartz and sulfides along bedding planes and fractures.

In the draft Phase I data report, the bedrock underlying the production wells had been tentatively assigned to the Berwick Formation based largely on location according to the available geologic maps. It is apparent from recent examination of the core and discussions with USGS personnel and others that this classification is incorrect and the bedrock beneath the Town of Ayer wells is more appropriately identified as Coal Mine Brook Formation, of Pennsylvanian age (R. Hon, Boston College, personal communication, 8/2000). This formation probably represents the distal facies of the Harvard Conglomerate, and is composed of what were formerly silty, marshy deposits. This interpretation is based in part on the presence of terrestrial plant fossils and the high organic carbon content of this rock; in places, this formation has historically hosted anthracite coal mines. The Coal Mine Brook Formation is preserved only in small slivers along fault lines. Because these are fresh-water deposits, and occur only locally, in small volume relative to the Berwick and equivalent rocks (Oakdale and Paxton Formations), it is unlikely that the Coal Mine Brook Formation is the ultimate source of the widespread arsenic that is found in groundwater in central Massachusetts and southern New Hampshire. However, sulfide minerals present in the Coal Mine Brook deposits may contribute to local occurrences of groundwater arsenic.

3.4.2 Arsenic Mineralogy

Sulfide minerals include a large number of compounds with the general structural formula A_mX_p. In these minerals X, the larger atom, represents anions such as S, As, Sb, Bi, Se, or Te. In a few minerals, S and As or Sb are present in nearly equal amounts. The smaller atom, A, is one or more of a group of metallic cations that includes Fe, Co, Ni, Cu, Zn, Ag, Cd, and Mo. The subscripts *m* and *p* indicate the number of atoms of each of the respective cation and anion components that yield an electrically-neutral mineral formula.

The group of sulfide minerals with the formula AX_2 includes pyrite (FeS_2), cobaltite (CoAsS), arsenopyrite (FeAsS), and gersdorffite (NiAsS). The substitution of small amounts of Ni and Co for Fe in pyrite is not uncommon, but the mineral bravoite $(Ni,Fe)S_2$, in which Fe is less than 50 mole percent, is rare. Arsenopyrite is the most abundant arsenic mineral. It forms at high to moderate temperatures and is often found in association with other sulfide minerals in contact-metamorphic rocks (Mason and Berry, 1968).

Arsenic may substitute for sulfur atoms in some sulfide minerals – for example, in pyrite or chalcopyrite ($CuFeS_2$), paired As-S atoms may substitute for S_2. Alternatively, arsenic may be present in pyrite or other sulfide minerals as a discrete phase (such as arsenopyrite). Both occurrences are commonly observed. In a letter report (Prof. M. Williams, Dept. of Geosciences, U. Mass. - Amherst to M. Deuger, Army BRAC Office, May 8, 1996), electron microprobe analysis of a sample of granite from a gravel pile on

Devens verified the presence of discrete grains of arsenopyrite as well as pyrite with detectable As.

Pyrrhotite ($Fe_{1-x}S$), niccolite (NiAs) and breithauptite (NiSb) belong to the niccolite group of sulfide minerals, all of which have AX-type structures (Mason and Berry, 1968). Pyrrhotite occurs primarily in basic igneous rocks but has also been reported from contact metamorphic rocks, in high temperature hydrothermal veins, and in sediments. Pyrrhotite has been found in association with pyrite, chalcopyrite ($CuFeS_2$), pentlandite $(Fe,Ni)_9S_8$, and other sulfide minerals. Experimentally, arsenic has been shown to substitute in the pyrrhotite crystal structure, and arsenopyrite has been found as a pseudomorph after pyrrhotite (Deer, et al., 1972).

In summary, the presence of sulfide mineralization in bedrock outcrops on and near Ft. Devens, the identification of sulfides in bedrock core samples from the Berwick Formation, the unequivocal identification of arsenopyrite and arsenic-bearing pyrite in a granite sample from a gravel pile at Devens, and preliminary analyses confirming the presence of arsenic in sulfides from bedrock underlying the Town of Ayer wells (this study; Section 4.6.5), indicate that arsenic minerals are commonly-observed, natural geologic constituents of the bedrock in the vicinity of Grove Pond.

Antimony (Sb) has also been observed in the Town of Ayer wells. In January 1999, Sb was detected at concentrations of 0.004--0.005 mg/L in unfiltered raw water samples, although levels prior to this date and subsequent repeated analyses have not detected Sb above the MDL (0.002 mg/L). Because of similarities in their chemical behavior and ionic radii, Sb and As may both substitute for S in sulfide minerals, as noted in the foregoing discussion of arsenic mineralogy. It is entirely plausible that the observed Sb in the Town of Ayer wells is naturally occurring, and may be traced back to bedrock sulfides.

3.5 Surficial Glacial Deposits

Weathered, unconsolidated, surficial deposits overlying bedrock in the vicinity of Grove Pond consist entirely of glacial and post-glacial sediments. These deposits include till, lacustrine deposits associated with glacial Lake Nashua, and sediments deposited from meltwater of glacial streams. These units, and their compositions, are summarized below (from ABB-ES, 1993):

- till: unconsolidated, ranges from unstratified gravel to silt, may be bouldery; is exposed in some ground-moraine areas of Ft. Devens (Main Post, near Lake George Street, and South Post, at and south of Whittemore Hill) and may also underlie some water-laid deposits.

- deltaic deposits: glacial Lake Nashua formed against the terminus of the Wisconsinan ice sheet as it retreated northward along the present-day Nashua River valley. As the glacier retreated, the lake level fell. At least six levels are recognized in the Ft. Devens area (Koteff, 1966; Jahns, 1953; in ABB-ES, 1993) and distinguished by their elevations and distributions of associated deposits. These stages are (in order of development): Clinton Stage, Pin Hill Stage, Old Mill Stage, Harvard Stage, Ayer Stage, and Groton Stage. These deposits consist mainly of sand and gravelly sand. Coarser sand and gravel are found in the topset beds of deltas built out into the lakes, and in streambeds carrying material to the lakes. Delta foreset beds typically consist of medium to fine sand, silt, and clay. Lake bottom sediments consist mainly of sand, silt, clay, mostly covered by delta deposits, and are seldom seen in glacial Lake Nashua deposits. It should be noted that "Although glaciofluvial and glaciolacustrine deposits are usually well-stratified, correlations between borings are difficult because of laterally abrupt changes typical of deposition in high-energy environment" (quote from ABB-ES, 1993).

- river-terrace sands and gravels; fine alluvial sands and silts beneath modern floodplains; and muck, peat, silt, and sand in swampy areas.

3.6 Hydrogeology

The groundwater hydrology of the Grove Pond area has been explored through various field investigations and numerical modeling (e.g., CDM, 1993; ETA, 1995). Grove Pond lies in a topographic depression, and the water table in the surficial aquifer generally mimics the topography, but with subdued amplitude. Under unstressed conditions (i.e., in the absence of pumping), groundwater flow in the immediate vicinity of the Town of Ayer wells is from southwest to northeast. Much of this flow has been assumed to discharge to the pond. In addition, in the deeper portion of the overburden aquifer, a component of the flow from the south may join a regional flow that tends to follow the surface-water drainage toward the west, ultimately discharging to the Nashua River. Similarly, flow in the area immediately north of the pond is toward the south, and the shallower portion of this flow again discharges to the pond, while the deeper portion likely joins the regional flow to the west. The hydraulic gradient at the pumping horizon in the unstressed state is approximately 0.008 ft/ft beneath the slope descending toward the pond from the Devens boundary, and, due to the influence of the pond, decreases to approximately 0.002 ft/ft near the Town of Ayer wells. (The gradients cited here are estimated from the water-level map shown in Figure 4-1, CDM, 1993). The apparent horizontal hydraulic conductivity for the aquifer at the scale of the capture zone for the production wells has been estimated at approximately 300 ft/day, based on a pumping test performed on the Ayer wells (CDM, 1993), as well as various independent determinations in the area. The ratio of horizontal to vertical hydraulic conductivity is estimated to be 10:1.

Under pumping conditions, the groundwater elevations are drawn down by several feet at the production wells, and flow is drawn from the surrounding area, including the aquifer beneath the pond. The conceptual model invoked by most studies to date represents the outwash sand beneath the pond as a "semi-confined" aquifer; that is, the lower-conductivity pond-bottom sediments "cap" the underlying sand, offering resistance to infiltration from the pond, and supporting a vertical head difference. Under pumping conditions, the head in the underlying sand is lower than that due to the standing pond water, and recharge from the pond to the aquifer is induced. In this scenario, the flux of pond water through the bottom sediment and into the underlying sandy aquifer is determined by the distribution of the groundwater potential in the aquifer and the thickness and vertical hydraulic conductivity of the pond-bottom sediment. It is emphasized that the hydraulic properties of the pond-bottom sediment, critical to calculating the induced infiltration, had not been measured prior to this study, nor had these properties been inferred from calibration of a site-specific numerical model. In model studies performed to date, the conductivity of the pond sediment layer has been assumed to be similar to that determined in nearby surface water bodies (CDM, 1993) or to be some fraction of stream-bottom values characteristic of the region (ETA, 1995).

The present investigation has provided more detailed hydrostratigraphic data in the neighborhood of the water-supply wells, and this information suggests modifications to the general conceptual model for the groundwater flow outlined in the foregoing paragraph. In particular, boring logs, slug tests, grain-size analyses, and examination of vertical variations in the groundwater geochemistry indicate that the shallow aquifer, from about 40 ft bgs to the surface, is a fining-upward sequence of sands and thin, interbedded silty sands. Hydraulic conductivities measured in the uppermost ~10-20 ft of this sequence are of the order of a few feet per day, in strong contrast to values of the order of hundreds of feet per day inferred at a depth of ~40-50 ft bgs. Thus, the pumping interval (~40-60 ft bgs) is highly conductive, and is overlain by a semi-confining sequence tens of feet thick. The semi-confining sequence tends to isolate the production horizon from the pond, and inhibits induced infiltration, regardless of the properties of the pond-bottom muck. The consequence of this hydrostratigraphic configuration is that the water-supply wells likely "reach" far outward radially within the high-conductivity screened interval, and cause a slow "leakage" from the overlying tighter domain. Details of the data collected in this study, as well as the conceptual model for the site hydrology, are discussed in sections 4 and 6 of this report.

Figure 3-1 shows the location of a north-south transect through the study area, and Figure 3-2 shows the corresponding vertical section to illustrate the spatial relationships of the well locations, ground surface, water table, Grove Pond, and inferred consolidated till or bedrock at the base of the aquifer. Note that wells MNG-7, MNG-3, 92-4, and 92-5 are projected as much as several hundred feet to the east onto this cross-section. Figure 3-3 shows the same section in the immediate neighborhood of the production wells with no vertical exaggeration in order to provide an undistorted view of the vertical relationships among the well screens, stratigraphy, and pond.

4.0 RESULTS OF THE FIELD INVESTIGATION

Results of all groundwater and surface water analyses are summarized in Tables 4-1 through 4-7. The following subsections provide brief descriptions of the data and key results.

4.1 Phase I Groundwater Investigation

A map showing the location of the Town of Ayer production wells, Grove Pond, and the monitoring wells is shown in Figure 2-1. As discussed previously, only wells in existence by July 1998 were sampled during Phase I of this study (Table 4-1; all unfiltered groundwater data). Table 4-1 also contains results obtained during the last Phase I sampling round, conducted in February 1999; these data were not available at the time of production of the initial, draft report (Gannett Fleming, 1999). Four of these existing wells (PW-1, PW-2, 92-1, and 92-3) and the pond were also sampled during the final confirmatory sampling round of Phase II, in February 2000. Although those results were obtained in fulfillment of Phase II Work Plan activities, they are included with the Phase I data (Table 4-2; all filtered), in order to maintain data organization by wells rather than by investigative phase.

The Town of Ayer production wells were sampled a total of 12 times (Table 2-3) between July 26, 1998 and February 22 and 23, 1999, and again on February 16 and 17, 2000. The flanking monitoring wells 92-3 and 92-1 (Figure 2-1) were sampled 13 times during this period and also sampled in February 2000. The upgradient wells MNG-3, MNG-7, and 92-4 were sampled three times between July 1998 and February 1999, and well 92-5 (on the north side of Grove Pond) was sampled only once, in October 1998. In all, 95 groundwater samples were collected from the wells that were the focus of Phase I Investigation. These samples include 8 duplicates, 14 samples that were collected using two different filtration methods, and 4 samples that were collected during the Phase II sampling round conducted in February 2000. Unfiltered samples were not collected during the final Phase II sampling round, because Phase I results showed little difference between filtered and unfiltered concentrations of the principal elements of concern (e.g., arsenic).

At the outset of the investigation, samples were filtered in the field using an air-pressured barrel apparatus with 0.45 μm filters. Shortly after the pumping wells were turned on, the use of 0.45 μm, disposable, in-line filter cartridges was adopted. In order to compare data from samples collected using the barrel apparatus with data collected from in-line-filtered samples, six of the samples of the two production wells and one sample from each of the two flanking wells were collected using both methods. Because two different laboratories analyzed the suite of PAL inorganics and arsenic, it was decided to compare filtration methods only on the bottles for the inorganics analyses using both methods. This decision was based on the larger number of analytes (22) on the PAL inorganics list for evaluation of variability, compared to the arsenic-only analyses. An examination of the data (presented in Section 4.9) shows that no significant bias was introduced by the change in filtration methodology.

The nominal production schedule established by the Town of Ayer was to pump from approximately 6:00 a.m. to 10:00 p.m. daily. Not unexpectedly, deviations were experienced throughout the first few days following startup. Consequently, the time of water sampling relative to the pumping of the wells on any given day is unknown. Water production was not metered during the first few days of operation. Available production records are summarized in Table D-5, Appendix D, of the Phase I Interim Data Report, (Gannett Fleming, 1999b).

In the following discussion of analytical results, the Devens groundwater background values (Table D-4, Appendix D) are cited for comparison. These background levels were established during the 1993 Remedial Investigation (ABB-ES, 1993). It is important to note that this background data set is based upon samples taken prior to the establishment of the EPA "low-flow" sampling protocol, and may be biased due to turbidity. Table D-4 also provides regulatory standards for drinking water for reference.

4.1.1 Metals, Unfiltered

Results for individual analytes in unfiltered samples are discussed briefly in this section. Data trends are not displayed graphically. However, results for unfiltered samples, in general, are similar to those for filtered samples, for which detailed plots are provided (see Section 4.1.2, Phase I Interim Data Report, Gannett Fleming, 1999b). Differences between results for unfiltered and filtered samples are discussed for individual elements where appropriate. This section discusses results from Phase I, including the final sampling round that was conducted in February 1999. The dissolved metals data (Table 4-2) were obtained using inductively-coupled plasma-source atomic emission spectrometry with ultrasonic sample nebulization (ICP Method 200.7, Methods for the Determination of Metals in Environmental Samples, Supplement I, EPA 600/R-94/111, May, 1994). Arsenic analyses were performed by the Massachusetts Department of Environmental Protection (MADEP) Wall Experimental Station, using graphite furnace atomic absorption spectrometry, EPA Method 200.9, with a detection limit of 0.001 mg/L.

Aluminum: In unfiltered water samples, Al concentrations detected in PW-1 were high in the first two days following the initiation of pumping (maximum of 349 µg/L). Aluminum then declined to 34.9 µg/L by day 3, and then to levels below the MDL (10.0 µg/L) for the remainder of the study, with the exception of two analyses of 14.9 µg/L and 15.4 µg/L on days 16 and 23, respectively.

Aluminum was not detected in PW-2, 92-1, and 92-3 above the MDL of 10.0 µg/L. The highest Al concentrations (up to 7,510 µg/L) were reported in MNG-7. In MNG-3, Al was detected at 65 µg/L. In 92-4, Al concentrations of 256 µg/L, 124 µg/L, and 365 µg/L were reported. In 92-5, Al was detected at 126 µg/L (the duplicate sample from this well showed 8.9 µg/L). Devens groundwater background Al is given as 6,870 µg/L.

Antimony: Antimony was not detected in any of the groundwater samples above the MDLs of 5.0 μg/L and 20 μg/L. Devens groundwater background Sb is given as 3.03 μg/L.

Arsenic: The highest concentrations of As in unfiltered groundwater samples were reported for the production wells. In both wells, the maximum concentrations were observed in the initial sampling round: 45 μg/L in PW-1, and 47 μg/L in PW-2. Arsenic concentrations in both production wells decreased rapidly within the first 2 days following initiation of pumping, to levels of approximately 20 μg/L in PW-1 and approximately 30 μg/L in PW-2. In PW-1, As remained at levels around 20 μg/L through August, but the October and February sampling rounds reported As at a level of approximately 30 μg/L. In PW-2, As concentrations had decreased to approximately 20 μg/L by August, but the October sampling round returned a value of 37 μg/L, similar to the concentration observed in PW-1 at that time. By February, the As in PW-2 had returned to approximately 30 μg/L.

On August 19, 1998, water at the treatment plant apparently was sampled twice. Arsenic values of 11 and 13 μg/L (for PW-1 and PW-2, respectively) were reported by MADEP. Averaged As at 21 μg/L (from both wells, combined at the tap in the treatment plant) was reported for the Town of Ayer for the same day. The same laboratory performed both of these analyses. Samples obtained for this study, collected on August 18, reported As at 24 μg/L and 16 μg/L for PW-1 and PW-2, respectively.

On October 15, 1998, As concentrations of 35 μg/L and 33 μg/L were reported to the Town of Ayer for PW-1 and PW-2, respectively. The unfiltered samples collected for this study on October 21 returned As concentrations of 34 μg/L (33 μg/L in a duplicate) and 37 μg/L for PW-1 and PW-2, respectively.

Arsenic was detected near or below the MDL of 1 μg/L in all of the other unfiltered groundwater samples collected from pre-existing monitoring wells in Phase I. Devens groundwater background As is given as 10.5 μg/L, although these background data may have been collected prior to the USEPA Region I requirement for low-flow sampling.

Barium: Barium was detected in all of the groundwater samples collected. In PW-1, Ba increased to a maximum concentration of 18.9 μg/L in approximately the first day following the onset of pumping; Ba then decreased to a minimum concentration of 7.7 μg/L after 9 days of pumping, and increased steadily thereafter, to levels between 12 and 14 μg/L. In PW-2, Ba increased from an initial concentration of 11 μg/L to 15.4 μg/L by day 9 of pumping, after which concentrations dropped slightly and then increased to around 17 μg/L during the February sampling.

The highest concentration of Ba (39.1 μg/L) was observed in groundwater collected from MNG-7. In 92-1, Ba concentrations remained relatively constant, between 6.2 μg/L and 6.8 μg/L, with a maximum concentration of 8.1 μg/L during the October sampling round.

In 92-3, Ba increased steadily throughout the study, from an initial concentration of 7.8 µg/L to 13.8 µg/L by February. Devens groundwater background Ba is given as 39.6 µg/L.

Beryllium: Beryllium was not detected in any of the unfiltered groundwater samples above the MDL, which varied between 0.5 µg/L and 2.0 µg/L. Devens groundwater background Be is given as 5.0 µg/L.

Cadmium: Cadmium was not detected in any of the unfiltered groundwater samples above the MDL of 1.5 µg/L. Devens groundwater background Cd is given as 4.01 µg/L.

Calcium: Calcium was observed in all of the unfiltered groundwater samples. In both of the production wells, Ca increased from initial concentrations of 12.7 mg/L and 19.3 mg/L for PW-1 and PW-2, respectively, to late-time concentrations around 30 mg/L in both wells. In 92-1, Ca increased slightly from an initial value between approximately 18 mg/L and 20 mg/L, to 23.8 mg/L by late October and 22 mg/L by February. In groundwater collected from 92-3, Ca increased steadily throughout the study, from an initial concentration of 19.1 mg/L to a concentration around 35 mg/L by February. Devens groundwater background Ca is given as 14.7 mg/L.

Chromium: Chromium was reported from MNG-3 at levels of 3.1 and 4.1 µg/L Cr was detected in one sample collected from MNG-7 at 62.1 µg/L, and in 92-4 at 4.3 and 5 µg/L. In all other groundwater samples, Cr was not detected above the MDL, which varied from 1.5 to 5.0 µg/L. Devens groundwater background Cr is given as 14.7 µg/L.

Cobalt: Cobalt was detected in the early samples collected from PW-1, at a maximum concentration of 4 µg/L in the initial sample, then decreasing to 1.6 µg/L by day 2. Cobalt was reported at 6.9 µg/L in a sample collected from MNG-7, and a maximum of 2 µg/L in a sample collected from 92-4. In all other samples, Co was not detected at concentrations above the MDL of 1.5 to 3.0 µg/L. Devens groundwater background Co is given as 25 µg/L.

Copper: Copper was reported from the first four rounds of sampling of PW-1, at concentrations between 1.8 and 2 µg/L. In contrast, the maximum Cu concentration detected in PW-2 was reported from the first sampling round, at 22 µg/L. Copper declined in PW-2 within the first three days of sampling to 2.6 µg/L and was not detectable thereafter above the MDL of 1.5 µg/L. Copper was detected once in groundwater collected from 92-4 (41.4 µg/L) and twice in MNG-7 (9.6 µg/L and 3.3 µg/L). In all other unfiltered groundwater samples, Cu was not detected above the MDL of 1.5 to 3.0 µg/L. Devens groundwater background Cu is given as 8.09 µg/L.

Iron: Highest concentrations of Fe appeared in the production wells. PW-1 reported an initial Fe concentration of 2.8 mg/L, which decreased steadily within the first 9 days of pumping and then increased again, back to 2.8 mg/L, by October and 2.19 mg/L by February. In PW-2, Fe concentrations rose from an initial value of 0.93 mg/L to 2 mg/L by day 3 of pumping, then decreased, then increased again to a maximum of 2.1 mg/L by late October and decreased during the February sampling to 1.6 mg/L. In 92-1, Fe varied between 0.24 and 1.8 mg/L and showed no time-dependent trend except for late-time increase. Iron detected in groundwater collected from 92-3 varied between 0.67 mg/L and 2.4 mg/L, with most of the higher concentrations reported from the samples taken between August and February. Devens groundwater background Fe is given as 9.1 mg/L.

Lead: Lead was not detected in any of the groundwater samples above the MDL of 5.0 to 10.0 µg/L. Devens groundwater background Pb is given as 4.25 µg/L.

Magnesium: In PW-1, Mg increased from 2.1 mg/L to 2.3 mg/L within the first day following onset of pumping. Magnesium decreased to 2 mg/L by day 3, then remained around 3.5 mg/L from October onward. In PW-2, Mg was constant at 2.5 mg/L until day 9, after which values increased to 3.2 mg/L by the last sampling round.

In 92-1, Mg varied between 2.1 mg/L and 2.4 mg/L, and reached a maximum of 2.8 mg/L in October. In 92-3, Mg increased steadily from an initial concentration of 1.9 mg/L to 3.8 mg/L by February. Devens groundwater background Mg is given as 3.48 mg/L.

Manganese: In PW-1, Mn increased from an initial concentration of 553 µg/L to 1,080 µg/L through the first day of pumping. Mn then decreased slightly and rose again, to a maximum of 2,380 µg/L by October, before decreasing to 2,340 µg/L in February. In PW-2, Mn increased steadily throughout the first 9 days of pumping, from 484 µg/L to 787 µg/L, then varied between 676 µg/L and 881 µg/L, with a maximum of 893 µg/L in the February sampling round. Manganese was much lower in 92-1, varying between 5.6 µg/L and 10.9 µg/L. In 92-3, Mn declined consistently from an initial concentration of 188 µg/L to 30.7 µg/L by October. Devens groundwater background Mn is given as 291 µg/L.

Mercury: Mercury was detected twice in unfiltered samples collected from PW-1, at concentrations of 0.51 µg/L and 0.90 µg/L. In all other samples, Hg was not detected above the MDL of 0.20 through 0.50 µg/L. Because of the lack of detection of Hg in the previous Phase I samples, Hg was not analyzed in the February sampling round. Devens groundwater background Hg is given as 0.243 µg/L.

Nickel: In PW-1, Ni was observed only in samples collected during the first day following onset of pumping. During this period, Ni concentrations in PW-1 declined from a maximum concentration of 10 µg/L to 7.2 µg/L and were not observed thereafter above the reporting limit. In PW-2, a value of 6.3 µg/L was reported for one sample. Nickel was reported once for groundwater collected from MNG-7 (43.9 µg/L) and once for groundwater collected from 92-4 (15.9 µg/L). In all other groundwater samples, Ni was not detected above the MDL of 6.0 µg/L. Devens groundwater background Ni is given as 34.3 µg/L.

Potassium: In groundwater collected from PW-1, K values remained relatively constant, around 2.5 mg/L, and began increasing in mid-August, to levels around 3 mg/L in October and February. In groundwater collected from PW-2, K followed a similar pattern, dropping from an initial concentration of 2.7 mg/L to 2.5 mg/L within the first day of pumping, but increasing to around 3 mg/L by the final sampling round. In groundwater collected from 92-1, K increased steadily throughout the study, from an initial concentration of 2.3 mg/L to 2.7 mg/L by February. In groundwater collected from 92-3, K also increased steadily, from an initial concentration of 2.9 mg/L to 4 mg/L by February. Potassium values varied between approximately 1 mg/L (MNG-7) and 3.7 mg/L (92-4) in all of the other wells. Devens groundwater background K is given as 2.37 mg/L.

Selenium: Selenium was not detected in any of the groundwater samples above the MDL of 10.0 µg/L. Devens groundwater background Se is given as 3.02 µg/L.

Silver: Silver was not detected in any of the groundwater samples above the MDLs, which were between 1.5 and 6.0 µg/L. Devens groundwater background Ag is given as 4.60 µg/L.

Sodium: Sodium detected in PW-1 was initially high (22.4 mg/L) but decreased immediately following the onset of pumping, to a minimum of 17.9 mg/L by day 2; Na then increased steadily for the remainder of the study, to a maximum of 24.9 mg/L by the February sampling round. Sodium behavior in PW-2 followed a similar trend; Na decreased from the initial value of 15.4 mg/L, to a minimum of 13.5 mg/L by day 9. Sodium then increased again, to a maximum of 17.4 mg/L in the October sampling round and 17.1 mg/L in February. In groundwater collected from 92-1, Na decreased from values between 14.1 and 14.6 mg/L over the first 3 days of pumping, to a minimum of 13.2 mg/L by late August. Sodium detected in groundwater collected from 92-1 increased to a maximum of 15.1 mg/L by October and was observed at approximately that level (14.9 mg/L) in February. In groundwater collected from 92-3, Na increased more or less steadily from an initial value of 21.3 mg/L to 26.4 mg/L by October and 26.2 mg/L in February. In the other wells, the minimum Na reported was 3.3 mg/L (MNG-7) and the maximum was 44.9 mg/L (92-5). Devens groundwater background Na is given as 10.8 mg/L.

Thallium: Thallium was not detected in any of the groundwater samples above the MDL of 20.0 to 40.0 µg/L. Devens groundwater background Tl is given as 6.99 µg/L.

Vanadium: Vanadium was observed once, in groundwater collected from MNG-7, at 8.8 µg/L. Otherwise, V was not detected in any of the other unfiltered groundwater samples above the MDL of 1.5 to 6.0 µg/L. Devens groundwater background V is given as 11 µg/L.

Zinc: Zinc was not detected in the production wells above the MDL of 12.0 µg/L; however, analyses of the October sampling round reported Zn at concentrations of 1.8 and 2.1 µg/L in PW-1, with a detection limit of 1.5 µg/L. Zinc, at 18.6 µg/L, is reported from the February sampling of PW-2. Zinc is also reported sporadically from the other monitoring wells. These wells, and maximum Zn concentrations, are: MNG-3, 29.3 µg/L; MNG-7, 41.3 µg/L in; 92-4, 607 µg/L; and 92-5, 76 µg/L in. In 92-3, Zn is reported in one sample, at 50.2 µg/L and in 92-1, zinc is detected once, at 11 µg/L (MDL 1.5 µg/L). Devens groundwater background Zn is given as 21.1µg/L.

4.1.2 Metals, Filtered

Results for individual analytes in filtered samples are discussed briefly in this section. Table 4-2 summarizes the ranges of results for filtered metals. The wells MNG-7, MNG-3, and 92-4 are upgradient and presumably represent water quality that is not impacted by pumping at the production wells. However, the Phase I results from these wells show that they sample groundwaters with quite different compositions; moreover, these wells were not sampled on the same schedule as the production wells and the flanking monitoring wells 92-1 (upgradient) and 92-3 (pondward) and therefore do not show trends through time. Data trends through time at the four key localities (PW-1, PW-2, 92-1, and 92-3) are displayed graphically for arsenic, iron, manganese, alkalinity, and chloride in Figures 4-1 through 4-5. Differences between results for unfiltered and filtered samples are discussed for individual elements where appropriate (see, e.g., aluminum). Results of both the February 1999 sampling round, at the conclusion of Phase I, and the February 2000 sampling round, concluding Phase II, are presented and discussed in this section. Data were obtained by the same method (ICP Method 200.7) that was used for the unfiltered metals.

<u>Aluminum:</u> In PW-1, Al decreased during the first day of pumping, from an initial concentration of 68 µg/L to less than 10 µg/L (the MDL). The maximum Al concentration detected in PW-1, 85 µg/L, was detected on the second day of pumping. Al concentrations in PW-1 declined thereafter to levels below the MDL by day 9 of pumping. Aluminum in filtered groundwater samples from all other wells was below the MDL, which varied between 5.0 and 100.0 µg/L.

Among all the analytes, the effect of groundwater sample filtration was greatest on Al. For example, the maximum Al concentration in unfiltered groundwater (349 µg/L) was observed in PW-1. Analysis of the filtered portion of the same sample reported nondetectable Al, at the MDL of 10.0 µg/L. Comparison of other samples from PW-1 show a two- to six-fold decrease in Al in the filtered samples.

<u>Antimony:</u> Sb was not detected in any of the filtered groundwater samples above the MDL of 5.0 – 20.0 µg/L.

<u>Arsenic:</u> (Fig. 4-1) In filtered samples collected from both PW-1 and PW-2, As concentrations are initially high, (45 µg/L in both wells) and decline within the first few days of pumping to lower values. In PW-1, As in the filtered samples dropped to levels around 20 µg/L by the morning after the startup of pumping and remained at that level until late August. Analysis of subsequent sampling rounds reported As in the filtered PW-1 sample at 33 µg/L in October, with comparable concentrations of 30 µg/L and 38.8

µg/L reported from the February 1999 and February 2000 sampling rounds, respectively. In PW-2, As decreased consistently from the initial maximum of 45 µg/L to 16 µg/L by late August. However, in the filtered sample from PW-2, elevated As (37 µg/L) was observed during the October sampling round. Arsenic was reported at concentrations of 35 µg/L and 33 µg/L for PW-1 and PW-2, respectively, from samples taken by the Town of Ayer on October 15. Arsenic detected in filtered samples collected from PW-2 were reported as 28 µg/L (avg.) and 40.5 µg/L in the February 1999 and February 2000 sampling rounds, respectively.

There is no apparent correlation between the observed increases in arsenic in October and February 2000 and either rainfall events or variations in the pumping schedule. No explanation for these values is offered at this time, except to note that these concentrations are consistent with historical fluctuations in arsenic concentrations in these wells (Table D-1; Fig. 1-3).

Filtration apparently had little effect on As concentrations in the production wells. A comparison of As concentrations in both unfiltered and filtered samples yields nearly identical values. This observation suggests that As is reaching the production wells either primarily in solution, or attached to particles that are smaller than 0.45 µm.

Arsenic was not detected above the MDL of 1 µg/L in filtered groundwater samples from any other wells (note: the MDL is 10.0 µg/L for the February 2000 sampling round, as these samples were analyzed by a different laboratory). Exceptions were two filtered samples of 92-4 that returned concentrations of 2 µg/L, and one filtered sample from MNG-3, also at 2 µg/L.

Barium: In PW-1, Ba in the filtered samples was initially low (6.7 µg/L) and then increased within the first day of pumping to a maximum of 18.7 µg/L. Ba then declined over the next two days, to a minimum of 7.7 µg/L, followed by an increase, to 14.8 µg/L during the October sampling round. In general, Ba in filtered samples from PW-2 consistently increased throughout the study, from an initial concentration of 10.9 µg/L to a maximum of 19.4 µg/L in October. In 92-1, Ba was initially low (6.3 µg/L) and reached a maximum value of 7.8 µg/L in the October sampling; in between, Ba concentrations varied from 6.8 µg/L to 7.2 µg/L. In 92-3, Ba generally increased throughout the investigation, from an initial minimum of 7.9 µg/L to a maximum of 13.5 µg/L in October. The maximum concentration of Ba reported from the filtered groundwater samples, 18.7 µg/L, was observed in MNG-3. The lowest Ba value reported, below the MDL of 1.5 µg/L, was reported from MNG-7.

It should be noted that barium concentrations from the February 2000 samples are not of the same order of magnitude as those obtained in previous rounds, but do not differ by 3 orders of magnitude (as in mg/L vs. µg/L). Discussion with lab personnel did not resolve this apparent discrepancy.

Beryllium: Be was not detected in any of the filtered groundwater samples above the MDLs of 0.5 through 2.0 µg/L.

Cadmium: Cd was not detected in any of the filtered groundwater samples above the MDLs of 1.5 through 3.0 µg/L.

Calcium: In both of the production wells, Ca followed the same time-dependent trends described above for the unfiltered samples. In filtered samples collected from PW-1, Ca increased throughout the study from an initial concentration of 12.3 mg/L to a maximum 30.7 mg/L in the October sampling round, then declined slightly to ~27.4 mg/L in February 2000. In PW-2, the increase was not as large; Ca was initially detected at 18.2 mg/L and remained around 28 mg/L from October to the February 2000 sampling round. Ca was detected at similar concentrations in the two flanking monitoring wells 92-1 and 92-3. In 92-1, Ca appears to increase slightly over the period of the study, from an initial minimum concentration of 17.7 mg/L to a maximum concentration of 23.7 mg/L in October. By February 1999 Ca in 92-1 decreased to 22.6 mg/L, and to 20.8 mg/L by February 2000. In 92-3, Ca increases from an initial minimum concentration of 18.4 mg/L (similar to 92-1 and PW-2) to a maximum concentration of 43.8 mg/L in February 2000. The only higher value reported for Ca from filtered groundwater samples was observed in the sample from 92-5, which returned 47 mg/L Ca. The lowest Ca value reported, 6 mg/L, was observed in MNG-7.

Cobalt: Co was detected in filtered samples from both PW-1 and PW-2. In the initial sample from PW-1, Co was detected at 2.5 µg/L, increasing to 4.3 µg/L within the first day of pumping. Co concentrations then decreased, to levels near or below the MDL of 1.5 µg/L, within another day of pumping. Only two filtered samples from PW-2 reported Co above the MDL; values of 1.6 and 1.7 µg/L were observed, also within the first two days after the onset of pumping.

Co was not detected in filtered groundwater samples from any other wells above the MDL of 1.5 µg/L, with the exception of one value (2.1 µg/L) in a sample from MNG-7.

Copper: Cu was not detected above the MDL of 1.5 µg/L in any of the filtered samples collected from PW-1. In marked contrast, Cu was present in the initial filtered sample collected from PW-2 at a concentration of 17.3 µg/L. In PW-2, Cu then declined to 2.4 µg/L by day 3 following the onset of pumping, and was not detected thereafter above the MDL of 1.5 µg/L.
In filtered groundwater samples from all other wells, Cu was not detected above the MDL of 1.5 µg/L.

Chromium: Cr was not detected in any of the filtered groundwater samples above the MDLs of 1.5 or 3.0 µg/L.

Iron: (Fig. 4-2) The initial sample collected from PW-1 contained 2.2 mg/L Fe, which rose to 2.5 mg/L by the end of the first 24 hrs of pumping; Fe concentrations then decreased to a minimum of 1.3 mg/L by day 3, and increased again, to a maximum of

2.71 mg/L in the February 2000 sampling round. Fe in PW-2 increased within the first day of sampling, from 0.95 mg/L to levels around 2 mg/L. Fe concentrations in PW-2 were relatively constant throughout the study, but decreased slightly (to 0.63 mg/L) by mid-August, then rose again to 2.1 mg/L by October. Fe concentrations in PW-2 decreased slightly by February 1999 (~1.6 mg/L), then increased to a maximum of 2.6 mg/L by February 2000. Fe in filtered samples from 92-1 varied between 0.096 mg/L (February 2000) and 0.44 mg/L (July 1998), with no strongly time-dependent trend apparent. In 92-3, Fe generally increased over the duration of the study, from an initial concentration of 0.75 mg/L to a maximum value of 3.4 mg/L (mid-August), declining to 1.26 mg/L by February 1999 and 1.74 mg/L in February 2000. Fe was detected at least once in each of the other monitoring wells, at concentrations ranging from 0.01 mg/L (MNG-3) to 2 mg/L (92-5).

Lead: Pb was not detected in any of the filtered groundwater samples above the MDL of 5.0 – 10.0 μg/L.

Magnesium: In filtered samples collected from PW-1, Mg remained relatively constant at approximately 2.0 to 2.2 mg/L throughout the study, increasing to 3.6 to 3.7 mg/L in the October sampling round and remaining at that level through February 2000. In PW-2, Mg concentrations were consistently measured at 2.5 mg/L, rising to 3.4 mg/L in the October round and remaining at approximately that level through February 2000. Mg in 92-1 varied between 2.1 and 2.3 mg/L during the study, but also increased (to levels between 2.6 and 2.8 mg/L) by February 2000. In 92-3, Mg increased consistently, from a minimum of 1.9 mg/L in the initial sampling round to a maximum of 5.3 mg/L in the last sampling round. In filtered samples from all other monitoring wells, Mg values ranged from 0.63 mg/L (MNG-7) to 4.8 mg/L (92-5).

Manganese: (Fig. 4-3) In filtered samples collected from PW-1, Mn reached a maximum concentration of 1,040 μg/L after the first day of pumping; Mn then declined to values between 800 and 900 μg/L until day 9, after which Mn increased steadily to a maximum concentration of 2,430 μg/L in October and remained at that level through the last sampling round. In PW-2, Mn increased throughout the study from an initial minimum concentration of 464 μg/L, to values over 900 μg/L by late August. Between August and February, Mn detected in PW-2 had decreased slightly but was measured at 1,070 μg/L in February 2000. Mn concentrations were approximately two orders of magnitude lower in 92-1 and an order of magnitude lower in 92-3, and decreased over time in both wells. Mn was also detected in the other monitoring wells, at values ranging from less than 1.0 μg/L (MNG-3, MNG-7) to 42.2 μg/L (92-5).

Mercury: Hg was not detected in any of the filtered groundwater samples above the MDL of 0.20 -- 0.50 μg/L. Because Hg was not observed in any filtered groundwater samples collected during the Phase I sampling rounds between July and October 1998, this element was removed from the analyte list in February 1999 and February 2000.

Nickel: In PW-1, Ni was detected at a concentration of 6.6 μg/L during the initial sampling round. Nickel concentrations subsequently increased to a maximum of 9.2

µg/L within the first day following the onset of pumping, and then decreased to below the MDL of 6.0 µg/L by the second day after pumping began and remained at that level for the duration of the study. Nickel was also detected in filtered samples collected from PW-2, also only during the first two days after pumping was initiated. In PW-2, Ni concentrations ranged from an initial value of 6.2 µg/L, to a maximum of 6.5 µg/L, before declining to below the MDL. Ni was not detected in filtered groundwater samples from any other wells above the MDL of 6.0 – 10.0 µg/L.

Potassium: In both of the production wells, concentrations of K in filtered samples were similar and relatively constant, between 2.3 mg/L and 3.3 mg/L. In these wells, K did not appear to vary systematically with time, although the highest concentrations in both wells were observed in filtered samples from the last three sampling rounds (October 1998 – February 2000). In filtered samples collected from 92-1, K was consistently observed at 2.4 mg/L to 2.6 mg/L, with a maximum concentration of 2.8 mg/L during the October and February 1998 sampling rounds. K was higher in 92-3 than in 92-1 or the production wells, with 3.2 mg/L reported for the initial sampling round, increasing to 5.0 mg/L by February 2000. Among the other monitoring wells, the lowest value of K, 0.81 mg/L, was reported from MNG-7 and the highest value, 3.8 mg/L, from MNG-3.

Selenium: Selenium was not detected in any of the filtered groundwater samples above the MDL of 10.0 µg/L.

Silver: Silver was not detected in any of the groundwater samples above the MDLs of 1.5 or 3.0 µg/L.

Sodium: In PW-1, Na declined during the first three days of pumping, from an initial value of 22.4 mg/L to values around 18 mg/L; Na increased thereafter, throughout the remainder of the study, to a maximum of 27.9 mg/L in the last sampling round. The behavior of Na in PW-2 was similar, declining from an initial concentration of 15.5 mg/L to 13.9 mg/L by day 3 of pumping; Na concentrations then increased, to 20.1 mg/L in February 2000. In 92-1, Na levels were more consistent, varying between 13.6 mg/L and 16 mg/L, and showed no apparent time-dependent trend. In 92-3, Na was approximately constant, between 21.7 mg/L and 23.5 mg/L, during the first three days following the onset of pumping. By late August, Na had increased to 26.3 mg/L and remained at this level before increasing to 35.8 mg/L in the last sampling round. In the other monitoring wells, Na was detected at a minimum concentration of 3.5 mg/L in MNG-7 and a maximum concentration of 45.0 mg/L in 92-5.

Thallium: Thallium was not detected in any of the filtered groundwater samples above the MDL of 20.0 – 100 µg/L.

Vanadium: Vanadium was not detected in any of the filtered groundwater samples above the MDL of 1.5 – 6.0 µg/L.

Zinc: Zn in filtered samples from PW-1 was detected only once, at a concentration of 12.5 µg/L, above the MDL of 12.0 µg/L, and twice (1.7 µg/L and 1.8 µg/L) above the

MDL of 1.5 μg/L. The February 2000 sampling round reports Zn at 50.1 μg/L in PW-1. In PW-2, Zn was detected at 6.3 μg/L in February 1999 and at 28.1 μg/L in February 2000. Zn was reported twice, at 52.4 μg/L and 45.2 μg/L, in 92-1, and also twice in 92-3, at 106 μg/L and 7.1 μg/L. In the other monitoring wells, Zn values ranged from a minimum of less than 6.0 μg/L (from MNG-7) to a maximum of 248 μg/L (92-4).

4.1.3 Anions and Alkalinity

Table 4-3 summarizes the ranges of results for Phase I and February 2000 Phase II for anions and alkalinity.

Alkalinity: (Fig. 4-4) In both of the production wells, alkalinity increased steadily throughout the study. In PW-1, alkalinity was a minimum of 22.2 mg/L (as $CaCO_3$) in the initial sampling round, increasing to 66.0 mg/L by February 2000. In PW-2, alkalinity increased from 30.1 mg/L in the initial round to 56.2 mg/L by February 2000. Alkalinity in 92-1 remained relatively constant over the duration of the study, varying between 33 mg/L and 35.5 mg/L. Alkalinity in 92-3 followed the same trend as in the production wells during the initial weeks of Phase I, increasing from an initial minimum concentration of 49.3 mg/L to 75.9 mg/L by the time of the October sampling, but decreasing thereafter, to 53.7 mg/L by February 2000. Among the other monitoring wells, the lowest alkalinity detected was 7.4 mg/L, in MNG-7; the highest was in 92-5, 62.2 mg/L.

Chloride: (Fig. 4-5) Chloride detected in PW-1 decreased within the first 9 days of the study, from an initial concentration of 40.4 mg/L, to a minimum of 31.7 mg/L; Cl increased steadily after that time, to a maximum of 59.1 mg/L in the last sampling round. Cl detected in PW-2 followed the same pattern, dropping from 33.2 mg/L to 25.5 mg/L by day 9, then increasing to a maximum of 42.6 mg/L by February 2000. In 92-1, Cl was observed to increase during the first three days following the onset of pumping, from 25.6 mg/L to 30.1 mg/L. During the remainder of the study, Cl decreased slightly and then increased, to 38.5 mg/L, by the February 2000 sampling round. In 92-3, Cl increased steadily throughout the sampling period, from an initial minimum of 29.2 mg/L to a maximum of 111 mg/L in February 2000. The lowest Cl value, 4.01 mg/L, was reported from MNG-7, and the highest values were detected in MNG-3 (69.2 mg/L) and 92-5 (107 mg/L).

Sulfate: In PW-1, SO_4 values were relatively constant over the first 9 days of the investigation, ranging between 11.1 and 11.3 mg/L; SO_4 decreased to a minimum of 10.7 mg/L around day 9, then increased again to 11.3 mg/L by October, decreasing thereafter to 8.7 mg/L by February 2000. In PW-2, SO_4 followed the same trend that was observed in PW-1, increasing within the first day after pumping began, from 14.4 mg/L to 15.3 mg/L. SO_4 then decreased, to a minimum of 14.1 mg/L, rising to 14.7 mg/L by October and falling to 13.3 mg/L by the last sampling round. In 92-1, SO_4 increased during the first three days of pumping, from 11.8 mg/L to 12.9 mg/L, then decreased through August, but increased from there through the February 2000 sampling round, to 15.4 mg/L. In 92-3, SO_4 increased consistently throughout the study, from an initial minimum of 13.6 mg/L to around 16--17 mg/L by February 2000. In the other monitoring wells, SO_4 ranged from 8.74 mg/L, in MNG-7, to 37.8 mg/L, in 92-5.

Nitrate/nitrite: In PW-1, NO_3/NO_2 increased from 1.66 mg/L in the initial sampling round to a maximum of 3.19 mg/L after the first day of pumping; NO_3/NO_2 values then decreased and remained constant but variable, between approximately 1.6 mg/L and 2.6 mg/L through the October sampling, after which it decreased through the end of the study. In PW-2, NO_3/NO_2 followed a similar pattern; the initial increase during the first day of pumping, to a maximum of 3.52 mg/L, was followed by a decrease and then varied between 1.62 mg/L and 2.76 mg/L thereafter. In 92-1, NO_3/NO_2 values were generally much higher than in the production wells. In this well, NO_3/NO_2 increased during the first three days of the study, from 4.17 mg/L, to 5.67 mg/L, and then decreased in August. NO_3/NO_2 then increased, from the October sampling round through February 2000. In 92-3, NO_3/NO_2 was detected at relatively low concentrations, ranging from 0.02 mg/L (as N), from the October sampling round, to a maximum of 1.8 mg/L (as N), in the last sampling round. In the remaining monitoring wells, NO_3/NO_2 values ranged from 1.23 mg/L (as N) in MNG-7 to 16.4 mg/L (MNG-3). Where the lab reported NO_3/NO_2 as "N," values were converted to mg/L NO_3 as concentrations of NO_2 are usually negligible.

Bromide: Bromide was not detected with certainty in any of the groundwater samples above the MDL of 0.10 mg/L. However, Br was included on the PAL because Town of Ayer used an organobromide salt to control vegetation in Grove Pond and it was thought that Br might serve as a tracer of pond water.

4.1.4 Field Parameters

Table 4-4 summarizes the ranges of results for the Phase I and February 2000 Phase II field parameters.

pH: pH in the production wells varied between 6.38 and 7.14 for PW-1, and between 6.39 and 7.12 for PW-2. In 92-1, pH varied between 6.59 and 7.32, and in 92-3, between 6.02 and 7.70. pH ranges for In the remaining monitoring wells, pH values ranged from a minimum of 6.01 (MNG-7) to a maximum of 7.42 (92-4).

Temperature: In PW-1, temperature rose rapidly within the first 24 hours after the onset of pumping, from 12.7 °C to 15 °C, after which it decreased and remained relatively constant, between 10 °C and 12 °C, for the duration of the study. Temperature in PW-2 appeared to fluctuate on a daily cycle, between approximately 12 °C and 14 °C, within the first three days after pumping began, then declined and remained stable, around 11 °C. The temperature for the 8/18/98 sampling was reported as 20.56 °C, but this is most likely an error. All four of the key wells showed an increase in temperature over the last three sampling rounds, from October 1998 through February 2000. In the other monitoring wells, temperatures ranged from a low of 11 °C in 92-5 to a maximum of 13.6 °C in MNG-7.

Conductivity: Conductivity values in PW-1 increased, from 205 µmhos/cm to 213 µmhos/cm the day after pumping began; conductivity then decreased to a minimum (148 µmhos/cm) on day 9, increased steadily to a maximum of 285 µmhos/cm in October, and decreased again by February 2000. In PW-2, initial conductivity values were more erratic than those in PW-1. However, around day 9, conductivity in PW-2 also reached a minimum (145 µmhos/cm) and increased from that point until October, when the maximum conductivity was reported for PW-2 (235 µmhos/cm). Conductivity in PW-2 then decreased, to 135 µmhos/cm in February 2000. In 92-1, conductivity in the initial sampling round was 186 µmhos/cm, increasing to a maximum of 216 µmhos/cm by the day after the onset of pumping. Conductivity in 92-1 also declined for the remaining portion of the study but rose in the October sampling round to 199 µmhos/cm before dropping to 177 µmhos/cm in February 2000. In 92-3, conductivity appeared to decrease during the first three days after the onset of pumping, then increased throughout August, reaching a maximum of 364 µmhos/cm in February 2000. In the other monitoring wells, conductivities ranged from a low of 44 µmhos/cm, in MNG-7, to a maximum of 440 µmhos/cm, in 92-5.

Dissolved Oxygen (DO): DO measurements in all wells appeared to be erratic; none of the wells showed any systematic temporal trends over the duration of the investigation. All of the monitoring wells located upgradient of the production wells reported relatively high DO; a mean of 5.33 mg/L DO was reported for 92-1. DO values in 92-3 were erratic but uniformly low: all values reported from 92-3 are less than 1 mg/L, with one reading of 2.5 mg/L.

4.2 Phase I and Phase II Surface Water

Six unfiltered surface water samples were collected in Grove Pond in late August, 1998. Five of these samples were located immediately offshore of the Town of Ayer wells, within 215 ft of the shoreline; the sixth sample was taken in the northwest corner of Grove Pond, immediately offshore of the former tannery site (Fig. 2-2). Although exact determination of the pond bottom was difficult due to the mass of vegetation at the sediment-water interface, every effort was made to locate the inlet port of the sampling pump at a height of six inches above the pond bottom. An additional unfiltered surface water sample was taken in February 1999, in the concluding sampling round of Phase I, at the same location as the cluster of five samples immediately offshore.

4.2.1 Metals, Unfiltered

The following analyses were performed by ICP-AES, Method 200.7. Arsenic was analyzed by GFAAS, Method 200.9.

Aluminum: In the unfiltered surface water samples, Al values ranged from 21.3 µg/L to 176 µg/L. Both the lowest and highest values detected were among the samples offshore of the production wells.

Antimony: Sb was not detected in any of the surface water samples above the MDLs of 5.0 or 20.0 μg/L.

Arsenic: As was detected in all of the unfiltered surface water samples above the MDL of 0.001 mg/L. In the samples closest to the production wells, As values ranged from 0.001 to 0.009 mg/L. In the sample collected from the northwest corner of the pond, near the former tannery site, 0.01 mg/L As was reported, with 0.009 mg/L As in the duplicate sample taken at this location.

Barium: In the surface water samples adjacent to the production wells, Ba ranged from 7.6 μg/L to 18.5 μg/L. Ba was reported at 22.3 μg/L from the sample near the former tannery site.

Beryllium: Be was not detected in any of the surface water samples above the MDLs of 0.50 μg/L and 2.0 μg/L.

Cadmium: Cd was not detected in any of the surface water samples above the MDLs of 1.5 μg/L and 3.0 μg/L.

Calcium: In five of the surface water samples closest to the production wells, Ca values were relatively similar, between 20.0 and 20.5 mg/L. In the sample (and its duplicate) collected from the northwest corner of the pond, Ca concentrations of 30.5 and 30.3 were reported.

Cobalt: Co was not detected in any of the surface water samples above the MDLs of 1.5 and 3.0 μg/L.

Copper: Cu was detected only in the sample taken in the northwest corner of the pond, at 3.4 μg/L. In the other surface water samples, Cu was not detected above the MDLs of 1.5 and 3.0 μg/L.

Chromium: Cr was detected only in the sample taken in the northwest corner of the pond, at 31.5 μg/L. In the other surface water samples, Cr was not detected above the MDL of 3.0 μg/L.

Iron: Fe in surface water samples was highly variable, with concentrations ranging from 0.12 mg/L to 2 mg/L. The six samples closest to the production wells reported both the minimum and maximum Fe observed, while the sample collected from the northwest corner returned a concentration of 1.8 mg/L. Fe and Mn concentrations co-varied; the sample with highest Fe reported also contained the highest Mn, and the lowest concentration of Fe was reported from the sample with lowest Mn.

Lead: Pb was detected only in the sample taken in the northwest corner of the pond, at 7.1 μg/L. However, in a duplicate sample taken at this location, Pb was not detected above the MDL of 5.0 μg/L. In the other six surface water samples, Pb was not detected above the MDLs of 5.0 and 10.0 μg/L.

Magnesium: Mg was detected at concentrations from 1.7 to 3.3 mg/L in all of the surface water samples. The highest values were reported for the sample and its duplicate that were taken in the northwest corner of the pond. The lowest value was reported from the February 2000 sampling round.

Manganese: Mn in surface water samples was highly variable. Of the six samples closest to the production wells, Mn ranged from a minimum of 18.2 µg/L to 1,040 µg/L, the maximum reported from any of the surface water samples. In the northwest corner of the pond, surface water Mn was detected at 389 µg/L (343 µg/L in the duplicate sample taken at this location).

Mercury: Hg was not detected in any of the surface water samples above the MDL of 0.50 µg/L, and was not analyzed in the February 2000 sampling event.

Nickel: Ni was not detected in any of the surface water samples above the MDL of 6.0 µg/L.

Potassium: In the surface water samples closest to the production wells, K ranged from 1.3 to 1.6 mg/L. The highest value, 1.8 mg/L, was reported from the sample taken in the northwest corner of the pond.

Selenium: Se was not detected in any of the surface water samples above the MDL of 10.0 µg/L.

Silver: Ag was not detected in any of the surface water samples above the MDLs of 3.0 or 6.0 µg/L.

Sodium: In the surface water samples closest to the production wells, Na ranged from 22.4 mg/L to 29.5 mg/L. In the sample collected from the northwest corner of the pond, Na was reported at 43.1 mg/L.

Thallium: Tl was not detected in any of the surface water samples above the MDLs of 20.0 and 40.0 µg/L.

Vanadium: V was not detected in any of the surface water samples above the MDLs of 1.5 and 6.0 µg/L.

Zinc: Zn, at 17.1 µg/L, was reported for only one out of six surface water samples. Zn was not detected in any of the other surface water samples above the MDLs of 6.0 and 12.0 µg/L.

4.2.2 Metals, Filtered

This section describes results from filtered surface water samples taken during Phase I, including the February 1999 sampling round, and results from the confirmatory Phase II sampling event in February 2000. Unfiltered surface water samples were not collected during the final Phase II sampling round, because data from Phase I showed little difference between filtered and unfiltered results for the major elements of concern (e.g., arsenic). Selected constituents are plotted, where appropriate, along with the filtered groundwater data referenced above (Sec. 4.1.2) in Figures 4-1 through 4-5. Analyses were performed by ICP-AES, Method 200.7. Arsenic was analyzed by GFAAS, Method 200.9.

Aluminum: Al was not detected in any of the filtered surface water samples above the MDL of 10.0 µg/L, except for the last sampling round, which reported 34.6 µg/L. As noted previously for the groundwater results, in Section 4.1.2, the effect of filtration is greatest on Al concentrations. Although every effort was made to collect surface water samples with minimum turbidity, the differences between filtered and unfiltered surface water Al concentrations (and also concentrations of Fe and Mn) suggest that these metals are associated with fine particulates that were removed by 0.45 µm filters.

Antimony: Sb was not detected in any of the filtered surface water samples above the MDLs of 5.0 and 20.0 µg/L.

Arsenic: (Fig. 4-1) In the filtered surface water samples closest to the production wells, As ranged from 1 to 7 µg/L. The sample taken in the northwest corner of the pond and a duplicate sample taken at that location reported the highest filtered surface water As values, 8 and 9 µg/L.

Barium: Ba in filtered surface water samples ranged from 7.2 to 14 µg/L in the samples closest to the production wells. In the northwest corner of the pond, Ba was detected at a maximum concentration of 18.4 µg/L.
Beryllium: Be was not detected in any of the filtered surface water samples above the MDLs of 0.50 and 2.0 µg/L.

Cadmium: Cd was not detected in any of the filtered surface water samples above the MDLs of 1.5 and 3.0 µg/L.

Calcium: In the filtered surface water samples closest to the production wells, Ca concentrations in the August 1998 sampling round were relatively uniform, between 18.4 and 19.1 mg/L. Ca at the sampling location in the northwest corner of the pond was reported at 28 mg/L, for the same sampling round. The large differences noted for Ca, Na, and Ba at that sample location suggest that the northwest corner of the pond is relatively stagnant. Both of the February sampling rounds returned significantly lower Ca values, 8.8 mg/L (1999) and 10.1 mg/L (2000).

Cobalt: Co was not detected in any of the filtered surface water samples above the MDLs of 1.5 and 3.0 µg/L.

Copper: Cu was not detected in any of the filtered surface water samples above the MDL of 1.5 and 3.0 µg/L.

Chromium: Cr was not detected in any of the filtered surface water samples above the MDL of 1.5 and 3.0 µg/L.

Iron: (Fig. 4-2) In the filtered surface water samples, Fe in the samples closest to the production wells varied between 0.08 and 0.8 mg/L. Fe in the sample from the northwest corner of the pond was within this range, at 0.28 mg/L (0.20 mg/L in the duplicate sample at this location). Filtration significantly reduced Fe concentrations in the surface water samples, indicating that Fe in Grove Pond surface water is transported primarily as particulates.

Lead: Pb was not detected in any of the filtered surface water samples above the MDLs of 5.0 and 10.0 µg/L.

Magnesium: Mg in the filtered surface water samples ranged from 1.7 mg/L to 3.3 mg/L. The highest concentrations were reported from the samples taken in the northwest corner of the pond. The lowest Mg values, 1.7 and 2.3 mg/L, were reported from the February 1999 and 2000 sampling rounds, respectively.

Manganese: (Fig. 4-3) Mn in the filtered surface water samples ranged from 18 to 801 µg/L. Both the minimum and maximum values were detected in the samples closest to the production wells. In general, the comparison of filtered and unfiltered Mn data indicates that filtration reduced Mn concentrations. This observation implies that Mn is also transported on particulates, but to a lesser extent than Fe or Al. One pair of unfiltered – filtered samples (SW5 and SW5F) reported values of 459 µg/L and 801 µg/L, respectively, suggesting that these data are suspect.

Mercury: Hg was not detected in any of the filtered surface water samples above the MDL of 0.50 µg/L and was subsequently removed from the PAL for the February 1999 and 2000 sampling rounds.

Nickel: Ni was not detected in any of the filtered surface water samples above the MDL of 6.0 µg/L.

Potassium: K in filtered surface water samples nearest the production wells ranged from 1.4 mg/L to 1.8 mg/L. The highest concentrations (1.9 mg/L) were observed in the northwest corner of the pond.

Selenium: Se was not detected in any of the filtered surface water samples above the MDL of 10.0 µg/L.

Silver: Ag was not detected in any of the filtered surface water samples above the MDL of 3.0 µg/L.

Sodium: Na in the surface water samples closest to the production wells ranged from 27.4 mg/L to 31.6 mg/L, in the August 25, 1998 sampling round. In the two samples from the northwest corner of the pond, taken at the same time, the Na concentration was around 45 mg/L. Na from the February samples, taken near the production wells, was reported at 22.1 mg/L for 1999 and 46.9 mg/L for 2000.

Thallium: Tl was not detected in any of the filtered surface water samples above the MDLs of 20.0, 40.0, and 100.0 µg/L.

Vanadium: V was not detected in any of the filtered surface water samples above the MDLs of 1.5 and 6.0 µg/L.

Zinc: Zn was not detected in any of the filtered surface water samples above the MDLs of 6.0 and 12.0 µg/L, with the exception of the last sampling round (February 2000), when a value of 10.1 µg/L was reported.

4.2.3 Anions and Alkalinity

This section includes the anion and alkalinity data from the final round of Phase I sampling in February 1999, as well as the data from the confirmatory round of Phase II, completed in February 2000. Results from surface water samples are plotted, where appropriate, along with the groundwater data referenced above (Sec. 4.1.3) in Figures 4-4 and 4-5.

Alkalinity: (Fig. 4-4) In August 1998, alkalinity was relatively uniform in the samples nearest the production wells, between 43.9 mg/L and 46.8 mg/L mg/L $CaCO_3$. In the two samples from the northwest corner of the pond, taken at the same time, alkalinity was reported at 72.9 mg/L (72.4 mg/L in the duplicate sample at this location). In both of the February sampling events, alkalinity was significantly lower, at 12.8 mg/L and 11.3 mg/L for 1999 and 2000, respectively. The decrease in alkalinity is consistent with the lower Ca and Mg concentrations that were also observed during these sampling rounds, and suggests that carbonate precipitation may be occurring during the winter months.

Chloride: (Fig. 4-5) Chloride followed the same pattern as alkalinity in the surface water samples. In the samples taken offshore of the production wells, Cl concentrations were between 47.2 mg/L and 53.4 mg/L. The sample from the pond's northwest corner returned a value of 71.3 mg/L (70.6 mg/L in the duplicate). During the February sampling rounds, Cl was reported at 38 mg/L and 87.3 mg/L, respectively, in a manner similar to the behavior of Na. These data suggest that changes in Grove Pond water composition reflects changes in input on a relatively short time scale – for example, dilution by runoff from snow melt (i.e., low Na and Cl measured in February 1999), or an increase in concentrations of these solutes due to road salt (i.e. elevated Na and Cl in February 2000).

Sulfate: In August 1998, SO_4 was relatively constant, between 6.8 and 7.9 mg/L, in the samples nearest the production wells. In the northwest corner, SO_4 was lower, 3.47 mg/L (3.32 mg/L in the duplicate). For both of the February sampling rounds, SO_4 was substantially higher near the production wells, at 9.34 and 10.5 mg/L for 1999 and 2000, respectively.

Nitrate/nitrite: NO_3/NO_2 was not detected with certainty in any of the surface water samples, except for one analysis at 0.13 mg/L. However, the February sampling rounds returned values of 0.07 and 0.3 mg/L (as N) for 1999 and 2000, respectively.

Bromide: Br was not detected in any of the surface water samples above the MDL of 0.10 mg/L.

4.2.4 Field Parameters

These data include the field water quality parameters from the last Phase I sampling round, in February 1999, as well as those from the confirmatory round of Phase II, in February 2000.

pH: pH in the surface water samples ranged from 6.62 to 6.97 in the 8/25/98 sampling round; the highest value observed (6.97) was in the northwest corner of the pond. In the two February sampling rounds, pH varied from 6.87 (1999) to 8.61 (2000).

Temperature: During the August 1998 surface water sampling round, temperatures ranged from 22.4 °C to 23.2 °C. The temperature of the water in the northwest corner of the pond registered 24.2 °C at that time. The February samples were taken beneath a thick layer of ice, in water that registered 1.34 °C (1999) and 0.17 °C (2000).

Conductivity: In August 1998, conductivities of the surface water samples closest to the production wells were between 244 and 257 µmhos/cm. The highest conductivity, 370 µmhos/cm, was obtained from water in the northwest corner of the pond. During the February sampling rounds, conductivities were significantly lower, at 98 and 177 µmhos/cm for 1999 and 2000, respectively.

Dissolved Oxygen (DO): DO measurements on the samples closest to the production wells were uniformly low, between 0.14 mg/L and 0.68 mg/L. In the northwest corner of the pond, the DO concentration was 2.16 mg/L.

Oxidation-Reduction Potential (ORP): ORP measured on the surface water samples collected offshore of the water-supply wells ranged from 8 to 89 mV in August 1998. Some of this variability may be due to variability in the distance of the pump intake from the pond bottom. Samples collected in the same area in February 1999 and again in February 2000 yielded ORP values of 164 and 43 mV, respectively. Water from the northwest cove of the pond, collected in August 1998, showed the lowest surface-water ORP measured, at 2 mV.

4.3 Phase II Groundwater

Because little difference between unfiltered and filtered groundwater was observed in the Phase I results, particularly for the elements of primary interest, the Phase II Work Plan specified only the collection and analysis of filtered groundwater samples. Accordingly, all Phase II groundwater samples were field-filtered using in-line, 0.45-µm, disc filters. This section contains a brief discussion of all groundwater data collected during Phase II (Tables 4-5, 4-6, and 4-7), including the vertical-profilc samples as well as those from the newly-installed wells. Four of the pre-existing wells that were the focus of Phase I (the two production wells, PW-1 and PW-2, and monitoring wells 92-1 and 92-3) were sampled during the final, Phase II confirmatory sampling round in February 2000; those data are reported with the Phase I results in Tables 4-2 through 4-4.

4.3.1 Metals, Filtered

The dissolved metals data from wells GF-1, GF-2, GF-3A and GF-3B, GF-4, and the in-pond borehole BH-1 (Table 4-5) were obtained using inductively-coupled plasma-source atomic emission spectroscopy with ultrasonic sample nebulization (ICP Method 200.7, Methods for the Determination of Metals in Environmental Samples, Supplement I, EPA 600/R-94/111, May, 1994).

The following elements were not detected above the MDLs (given in Table 4-5) in any of the groundwater samples: silver, beryllium, chromium, antimony, selenium, thallium, and vanadium. Of the remaining PAL metals, aluminum, cobalt, copper, and nickel were detected sporadically.

Arsenic: (Fig. 4-6) Arsenic was detected in all five boreholes. Wells GF-1 and GF-2 reported As at less than the MDL of 5.0 µg/L and 32 µg/L, respectively, for samples that were taken immediately beneath the water table. Both GF-1 and GF-2 showed an increase in As near bedrock, and maximum values of 108 and 139 µg/L, respectively, in bedrock groundwater. The vertical profile from GF-3A reported 28.4 µg/L As in the first sample under the water table, then a decrease to < 5.0 µg/L five feet below the first sample. From that point on, As increased steadily, to a maximum of 189 µg/L in the sample from the 43-45 ft depth interval bgs (175.32 ft. MSL). Arsenic was not observed above the MDL in any samples below 43-45 ft until the top of bedrock was encountered, where As was measured slightly above the MDL of 20.0 µg/L. Well GF-3B was sampled twice, once at completion and again during the confirmatory round. For these two samples, As concentrations were 44.7 µg/L and 27.9 µg/L, respectively. In well GF-4, the As profile resembled that from GF-3A, with non-detectable As in the sample at the top of the water table, but then a systematic increase with depth to a maximum of 187 µg/L in the sample from 26-28 ft bgs (198.09 ft. MSL). The in-pond borehole, BH-1, showed similar behavior. Arsenic was not detected until the sample from 16-18 ft bps, (200 ft. MSL) where a concentration of 98.4 µg/L was observed. Arsenic was detected in the next two samples below this interval, reaching a maximum of 188 µg/L at 26-28 ft bps (190 ft. MSL) while all samples below this depth reported no As above the MDL.

Barium: Barium showed no systematic behavior in GF-1 and GF-2. In GF-3A, Ba was relatively high in the upper 35 ft, reaching at maximum of 462 µg/L. Below this depth, concentrations were generally lower and varied sporadically. In GF-4 and BH-1, Ba was highest in the uppermost samples from both, at 308 and 332 µg/L, respectively, then varied sporadically, at lower concentrations, in the remaining samples.

Cadmium: Cadmium was observed only in three samples, all from GF-4, at concentrations near the MDL of 1.5 µg/L. The maximum, 2.2 µg/L, was measured in the sample from 26-28 ft bgs (198.09 ft. MSL).

Calcium: In GF-1, GF-2, GF-3A and 3B, and BH-1, dissolved Ca is uniformly low (generally, <20 mg/L) in the upper 45 ft of the aquifer, and higher with depth. Intriguing results emerged from the profile sampling in GF-3A. Samples from this borehole that were taken between 18-20 ft bgs (200.32 ft. MSL) and 43-45 ft bgs (175.32 ft. MSL) are consistently around 15 mg/L. Below the 68-70 ft bgs (150.32 ft. MSL) sampling interval, Ca ranges from 37.2 mg/L to 64.4 mg/L.

Three samples that were collected between 48-50 ft bgs (170.32 ft. MSL) and 63-65 ft bgs (155.32 ft. MSL) reported unusually low values (between approximately 3 and 5 mg/L). For GF3AGW09 (48-50 ft bgs), Ca is reported as 2.9 mg/L; for GF3AGW11 (58-60 ft bgs), Ca is 3.8 mg/L, and for GF3AGW12, (63-65 ft bgs), Ca is 4.9 mg/L. These low values are suspect; charge balance calculations on the data from GF-3A groundwater samples yielded differences less than 10% for all except these three. The charge balances on these three samples showed a significant cation deficiency, suggesting that these data are possibly the result of laboratory error. These data are critical to the construction of Piper diagrams, discussed in Section 5.2. Assuming laboratory error, Ca values were adjusted to correct the charge balance. The corrected values for GF3AGW09, GF3AGW11, and GF3AGW12 are, respectively, 35.3 mg/L, 42.8 mg/L, and 54.2 mg/L. These values are consistent with the general trend observed in the groundwater Ca profile in GF-3A.

In GF-4, Ca ranges from 27.8 mg/L in the 11-13 ft bgs (218.09 ft. MSL) sample, to 23.5 mg/L at 21-23 ft bgs (203.09 ft MSL), below which Ca values range from 32.3 and 42.3 mg/L, generally increasing with depth. In BH-1, Ca was elevated in the two deepest samples, taken below 60 ft bgs.

Iron: (Fig. 4-7) The vertical profiles of dissolved Fe generally followed the same pattern in GF-3A, GF-4, and BH-1. Fe concentrations were low, ranging from <1 mg/L (GF-1, GF-4) in samples taken near the top of the aquifer. Fe concentrations increased in all profiles with increasing depth; a maximum of 21.9 mg/L was measured in the sample from GF-3A, 28-30 ft bgs (190.32 ft. MSL). Below depths of approximately 40 to45 ft bgs in all boreholes, Fe decreased again and remained low (in general, <1 mg/L) in the deep aquifer.

Lead: In GF-3A, dissolved lead was reported above the detection limit in four samples between 48 and 70 ft bgs, with a maximum of 18.9 µg/L in the 53-55 ft bgs (165.32 ft. MSL) sampling interval. It is noted that this is the same stratigraphic horizon from which anomalously high Cl is reported for this borehole (Section 4.3.2). Lead was not detected above the detection limit in any other Phase II groundwater samples.

Magnesium: In GF-1 and GF-2, Mg is low in the upper part of the aquifer (1-2 mg/L) and higher (10-12 mg/L) in the bedrock groundwater. The Mg profile in GF-3A is consistent with the trends observed in GF-1 and GF-2, i.e. elevated in the upper part of the aquifer (>3.5 mg/L), then decreasing to <3 mg/L to the 43-45 ft bgs (175.32 ft. MSL) interval, with generally higher values (≥ 4—5 mg/L, with a maximum of 10.7 mg/L) between ~50 ft bgs and bedrock.

Manganese: Vertical variation in Mn concentrations followed the same pattern as Fe: generally, Mn was low in samples near the top of the aquifer and increased with depth to 30-50 ft bgs (43-45 ft bgs (175.32 ft. MSL) in GF-3A, 48-50 ft bgs (176.09 ft. MSL) in GF-4, 26-28 ft bgs (190 ft MSL) in BH-1). Below this zone of elevated Mn, values dropped sharply, to <1 mg/L and generally remained low throughout the remaining samples.

Potassium: In the GF-3A vertical profile, K was lowest (1.9 mg/L) in the 18-20 ft bgs (200.32 ft MSL) interval, below which K increased to a maximum of 7.2 mg/L in the sample taken in the top of bedrock. A similar trend was observed in GF-4, with a minimum of 2.8 mg/L at 41-43 ft bgs (183.09 ft MSL), increasing to 5.7 mg/L at 73-75 ft bgs (151.09 ft MSL). In BH-1, the inverse behavior was noted: K was lower in the uppermost part of the aquifer and reached a maximum of 4.9 at 36-38 ft bgs (180 ft MSL), below which K generally decreased.

Sodium: Na values ranged from a minimum of 16 mg/L in GF-4 to a maximum of 54.3 mg/L in BH-1. Na varied erratically in the vertical profiles seen in GF-3A and GF-4, but in BH-1 Na increased systematically to the 41-43 ft bgs (175 ft MSL) sampling interval, below which concentrations decreased.

Zinc: In GF-3A, Zn was high (several hundreds of µg/L) down to 33-35 ft bgs (185.32 ft MSL); below this depth, Zn was significantly lower (<100 µg/L) in all samples. Zn was low (<100 µg/L) in GF-4 samples from the interval between 16 and 28 ft bgs, and again in the deeper part of the aquifer, between 78 and 85 ft bgs, and higher in the middle portion of the aquifer. In BH-1, Zn was elevated in the upper 48 ft of the aquifer, but low (109 µg/L or less) between 58 and 68 ft bgs.

4.3.2 Anions and Alkalinity

Alkalinity: The lowest alkalinity (35.5 mg/L, as $CaCO_3$) was detected in the uppermost sample from the GF-3A profile. In GF-3A, alkalinity increased steadily with depth through the upper 45 feet of overburden, then fluctuated between 40.4 and 45.8 mg/L through the next 15 feet. Alkalinity in samples from 63-65 ft bgs (155.32 ft MSL) and below was relatively high (>100 mg/L in all but two samples) and remained around that level to bedrock. GF-4 also showed a pattern of increasing alkalinity with depth, to a maximum of 97.6 mg/L at 73-75 ft bgs (151.09 ft MSL). A similar trend was observed in BH-1, with the exception of two readings of 20.2 mg/L in samples from 36-38 ft bgs (180 ft MSL) and 41-43 ft bgs (175 ft MSL).

Chloride: (Fig. 4-8) In GF-3A, chloride was lowest in the upper 20 ft of the aquifer, between 47 and 54 mg/L, below which Cl increased with depth, to a maximum of 111 mg/L at 53-55 ft bgs (165.32 ft MSL). The highest chloride values in GF-3A were observed in the interval between 48 ft and 60 ft bgs. Below this zone, chloride remained elevated (~49 to 80 mg/L) to bedrock. A similar trend was observed in BH-1, increasing from the near surface to a maximum of 100 mg/L at a depth of 41-43 ft bps (175 ft MSL). In GF-4, however, chloride showed no systematic increase or decrease within the uppermost 50 ft of overburden; all values were between 42 and 53 mg/L. Between 48 ft and 75 ft bgs, Cl was relatively low (~26-27 mg/L) but somewhat higher (~42 and 33 mg/L) in the lowest two samples. Chloride in the uppermost samples from both GF-1 and GF-2 was consistent with values measured in the corresponding portion of the section in GF-3A. Bedrock samples from GF-1 reported values lower than those observed in the top-of-bedrock samples from GF-3A, and bedrock groundwater from GF-2 reported Cl at 8-18 mg/L.

Sulfate: The highest value of SO_4, 44.2 mg/L, was detected in the near-surface sample 3-5 ft bgs (215.32 ft MSL) from GF-3A. Below that depth, SO_4 decreased to a minimum of 0.48 mg/L at 33-35 ft bgs (185.32 ft MSL). Sulfate remained relatively constant, between 13 and 17 mg/L, from 48-50 ft bgs (170.32 ft MSL) to the top of bedrock. The SO_4 profile from GF-4 was similar, except that the lowest values, between 5 and 9 mg/L, in the interval from 16 ft to 50 ft bgs, were higher than the lowest values in GF-3A. In BH-1, SO_4 was initially low and remained low (< 4 mg/L) in the uppermost 28 ft, below which SO_4 values varied between 11.2 and 14.3 mg/L.

NO_3/NO_2: With one exception, N was not detected in any samples from GF-3A until the sampling interval at 48-50 ft bgs (170.32 ft MSL). Below this depth, N levels fluctuated erratically but were highest (>1 mg/L) in samples from 53-55 ft bgs (165.32 ft MSL) and 58-60 ft bgs (160.32 ft MSL). In GF-4, N was highest (0.22 and 0.2 mg/L) in samples from 36-38 ft bgs (188.09 ft MSL) and 41-43 ft bgs (183.09 ft MSL) and lowest (0.1 mg/L) in groundwater at the bottom of the borehole. Maximum N values in BH-1, up to 3.2 mg/L, were detected in the middle-depth samples, between 36 and 48 ft bps.

Bromide (Br) and fluoride (F) were reported by the laboratory as non-detects (Table 4-6), with the exception of a few values for F in the bedrock water samples from GF-1 and GF-2. Ortho-phosphate (o-PO_4) was also reported, as non-detects everywhere, but with the caution that samples had exceeded their hold times. These analytes were not requested and were not listed on the PAL.

4.3.3 Field Parameters

Field parameters (Table 4-7) that were measured include pH, temperature, conductivity, turbidity, dissolved oxygen (DO), total dissolved solids (TDS), and oxidation-reduction potential (ORP). Of these, pH showed no strong patterns in any of the vertical profiles. Extremely high values, between 8 and 10, were observed in the two bedrock wells, GF-1 and GF-2. These elevated values may be due, at least in part, to reactions between groundwater and the cement that was used in installation of the permanent monitoring well screens.

In GF-3A, GF-4, and BH-1, the most striking trends were observed in the vertical profiles of ORP (Fig. 4-9). In all three of these boreholes, ORP was initially low in the upper 20 to 40 ft bgs. From depths that ranged from ~35 to about 40 ft bgs, ORP increased in all three profiles, to maxima that ranged from 10 mV at 48-50 ft bgs (176.09 ft MSL) in GF-4 to 168 mV at 41-43 ft bgs (183.09 ft MSL) in BH-1, then decreased again toward the bottoms of the boreholes. Minimum ORP readings were recorded at -192 mV at 43-45 ft bgs (175.32 ft MSL) in GF-3, -313 mV at 85 ft bgs (140.09 ft MSL) in GF-4 and -83 mV at 26-28 ft bgs (190 ft MSL) in BH-1. Bedrock groundwater in GF-1 and GF-2 was extremely reducing, with ORPs of <-300 mV and -230 mV, respectively.

4.4 Phase II Soils

Total Metals:

The following elements were not detected above the reporting limits given in Table 4-8: silver, arsenic, beryllium (two detections above the reporting limit), cadmium, sodium (two detections), antimony, selenium, and thallium.

Although arsenic was included in the project analyte list (PAL), results (Table 4-8) show no reportable values in 11 out of 15 soil samples because the laboratory was unable to meet the requested detection limit of 10 mg/kg; arsenic was below the MDL in the remaining four samples. In the absence of measurable arsenic in the soil samples, it was not possible to quantify partitioning between arsenic occurring in solid phases and as dissolved species in the groundwater, as intended. Detection limits that were achieved for arsenic in soil samples ranged from 10 mg/kg to 100 mg/kg.

In GF-1, profiles of the PAL metals demonstrate a distinct trend (shown in Fig. 4-8). Aluminum, arsenic, cobalt, copper, iron, manganese, nickel, and zinc are all relatively depleted in several intervals. A possible interpretation is that the minima represent periods of subaerial exposure and weathering, followed by episodes of continued sedimentation. However, these data should not be overinterpreted because the analytical procedure does not entail a total sample digestion. Also, silica was not included as an analyte, but represents but represents a major component of the overburden materials. Without additional information, definitive conclusions relating the soil metals distributions (Fig. 4-10) to the depositional and weathering history cannot be drawn.

TOC: Analysis of Total Organic Carbon was performed by ESAT personnel according to MISTOC3. SOP. It was noted by the laboratory that results of many of the samples submitted for TOC analysis were compromised due to the abundance of stones, pebbles, stone fragments, and coarse sand. Such material is unsuitable for TOC analysis, as it is difficult to prepare adequate aliquots of representative material. Due to the heterogeneous and coarse nature of the Grove Pond samples, TOC results are biased toward the finer particle sizes. Results are presented in Table 4-9.

4.5 Phase II Pond Results

4.5.1 Sediments: Total Metals

Total metals: Ten surface sediment samples, nine samples from cores through the pond-bottom sediment, one sediment sample from the in-pond borehole, and two additional surface-sediment samples were analyzed for PAL metals (Table 4-10). Elements not detected above the reporting limits were: Ag, As, Be, Cd, K, Na, Sb, Se, and Tl. Arsenic was not detected above the reporting limit, which varied from 25.0 mg/kg to 125 mg/kg and exceeded the laboratory's target of 10-20 mg/kg. Without reportable arsenic in the bulk-sediment analyses, it is not possible to quantify partitioning of arsenic between pore waters and solid phases in pond bottom sediments, as planned.

Elemental concentrations showed significant variation in the ten surface sediment samples. In the soft-sediment core samples, the highest concentrations were consistently observed in the uppermost sample (approximately the top 4 inches) from each core.

4.5.2 Pore Waters: Metals, Unfiltered

Pore waters were obtained from the surface sediment and the soft sediment core samples by centrifugation. Aliquots were analyzed both unfiltered and after 0.45-µm filtration. Although no arsenic was reported from the bulk-sediment analyses, a detection limit of 5.0 µg/L was achieved for the pore water arsenic analyses.

Unfiltered pore water results are reported in Table 4-11. Inorganics not detected in unfiltered pore water above the reporting limits are: Ag, Be, Sb, Se, and Tl. Arsenic in unfiltered pore water ranges from 38.2 µg/L to 138 µg/L. Both Fe and Mn are high: Fe ranges from 1,480 µg/L to 5,000 µg/L, and Mn varies between 538 and 3240 µg/L.

4.5.3 Pore Waters: Metals, Filtered

Filtered pore water results are reported in Table 4-12. Inorganics not detected in filtered pore water above the reporting limits are: Ag, Be, Co (with one exception), Ni, Pb (with two exceptions), Sb, Se, and Tl. Arsenic in filtered pore water is lower than in the unfiltered samples, ranging from 35.9 µg/L to 111 µg/L. Aluminum, cadmium, cobalt, copper, chromium, lead, iron, manganese, and vanadium are also considerably lower in the filtered pore waters, with Fe and Al showing the largest differences. This observation suggests that the higher concentrations in the unfiltered samples are due to the presence of fine particulates (such as clays) or colloidal material (including Fe and Al hydroxides) that remained in suspension after centrifugation. These particles are well-known for their ability to scavenge dissolved metals, and thus are likely to account for the observed differences between the filtered and unfiltered pore waters.

Concentrations of the major cations – Ca, K, Mg, and Na – are approximately the same in both unfiltered and filtered pore waters. These elements are likely to be present as species in solution. The values for Ba and Zn in filtered pore waters are significantly higher than in the unfiltered samples, possibly indicating a high degree of analytical uncertainty.

The observed range of arsenic concentrations (35.9 µg/L to 111 µg/L), measured in pore water obtained by centrifugation of samples of Grove Pond bottom sediment, are within the range that was estimated previously, using data from previous work on Plow Shop Pond sediments (ABB-ES, 1995). A partition coefficient was derived from Plow Shop Pond pore waters, bulk-sediment chemistry, and TOC. The same partition coefficient was applied to Grove Pond samples, using bulk-sediment inorganic and TOC data from the same source, to predict pore water arsenic concentrations for Grove Pond. Using this approach, the predicted Grove Pond pore water concentrations ranged from 36 to 285 µg/L, with a mean of 144 µg/L (see Table 6-2, Phase I Interim Data Report, Gannett Fleming, 1999b). The agreement between the measurements obtained in the present study with those calculated based on the partitioning argument merely confirms the similarity between the two ponds and suggests that processes controlling arsenic mobility in pond-bottom sediments are the same at both locations.

4.5.4 Soft-Sediment Cores

Only three of the samples taken from the soft-sediment cores yielded sufficient volumes of pore water for chemical analysis (in Table 4-13). In all three of these samples, the pore water arsenic concentrations range from 4.7 to 11.1 µg/L and are approximately an order of magnitude lower than in pore water from the pond-bottom sediments.

Solids were also analyzed (Table 4-14) but the laboratory failed to meet the requested detection limits for arsenic.

4.6 Phase II Bedrock Results

4.6.1 Total Metals

Cores from both GF-1 and GF-2 were described as fragmented, metamorphosed, and from a cataclastic, unmapped fault zone (R. Robinson, USGS, personal communication, 7/2000). Two samples from the bedrock core were analyzed by x-ray fluorescence (XRF) by the USGS. Results are presented in Table 4-15. Total arsenic concentrations of 24.8 mg/kg and 11.2 mg/kg were detected in samples GF-1-C-2-1.0 and GF-2-C-2-1.58, respectively. Although these concentrations are well above the average arsenic abundance in granitic rocks (approximately 1.5 mg/kg; Krauskopf, 1967), they are well within the concentration range that appears to be typical of the bedrock types that have been implicated as a possible cause of elevated arsenic in New England drinking water wells. In a recent investigation of the relationship between dissolved arsenic in drinking water and related bedrock lithogeochemistry, the USGS reported that arsenic ranged from 21 mg/kg to 710 mg/kg in bedrock cores in the area around Pepperell, MA, where elevated arsenic in drinking water had been observed (Ayotte, et al., 1999). The values reported here, from cores of the Coal Mine Brook Formation, are at the lower end of this range. It is emphasized, however, that sub-sampling of the core for XRF analysis was not necessarily representative of the bulk rock, due to heterogeneous distribution of minerals at small length scales. Subsequent microscope examination of thin sections (Section 4.6.2) indicated that sulfides were present in thin bands or zones within the host conglomerate. Dilution of the material selected for XRF by non-arsenical minerals in the rock matrix may yield inaccurate concentrations, or at least values that are difficult to interpret as representing the whole-rock arsenic content.

4.6.2 Thin Section Mineralogy

Five thin sections were made from subsamples of the bedrock core and examined by reflected-light microscopy. Of these, pyrite was detected in only one section (R. Hon, personal communication, 7/00). From a cursory examination of these sections, it appears that three generations of pyrite are present in the silty portion of the bedrock, based on morphology of the sulfide grains. Pyrite occurs in a random habit, infilling interstitial spaces in the silty matrix along structural deformation planes. A second morphology is slightly more euhedral, and only one grain approximated the cubic shape that is typical of pyrite. Because this was a cursory examination in preparation for preliminary electron microprobe analysis, no other minerals were described from the thin sections at this time.

4.6.3 X-Ray Diffraction Results

The USGS submitted four samples from the bedrock core for analysis by x-ray powder diffraction (XRD). Of particular interest was the identification of the bright yellow-green material that was observed on fractured surfaces of the core. Details of the sample preparation, analysis, and data interpretation are provided in Appendix E (USGS preliminary report), including diffraction patterns and principal lines that were used for mineral identification.

Two of the four samples were described as "waxy yellow material" that was hand-picked from the core for XRD preparation and analysis. Results are included in Appendix E, Attachments 1 and 2, for samples GF1 C-1 0.92-1.08 and GF1 C1 4.25-4.5, respectively. The third sample, GF1 C1 4.58-4.75 (App. E, Attachment 3) contained two types of fracture coatings: a waxy, yellow to yellow-green material similar in appearance to the material in the first two samples, and a rusty orange coating. The fourth sample (GF1 C-2 4.83-5.00; Appendix E, Attachment 4) consisted of a powdery white coating on the 'sooty black drill core' (alluding perhaps to the presence of graphite).

In summary, the USGS did not report any discrete arsenic phases in the bedrock core, such as arsenopyrite, orpiment, or realgar, based on the results of XRD analysis. The yellow-green mineral that was observed as fracture coatings was identified as a mixture of iron-rich clays, primarily nontronite. This species is an iron-rich montmorillonite, with the structural formula $Al_2Si_4O_{10}(OH)_2 \cdot xH_2O$, in which the aluminum is largely replaced by Fe^{3+}. This phase was identified from the major diffraction peaks at 6.049° and 19.580° 2θ. Other clays present in the diffraction pattern from this material included phlogopite, $KMg_3(Si_3Al)O_{10}(OH)_2$ (major peak at 12.510° 2θ) and clinochlore, $(Mg_5Al)(Si,Al)_4O_{10}(OH)_8$ (major peaks at 12.510°, 18.825°, and 25.135° 2θ), both of which may have sites occupied by iron. In addition, the orange-colored phase seen in sample GF-1-C1 4.58-4.75 was found to contain primarily goethite (FeOOH) as well as quartz (SiO_2) and rhodochrosite ($MnCO_3$). The white coating from sample GF-1-C-2 4.83-5.00 contained quartz, clinochlore, mica (muscovite, $KAl_2Si_3O_{10}(OH)_2$), and feldspar (albite, $NaAlSi_3O_8$). These minerals are formed by chemical reactions that take place in groundwater in contact with native bedrock.

4.6.4 Scanning Electron Microscopy

The same samples that were analyzed by XRD were also examined by scanning electron microscopy (SEM) equipped with an x-ray energy-dispersive system (EDS) for elemental analysis. The SEM images are useful for detailed examination of crystal size and morphology (see, e.g., Attachment 1). Unfortunately, no sulfide minerals were identified in the samples that were submitted for XRD or SEM analysis, so no information was obtained that bears on timing or composition of potentially arsenic-bearing sulfide mineralization. No arsenic was observed in any of the samples that were analyzed with EDS. However, it is noted that elements must be present at concentrations of roughly one-half to one percent by weight in order to be detected by this analytical method.

4.6.5 Electron Microprobe Results

Semi-quantitative analysis by electron microprobe was conducted by Professor Rudolph Hon (Geology and Geophysics Department, Boston College) on thin sections prepared by USGS from the GF1 and GF2 bedrock cores. Dr. Hon examined three sections from GF-1, two from the upper portion of the core and one from slightly deeper; and two sections from GF-2. From the small number of sections available for microprobe examination, it is not possible to assess whether these samples are representative of the bedrock unit as a whole, nor is it possible to use these results to evaluate mineralogical variability in the bedrock lithology. The primary goals of requesting microprobe analysis of bedrock samples were:

- to determine whether sulfides – specifically, arsenic-bearing sulfides – or other arsenic phases were present in the bedrock underlying the Town of Ayer wells,
- to quantify amounts of arsenic, sulfur, and other constituents of such phases, if present. This information enables the inference of stoichiometry and hence mineral identification.

Initially, the thin sections were examined with reflected-light optical microscopy. No sulfide phases were found in the thin sections from GF-2. However, abundant pyrite, occurring in a variety of morphologies, was observed in silty portions of the thin sections from GF-1.

Further examination was conducted with the electron microprobe, using both the backscattered electron imaging (BEI) and element mapping modes, in order to identify metallic sulfide phases, especially those containing arsenic. When such phases were positively identified, quantitative analyses were performed. The results are attached as Appendix F. Probe analyses showed that a number of grains consisted primarily of Fe and S, averaging 45.94 weight percent and 56.24 weight percent, respectively. Correcting these elemental weight percents for atomic mass yields the stoichiometric formula, FeS_2. Although the microprobe does not provide crystallographic information, this phase is assumed to be pyrite. It is likely that the mineral marcasite was the primary iron sulfide to form in the reducing, organic-rich environment of the Coal Mine Brook sediments. Marcasite has the same chemical formula as pyrite, FeS_2. However, these minerals differ in their crystal structure: pyrite is an isometric mineral, while marcasite is orthorhombic, the same crystal system to which arsenopyrite (FeAsS) belongs. However, none of the pyrite grains analyzed by electron microprobe contained sufficient arsenic to be identified as arsenopyrite. Electron microprobe results indicated that pyrite with a random-infilling morphology had no detectable arsenic, at a detection limit of approximately one-tenth of a weight percent. The pyrite with a slightly more euhedral shape had slightly more arsenic, and the most euhedral pyrite grains contained arsenic up to 0.26 weight percent.

The absence of positively-identified arsenopyrite was unexpected; this phase has been reported from samples of the Berwick Formation from outcrops on former Fort Devens. However, it is possible that this cursory examination, of a limited number of thin sections from a limited sampling of the GF-1 and GF-2 cores, was simply inadequate to confirm its presence in bedrock beneath the Town of Ayer wells.

On the other hand, the observation of a number of non-pyritic, euhedral, sulfide grains containing significant quantities of arsenic was equally surprising (e.g., Fig. 4-11, showing the backscattered electron image; note the bright hexagonal crystal in the upper right portion of the photograph.) Element maps of this field of view (Fig. 4-12, a, b, and c) for Fe, S, and As are distinctly different from the surrounding material (identified as pyrite). Electron microprobe analysis of this and other similar grains reported an average composition of 21.35 wt. % Co, 6.79 wt. % Fe, 6.35 wt. % Ni, 43.16 wt. % As, and 21.98 wt. % S. From the stoichiometric formula obtained from these results, the mineral was identified as cobaltite (CoAsS) containing Fe and Ni.

Even with the information obtained from the electron microprobe study, it is not possible to do more than speculate on the manner in which arsenic was introduced to the system, or when it precipitated in the sulfides found in the bedrock, or the conditions under which the arsenic-bearing sulfides formed. It is clear that minerals containing significant arsenic (~30 to 50 wt. %) are present in the bedrock beneath the Town wells. Furthermore, it is likely that glacial comminution and localized transport redistributed these minerals throughout the overburden. When sulfide minerals are removed from an environment in which they are thermodynamically stable, they become vulnerable to chemical alteration (e.g., oxidation of Fe and S, in the case of pyrite) and thereby more susceptible to mobilization and eventually precipitation. None of the information presented in this study precludes the possibility that sulfide minerals from underlying bedrock were mechanically and chemically weathered, during and after glaciation, and that these processes resulted in the deposition of iron (or manganese, or aluminum) oxyhydroxide coatings on mineral surfaces throughout the overburden. These surfaces, in turn, would readily adsorb arsenic as well as other metals commonly found in the bedrock sulfide minerals (e.g., Co, Ni, Cu) and retain them as long as redox conditions favored the stability of the oxide phase. However, under reducing conditions, the substrate dissolves, a process known as "reductive dissolution." and the sorbed species are released into solution. Reducing conditions can develop readily when oxidation of buried organic matter proceeds faster than oxygen can enter the system (i.e., by recharging the aquifer with oxygenated groundwater or by diffusion of oxygen into the aquifer). Such a scenario has been put forth as an explanation for the release of arsenic in Bangladesh groundwater (Nickson, et al., 2000).

4.7 Isotope Results (Phase I and Phase II, groundwater and surface water)

The isotopes of oxygen and hydrogen are commonly used as passive environmental tracers, particularly in hydrologic studies, because they are naturally occurring, their relative abundances are well-known, and they can be easily measured by mass spectrometry. The ratios of the isotopes in a water molecule, $^{18}O/^{16}O$ and $^{2}H/^{1}H$, are referenced to an arbitrary standard, such as Vienna Standard Mean Ocean Water, VSMOW. Isotopic ratios are expressed as parts per mille, or parts per thousand (‰), using the following notation:

$$\delta‰ = [(R-R_{standard})/R_{standard}] \times 1000$$

where R and $R_{standard}$ represent the isotopic ratios in the sample and in the standard, respectively. The heavier isotopes of oxygen, ^{18}O, and hydrogen, ^{2}H (more commonly represented as D, or deuterium) behave slightly differently from their lighter counterparts when water undergoes such processes as evaporation, condensation, freezing, or melting, or in biological cycling. These processes alter the isotopic composition of a given water mass, by relative enrichment or depletion of the isotopes – i.e., fractionation. Isotopic fractionation in precipitation, such as rain or snow, is dependent on temperature as well as latitude, resulting in seasonal and continental trends. However, the isotopic composition of any individual precipitation event is variable and unpredictable.

In deep groundwater, the ^{18}O and D content is subject to variation due to chemical reactions at elevated temperatures. However, the isotopic composition of shallow, groundwater systems, i.e., the Grove Pond aquifer, are not significantly affected by chemical processes because the water temperature remains relatively low. The isotopic signature of shallow groundwater is determined by the composition of the precipitation falling in the recharge area and the degree of evaporation to which this precipitation is subjected prior to infiltrating the soil. Once this water leaves the shallow soil zone, its isotopic signature is fixed and, in many cases, may be used to determine source area(s) and mixing (see, e.g., Freeze and Cherry, 1979).

From a compilation of global precipitation data, a line correlating ^{18}O and D.content has been derived:

$$\delta D‰ = 8\ \delta^{18}O‰ + 10$$

This equation, known as the Meteoric Water Line, is used as the basis against which the isotopic compositions of groundwater and surface waters can be compared. Linear correlations of precipitation at any given site are generally close to this line, although some variation may be present due to local conditions.

Surface water that undergoes significant evaporation becomes enriched in the heavier isotopes, ^{18}O and D. Conversely, the water vapor is enriched in the lighter isotopes, ^{16}O and H, because water composed of these isotopes has a higher vapor pressure than $H_2{}^{18}O$ or water containing D. Consequently, playa lakes and other bodies of water in closed basins have isotopic compositions below the Meteoric Water Line, along a trajectory with a smaller slope. For a more detailed discussion of isotope behavior, the reader is referred to Faure, 1977, Chapter 18.

The isotopic composition of Grove Pond surface water (Table 4-16, Fig. 4-13) lies close to the Meteoric Water Line but does not show marked effects of evaporation. The isotopic compositions of the groundwater samples are significantly different from the surface water results, even when the analytical precision of the isotopic measurements is taken into consideration. The standard deviations of these measurements are 1.0‰ for δD, and 0.1‰ to 0.2‰ for ^{18}O. Although the groundwater samples deviate slightly from the Meteoric Water Line, the groundwater data in Figure 4-13 are fit by a line with coefficients that are close to those given above:

$$\delta D‰ = 8\ \delta^{18}O‰ + 14$$

In September 2000, additional samples from wells installed during the Phase II work were submitted for isotope analysis by the USGS. This suite included one sample from GF-3B (screened interval 8 to 13 ft bgs, at the top of the shallow aquifer water), one sample from the GF-3A well screen (deep aquifer water, just above bedrock), samples from the two bedrock wells GF-1 and GF-2 immediately adjacent to the production wells, and one Grove Pond surface water sample. These results (Fig. 4-13 and Table 4-16) show that most of the groundwater samples from the production wells, the flanking monitoring wells 92-1 and 92-3, and groundwater from GF-3A have approximately the same isotopic composition, with $\delta^{18}O$ values between –8 and –9 per mil, and δD values between about –53 and –57 per mil. The exceptions are the two bedrock wells, the surface water samples, and groundwater from GF-3B. The isotopic composition of groundwater from GF-2 is significantly lighter than the majority of the other wells, and both MNG-7 and GF-1 are slightly heavier than GF-2. The surface water samples report $\delta^{18}O$ values in the range –7.3 to –7.4 per mil and δD values between –46 and –50 per mil. The sample from GF-3B has the heaviest composition, with $\delta^{18}O = -6.16$ and $\delta D = -41.14$.

The surface water samples are isotopically heavier than all of the groundwaters, with the exception of the sample from GF-3B. Grove Pond is relatively shallow and subject to intense evaporation and evapotranspiration, especially during the summer months. In addition, the isotopic composition of Grove Pond surface water is also subject to variations over relatively short time scales due to inflow (from upstream, surface runoff, and groundwater discharge), local precipitation events, temperature at the time of precipitation, etc. The surface water samples (Fig. 4-13) were taken during sampling rounds in August 1998, when the effects of evaporation and evapotranspiration should have been extreme; and in February 2000, when other sources of water to the pond were more likely to dominate surface water isotopic composition. These data are reasonably tightly-grouped, suggesting that the magnitude of the isotopic variability within the pond is still less than the differences between the pond and GF-3B or between the pond and any of the other groundwater samples.

Dansgaard (1964, cited in Faure, 1977) showed that the $\delta^{18}O$ content of average annual precipitation is linearly correlated with average annual air temperature:

$$\delta^{18}O = 0.695T - 13.6,$$

where T represents temperature in °C. From the average annual temperature in the study area, 14.4 °C (from Section 3.2), and the equation given above for the meteoric water line that approximates the Grove Pond isotope data, the predicted isotopic composition of precipitation in the study area is –3.59 per mil for $\delta^{18}O$ and –14.7 per mil for δD. The sample from GF-3B is lighter than these values, but still significantly heavier than either the surface water or all of the other groundwater samples. A possible interpretation of the data from GF-3B, taken near the top of the overburden aquifer, is that this sample represents relatively recently-infiltrated meteoric water. Data from the surface water sampling rounds, lying near the meteoric water line approximately midway between the groundwater data and the sample from GF-3B, suggest that the pond may be the result of mixing of this relatively recent water (isotopically heaviest) with the deeper and isotopically lighter groundwater, in approximately 50:50 proportions. In other words, about half of the pond water may be composed of discharging groundwater, and the other half derives from other sources, e.g. the contribution from upstream, surface runoff, storm drains, recent precipitation, etc.

Four wells – PW-1, PW-2, 92-1, and 92-3 – were sampled in August and also in October 1998. In three sample pairs out of the four, the magnitude of the difference between the August and October data was approximately the same, on average, about 0.4‰. In the fourth well, 92-1, only the δD values differed between August and October (by approximately 1‰, or one standard deviation). However, the differences in δD and $\delta^{18}O$ from the two sampling rounds in both production wells and in 92-3 are larger than the standard deviation, and all three pairs of data move in the same direction, i.e., toward heavier compositions, in the October sampling round.

Although the paucity of data severely constrains the following interpretation, the observed differences between the August and October 1998 sampling rounds of PW-1, PW-2, and 92-3 may be significant. Concentrations of some of the other PAL elements (e.g., arsenic, chloride) change markedly between August and October and may indicate that the system is approaching 'steady state' with respect to the pumping wells by the latter sampling round. If we assume that this is indeed the case, then the observed changes in isotopic composition of PW-1, PW-2, and 92-3 may be the result of mixing a heavier end-member (e.g., GF-3B) with lighter groundwater (such as that at 92-1, or GF-3A). Let us further assume that the result from GF-3B is the isotopic signature of the 'upper aquifer' water (upper ~40 feet); this is probably not truly representative of all of the groundwater in this unit, as it may become increasingly lighter with increased depth, eventually reaching a composition similar to the other groundwater samples (e.g., GF-3A). Isotope samples were not collected during the Phase II vertical-profile sampling, so this assumption cannot be verified with the present dataset. Nevertheless, if we take the initial (August) results from PW1, for example, as 'ambient' groundwater ($C_{i(gw)}$) and assume that data from the October round represents mixing of a distinctly different composition from the upper aquifer ($C_{i(u)}$), the fraction of the mixture sampled in the production wells ($C_{i(pw)}$) that is derived from the upper aquifer can be expressed as:

$$Q_u/Q_{pw} = [C_{i(pw)} - C_{i(gw)}]/[C_{i(u)} - C_{i(gw)}]$$

where C_i can represent any single, conservative, chemical constituent, and Q_u and Q_{pw} are the fluxes from the upper aquifer and a production well, respectively. In PW-1, for both δD and $\delta^{18}O$, this calculation yields $Q_u/Q_{pw} = 0.09$, suggesting that nearly 10% of the mass fraction of production well water is derived from the upper aquifer. For PW-2, $Q_u/Q_{pw} = 0.125$ and 0.08 from the $\delta^{18}O$ and δD values, respectively. These numbers are also consistent with a contribution of approximately 10% of the upper aquifer water to the production wells. Using the same approach to explain the mixing in 92-3 yields 0.055 and 0.126 from the $\delta^{18}O$ and δD values, respectively; however, in the case of 92-3 there is independent evidence (discussed elsewhere in this report) indicating that 92-3 draws high-chloride water from the north side of the pond. This water may very well be isotopically heavier than the ambient groundwater (e.g. the 92-3 August 1998 sampling round), and possibly even heavier than the sample from GF3B, as it appears to carry a chemical signature that is consistent with fast travel from the time of infiltration.

Despite the limitations imposed by the assumptions described above, these data imply that the upper aquifer is contributing only 10% to the production wells, considerably less than the mass fraction suggested by the major element chemistry (discussed in Section 5.2). However, in the argument put forth here, GF-3B is considered to be an end member in the absence of additional isotopic data from the vertical profile samples. Since this sample comes from the top of the upper aquifer, and not the lower part, from which the production wells are assumed to be drawing, 10% is likely a minimum estimate.

It is acknowledged that this argument is highly speculative. Nevertheless, the conclusions from the stable-isotope data are consistent with the conceptual model that has emerged from this investigation. The compositional ranges of the production wells are consistent with the general isotopic composition of the aquifer, as represented by the samples from MNG-3, 92-1, 92-3, and GF-3A. The bedrock wells, GF-1 and GF-2, are the lightest of all wells sampled, but reasons for the differences in isotopic composition between these two wells remain unexplained.

Based on the information presented above and discussion with USGS personnel (F. Lyford, personal communication, 2000), the following general conclusions are drawn from the isotope data.

- Most of the production water is drawn from the same stratigraphic horizon as the surrounding well screens: Groundwater from the production wells is isotopically similar to samples from the surrounding wells, even though the locations of individual points may vary seasonally or due to the influence of individual precipitation events.

- The isotopic composition of Grove Pond surface water is distinctly different from most of the groundwater samples. Even with the caveat that the isotopic composition of surface water may vary over a wider range than our samples indicate, surface water from Grove Pond does not appear to influence the composition of the producing horizon. On the contrary, it is possible that pond water itself is the product of mixing, i.e., of deeper overburden aquifer water (isotopically lighter) and more recent infiltration (heavier).

These conclusions are consistent with the conceptual model; the isotopic results support conclusions drawn independently from the major-element chemistry suggesting that the bulk of the production water is derived from the surficial aquifer. Any contribution from Grove Pond surface water is volumetrically insignificant.

4.8 Physical Characterization

4.8.1 Lithologic Description

The overburden material consists of glacially-derived layers of poorly-sorted, coarse to fine sand, silt, and gravel, with occasional rock fragments. In places (noted on the lithologic logs, Appendix B), iron oxidation was observed. Traces of clay were present but infrequent. The heterogeneous nature of the overburden and the absence of distinctive layers or lenses preclude cross-borehole correlation of the lithologic logs. However, it is apparent from the logs that the upper part of the aquifer (see, e.g., the lithologic log from GF-1) contains qualitatively more silt, while the lower portion of the aquifer comprises a greater proportion of sand and gravel. A gray, clayey layer of till, approximately five feet thick, was encountered immediately above bedrock in GF-1. This till layer was noted only as a thin layer in GF-2, overlain by uniformly medium to coarse gray sand. The overburden sampled during installation of GF-3A is similarly composed of fine to coarse sand, silt, and gravel. The presence of the gray, silty layer reported at 34 to 47 ft bgs during the 1992 installation of monitoring well 92-3 (CDM, 1993) was not confirmed by the GF-3A boring. The lithologic information from GF-4 is more limited. Due to problems with running sand in the GF-4 borehole, soil samples were not collected below the 50-52 ft bgs interval.

Boreholes GF-1 and GF-2 were extended into bedrock, which was identified as a black, graphitic, metamorphosed, conglomerate. Borehole GF-4 encountered probable bedrock, but no core was obtained. Drill cuttings obtained from bedrock at the GF-4 location were fine-grained, and white to light gray in appearance, consistent with a quartz-feldspar composition. These observations suggested that bedrock beneath GF-4 is a different rock type from the lithology underlying GF-1 and GF-2, and that GF-4 bedrock is probably granitic.

4.8.2 Geophysical Logging Results

New monitoring wells GF-1, GF-2, and GF-3A, and the "in-pond" borehole BH-1 were logged with natural-gamma, electromagnetic (spontaneous-potential (SP), conductivity, fluid resistivity), and fluid temperature tools (App. A). All logs were obtained through the 2-inch PVC well casings. (Note that the PVC casing in BH-1 was installed solely for the purpose of the geophysical logging, and subsequently was abandoned in place.) The natural-gamma and electromagnetic logs are expected to be most sensitive to the presence of clays within the aquifer material. Thus, the principal objective of these logs was to attempt to discriminate any finer-grained stratigraphic intervals that may influence the hydraulics. Finer-grained materials generally correspond to lower hydraulic conductivity. The hydraulic properties of the section, in turn, exert a strong influence on the groundwater chemistry through their control on transport rates.

In general, the geophysical logging supports the visual description of the overburden as relatively homogeneous sand and gravel on the larger scale of the entire section, but heterogeneous on a fine scale. Few discrete stratigraphic intervals several feet thick with distinct characteristics are identified by the geophysics. The low clay content of the aquifer is reflected in the low gamma counts and low electrical conductivity recorded in all the logs. An exception is the bottom-most portion of GF-1, where the dense gray clay observed in the split spoons is clearly indicated by a significant increase in gamma counts and a very large increase in conductivity (note the logarithmic scale on the conductivity profiles for GF-1 and GF-2). Low-amplitude, fine-scale variation in gamma counts and conductivity is revealed throughout the section, possibly reflecting small variations in texture. It is noted that such small-scale interbeds of finer-grained material give rise to anisotropy in the hydraulic conductivity, with the overall vertical conductivity typically much lower than the overall horizontal conductivity.

A few intervals appear to be correlatable on the basis of the natural gamma logs, although the lithologic interpretation of the fluctuations in gamma counts is somewhat ambiguous. The Geophysical Applications, Inc., report (Appendix A, p. 5) cautions that higher gamma counts not associated with higher EM conductivity may be due to greater concentrations of mafic minerals, rather than to finer-grained texture. There is a correlatable zone of higher gamma counts between GF-2 (~204-208 ft msl), GF-3A (~204-207 ft msl), and BH-1 (~203-208 ft msl), which may represent an interval of finer material. If this is indeed a continuous layer of low hydraulic conductivity, it may play a key role in confining the underlying sandier portions.of the aquifer. This is underlain immediately by a zone of relatively low gamma counts in the interval ~197-204 ft msl in GF-1, ~195-203 ft msl in GF-3A, and ~195-202 ft msl in BH-1, possibly representing a continuous, clean, sandy unit. There is a zone of peak gamma counts at greater depth that correlates from GF-2 to GF-3A to BH-1, centered at an elevation of about 185 ft msl. Again, this may represent a continuous fine-grained unit, which would act as a semi-confining layer to the underlying production horizon (~157-177 ft msl at PW-2). Two bands of correlatable low gamma counts are identifiable within the production horizon, possibly representing high-conductivity, clean sands and gravels. Minima in the natural gamma profiles occur at ~169 ft msl in GF-2, ~170 ft msl in GF-3A, and ~171 ft msl in BH-1; and again at ~161 ft msl in GF-2, ~161 ft msl in GF-3A, and ~161 ft msl in BH-1. A thick interval (at least 25 ft) of low gamma counts occurs at depth (~125-150 ft msl) in GF-2 and GF-3A, suggesting a sequence of clean sands and gravels, consistent with the visual description of the corresponding split-spoon samples (Appendix B).

The spontaneous potential log is of limited usefulness in cased wells. However, one feature of note is the occurrence of spikes in SP at evenly-spaced, 10-ft intervals in GF-1 from 20 to 30 feet and from 70 to 110 feet bgs. These spikes appear to correspond to the joints in the PVC well casing. The cause of the increase in potential at the pipe joints is unknown, but this could be an indication of leaks, allowing external aquifer water to enter the casing at these locations.

The temperature logs exhibit some of the most striking variation among the parameters measured in the boreholes. Most show the expected minimum in temperature at the surface, reflecting the falling mean air temperatures prevailing in late November, when the holes were logged. Temperature increases to a maximum at a depth of about 20 feet, showing the downward transport of the previous summer's maximum surface temperature. At greater depth, the temperature again decreases, as heat transfer has transported the previous spring's cooler temperatures farther down. Well GF-1 shows a striking thermal anomaly from 57 to 65 feet, where a distinct interval of warmer temperature was found. This monitoring well is immediately adjacent to pumping well PW-1, which is screened from 42 to 62 ft bgs. It is apparent that water being drawn toward the production well is warmer than the ambient water at that depth. The discrete interval from 57 to 65 feet may represent a zone of higher hydraulic conductivity where the flow velocity is relatively high, and advective transport of heat is greater than in adjacent intervals. The ultimate source of the warmer water in this zone is unknown, although the remainder of the thermal profiles would suggest that it must originate higher in the aquifer. The temperature profile in GF-2 also shows what appears to be a thermal anomaly, with a warm "kink" in the profile in the vicinity of 25 to 35 feet. Again, this may represent a shallower, hydraulically conductive zone of higher groundwater velocity approaching pumping well PW-2. The temperature profile in GF-3A also shows a "flat" segment from about 35 to 45 feet, again suggesting advection of anomalously warm water along this horizon. The "in-pond" borehole, BH-1, exhibits a temperature profile that more closely approximates a conduction-dominated subsurface thermal regime, as might be expected at this location, farther removed from the strong advection induced by the pumping wells.

4.8.3 Slug Test Results and Grain Size Analyses

Several types of data were collected to characterize the hydraulic properties of the subsurface materials. These include slug tests performed in the drive point, open boreholes, and screened wells, as well as characterization of the grain-size distribution of bulk soil samples.

Slug tests were performed at 23 locations scattered throughout the system. These included 8 in the 2-inch drive point, 4 in open holes, and 11 in permanent, screened monitoring wells. An effort was made to perform slug tests in randomly selected intervals throughout the section, as well as in intervals of potential importance, such as the top of weathered bedrock. Both a falling-head test and a rising-head test were performed at most locations. A total of 47 slug tests were logged. All tests that showed a monotonically declining head change were analyzed by the method of Bouwer and Rice (1976) using the software package ADEPT (Levy, 1995). Several slug tests showed an oscillatory response, in which the inertia of the water in the wellbore is significant relative to the viscous drag within the aquifer. These tests were analyzed by the method of Kipp (1985), also coded in ADEPT. It is acknowledged that the configuration of the wells was not that idealized in the Kipp model, which assumes a confined layer with a fully penetrating well screen. Nonetheless, the model allows inference of at least qualitative information regarding the aquifer properties without elaborate analysis.

Results of the slug-test analyses are summarized in Table 4-17. Figure 4-14 shows all inferred hydraulic conductivities (symbolized by K) plotted against elevation in order to reveal any systematic variation with depth. Although the data coverage is sporadic, there is a suggestion of an overall increase in conductivity with depth from the surface down to a depth of about 50 ft bgs, or an elevation of about 170 ft msl. For example, the conductivity inferred in GF-3B, screened from 8-13 ft bgs (elevation ~206-211 ft msl), is 1-2 ft/d. Conductivity inferred in 92-1 and 92-3, screened from 49-55 ft bgs (elevations ~167-173 ft msl and ~163-169 ft msl, respectively), in the middle of the pumping interval, is approximately 200 ft/d. Relatively few slug tests were performed in the deeper overburden. The low K values shown around 145 ft msl are from GF-4, near the bedrock interface. High conductivities were inferred in the deep overburden at GF-1 and GF-3A at an elevation of ~120 ft msl, consistent with the observation of clean sand and gravel at this depth, and with the zone of very low natural gamma counts noted in the geophysical logs. The weathered top-of-rock zone exhibited varied response, with very high effective conductivity (~300-600 ft/d) at GF-1, and moderate K (~20 ft/d) at GF-2. The effective conductivity of the fractured bedrock in the screened interval at GF-1 (~101-106 ft msl, or about 5-10 ft beneath the bedrock/overburden interface) was measured at ~4 ft/d.

While all slug test results are shown together on Figure 4-14 in order to reveal gross trends, it is emphasized that the data were not collected in the same manner for each test. The data set includes tests conducted in a 2-foot drive point, in screened and sand-packed monitoring wells over intervals from 5 to 19 feet, and in open borehole intervals as small as 1 foot. The drive point, in particular, is likely to encounter rather variable conditions due to disturbance in the immediate vicinity of the drive point, clogging of the screen by fine particulates, running sands within the drill casing, etc. In addition, because the slug tests in some of the faster zones exhibited an oscillatory response, the data analysis was performed with two different models. Therefore, the conductivities inferred from slug tests in this study should be interpreted only as qualitative indicators of the relative magnitudes of the hydraulic properties.

Note that the hydraulic conductivities inferred from the slug tests within the production horizon (i.e., ~157-178 ft msl) are generally consistent with, but somewhat smaller (~200 ft/d) than, those inferred from the model calibration based on the 1992 pumping test (~300 ft/d) (CDM, 1993). It is not uncommon to find that conductivities estimated by pumping tests, which are representative of material over length scales of hundreds of feet, are larger than those estimated from slug tests, which sample over a length scale of a few feet. Furthermore, note that the overburden thickness proved to be much greater than believed in 1993 (unverified at that time by borings drilled to refusal), and the deep aquifer near the supply wells is highly conductive. Thus, the wells produce from a thicker zone than that represented in the 1993 numerical model (CDM, 1993), and the hydraulic conductivity can be lower, yet still result in a similar transmissivity.

Grain-size analyses were obtained on thirteen soil samples selected from various locales to provide further insight into stratigraphic variations in texture and, consequently, hydraulic properties. Three samples from boring BH-1 were sieved through 4.75, 2.0, 0.425, and 0.075 mm screens. In recognition that better resolution within the coarse to medium sand fractions was desirable, the remaining ten samples (2 from GF-3A, 1 from GF-4, 1 from soft-sediment core SC-1, and 6 from GF-1) were sieved through 2.0, 0.850, 0.425, 0.250, and 0.106 mm screens. Results are summarized in Table 4-18.

Various empirical formulae have been developed to estimate hydraulic conductivity from grain-size data. In the present case, the limited number of size fractions separated for each sample precluded the application of any models requiring detailed statistics on the size distribution. The Shepherd model (Shepherd, 1989) is an empirical model based on correlation of data from various sedimentary environments, and utilizes only the median grain size, D_{50}. The median grain size was determined for each sample by linear interpolation between the logarithms of the size fractions. The median diameters for the seven samples fall in the range 0.21 to 1.13 mm (Fig. 4-15). The Shepherd correlation for "channel sands" was used, as the materials sampled are predominantly sands interpreted to be from a fluviodeltaic environment:

$$K = 450 D_{50}^{1.65}$$

where the median grain size is given in mm and the result is in ft/d. Results are summarized in Table 4-19 and displayed in Figure 4-15. Calculated conductivities range from 14 to 550 ft/d, generally consistent with the results of the slug tests.

The hydraulic conductivities estimated from median grain size show a general spatial distribution quite similar to that suggested by the available slug tests. In particular, conductivity appears to increase with depth to the screened horizon of the pumping wells, indicating that the production interval is a relatively fast zone, and is overlain by a semi-confining layer of significantly lower conductivity. In GF-1, the minimum calculated conductivity, 34 ft/d, is in the 201-203 ft msl (18-20 ft bgs) interval. The maximum, 550 ft/d, is in the production horizon in the interval 176-178 ft msl (44-46 ft bgs).

Note that the Phase II Work Plan (Gannett Fleming, 1999) called for 19 grain-size analyses to be performed on split-spoon samples collected throughout the drilling footage. Due to an oversight at the laboratory, only thirteen samples were analyzed, most several months after the drilling was completed. However, the deviation from the Work Plan provided an opportunity to examine grain-size variations systematically across the critical geochemical transition identified in the neighborhood of 170-175 ft msl at GF-3A. The sharp change in the redox, iron, and arsenic profiles identified in this interval was unknown at the time of development of the Work Plan, and the original target intervals for grain-size analyses were chosen randomly. Having discovered this important zone, six samples were selected from archived material collected from the boring for GF-1 in the elevation range ~160-204 ft msl (18-62 ft bgs), spanning the shallow aquifer from near the water table to the pumping interval. These samples show a systematic increase in median grain size from the shallowest sample to the top of the pumping horizon. The calculated conductivity for the sample from ~202-204 ft msl (18-20 ft bgs) is 34 ft/d; that for the interval ~176-178 ft msl (44-46 ft bgs) is 548 ft/d. Two additional samples from within the pumping horizon yield calculated K values greater than 200 ft/d. This trend is consistent with the conclusion that the shallowest aquifer material serves as a semi-confining domain that overlies the relatively fast production zone.

4.8.4 Additional Hydraulic Characterization

The overburden aquifer at the Grove Pond well site proved to be quite difficult to subdivide based on visual inspection of material recovered in split spoons. It is predominantly sand and gravel, with occasional silty interbeds from the ground surface to bedrock. The geophysical logging shows some small-scale variability, but again does not differentiate clearly any large-scale stratrigraphy. This is principally because the geophysics is most sensitive to variations in clay mineral content, while the Grove Pond sequence is generally quite low in clays. The slug tests and grain-size analyses suggest an overall coarsening downward, and concomitant increase in hydraulic conductivity, from the surface down to the screened interval of the pumping wells, at about 50 ft bgs. Slug-test and grain-size data are sparser for the deeper aquifer, but available results suggest a domain of intermediate conductivity (i.e., up to tens of feet per day) from perhaps 55 to 75 ft bgs (~145-165 ft msl), underlain by a thick, clean sand with high conductivity (i.e., hundreds of feet per day) from about 75 to 100 ft bgs (~120-145 ft msl). Because of the potential importance of the hydrologic influence on the groundwater geochemistry, additional support for the stratigraphic interpretation was sought in other data collected during the drilling program.

Blow Counts

Blow counts were recorded by the on-site geologist as the drill casing was advanced through the overburden. The number of blows was recorded for each 6-inch increment. Over each two-foot interval, the blow counts for the second and third increment were summed to generate the number of blows per foot of advance representative of that interval. This measure of the difficulty of penetration is designated "N." Figure 4-16 shows blow-count profiles for GF-1, GF-2, GF-3A, and BH-1; note that the profiles for the last three borings are shifted on the figure by 30, 70, and 90 units, respectively, in order to separate them for display. All show a remarkably similar and systematic pattern of increasing N with depth from the surface down to the production horizon. All start with a few blows per foot near the ground surface, and reach a maximum at or within the pumping interval. In GF-1, the maximum N is 47 blows per foot at 51 ft bgs (~171 ft msl). If GF-2, the maximum N is 54 blows per foot at 51 ft bgs (~171 ft msl). In GF-3A, the maximum N is 42 blows per foot at 41 ft bgs (~178 ft msl). GF-3A also exhibits a local maximum of N = 35 at 91 ft bgs (~128 ft msl), within the thick clean sand unit identified on the natural gamma log and by slug tests in the screened monitoring well at GF-3A (97-102 ft bgs; ~117-122 ft msl).

The blow counts reflect the mechanical properties of the material through which the drill casing is being advanced. In general, coarser, better-sorted sands and gravels are more difficult to penetrate. Thus, the blow-count profiles are quite consistent with the hydraulic properties inferred from the slug tests and grain-size analyses. The upper ~50 ft of the aquifer appears to be a fining-upward sequence overall, with clean sand and gravel in the production interval, grading upward to more predominant fine sands and silts. The lower one quarter to one half of the screened interval appears to be somewhat finer-grained, and this texture prevails through a zone of perhaps 20 ft in thickness. Clean, coarse sand and gravel again dominate at the bottom of the overburden in the area immediately north of the production wells. A notable exception is the patch of dense, gray, clayey till encountered immediately above bedrock at GF-1.

Specific Capacity

Additional information concerning the hydrostratigraphy can be extracted from the drawdowns associated with purging the screened drive point for water sampling. From this information, the specific capacity can be calculated. Specific capacity is defined as the volume flow rate pumped divided by the drawdown, and is given, for example, in (ft^3/day)/ft. Specific capacity is a simple and direct measure of the ease with which an aquifer yields water. Dimensional analysis or inspection of various classical idealizations of flow to a well (e.g., the Thiem equation for drawdown in steady flow to a fully penetrating well in a confined aquifer) suggests that transmissivity is proportional to the specific capacity. Empirical correlations have been sought as well, for example, in the form of a power law relation between transmissivity and specific capacity. It is speculated that the original installation of the supply wells at Grove Pond in the 1940s and 1950s likely identified the high-conductivity horizon in which the wells are screened by acquiring specific capacity data as test holes were advanced.

Calculation of specific capacity was not planned at the time of design of the Grove Pond investigation, and the recording of purge rates and drawdowns for each water sample taken from the drive point was not required of the field team. However, these data were recorded for most intervals as the boring for GF-3A was advanced. The results are tabulated in Table 4-20 and displayed as a function of elevation in Figure 4-17. For a few intervals, the pertinent data were not recorded; for a few others, a steady state was not achieved, and specific capacity could not be determined. The data support the same general interpretation that emerges from examination of the slug tests, grain-size analyses, and blow count profiles. The minimum specific capacity, ~11 (ft^3/day)/ft, was found in the first interval for which it could be calculated, 19 ft bgs (~200 ft msl). The specific capacity increased continuously through the upper aquifer to a maximum of 254 (ft^3/day)/ft just above (34 ft bgs; ~185 ft msl) and within (59 ft bgs; ~160 ft msl) the pumping horizon. Below the production interval, the specific capacity is lower at the one location where data are available between 130 and 155 ft msl. Another high specific capacity, 235 (ft^3/day)/ft, was measured at 92 ft bgs (~127 ft msl), within the deep conductive zone identified by independent methods.

4.8.5 Piezometer Data

A central goal of this investigation is to characterize the potential transport pathway from arsenic-contaminated bottom sediment in the pond to groundwater in the underlying aquifer. A critical element of this assessment is to quantify the downward flux of water from the pond, through the organic-rich, silty, pond-bottom sediment, and into the underlying sand-and-gravel aquifer. Two, independent approaches to this characterization were undertaken. First, an array of piezometers was installed in the area immediately offshore of the production wells, in order to obtain a direct measure of the head drop across the pond-bottom sediments under various conditions of pumping. In conjunction with this, undisturbed sub-samples were taken from soft-sediment cores driven through the pond bottom into the top of the sand and gravel. The vertical conductivity of the material in these core samples was then determined by falling-head permeameter. The combination of the head-drop data from the piezometers and the hydraulic conductivity allows calculation of the vertical flux of pond water induced by the pumping wells. The second approach is to obtain a direct measure of flux by means of seepage meters installed in the offshore area.

Six piezometers were installed in an array covering the area offshore of the production wells (Figure 2-8). The spread of piezometers was intended to provide an indication of the spatial variation of drawdown at the top of the aquifer while the wells are pumping. The sand and gravel underlying the pond is expected to respond as a semi-confined aquifer; that is, the pumping wells are expected to cause drawdown in the sand and gravel that is overlain by lower conductivity pond-bottom sediment. The head drop across the pond-bottom sediment results in a vertical gradient that then draws pond water downward. In an ideal system, with a homogeneous aquifer overlain by a uniform layer of pond sediment, it is expected that the drawdown would decrease with distance from the pumping wells.

The piezometers are 1-inch galvanized steel, 10 feet in length, with a 1-foot stainless steel screen. They were driven into the pond bottom by a hammer on the barge-mounted drill rig. The piezometers were driven to a depth that left 2 to 3 feet of stickup above the pond surface. For the typical 3-foot depth of the pond, and 3 feet of pond sediment, this put the piezometer screen about 1-2 feet into the sand and gravel. Water levels were measured in the piezometer array in four rounds at various times of day (Table 4-21). Levels inside the piezometers and to the pond surface on the outside of the piezometers were measured in each round. The difference represents the head difference between the surface water and the groundwater at the top of the underlying aquifer. Although the production wells were nominally on a schedule of start-up around 6 a.m. each day, they were in fact operated on a sporadic basis, depending upon demand from the Town of Ayer water system. Detailed records of the pumping rates on an hour-by-hour basis are not available. The drawdowns are displayed in Figure 4-18 as a function of the time of day; however, it is apparent that the time is not correlated with the pumping. The convention adopted here is that drawdowns are positive; that is, positive head differences indicate greater static head in the pond than in the underlying aquifer. A positive drawdown indicates a head gradient that will drive downward flow. Essentially all drawdowns measured are positive; the two values of -0.01 ft are within the precision of the depth-to-water gauge, and can be regarded as zeros. The measured drawdowns range up to 0.4 feet, measured at PZ-6. It is apparent that the pumping wells were operating for the data rounds obtained at about 8:15 and 10:00 a.m., when the drawdowns are at a maximum. The drawdowns at these times are quite similar, suggesting that the head field may have been fully established. The measured drawdowns were a minimum in the round completed at about 9:30 a.m., suggesting that the pumps may have been off or had been on for only a short period of time, and the drawdowns were measured in a "relaxed" state. The round taken around noon was obtained on the same day as the 9:30 round, and shows that the effect of the pumping increased over this time interval. In general, the drawdowns decrease with distance from the pumping wells (Fig. 4-19), as expected. A major exception is piezometer PZ-1, which is closest to the wells, but shows essentially no response in any round. This probably reflects the spatial heterogeneity of the aquifer properties (e.g., a low-conductivity domain may underlie PZ-1). Other possible explanations may lie with the piezometer installation; PZ-1 may not have penetrated into the sand, or its screen may have been clogged.

4.8.6 Vertical Hydraulic Conductivity Measurements

The soft-sediment cores collected through the pond-bottom sediment and into the top of the sandy aquifer beneath were sub-sampled in order to perform direct, laboratory measurements of the vertical hydraulic conductivity of the material lying between the surface water and groundwater. This property is often parameterized as the "leakance" in modeling that takes into account groundwater - surface water interaction. For example, in the 1992 CDM groundwater model (CDM, 1993) used to interpret the pumping test and to delineate the Zone II area for the supply wells, the pond-bottom sediment was assigned a vertical conductivity of 0.2 to 0.5 ft/day. This range was based on typical values reported for the region by the USGS. No direct measurements or inferences based on model calibration had been obtained for Grove Pond prior to the present investigation.

Soft-sediment core SC-1 was advanced about six feet into the bottom, and cores SC-2 and SC-3 were driven two to three feet into the sediment. The cores revealed black, organic material at the top, grading downward into a gray, silty sand, becoming coarser with depth. Four sub-cores, 4 to 6 inches in length; were cut from the cores for the vertical conductivity measurements. From SC-1, sections from the intervals 0.8 – 1.2 ft and 2.65 – 2.95 ft from the top of the core were selected. The former was organic-rich, gray, medium sand; the latter was a clean, coarse sand with gravel. A section of essentially all peaty, organic material from 0.7 – 1.1 ft below the top of core was chosen from SC-2. Another interval of organic-rich, medium sand was chosen from SC-3, from a depth of 0.6 – 1.0 ft below the top of the core.

Vertical conductivity was determined by constant-head permeameter for each of the four soft-sediment core sections. For each sample, the volume flux was measured at several different head drops in order to verify linearity, i.e., to ensure that the flow obtained in the permeameter was in the Darcy regime. In addition, a fit to the data for flux vs. head drop averages over several runs, and thus accounts for experimental variability. Vertical conductivities determined for the four samples range from 37 to 403 ft/day:

Sediment Core	Depth Interval (ft)	Material	K_v (ft/day)	K_v (cm/s)
SC-1	0.8 – 1.2	Organic-rich, gray, med. sand	114	0.040
SC-1	2.65 – 2.95	Clean, coarse sand and gravel	403	0.14
SC-2	0.7 – 1.1	Black peat	49	0.017
SC-3	0.6 – 1.0	Organic-rich, gray, med. sand	37	0.013

These values are very large in comparison to typical estimates of sediment conductivities. There may be a number of possible explanations for this result. First, it is possible that the flow through the core itself and/or through the permeameter cell bypassed the sediment (e.g., along an annular gap between the core sleeve and the material). The linearity of the flow rate versus head drop data shows that the flow was laminar, but cannot guarantee that the flow was uniform. Second, it is possible that the sampling did not select the lowest-conductivity material present in the cores. The top two sub-samples from each core were reserved for bulk-sediment chemical analysis and for pore-water extraction and analysis. If the tightest material lay close to the sediment-water interface, it was not subjected to the conductivity measurements.

The vertical hydraulic conductivity measurements are believed to be suspect, and are not considered further. However, it is noted that the conceptual model that has emerged from the present investigation does not appeal to the pond-bottom sediment as the principal limit to induced recharge from surface water. Rather, the screened interval at the pumping wells is isolated primarily by the thick, fining-upward sequence of sediments that occupies the upper aquifer. This sequence reaches horizontal hydraulic conductivities as low as a few feet per day, as indicated by slug tests and grain-size analyses. The semi-confining layer in the shallowest aquifer tends to isolate the pumped interval from the pond, regardless of the properties of the thin veneer of pond-bottom muck.

4.8.7 Seepage Meter Data

Four seepage meters were deployed in the pond (Fig, 2-7) in October 2000. Seepage meters are designed to provide a direct measure of the seepage flux, whether upward (discharge of groundwater to surface water) or downward (recharge of groundwater by surface water) over the area occupied by the device. In the present case, the seepage meters were constructed from halves of polyethylene beverage drums 23 inches in diameter. Vents consisting of half-inch PVC pipe were fixed to the top of each drum, and were long enough to stand well above the pond surface when the meters were installed. A second port was fixed to the top of each meter, to which 3/8-inch Tygon tubing was attached. The drums were placed in the water, de-aired, seated in the pond-bottom muck as firmly as possible, and left to equilibrate for approximately one hour (e.g., to allow deformation of the drum to relax, rebound of the sediment around the rim, equalization of the internal water pressure to hydrostatic, etc.). The water reservoirs consisted of heavy-duty, rubber, hot-water bottles with a length of tubing, a ball valve, and a brass quick-connect fitting attached. Because the seepage meters were deployed offshore of the pumping wells, and a downward flux of surface water was anticipated, the reservoir bottles were filled with a pre-measured volume of water (1 liter), and de-aired with the valves open. The valves were then closed, the reservoirs were attached to the drums by the quick-connect fitting, and the valves were opened. After periods of three to four days, the valves were closed, the bags detached, and the volume remaining in the bags was measured. The average seepage flux over the measurement period is simply the volume change divided by the time interval, divided by the cross-sectional area of the meter.

The seepage meters were deployed over four time intervals, the third of which spanned a three-day shutdown of the water-supply wells. Results are summarized in Table 4-22. All measured fluxes were downward or zero; none of the reservoir bottles accumulated water. The measured fluxes are in the range 0 to 3.4×10^{-3} ft/day (0 – 1.2×10^{-6} cm/s). Meters #3 and #4 measured approximately a 90% decline in average flux during the period of the well shutdown, relative to the pre-shutdown fluxes measured at these points, suggesting that the seepage meters were sensitive to the change in groundwater extraction. Meter #1 consistently yielded zero flux before and during the shutdown, perhaps reflecting a relatively "dead" spot in the pond bottom (e.g., a "patch" of very low conductivity muck). Meter #2 showed a small increase in downward flux over the shutdown. The fourth period of deployment, following the restart of the wells, yielded rather erratic results (e.g., very small apparent fluxes in meters #3 and #4). A possible reason for these inconsistent results is that the air and water temperatures were falling rapidly at this time, and the Tygon tubing tended to stiffen and crimp under these conditions, possibly restricting the exchange of water between the drums and reservoir bags.

The seepage meters did not detect discharge of groundwater to the pond during the shutdown period. However, note that the measurements averaged over a period of approximately 68 hours, which started roughly at the time of the well shutdown. A period of relaxation of the drawdown due to the pumping is expected at the beginning of this period. In addition, the wells were restarted several hours before the end of the measurement period. Therefore, the results imply that the downward fluxes associated with the pre-test pumping and with the restart in the final hours of this measurement period predominated over any discharging groundwater that may have established itself in the interim.

It is emphasized that data from seepage meters are widely regarded as highly uncertain, due to the difficulty of ensuring that the systems are completely de-aired, the drums are seated firmly in the sediment, the drums are undisturbed during servicing of the reservoir bags, etc. In addition, seepage discharge or recharge is known to be quite heterogeneous, due to localization of flow in "patches" of more conductive material. Therefore, there is no guarantee that a few meters sample representative areas. For these reasons, the present data are taken to be qualitative, indicating only the order of magnitude of the seepage flux. Nonetheless, this order-of-magnitude estimate provides some perspective on infiltration induced by the pumping wells. The piezometer array suggested that the head perturbation due to pumping, just below the pond sediment layer, drops off with distance from the wells, and affects an area perhaps 300 feet in radius. (Piezometer PZ-3, located approximately 200 ft offshore, the farthest piezometer from the wells, registered a maximum drawdown of 0.2 ft.) If the maximum measured seepage flux of 0.0034 ft/day is assumed to prevail over a 300-foot radius semi-circular area in the pond ($1.4\text{x}10^5$ ft^2), this totals 480 ft^3/day. For comparison, the pumping wells typically average about 1200 gallons per minute for ten hours per day, or about $9.6\text{x}10^4$ ft^3/day. Thus, the conservatively estimated seepage recharge is less than 1% of the typical well discharge. This result is consistent with the conclusions reached based on the chemical indicators of mixing of surface water with groundwater at the supply wells, which indicated that Grove Pond contributes negligibly to the well production.

4.8.8 Results from the Pressure Transducers

Water levels recorded in monitoring wells 92-1, GF-1, GF-3B, GF-3A, and 92-3 are shown in Figures 4-20 to 4-27.

Wells GF-1 and GF-3B were logged continuously for 14 days. Results for this entire period are shown in Figures 4-20 and 4-21. The record for GF-1, screened in the bedrock immediately adjacent to supply well PW-1, shows variations in water level greater than 3 feet. Drawdown in the screened interval of PW-1 was not measured in this study; however, in the 1992 pumping test at approximately the same extraction rate (i.e., ~700 gpm from each production well), a drawdown of 19.82 feet was recorded at PW-1; a correction for well losses indicated a drawdown adjacent to the well of 7.7 feet. Relative to the latter estimate, the measured drawdown in the bedrock monitoring well, screened some 56 to 61 feet below the bottom of the PW-1 screen, is quite significant (approximately 50% of the estimated drawdown at the pumping well). This suggests good hydraulic connection between the overburden and the shallow bedrock. It is noted that the core collected during the installation of GF-1 showed massive, unfractured rock from about 111 to 115 ft bgs, only a few fractures to 119 ft, and dense fractures with clay infilling from 119 to 122 ft bgs. The well is screened from 116 to 121 ft bgs. Thus, although the screened interval within the bedrock appears to be well isolated from the overburden locally, it appears that the fractures intersecting the monitoring well screen are well connected to the overburden. In addition, it is noted that the response of GF-1 to changes in pumping is quite rapid. Each shutdown and restart of the pumping wells is reflected in the water level at GF-1 with a sharp rise or fall, a significant fraction of which is achieved within tens of minutes. The rapid response suggests a relatively high hydraulic diffusivity along the path between the pumping well screen and the GF-1 screen.

The transducer record from GF-3B is shown in Figure 4-21. Note that the variation in water level at this well is about 0.5 ft over the entire monitoring period. This very restricted range is due to the close proximity of the pond to this shallow (8 to 13 ft bgs) monitoring well. The pond level imposes a strong constraint on the head in the uppermost aquifer. It is also notable in the record from GF-3B that the rapid fluctuations in head seen in GF-1 accompanying each pumping cycle are strongly damped. For example, during the week of 10/20 to 10/27, during normal operations of the wellfield, GF-3B recorded a continued, overall decline in water level, with a superposed rise during the shutdowns occurring from the afternoon of 10/25 to the morning of 10/26. That is, while GF-1 responded quickly to each cycle of pumping, GF-3B responded to the longer-term, averaged extraction over the week. The relatively slow response suggests a low hydraulic diffusivity along the pathway from the GF-3B well screen to the zone of large and rapid head fluctuations in the underlying production horizon.

Figures 4-22 to 4-26 show the response of the five monitored wells to the shutdown from the afternoon of 10/27 to the morning of 10/30. Well 92-1 (Figure 4-22) exhibits the expected large-amplitude and rapid response of the pumping-well screened interval. The head recovery at this location is nearly 4 feet following the shutdown, with the first foot of rebound occurring over about 30 minutes. Upon startup of the supply wells at about 08:00 EDT on 10/30, the drawdown is again rapid, with the first 1 foot decline occurring over approximately 90 minutes. Well 92-1 is hydraulically connected to the pumping wells through a highly diffusive layer, as expected. The record for GF-1 (Fig. 4-23), screened in the bedrock immediately adjacent to PW-1, is nearly identical to that for 92-1, indicating that the hydraulic connection to bedrock beneath the supply well is very fast, an interpretation that is consistent with relatively high vertical conductivity in the deep overburden aquifer, and open fracture connections between the bedrock and overburden. The water level at GF-3B (Fig. 4-24), screened in the shallow (8 to 13 ft bgs) aquifer adjacent to the pond, responded to the shutdown with a rise of about 0.45 ft, constrained by the proximity of the pond. Note again that the response of GF-3B to the shutdown and restart is highly damped, showing a protracted rise over the entire 65-hour period of no pumping, and a fairly smooth drawdown over the following several days, during which the pumping wells were operated sporadically. This behavior further supports the conclusion that the domain between the GF-3B well screen and the underlying production horizon is characterized by relatively low hydraulic diffusivity, in turn reflecting a low vertical conductivity in the shallow overburden.

Figure 4-25 shows the water levels measured at GF-3A, screened at the base of the overburden (97 to 102 ft bgs). Rebound following the shutdown is very rapid at this location, "overshoots" by a fraction of a foot, and then falls slightly over the following day, even while water at well 92-1 is still rising smoothly. Following restart, GF-3A responds very much like 92-1, both in magnitude and in rates of change. This behavior suggests relatively high hydraulic diffusivity, both horizontally and vertically, in the lower aquifer. Figure 4-26 shows the response at monitoring well 92-3, located adjacent to the pond, and screened within the extraction zone of the supply wells. Although the unstable transducer resulted in "noisy" data for this well, the overall trend is apparent, and is very similar to that observed in the deep overburden at GF-3A. Well 92-3 again shows the "overshoot" of the rebound following cessation of pumping. It is also noted that the elevation in 92-3 (as inferred from the central tendency of the noisy data) is consistently lower than that at both GF-3A and GF-3B, indicating vertical gradients driving flow toward the extraction interval, both upward from below and downward from above.

Figure 4-27 shows the records for the well cluster, GF-3B (shallow), 92-3 (intermediate), and GF-3A (deep) for a period of about two hours on the afternoon of November 3, 2000. Following intermittent pumping earlier in the day, both supply wells were restarted at approximately 14:05 EST, and PW-2 was shut down at about 15:20 EST, while PW-1 remained on. A stable transducer was installed in 92-3 during this time interval in order to collect more precise data on the response in the vicinity of the well cluster. Well 92-3 exhibits the lowest head throughout this period, again indicating that both recovery and extraction within the pumping horizon is supplied by flow from below and above. GF-3A exhibits a response very similar to that of 92-3, again suggesting high hydraulic diffusivity and good connectivity in the deeper aquifer. The water level at GF-3B changes very little, possibly showing an overall fall of 0.01 ft over the two hours. Once again, the head in the shallow aquifer is strongly constrained by the nearby pond, and changes in the underlying production horizon are strongly damped out, indicating relatively low vertical diffusivity. The results for the well cluster during this two-hour period are consistent with the foregoing discussion based on the observations over the previous two weeks.

4.8.9 Borehole Temperature Profiles

Examination of the geophysical logs (App. A), recorded in mid-November 1999, reveals what appear to be significant temperature anomalies in some intervals. In particular, monitoring well GF-1 showed a zone of warmer water corresponding roughly to the screened horizon of the adjacent pumping well, PW-1. From approximately 55 to 63 ft bgs (~159 – 167 ft msl), the temperature profile was flat, at about 14.3 °C. The only domain in which similar warm temperatures were observed in the GF-1 profile is shallower than about 27 ft bgs. In GF-3A, located between GF-1 and the pond, there is no point in the temperature profile that reached this temperature; the maximum recorded was about 13.5 °C. In BH-1, drilled in the pond, water 14.3 °C or warmer is encountered in the interval ~15-25 ft bgs. Thus, there is a strong suggestion that the anomalously warm water found at ~55-63 ft bgs in GF-1 represents water drawn relatively quickly along a pathway from a shallower depth. The warmer water represents propagation of the previous summer's maximum temperatures toward the pumping well screen by advection. The ultimate source of this warmer water is difficult to determine unequivocally on the basis of temperature alone.

Additional temperature profiles were obtained in GF-1 in early summer of 2001. The purpose of these data was to provide further insight into the advective transport of heat and its possible implications for groundwater – surface water interaction at the site. The geophysical logs were recorded in late fall, at a time of falling surface temperatures. A zone of relatively warm groundwater at depth suggests the presence of water that resided at a shallower depth or at the surface some months previously, and was arriving at the pumping well in November, still carrying some of the heat acquired earlier. Thermal profiles were obtained in GF-1 on May 18, 2001, and on June 14, 2001, in order to examine a period of increasing surface temperature, when one might expect to observe the effect of the previous winter's relatively cold surface temperatures on the pumping horizon.

A thermocouple and datalogger were attached to a tape and lowered incrementally down the well casing at GF-1. The device was held at each fixed depth for at least one minute to allow the thermocouple to equilibrate. Time and depth were recorded by hand, and correlated later with the time and temperature recorded by the datalogger. The resulting temperature profiles are shown in Figure 4-28. The profiles show a sharp warming at the water table as mean air temperatures rise through May and June. The previous winter's colder temperatures have propagated downward, with a local minimum of 5.5 °C appearing in the May profile at ~15 ft bgs (~207 ft msl), and a deeper minimum of 6.2 °C at ~35-40 ft bgs (~181-186 ft msl). In the June profile, the shallower minimum is absent, the deeper minimum is colder, 4.7 °C, and appears at greater depth, ~42-47 ft bgs (~174-179 ft msl). In both May and June, there is a steep vertical temperature gradient within and just below the pumping horizon, with a sharp drop in temperature to approximately 71 ft bgs (~150 ft msl). The late-spring to early-summer temperature profiles indicate the presence of cold water at depth, evidently originating at or near the surface during the winter, and carrying that temperature deficit to the production zone of the supply wells by advection.

Figure 4-29 shows the *change* in temperature between May 18 and June 14. At the water table, the change is sharply positive (> 6 °C), as expected during a period of rising mean air temperatures. Temperature changes become negative at a depth of ~22 ft bgs (~200 ft msl), below which the temperature decreased from May to June. Note that this is expected even under conduction-dominated heat transfer, as the winter's cold propagates downward from the surface. Water temperatures in the shallow subsurface at this location are likely influenced by two phenomena caused by its close proximity to the pumping well, PW-1. First, the water table fluctuates by several feet with the pumping cycle. Second, when the well is pumping, shallow groundwater in the vicinity of GF-1 flows downward toward the top of the production screen, resulting in vertical advective heat transport. It is particularly striking that the change from May to June reaches a maximum of approximately 2 °C at a depth of ~53 ft bgs (~168 ft msl), at the center of the PW-1 well screen (~ 158 – 178 ft msl). Again, this is a strong indication that cold, "winter water" is arriving at the pumping well, with the temperature of this water falling significantly during a period of warming at the surface. The available data do not identify the time at which the minimum groundwater temperature reaches the pumping well. However, this arrival in 2001 was some time after May 18. Average air temperatures are typically at a minimum in December and/or January. This suggests a travel time of the order of several months from the source of the thermally anomalous water to the production wells.

One interpretation is that the water in the production horizon to the north of the wells (i.e., as penetrated by GF-1, GF-3A, 92-3, and BH-1) originates from recharge north of the pond, in the vicinity of the Town of Ayer. If the hydraulically conductive zone corresponding to the production horizon "daylights" north of the pond, cold water that infiltrates during winter and early spring thaws could arrive at the supply wells in early summer. (Note that January to March of 2001 was a period of record snowfall, and the spring melting likely resulted in an unusually great recharge of cold water to the subsurface. Total precipitation in March 2001 at Worcester, MA, was 9.02 inches, compared to a 100-year average of 3.76 inches.) The implied travel time is roughly consistent with that estimated based on the hydrology alone. Furthermore, the water chemistry within the extraction horizon appears to exhibit urban characteristics (e.g., high chloride and nitrate), consistent with an origin in the developed area north of the pond, and consistent with analysis of groundwater from 92-5, located on the north shore in Pirone Park.

4.9 QA/QC

Two Quality Assurance (QA) issues are addressed briefly in this section. First, an assessment of the total precision of the analytical results is provided. Second, the influence of field filtration methods is assessed.

4.9.1 Total Precision of Analytical Results

"Total precision" is defined here as a measure of the reproducibility of analytical results, based on field duplicate samples collected and analyzed under the same protocols. In particular, standard QA procedures call for collection of one field duplicate for every ten samples taken in the program. In the present case, this resulted in a total of eight duplicate pairs (Table 4-2 in the Phase I Interim Data report, Gannett Fleming, 1999b), including seven groundwater sample events and one surface-water sample event. Of the seven groundwater sample pairs, six were obtained under the same protocol, while the seventh was obtained using a different filter. (See Section 4.3.2 for an analysis of the influence of the filtration method.) Therefore, the following assessment is based on the six duplicate pairs sampled with the in-line filter. The evaluation is intended to provide a quantitative measure of the variability observed in samples that are nominally identical. Sources of this variability include real differences in groundwater chemistry due to the small separation in time of sampling twice in succession, differences introduced by small variations in sample-collecting and sample-handling procedures, and differences due to variations in laboratory analytical procedures.

The measure of precision chosen for this evaluation is the average fractional difference between analyses of duplicate pairs, normalized by the mean of the pair. For concentrations c_A and c_B of a given species in duplicate samples A and B, respectively, the variability is characterized by the quantity

$$P = \frac{|c_A - c_B|}{(c_A + c_B)/2}$$

Table 4-2 (in Gannett Fleming, 1999b) shows the average value of *P* calculated for each species among the six groundwater sample duplicate pairs. Only analyses that returned values above the MDL are included in the average for each species. This procedure yields average values of P for Ca, Mg, Na, K, Ba, Fe, Mn, Zn, and As. Other constituents yielded no analyses above MDL for any pair. For most of the species named, the average variability among duplicate pairs is of the order 0.01, or about 1%. Iron is slightly higher, at about 3%, principally because of relatively low precision in the analyses; the laboratory reports only two significant figures for iron concentrations. Zinc analyses show high variability (average P of 0.42), due in part to a small number of samples (three above MDL), and due to a single widely disparate pair (MNG3GW002 and MNG3GW003 at 84.3 µg/L and 25.7 µg/L, respectively). Arsenic analyses on the six duplicate pairs show average variability by this measure of about 7%, the elevated value again due principally to a single disparate pair (PW1GW010F and PW1GW011F at 0.022 mg/L and 0.016 mg/L, respectively). Overall, this assessment indicates that the sampling and analysis yielded highly reproducible results.

4.9.2 Influence of Filtration Method on Analytical Results

It was noted in Section 4.1 that the filtration method used on the groundwater samples was changed after the first three rounds of samples at the production wells and adjacent monitoring wells. In order to consider trends that span the change in sampling protocol, it is necessary to establish that the filtration hardware did not significantly affect the analytical results. The earliest rounds of sampling employed a barrel filter, through which the water is forced by air pressure provided by a hand pump. The remainder of the program employed a passive, disposable, in-line filter placed between the pump outlet and the sample bottle. A concern with the barrel filter is that aeration of the water during sampling may oxidize some redox-sensitive elements, e.g., Fe and Mn. These oxides, in turn, could scavenge other metals, and result in concentrations that are biased low. Both the barrel filter and the in-line filter used are characterized by 0.45 µm pore size according to their manufacturers.

In order to test the influence of the filtration method on analytical results, six rounds of samples were collected at the production wells, PW-1 and PW-2, using both the barrel and the in-line filters (one sample by each method in each round), and one such round was collected at each of the adjacent monitoring wells, 92-1 and 92-3. These pairs of filtered samples were submitted for analysis for PAL metals.

The analytical data were examined to identify any systematic bias due to filtration method, if present. Manganese provides the best data on which to base this assessment for several reasons. First, as noted above, manganese is subject to precipitation as an oxide and removal by the filter, so that an effect due to aeration in the barrel filter is likely to be revealed, if present. Second, manganese was present at concentrations above the MDL for all 14 sample pairs, so that a maximum number of samples is available for statistical analysis. Third, manganese exhibits a wide range of concentrations in the samples taken in this study. Finally, the laboratory was able to achieve relatively high precision in its manganese analyses (compared, for example, to iron). Figure 4-30 shows manganese concentrations for in-line filtered samples versus those for the corresponding barrel-filtered samples. The line indicates the "ideal" case, i.e., perfect correlation of analyses. Qualitatively, it is clear that all 14 sample pairs plot close to the ideal line, indicating close agreement between analyses on samples filtered by the two methods. Furthermore, there is no apparent tendency for points to fall to one side or the other of the line indicating ideal correlation; approximately equal numbers of points plot above and below the line. Thus, the paired samples indicate no tendency for the barrel filter to result in Mn analyses that are biased low.

It is also useful to assess the variability that may be introduced to the analytical results by the filtration methods. The variability between duplicate samples, in which both samples were collected with in-line filters, was quantified in Section 4.9.1. The same measure of variability can be calculated for the sample pairs under consideration in this section, in which one was collected with the barrel filter and the other with an in-line filter. If the barrel / in-line sample pairs show variability of a magnitude similar to that found for the in-line-filtered duplicate pairs, then one might conclude that the difference in filtration methods does not introduce significant additional variability to the analytical results. The parameter P, defined in Section 4.9.1, is calculated for each analyte and for each of the 14 barrel / in-line sample pairs. The parameter is then averaged over all 14 pairs for each analyte, excluding any pair for which one or both analyses were below the MDL. The results of these calculations are shown in Table 4-3 in the Phase I Interim Data report (Gannett Fleming, 1999b). The variability among sample pairs taken using the different filters is of the same order of magnitude (1-6%) as that among field duplicate pairs taken with in-line filters (1-3%), although consistently somewhat higher. Note that some of this difference may be attributable to the small sample size, particularly for pairs both sampled using the in-line filter. While the variability between sample pairs taken using the barrel filter is somewhat higher, no consistent bias toward higher or lower concentrations is observed. It is concluded that the change of filter type after the first few rounds of sampling represents a source of variability in the analytical data that is not significantly greater than the variability inherent to the entire sampling and analysis procedure. Therefore, results for samples collected by both filtration methods can be considered together and interpreted as a single, internally consistent data set.

Note that the analytical laboratories performed their own, internal, QA/QC checks, which are detailed on the original laboratory report sheets. These will be made available upon request.

5.0 PRELIMINARY ASSESSMENT OF INDUCED INFILTRATION

5.1 Conclusions from Previous Work

Previous estimates of the mixing ratio for pond water drawn to the production wells via induced infiltration have yielded a wide range of results. Estimates have been based both on model calculations and on inferences from a pumping test at the Town of Ayer wells. Model studies have yielded estimates that range from 0% (anecdotal reference) to 96% (CDM, 1993), depending upon the assumptions made. The low estimate results from an assumption that the pond is separated from the underlying aquifer by a relatively impermeable stratum. The high estimate results from numerical simulations in support of a Zone II delineation (CDM, 1993), based on an extreme drought condition, in which no infiltration of rainwater is available to recharge the aquifer for a period of six months. Under these conditions, and given the hydrostratigraphy assumed in the model, production at the wells must draw almost entirely from the nearby pond. Results from numerical simulations of pumping tests conducted on the Town of Ayer Grove Pond wells in 1992 indicate induced infiltration in the range from 61% to 68% (CDM, 1993). These estimates are discussed in detail in the following section.

5.1.1 CDM Pumping Tests (1992)

Two pumping tests were conducted in 1992 in order to evaluate the capacity of the supply wells and to support a Zone II delineation (CDM, 1993). The wells were pumped at an average combined flow rate of 1380 gpm for 14 days in May and June, and a second test was run at 1400 gpm for 23 days in September. The second test was conducted in order to evaluate the aquifer response under low water conditions.

A numerical model of the aquifer system was developed by CDM (1993), in which the overburden was represented by four stratigraphic layers. The total overburden thickness in the area of the Ayer wells was constrained by results from a seismic refraction survey. Initial estimates of the hydraulic properties were based on independent data, such as grain-size distributions from soil samples. The model was then calibrated to obtain a satisfactory match of the simulated and observed water levels. The hydraulic conductivity inferred for the area surrounding the pumping wells was 300 ft/d. This high-conductivity material was assumed to extend beneath the pond to a depth of about 20 feet (elevation ~200 ft msl), and was assumed to be continuous beneath the pond in the screened interval of the pumping wells (~160 to 180 ft msl). Between these two layers of high conductivity, a domain of lower K (60 ft/d) was assumed to coincide roughly with the outline of Grove Pond in the depth interval ~20-45 ft bgs. The presence of this silty layer was based principally on observations made in the boring log for monitoring well 92-3. The model assumed that the screened interval of the supply wells is underlain by another silty horizon less than 10 feet thick, in turn lying on impermeable bedrock. The silt at the base of the overburden was assigned a permeability of 20 ft/d. The calibrated model calculated that 61% to 68% of the total production at the supply wells in the pumping tests was drawn from Grove Pond by induced infiltration.

The present study leads to a quite different conclusion with respect to induced infiltration, having found no chemical indicators of the presence of pond water within the pumping horizon at intervening monitoring wells or in the extracted water. However, the present study also revealed several significant differences in thc hydrologic setting. First, recall that no boreholes had been advanced to refusal in the vicinity of the supply wells in 1992; depth to bedrock was inferred from a seismic refraction survey, which indicated bedrock at about 35 ft below the bottom of the well screen at PW-2 and at about 5 ft below the screen at PW-1. In this study, borings were advanced to bedrock adjacent to the two supply wells, and the distance from the bottom of the screens to bedrock was found to be about 50 ft. At 92-3, between the supply wells and the pond, the 1992 model estimated approximately 20 ft of overburden between the bottom of the monitoring well screen and bedrock. Drilling in this study at GF-3A, immediately adjacent to 92-3, encountered bedrock at ~117 ft msl, about 46 ft below the bottom of the 92-3 screen. Therefore, the saturated overburden is much thicker than previously estimated. Furthermore, portions of the deep overburden were found to be coarse sand and gravel, with high conductivity. This implies that more of the production at the pumping wells can be drawn from the deep aquifer, without the necessity of drawing as much water from the pond.

A second difference from the conceptual model invoked to interpret the pumping test is that more details of the hydrostratigraphy are now known. Slug tests, grain-size analyses, and specific capacity measurements collected while advancing new borings indicate that the hydraulic conductivity is a minimum in the shallowest overburden, with K of the order of a few feet per day. The conductivity generally increases with depth into the extraction horizon, where it reaches hundreds of feet per day. Thus, the results from the present study suggest that the shallowest aquifer material functions as a semi-confining layer, and tends to isolate the pumping interval from rapid interaction with the surface water. In contrast, the numerical model used to interpret the 1992 pumping test invoked continuous sand and gravel with K = 300 ft/d from the pond to the well screens. The silty layer in the numerical model at ~30-45 ft below the pond, assigned a conductivity of 60 ft/d, is consistent with the intermediate conductivities inferred in this depth range in the present study. However, the 1992 numerical model had an overlying layer of coarse sand and gravel with K = 300 ft/d, while data from the present study indicates that the conductivity of the shallower domain is much smaller. Furthermore, data from the present investigation suggests continuity of the low-conductivity material between the pond and the pumping wells. Thus, the conductivity structure assumed for the 1992 modeling tends to bias the results toward an overestimation of induced infiltration.

Finally, it is noted that the 1992 numerical model generally overpredicts the measured drawdowns. Simulation of the May-June pumping test yielded the following drawdowns and residuals for monitoring wells utilized in the present study:

Well	Measured Drawdown	Calculated Drawdown	Measured - Simulated
92-1	6.39	7.94	-1.55
92-3	6.33	5.23	+1.1
92-4	4.7	3.33	+1.37
92-5	0.2	0.16	+0. 04
MNG-3	3.7	2.68	+1.02
MNG-7	0.56	0.72	-0.16

Simulation of the September pumping test yielded:

Well	Measured Drawdown	Calculated Drawdown	Measured - Simulated
92-1	6.37	7.76	-1.39
92-3	6.16	5.11	+1.05
92-4	4.51	3.11	+1.4
92-5	0.32	0.14	+0.18
MNG-3	3.41	2.4	+1.01
MNG-7	1.67	0.44	+1.23

Note that the drawdown at 92-1 is significantly overpredicted. However, 92-1 is 80 ft from each of the pumping wells, a distance smaller than the finite-difference grid spacing of 100 ft. Therefore, the spatial resolution of the hydraulic gradients near the pumping wells is not adequate to obtain accurate drawdown predictions at 92-1. The general underprediction of drawdowns across large distances in the model could be due to a number of incorrect assumptions embedded in the model. One is that the hydraulic conductivities assumed in the model may be too high. An alternative or an additional factor may be that the modeled system is too "open" at the surface, allowing more localized drawdown, and supply of more of the well discharge from Grove Pond. A semi-confined pumping horizon, as interpreted in the present study, would result in greater drawdown at greater distance from the supply wells.

5.1.2 Microparticulate Analysis

Due to concern for possible water-quality effects associated with induced infiltration of surface water, the Town of Ayer has obtained microscopic particulate analyses (MPA) on the raw well water (CDM, 1992). This procedure seeks to identify various microorganisms associated with surface water, which often appear in groundwater pumped in close proximity to surface-water bodies. Samples collected in both fall of 1992 and spring of 1993 showed that "... none of the biological indicators listed in the Risk Assessment Tables of the EPA Consensus Method for Microscopic Particulate Analysis were observed in any of the three samples" (CDM, 1993). More recent sampling and analysis yielded the same outcome (personal communication, R. Linde, 2001). These results provide independent support for the conclusion that induced infiltration from Grove Pond is minimal.

5.2 Preliminary Interpretation From This Study

It is apparent from examining the data collected in this study that the overburden aquifer derives its major-element chemical signature from a number of common mineral reactions:

(a) for carbonates:

$$CaCO_3 + H^+ \Leftrightarrow Ca^{+2} + HCO_3^-$$

$$MgCO_3 + H^+ \Leftrightarrow Mg^{+2} + HCO_3^-$$

$$FeCO_3 + H^+ \Leftrightarrow Fe^{+2} + HCO_3^-$$

(b) for chlorides (e.g., road salt):

$$NaCl \Leftrightarrow Na^+ + Cl^-$$

(c) for the reduction of ferric iron, Fe^{+3} (as FeOOH), through the oxidation of organic matter:

$$4\,FeOOH + CH_2O + 7\,H^+ \Leftrightarrow 4\,Fe^{+2} + HCO_3^- + 6\,H_2O$$

If the chemical "signature" of surface water and various groundwater subdomains are demonstrably distinct, mixing of these sources at the production wells can, in principle, be quantified. A comprehensive approach to determining mixing ratios involves the use of Piper diagrams (Piper, 1944) to quantify mixing of waters of different compositions. In these diagrams, the relative abundances of major ions in groundwater samples are plotted. A Piper diagram consists of two ternary plots, one with mole percentages of the major cations (Ca, Mg, and Na + K) and the other with anions (Cl^-, SO_4^{2-}, and CO_3^{2-} + HCO_3^-). The two pairs of components, Na + K and CO_3^{2-} + HCO_3^-, are added together because in most waters the concentrations of Na^+ and HCO_3^- are high relative to K^+ and CO_3^{2-}. These points are plotted on each of the ternary diagrams and then projected onto a diamond-shaped field that represents all six components. Numerous analyses can be plotted on a single diagram, thus providing a relatively quick and accurate visual comparison of different groups of groundwater compositions. In addition, mixing trends between different groundwaters can often be determined both visually, from inspection of the plots, and quantitatively, using readily available software.

The purpose of using this simple graphical representation of hydrochemical "facies" was principally to determine whether the production wells appeared to be consistent with linear, binary mixing of waters with two different chemical compositions. Specific objectives of this approach were:

1. To determine the appropriate end-member compositions (from one or more of the monitoring wells, from the groundwater profile sampling, and/or from pond water) that yield the observed mixtures in the production wells;

2. To determine if the production well compositions change with time; and

3. To provide a quantitative estimate of relative mixing proportions when steady-state has been established.

While this approach is computationally simplistic, it is based on "ground-truth," i.e. real, site-specific data, as opposed to modeling results using approximations for key parameters. Figure 5-1 is an example of a complete Piper plot; compositions of the production wells are shown as "X" and "Y," corresponding to PW-1 and PW-2, respectively, and the data are from the 2/00 confirmatory sampling round. Circles represent the major-element compositions of the groundwater profile samples taken at GF-3A. Figures 5-2 through 5-5 show portions of the six-component field, enlarged for clarity. Figure 5-2 shows the production wells as X and Y, with the GF-3A profile samples. Darkened circles are the samples from the upper aquifer that contain detectable arsenic; note that these samples constitute a distinct cluster, or hydrochemical facies. The samples from the lower aquifer are similarly grouped. The three outlying points to the upper right of the mixing line are the high-chloride samples from the pumping horizon (~48-60 ft bgs). The square is a calculated mixture of 45% water from the upper aquifer, and 55% from the lower aquifer. Figure 5-3 shows the in-pond borehole results; again, darkened circles represent arsenic-bearing groundwater and are similar to the location of the upper aquifer points in Figure 5-2. The surface water compositions (marked by "w" on Figure 5-4) are from data obtained during the 8/98, 2/99, and 2/00 sampling rounds. The two bedrock wells GF-1 and GF-2, both "B" on Figure 5-5, represent data from the 2/00 sampling round.

The use of major-element chemistry is a simple method of quantifying compositional variability, and the data undoubtedly reflect both sampling and analytical uncertainties. However, in spite of these limitations, several features of the data shown on these figures should be noted. It is clear that the deep and shallow aquifer waters constitute significantly different compositional populations, and both are distinctly different from the bedrock compositions (GF-1 is closer to the "deep aquifer" population). The surface water samples are significantly scattered and apparently reflect the effects of seasonal variation. Finally, the production wells lie on a line connecting the shallow- and deep-aquifer waters, suggesting that the supply wells are producing water that is a mixture of these end-member compositions. Using the shallow- and deep-aquifer waters as potential end-members, various mixtures were computed. The point on Figure 5-2 marked by the square represents a mixture consisting of 55% deep aquifer water (the average of samples GF3A12—25) and 45% shallow aquifer water (GF3A1—8). This composition approximates the production-well water reasonably well.

Results from the Piper calculations address the questions listed above:

1. Analyses of major-element data from Phase I and the profile sampling conducted during Phase II indicate that the production well compositions are consistent with a mixture of water from the upper part of the groundwater profile in GF-3A (18 to 45 ft bgs) with water from the deeper, oxidizing portion (68 to 104 ft bgs). The high-chloride water that is thought to originate on the north side of the pond may be present in the production wells as a contribution to the "deep aquifer" composition.

2. Compositions of the production wells and the flanking monitoring wells change with time. Initially, compositions of groundwater from PW-1 and PW-2 move along lines approximately normal to the mixing line between deep and shallow aquifer, but then the trend is toward the deep aquifer composition. The composition of 92-1, the nearest upgradient well, remains approximately constant. The composition of 92-3 also changes with time, moving toward the area of the diagram with the data from the production well mid-screen depth interval (45-60 ft). This observation is significant, as the change in water composition at this location appears to represent the travel time of groundwater moving from the north side of the pond and intercepted by the 92-3 well screen. Although it is not possible to estimate this 'breakthrough' time with any certainty, it is clearly of the order of several months (see, e.g., Fig. 5-6).

3. Mixing ratios, derived by the assumption of linear binary mixing, indicate that the production well compositions are consistent with a mixture of nearly equal parts deep-aquifer water and shallow aquifer water.

Variations in surface water composition are not surprising, because Grove Pond is shallow and subject to evaporation, especially during the summer months. In addition, differences among the synoptic surface water samples were observed. The five samples taken during Phase I immediately offshore of the production well area show marked differences in certain elements compared to the samples from the northwest corner. Concentrations of several elements (Ba, Ca, K, Mg, Na), dissolved oxygen, alkalinity, chloride, conductivity, pH, and temperature were lower in these five samples than in those from the northwest corner. In contrast, water in the northwest corner of the pond showed higher values of pH, temperature, conductivity, DO, alkalinity, and chloride, but lower sulfate, than the five-sample cluster. The highest surface water arsenic concentrations (8 and 9 µg/L) were reported from the northwest corner samples. These results suggest that coves and embayments may be very stagnant, while the rest of the open pond water is relatively well-mixed. The two winter sampling rounds, in February 1999 and February 2000, also show marked differences in surface water chemistry. Chloride in particular varies significantly, from an average of approximately 50 mg/L during the summer, to a minimum of 38 mg/L in February 1999 and a maximum of 87 mg/L in February 2000. Sodium varies in a similar manner, averaging 29 mg/kg during the summer sampling and showing a minimum of 22 mg/L and a maximum of 47 mg/L in February 1999 and February 2000, respectively. These excursions in major element concentrations and the general correlation between Na and Cl (molar ratios near unity) probably reflect the rapid response of surface water to dilution by snowmelt runoff and the influx of road salt.

It is highly probable that surface water is contributing to the composition of the 'upper aquifer' over some time scale, through slow infiltration through the low-conductivity upper sedimentary unit. The major-element chemistry suggests that this time scale is sufficiently long for the upper aquifer water to acquire and maintain its distinct chemical composition, in contrast to the marked seasonal changes observed in the surface water. The seepage meter data indicates that 'induced infiltration' of surface water directly from the pond to the production wells is not volumetrically significant. Rather, the major-element chemistry points toward 'leakage' of upper aquifer water (albeit related to surface water, however distantly in space and time) as a significant component of the production well water.

6.0 DEVELOPMENT OF CONCEPTUAL MODELS: POSSIBLE ARSENIC SOURCES

The following subsections address a number of possible conceptual models for the source of the arsenic observed at the production wells, PW-1 and PW-2. Elements of these models have been put forward in various contexts in the past, or have emerged during the course of this study. Each model proposes a possible source for the arsenic, as well as transport processes that may influence its mobility in the environment. Each scenario is evaluated in view of the data obtained in this study, and arguments for and against each conceptual model are summarized. The weight of evidence collected to date appears to favor the 'reductive dissolution' theory for liberation of arsenic and other sorbed constituents from ferric oxyhydroxide surfaces within the overburden. However, this study is by no means complete. In particular, questions regarding the ultimate source of arsenic in the underlying bedrock (nature, abundance, and distribution of cobaltite and possibly other arsenic sulfide phases); the timing and mechanism(s) responsible for the distribution of arsenic, iron, manganese, and other trace elements throughout the overburden; and the post-glacial depositional and diagenetic history of the overburden deposits have not been answered completely or unambiguously. Nevertheless, in spite of these and any other issues not directly addressed in this report, the data presented herein do not support any model that relates arsenic in the Town of Ayer water supply wells to Grove Pond bottom water, pore water, or bottom sediments.

6.1 Environmental Behavior of Arsenic

6.1.1 Arsenic(V) and Arsenic(III)

The most common oxidation states in which arsenic occurs in the natural environment are +3, +5, and –3. In solution, the principal inorganic species are referred to as arsenate, or As(V), usually without regard to degree of protonation, and arsenite, As(III). Under moderately oxidizing conditions (ORP > 100 mV), arsenic occurs predominantly as As(V), while As(III) is present under moderately reducing conditions. Of the two species, arsenate and arsenite, As(V) sorbs more strongly, to hydroxide surfaces of iron, manganese, and aluminum. Because As(III) species sorb less strongly, arsenic in the trivalent state is more mobile and more toxic. The solubility, toxicity, mobility, and bioavailability of As(V) and As(III) have been addressed at length in a number of papers in the recent literature. Some excellent sources are the review papers by Bhumbla and Keefer, 1994; Smith, et al., 1998; and Cullen and Reimer, 1989.

In oxygenated fresh waters in the pH range from ~5 to 9, the dominant As(V) species are $H_2AsO_4^-$ (from pH <3 to around pH 7) and $HAsO_4^{-2}$ (to pH ~11). As(III) in this pH range occurs predominantly as $H_3AsO_3^0$ (see, e.g., Cherry, et al., 1979). The pH values measured in Grove Pond groundwater and surface water lie within this range, so it is expected that these are the primary species of arsenic present in this system. In anoxic systems, As(III) is the thermodynamically significant form. Under extremely reducing, acidic conditions and in the presence of sulfur, As_2S_3 (the mineral orpiment) or AsS (realgar) may form. At neutral to alkaline pH, thioarsenite species (represented as AsS_3^{3-}) become important.

The redox behavior of arsenic in natural systems is complex. Thermodynamically, As(V) should be the dominant form relative to As(III). A recent study of arsenic in groundwater in a glacial-till aquitard system presents evidence of the suitability of using the As(V)/As(III) redox couple as an indicator of the oxidation-reduction potential of the system (Yan, et al., 2000). However, thermodynamically predicted As(V)/As(III) ratios are rarely observed, and it is probable that relative concentrations of these species are affected by microbial reactions. Both pH and microbial activity influence the oxidation of arsenite to arsenate, and the reduction of arsenate to arsenite. A more detailed description of these processes, as well as an extensive discussion of the bacterial methylation of arsenic, and a discussion of the uptake of arsenic by terrestrial and aquatic plants, is found in Cullen and Reimer (1989).

6.1.2 Geochemical Modeling

Arsenic Speciation in Groundwater

Because only total dissolved arsenic was analyzed in this investigation, the geochemical equilibrium code PHREEQC (Parkhurst and Appelo, 1999) was used to predict arsenic speciation under the *in situ* conditions of Grove Pond groundwater. From the GF-3A vertical-profile data, it is apparent that the theoretical concentration of As(III) is much greater than As(V) throughout the upper 40 feet of overburden, where ORP reaches a minimum of –192 mV. This result is consistent with what would be expected under reducing conditions, where As(III) is more mobile and less strongly sorbed. Under these conditions, the dominant species is $H_3AsO_3^0$. Where ORP is positive, within the producing horizon, PHREEQC predicts an increase in As(V) concentration relative to As(III). Since no arsenic was observed above the MDL in this interval, calculations were based on the detection limits. Where ORP reaches a maximum of 107 mV (GF3AGW11, 58—60 ft bgs; 160.32 ft MSL), in the middle of the producing horizon, the predicted ratio of As(III) to As(V) is close to unity, with As(III) existing predominantly as $H_3AsO_3^0$ (1.77×10^{-8} M), and the As(V) species consisting of $H_2AsO_4^-$ and $HAsO_4^{-2}$ (1.30×10^{-8} M and 2.70×10^{-9} M, respectively). Below the producing horizon, ORP decreases again and the predicted form is $H_3AsO_3^0$.

Arsenic Adsorption

The sorption of arsenic onto iron, aluminum, and manganese oxide phases, as well as onto clay mineral surfaces, has been addressed in numerous studies (see, e.g., Stumm and Morgan, 1996; Masscheleyn, et al., 1991; Cullen and Reimer, 1989; Korte and Fernando, 1991). Because iron is quantitatively more abundant than either manganese or aluminum in both Grove Pond soil and groundwater samples, and also because the requisite thermodynamic data for modeling sorption onto Mn or Al surfaces are not available, the remainder of the discussion on sorption will focus primarily on iron.

The precipitated iron compounds are referred to interchangeably as hydrous oxides, oxyhydroxides, and hydroxides and represented as Fe_2O_3, FeOOH, and $Fe(OH)_3$, respectively. Sorption or coprecipitation by these solid ferric iron phases is an important part of the process of removal of a number of dissolved metals from solution, including arsenic. The abundance of iron and manganese in the water produced by the Town of Ayer wells and the observed correlations between dissolved iron and arsenic (Figs. 6-1 and 6-2) suggest that surface sorption by ferric iron phases may be the dominant mechanism affecting arsenic transport in the aquifer.

In addition to predicting arsenic speciation in solution, PHREEQC was also used to calculate the concentration of arsenic that potentially could be sorbed onto hydrous ferric oxide (HFO) surfaces, from the GF-3A groundwater analyses and soil data from GF-1. PHREEQC uses the diffuse double-layer model described in Dzombak and Morel (1990) and requires the user to input values for the concentration of binding sites, specific surface area of the solid phase in m^2/g, and the number of grams of sediment associated with a liter of solution. Values for these parameters were recommended by K. Stollenwerk (personal communication, 2001) based on measurements obtained by the USGS for a sand and gravel aquifer on Cape Cod (K. Stollenwerk, personal communication), as follows: The site concentration was estimated from the extractable iron concentrations for each sample and the assumption of 0.005 moles of binding sites per mole of iron (from Dzombak and Morel, 1990; Davis and Kent, 1992). Surface area was measured directly, and a value of 1 m^2/g was used in these calculations, and the solid mass associated with one liter of solution was set equal to 5.0 kg (K. Stollenwerk, personal communication, 2001).[2]

Because the laboratory did not meet the requested arsenic detection limits for the soil samples from the GF3A profile, the computational results are qualified because they are not co-located spatially, as they were taken from two different boreholes. However, because the three groundwater profiles from BH-1, GF-3A, and GF-4 all show similar spatial trends, especially in ORP and dissolved iron and arsenic, it seems reasonable to assume that the subsurface stratigraphy and hydrogeochemical facies are, in general, laterally homogeneous on some gross scale, at least of the order of ~200 ft. In the absence of more detailed analytical information, the following results were computed using groundwater-soil pairs co-located as closely as possible using the sample elevations.

Results from PHREEQC indicate that the dominant surface species throughout the reducing portion of the aquifer is $Hfo\_wH_2AsO_3$ (where Hfo_w represents a weakly-sorbing site on the oxide surface). As an example, with the groundwater data from sample GF3AGW08 (As = 189 µg/L; elevation 175.32 ft MSL), the code predicts that

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[2] Since PHREEQC output is given in terms of number of moles per liter of solution that is presumed to be in equilibrium with the soil, it is necessary to compute the grams of sediment in an aquifer volume that yields 1 liter of solution: Assuming a soil porosity of 0.35 and solid density of 2.65 g/cm^3, this liter of solution is associated with a soil mass of 4.9 kg.

1.40E-3 moles of this species should be present at equilibrium. Adjusting this solution concentration to a mass fraction, the predicted soil arsenic concentration for this sample is 21.36 mg/kg. As noted in the preceding paragraph, the groundwater and soil samples for this exercise are not precisely co-located; for comparison, laboratory analysis of the soil samples from the GF1 boring at 172.84 ft MSL yielded an arsenic concentration of 21.29 mg/kg. Relatively few soil samples were analyzed, and only a subset of these can be approximately correlated spatially with groundwater samples. However, the linear regression on the seven pairs of computational vs. laboratory-derived results (tabulated below) that can be compared yielded a slope of 1.17 and correlation coefficient, R^2, of 0.79.

Soil Sample	Elevation (ft MSL)	Arsenic, measured (mg/kg)	Groundwater Sample	Elevation (ft MSL)	Arsenic, calculated[3] (mg/kg)
GF1-22-24	198.84	10.58	GF3AGW03	200.32	3.37
GF1-26-28	194.84	10.32	GF3AGW04	195.32	4.95
GF1-30-32	190.84	22.41	GF3AGW05	190.32	14.19
GF1-34-36	186.84	13.58	GF3AGW06	185.32	10.53
GF1-42-44	178.84	17.84	GF3AGW07	180.32	20.27
GF1-48-50	172.84	21.29	GF3AGW08	175.32	21.36
GF1-62-64	158.84	5.8	GF3AGW11	160.32	1.02

In the producing horizon, very little arsenic is in solution, because the HFO surface is less soluble under the more oxidizing conditions encountered in this interval. At the maximum ORP observed, if the total dissolved arsenic concentration is assumed to be 5 µg/L (the lowest detection limit reported by the laboratory), PHREEQC predicts a sorbed concentration in equilibrium with this sample of 1.02 mg/kg. Arsenic concentrations in soil samples throughout this interval may be much higher, but the sorbed arsenic fraction cannot be calculated in the manner described above unless dissolved arsenic is present. Although this approach may not yield numbers that exactly match measured soil arsenic, given the assumptions needed to perform these calculations (fraction of Fe extracted by the soil analytical method that represents HFO, estimated moles of active sites per mole of HFO, soil porosity, etc.), the agreement in the data presented here supports the reductive-dissolution mechanism.

In addition to the observed association of dissolved iron with arsenic, the correlations between solid-phase concentrations of iron and other metals support the surface-sorption scenario (Fig. 6-3). From the soil data (tabulated below) the linear regression of the iron data against each of several other elements yields the following correlation coefficients (R^2):

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[3] log *k* for the formation of $Hfo\_wH_2AsO_3$ was altered from 5.41 (in the WATEQ4f data base) to 5.61 in these calculations. Because these equilibrium constants are often derived from laboratory experiments where pure-phase HFO is used and the surface properties may differ significantly from naturally-occurring HFO at a particular site, it is common practice to adjust the equilibrium constant to achieve a better fit to field data. In this case, the change is relatively small.

Fe vs.:	**GF1 data only**	**GF3A data only**	**All Data**
Al	0.9615	0.9439	0.9477
As	0.752	N/A	0.3238
Co	0.9261	0.9393	0.9019
Cu	0.8271	0.6672	0.7055
Mn	0.6969	0.6643	0.4955
Ni	0.961	0.827	0.8474
Zn	0.961	0.9074	0.9241

*N/A not analyzed

It is apparent from these soil data that solid-phase iron is closely associated with other metals. All of the elements tabulated above are sensitive to pH and ORP and can be relatively mobile under ranges of pH and ORP that are typically encountered in groundwater. It is not surprising, then, that when conditions favor the precipitation of Fe(III) as a solid (e.g., hydrous ferric oxide), arsenic and numerous other trace metals are scavenged simultaneously. The regression results shown here indicate that the correlation between arsenic and iron is weaker than between other metals and iron. It is likely that this observation is related to the occurrence of arsenic as an oxyanion, which exhibits different sorption behavior from that of the other metals that are present in solution as cations.

The correlation between arsenic and aluminum is comparable to that of arsenic and iron, and suggests that aluminum oxyhydroxide or hydroxide phases may also control arsenic sorption. The significance of this mechanism has been reported by Livesey and Huang (1981) and may be relevant for the Grove Pond soils. The saturation indices calculated by PHREEQC suggest the possible presence of a number of Al-containing phases including amorphous $Al(OH)_3$, boehmite and diaspore (both AlOOH), and gibbsite ($Al(OH)_3$), in addition to hydrous ferric iron phases. However, it must be noted that silica was not on the analyte list, and therefore no aluminosilicate phases, such as clay minerals, are predicted by PHREEQC. Although arsenic may be adsorbed at the edges of clay particles, this mechanism is not likely to be as significant as the sorption of arsenic by the oxides of iron, manganese, and aluminum (Cullen and Reimer, 1989; Korte and Fernando, 1991). Moreover, the results of the geophysical logging do not support the presence of large amounts of clay minerals in the overburden.

In summary, adsorption onto iron-, manganese-, and/or aluminum-oxyhydroxide-coated mineral surfaces appears to be the key process controlling arsenic mobility in the Grove Pond system. No evidence from either the soil or groundwater data, or the geochemical modeling results, supports any other mechanism, such as the dissolution/precipitation of a discrete arsenic phase. The saturation indices calculated by PHREEQC from the GF-3A groundwater chemistry indicate that dissolved arsenic concentrations may be controlled by the solubility of the solid barium phase, $Ba_3(AsO_4)_2$. While this result is commonly reported in the literature (e.g., Cullen and Reimer, 1989; Korte and Fernando, 1991, etc.), it is generally viewed with some skepticism due to the lack of field evidence for this phase, as well as a lack of confidence in the thermodynamic data used to predict its occurrence.

6.1.3 Anthropogenic Arsenic

From the late 1800s until the use of dichlorodiphenyltrichloroethane (DDT) became widespread in the 1940s, arsenic was used in a variety of agricultural pesticides, particularly in orchards. Formulations included lead arsenate ($PbAsO_4$), calcium arsenate ($CaAsO_4$), magnesium arsenate ($MgAsO_4$), zinc arsenate ($ZnAsO_4$), zinc arsenite ($Zn(AsO_2)_2$), and "Paris green" (copper acetate – copper arsenite, $Cu(CH_3COO)_2{\cdot}3Cu(AsO_2)_2$) (Anastasia and Kender, 1973; Merry, et al., 1983; in Smith, et al., 1998). The apple-growing industry is presently active in close proximity to Grove Pond, and was likely more extensive historically. Thus, pesticide application has been suggested as a potential source of arsenic to the pond.

The movement of arsenic in soil is complex and is controlled by a number of factors. Arsenic may be lost from surface soils through downward transport by leaching or by sorption onto colloids. Loss may be accentuated in soils with low organic or clay mineral content, or by displacement by phosphate-containing amendments. Arsenic may volatilize, although loss via this mechanism is difficult to quantify. Studies of arsenic that has accumulated in soils as a result of surface applications (e.g. orchard-spraying) indicate that arsenic concentrations are much lower (less than half the surface concentration) in subsurface soils (150-300 mm layer) than in the surface layers (0-150 mm; Smith, et al., 1998). No evidence to date indicates that arsenic in Grove Pond sediments, or arsenic in the aquifer, originates from orchard spraying.

It has been suggested that sulfuric acid was used by the tannery in de-hairing animal hides and that possibly the acid contained arsenic as an impurity. However, pyrite is the principal ore mineral used for the production of sulfuric acid, and its crystal structure precludes the incorporation of more than relatively small amounts of other elements, including arsenic (up to a few tenths of a weight percent), although other minerals such as arsenopyrite (FeAsS) and cobaltite may be present as inclusions within pyrite crystals. It is likely that sulfuric acid used for tannery-related purposes was not highly refined and may have contained impurities. The volume of arsenic that could potentially have been introduced into Grove Pond sediments and groundwater via this source has not been estimated and indeed would be difficult to quantify, but it is probably negligible relative to the concentrations found in the aquifer soils. Sodium arsenite was the active ingredient in the pesticide used extensively to treat animal hides since approximately the early 1900's (Sadler, et al., 1994), but with information presently available, it is not possible to estimate quantities that might have been consumed at the tannery or even to confirm that the tannery used this formulation at all. Moreover, it is difficult to propose a mechanism by which arsenic released at a point source (the tannery), at a distance of approximately half-mile downstream, would be distributed throughout a broadly continuous subsurface soil layer down to a depth of approximately 45 ft bgs.

6.2 Previous Hypotheses

6.2.1 Pond Sediments

It has been postulated that arsenic known to be present in pond-bottom sediment is somehow mobilized into pore water and transported downward to the underlying aquifer by infiltration induced by the pumping wells. This section addresses the partitioning of arsenic from the sediment into pore water.

Because sediment/pore water data from Grove Pond were not available at the time Phase I activities were completed, an alternative investigation of arsenic partitioning in pond sediments was initiated. The 1995 Sediment Evaluation report (ABB-ES, 1995a) includes analyses of ten sediment/pore water sample pairs from adjacent Plow Shop Pond. In order to extrapolate results based on data collected in Plow Shop Pond to Grove Pond sediments, assumptions of similarities in hydrology, geologic setting, meteorological conditions, and geochemical partitioning mechanisms in the sediments are implicit. Data representing 16 samples from Grove Pond (from approximately the eastern half of the Pond, in the vicinity of the Town of Ayer wells) were selected from the 1995 Sediment Evaluation report for comparison to Plow Shop Pond sediments. One additional sample (GRD95-26X3), from the 3-ft depth interval at a sampling location near the former tannery site, was selected for this data set for a 'worst-case' calculation, because this sample contained the highest observed bulk-sediment As concentration in Grove Pond (1300 µg/g). Based on data compiled in the Sediment Evaluation report, average total organic carbon (TOC) content of sediments in both ponds are similar, although the range of TOC concentrations is larger in Grove Pond. Arsenic concentrations are generally higher in Plow Shop Pond sediments. In the selected 1995 Grove Pond samples, TOC ranged from 38,100 µg/g to 645,000 µg/g, and As from 20.8 µg/g to 220 µg/g (excluding GRD95-26X3). These data and those from the Plow Shop Pond samples are summarized in Table 6-1 in the Phase I Interim Data Report (Gannett Fleming, 1999b).

In the ten Plow Shop Pond samples for which pore water data are available, TOC ranged from 116,000 µg/g to 308,000 µg/g, and As from 170 µg/g to 2700 µg/g (Table 6-1 in the Phase I Interim Data Report, Gannett Fleming, 1999b). A partition coefficient, representing the ratio of the concentration of As in sediment to the concentration in pore water, was derived from a linear regression of Plow Shop Pond pore water and sediment data. In order to make comparisons between samples within the Plow Shop Pond data set, as well as to samples from Grove Pond, all As data were normalized to TOC content. Nine of the ten sediment samples from the Plow Shop Pond data set had bulk-sediment As concentrations between 170 µg/g and 650 µg/g As (657 µg/g to 2138 µg/g TOC-normalized As). In the tenth sample, the TOC-normalized As concentration was 16,770 µg/g, approximately eight times higher than the sample with the next highest TOC-normalized As content and more than 40 times higher than the mean TOC-normalized As content of the Grove Pond sediments (excluding GRD95-26X3). Due to the effect that this outlier would have on a linear regression, this tenth sample was dropped from the data set for the calculation of a distribution coefficient (see Fig. 6-1, Phase I Interim Data Report, Gannett Fleming, 1999b).

In comparison, bulk-sediment As in the Grove Pond data set ranged from 20.8 μg/g to 220 μg/g (97 μg/g to 773 μg/g TOC-normalized As, using the TOC values from the 1995 Sediment Evaluation report). With the known TOC-normalized As concentrations from Grove Pond and the partition coefficient derived from the Plow Shop Pond sediment/pore water data set, Grove Pond pore water As concentrations were predicted to range from 36 μg/L to 285 μg/L (Table 6-2, Phase I Interim Data Report, Gannett Fleming, 1999b). The predicted pore water As concentration in sample GRD95-26X3 is 1970 μg/L. Because no arsenic was reported from any of the Phase II sediment samples due to the high and variable detection limits for those analyses, a site-specific partition coefficient could not be calculated for Grove Pond sediments. Nevertheless, the measured pore water arsenic concentrations range from 38.2 μg/L to 138 μg/L (in unfiltered samples), in good agreement with levels predicted by using the partition coefficient derived from the Plow Shop Pond data.

Because arsenic-rich pore water would have to be pulled through several feet of organic-rich pond bottom sediments in order to reach the production wells, concentrations would be expected to be significantly lower, primarily due to sorption or precipitation, by the time pore water arrives at the production well screens. Although only three samples from cores through the pond bottom yielded sufficient quantities of pore water for chemical analysis, the maximum arsenic detected from these samples was 11 μg/L, approximately an order of magnitude less than concentrations observed in pond bottom-sediment pore waters. It should also be noted that, in all three groundwater profiles (GF-3A, GF-4, and BH-1), arsenic was not detected in samples taken at or near the top of the aquifer. Finally, arsenic concentrations in groundwater were observed to *increase* with depth in the three profiled borings (GF-3A, GF-4, and BH-1) from the water table to the extraction horizon (~40 ft bgs). This distribution contradicts any model that invokes downward advection from a surface source.

6.2.2 Local Upgradient Source

Because the Grove Pond wells are located immediately adjacent to, and downgradient of, the former Fort Devens, which is known to have handled a variety of hazardous materials historically, this area must be considered a potential source of the arsenic observed in the Town of Ayer wells. Whether of anthropogenic origin due to historic practices on the base, or of natural origin due to characteristics of the hydrogeological setting of Devens, arsenic in groundwater flowing off the base and toward the Grove Pond wells might be expected to manifest itself in the upgradient monitoring wells MNG-3, MNG-7, and 92-4. This possibility was raised in the review of historic groundwater quality investigations, which revealed that a sample from MNG-7 taken as part of the establishment of the Wellhead Protection Monitoring Network (ENSR, 1993) showed arsenic at 34 μg/L, and nearby monitoring well MNG-6 yielded arsenic at 84. μg/L. However, it is noted that these wells were sampled prior to the establishment of the EPA "low-flow" sampling protocol, and may have been subject to turbidity. In contrast, the two rounds of sampling at each of MNG-3, MNG-7, and 92-4 in this study yielded maximum arsenic levels of 2 μg/L in filtered samples and 4 μg/L (in 92-4 on August 27, 1998) in unfiltered samples collected by the low-flow method. Thus, this study indicates no source of arsenic from former Fort Devens (or the current Massachusetts National Guard facility immediately adjacent to the Town of Ayer property) in the overburden aquifer, at least along flow paths that intersect the screens of monitoring wells MNG-3, MNG-7, and 92-4.

6.2.3 Gravel Pack Source

During Phase I, this study also considered the possibility that the gravel packs encasing the production wells may be contributing arsenic. This hypothesis was suggested by the apparent absence of detectable As in any of the surrounding monitoring wells, and the documented presence of As in locally-derived gravel piles on the Base. Although detailed information on the original construction of the production wells is limited, it appears that highly siliceous Cape May gravel (from Cape May, NJ) was used in PW-2. In subsequent conversations with personnel from D.L. Maher (installers of the original wells) and Tata & Howard (who directed the recent redevelopment), it appears that any gravel used during the original installation of the wells would not have been local crushed stone or granite aggregate.

To discount completely the argument that As could be emanating from gravel packs surrounding the production wells, a mass balance calculation was performed. The original, hand-drawn well log for PW-2 indicates that 35 tons of gravel were used; the mass balance calculation assumes that this material *is* locally-derived granite, with arsenic concentration of order 100 mg/kg.[4] Accurate records of the wells' production history do not exist, and it is known only anecdotally that the wells were pumped sporadically (probably no more than a few times annually prior to startup in July 1998; R. Linde, personal communication, 1999). This calculation assumes a pumping rate of 650 gpm for a total of five 8-hr days per year for 50 years, with an average arsenic concentration of 0.020 mg/L. The result of this exercise suggests that the wells produced approximately twice as much arsenic as would have been available if the entire gravel pack had dissolved completely.

6.2.4 Deep Aquifer / Bedrock Source

The presence of arsenic in the Town of Ayer wells is consistent with other occurrences in groundwaters in bedrock wells in central Massachusetts and southern New Hampshire (e.g., Ayotte, et al., 1999; Peters, et al., 1999; Reitzel, date unknown), and the known presence and distribution of arsenic-bearing minerals. In addition, another nearby production well, pumped at a capacity that is comparable to the Town of Ayer wells, has reported arsenic at concentrations of ~20 to 30 μg/L, along with nondetectable levels of iron. This well is screened at bedrock (see Fig. D-3, Phase I Interim Data Report,

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[4] This number is an order-of-magnitude estimate based on data provided in correspondence between MADEP and Army (letter of 1/4/96 from D. L. Welsh to H. C. Hunt), reporting arsenic concentrations in stockpiled gravel ranging from 117 to 378 mg/kg; and analytical results provided in a memo by G. L. Miller (MFR Update 1/29/96 – Arsenic Rock Pile) in which arsenic is reported at 52.1 mg/kg.

Gannett Fleming, 1999b), at a location where bedrock may be the same unit as that underlying Grove Pond. The unnamed well is not located near any known arsenic source, nor is it receiving any induced infiltration from any pond, as the nearest body of surface water is more than half a mile away. Although limited, the data from this unnamed well are consistent with observed concentrations of both iron and arsenic in groundwater from bedrock underlying the Town of Ayer wells.

The data obtained in the Grove Pond investigation confirm both the presence of arsenic-bearing sulfide minerals in underlying bedrock, and elevated levels of arsenic in bedrock groundwater. However, mixing ratios derived from major-element chemistry indicate that bedrock water may be present in the production wells as only a relatively small contribution to the "deep aquifer" composition as represented on the Piper diagrams (Section 5.2; Figs. 5-2 and 5-5). In addition to the mixing calculations, the vertical distance from the bottom of the production well screens to bedrock (about 50 ft), and the intervening oxidizing conditions (at least 20 feet, from about 60 to 80 ft bgs) argue against a significant contribution of bedrock water directly to the wells.

It is tempting to correlate the early-time, high As concentrations at the outset of Phase I with other trace metals observed in the production wells (i.e., Co and Ni in PW-1; Cu in PW-2). As discussed in Section 3.4.2, arsenic commonly occurs in a number of sulfide minerals, including those containing Cu (chalcopyrite), and Co and Ni (cobaltite, pyrite). One may then speculate that the two production wells are located over two different fracture zones, each with distinct sulfide mineralogies. However, the late-time (October 1998) excursion of As concentrations, observed by sampling in this study as well as the Town of Ayer's analyses, was not accompanied by increases in Cu, Co, and Ni, as would be expected if fracture-zone sulfide minerals were the source.

An alternative explanation for the association of As with Cu, Co, and Ni in early-time samples may lie in the wells' rehabilitation history. A new stainless steel screen was inserted into PW-1, inside the old screen, and PW-2 retained its original silicon bronze screen. The strong correlation between As and Cu in PW-2 may be due to residual effects of surging with HCl and other chemicals prior to startup. Similarly, the corresponding association of As with Co and Ni in PW-1 may be a residual effect of the rehabilitation activities on the new stainless steel screen (the absence of detectable Cr, though, is an open question). The early-time appearance of Al in PW-1 may also be due to the presence of extremely fine, possibly colloidal, inorganic particulates (especially clay minerals) remaining in suspension after the initial cleaning revealed that the bottom of the old screen was extremely degraded. This explanation is consistent with the early-time appearance of these metals; the increase in As observed in October 1998, which was *not* accompanied by increases in any of these metals, is consistent with natural fluctuations in As that have been observed throughout the wells' history.

At present, there is no explanation for these fluctuations. During the course of this investigation, attempts were made to correlate the range of observed arsenic values with changes in either local precipitation (which might affect recharge, either to the overburden aquifer, or through the deep aquifer or bedrock) or changes in production from the wells. No correlation with either of these influences is apparent, from the limited data.

6.3 Conceptual Model (This Study): Mobilization of Arsenic by Reducing Water

Results of this investigation suggest that naturally-occurring arsenic, derived from arsenic-bearing minerals in bedrock, is adsorbed onto Fe- and/or Mn- and Al-oxyhydroxide coatings on the glacial deposits comprising the aquifer. When contacted by reducing waters, these oxide coatings dissolve and release iron, manganese, arsenic, and other elements into solution. This mechanism has been discussed recently in conjunction with observations of elevated arsenic in groundwater at numerous sites worldwide (e.g., Matisoff, et al., 1983; Cullen and Reimer, 1989; Smedley and Kinniburgh, 2002). The presence of elevated concentrations of dissolved arsenic, iron, and manganese, and the correlation of these elements, both temporally in the Town of Ayer production wells, and stratigraphically in their vicinity, is consistent with this mechanism.

The simplest stratigraphic model for the Grove Pond site is composed of three layers:

1. The upper aquifer (to ~45 ft bgs) consists of a vertically heterogeneous unit of much lower conductivity, characterized by low ORP and high dissolved iron and arsenic. On a scale of centimeters to a meter, the unit is composed of sands, sandy silt, and gravel, with correspondingly variable hydraulic conductivities, but overall the gross conductivity is lower than that of the underlying layer. The conductivity is of the order of a few feet per day in the shallow subsurface, and generally increases with depth to the producing horizon;

2. The producing horizon is a relatively fast sand-and-gravel layer from about 48 ft to 65 ft bgs. This interpretation is based in part on boring and geophysical logs and also from the groundwater chemistry observed in the GF-3A and BH-1 profiles. The groundwater through this zone is oxidizing and the upper portion is characterized by high chloride and nitrate and lower alkalinity;

3. The "fast layer" is underlain by interbedded materials of variable conductivity, overlying bedrock.

Overall, the low vertical conductivity of the interbedded sands and silts comprising the upper ~40 feet of the aquifer inhibits transport of groundwater from the pond downward to the pumping horizon. The lateral extent of this hydrostratigraphic structure is unknown. Continuity was found on the scale of GF-3A to GF-4 to BH-1, separated by ~200 ft. However, it is noted that the Devens well field, approximately 1000 ft west of GF-4, appears to be screened in oxidizing groundwater at depths ranging from 30 to 48 ft bgs (sec. 1.3.4), based on the high sulfate and non-detectable iron in these wells. Evidently, then, the gross hydrostratigraphic units identified near the Town of Ayer wells either vary in thickness or are not continuous on a scale of the order of 1000 ft. Redox conditions, in turn, can be expected to vary spatially over similar scales.

Evidence from the Phase I work and subsequent sampling of the upgradient wells (MNG-7, MNG-3, 92-1 and 92-4) suggest that groundwater entering the screens of those wells is oxidizing. In the single sampling event at 92-5, ORP was not determined, but the high sulfate and low iron are indicative of oxidizing conditions and suggest that this well, too, may be completed in a sandy layer. In the most simplistic scenario for the production wells, the contact between layers 1 and 2, as described above, occurs in the upper portion of the well screens. This scenario is consistent with the chemical mixing argument developed in Section 5.2. The following sections present a detailed discussion of the conceptual model for arsenic in the Town of Ayer wells, in which all of the relevant geologic, hydrologic, and geochemical data collected during this investigation are assimilated.

6.3.1 Geologic Setting

A detailed investigation of the Quaternary geology of the study area was beyond the scope of this study. Consequently, much of the following section is qualitative and speculative, but the objective of this section is to develop a description of the geological setting that is consistent with information collected to date, in order to construct a geological framework for the conceptual model of arsenic source and transport.

It is likely that the Wisconsinan glaciation (during the period from ~70,000 yrs to 10,000 yrs b.p.) followed the existing topography in the immediate vicinity of Grove Pond. Results of the geophysical survey and from bedrock coring indicate that the study area may be underlain by one or more faults. Erosion of the basal surface by the glaciers may have been influenced by this fault zone, and the resulting sedimentary deposits would likely reflect the local bedrock mineralogy. Metal sulfides such as pyrite and cobaltite, containing arsenic at concentrations ranging from a few tenths of a weight percent to ~45 weight percent, respectively, have now been positively identified in bedrock beneath the production wells. Subsequent *in situ* weathering of the glacially deposited sands, gravels, and rock fragments likely resulted in mobilization and redistribution of redox-sensitive elements, notably iron, manganese, and arsenic. The development of the present-day groundwater redox profile may be related to the former presence of glacial Lake Nashua and/or other geomorphic features. Although the timing of the development of this profile is, at present, unknown, the information presented in this study is consistent with both the presence of organic carbon (e.g., in the hypothesized lacustrine environment) and the occurrence of hydraulically tighter, siltier material in the upper sands and gravel.

The overburden aquifer at the Town of Ayer wells appears to be a fluviodeltaic sequence, consistent with ice-marginal fluvial and ice-marginal deltaic morphosequences, as described by Stone, et al. (1999). The aquifer is composed of a coarsening-upward sequence of sand and gravel from the bedrock or patchy basal till at ~112 ft msl to the top of the pumping horizon at ~170-175 ft msl. The upper ~45 ft of the aquifer is a fining-upward sequence, presumably representing a lower-energy depositional environment. More prevalent silty interbeds in the shallowest aquifer may represent lacustrine intervals. Hydraulic conductivities inferred from slug tests, grain size analyses, and specific capacity data increase downward from the shallowest aquifer, where K is of the order of a few feet per day, to the pumping horizon, where K is of the order of several hundred feet per day. The fine structure, including thin, silty interbeds, results in vertical hydraulic conductivities overall that are likely one to two orders of magnitude lower than the horizontal conductivities. The low-conductivity domain in the shallowest subsurface results in long residence times for groundwater in the upper aquifer, and the low effective vertical conductivity inhibits recharge by oxygenated water from the surface. This hydrostratigraphic control on transport rates is conducive to the development of reducing conditions in the upper aquifer.

In a simplified representation of the oxidation of organic matter, naturally occurring organic carbon is consumed by oxygen in equimolar quantities, e.g.:

$$CH_2O + O_2 \rightarrow CO_2 + H_2O$$

Although data for TOC in the Grove Pond soil samples are sparse and qualified by the analyst (Table 4-9) due to the extremely heterogeneous nature of the overburden material, an average TOC value for soils in the upper part of the aquifer is about 750 mg/kg. At saturation, the concentration of dissolved oxygen in groundwater would be approximately 10 mg/L or 0.3125 mM. Consumption of 0.3 mM O_2 (the maximum that could be available, assuming O_2 saturation of groundwater) would result in the oxidation of 0.3 mM organic matter, or about 4 mg organic carbon. When normalized to the mass of soil associated with a liter of solution (~5 kg, at a porosity of 35%), the depletion of all dissolved oxygen in the groundwater results in the oxidation of approximately 0.1% of the TOC that is present in the upper aquifer. Groundwater in this part of the aquifer will remain anaerobic as long as the rate of removal (through the oxidation of organic matter) exceeds the rate at which oxygen can enter the system, e.g. by recharge with aerobic groundwater or through diffusion. The presence of siltier, lower-K lenses or stringers throughout the upper aquifer precludes the rapid influx of oxygenated groundwater, and the diffusion of atmospheric oxygen into the system is too slow to be effective.

Soil chemistry was also considered in attempting to interpret depositional environments. The profiles shown in Figure 4-10 show a zone above about 25 ft bgs (~195 ft MSL) that is depleted in all metals relative to the underlying soils, possibly representing a weathering horizon. Between approximately 25 ft and 40 ft bgs (195 to 180 ft MSL), and between 40 ft and 60 ft bgs (180 to 160 ft MSL), the soil profiles show an increase in concentrations of all of the PAL metals. These maxima may represent two episodes of deposition, separated by another subaerial weathering horizon, inferred from the depleted zone around 40 ft bgs (~180 ft MSL).

Qualitatively, the observed redox profile is also consistent with the presence of relatively fine-grained, low-conductivity material overlying the coarser-grained, highly conductive, sand/gravel lower aquifer. The ORP profiles measured in groundwater clearly indicate that reducing conditions prevail in the upper 30--40 ft of the aquifer. Below this depth, the environment is oxidizing, but becomes reducing again at the bedrock interface. The presence of an oxidizing zone is consistent with a coarsening-upward deltaic sequence, creating a high-hydraulic-conductivity "fast path," composed of coarse sand and gravel, carrying relatively well-oxygenated groundwater. Vertical profiles of key redox-sensitive elements in groundwater (including arsenic, iron, manganese, and sulfate) as well as chloride and nitrate are consistent with this scenario. It must also be noted that the redox profiles were measured only under pumping conditions; it is not known what the ambient conditions would look like in the absence of pumping, or the extent to which the production wells affect the local redox conditions as measured in the groundwater profiles.

The water sampled along the profile at GF-3A at approximately the mid-point of the production well screens is characterized by unusually high chloride and nitrate, elevated lead, and lower pH and alkalinity than groundwater from above or below the high-chloride interval, all of which may signify urban impact. The high chloride concentrations observed in the GF-3A groundwater profile between approximately 35 ft and 70 ft bgs (185 and 150 ft MSL) possibly reflect road salt in the area of recharge to the north, i.e., the Town of Ayer, indicating that water is coming from the far side of the pond. This conclusion is also supported by the drawdown of 0.32 ft that was observed in well 92-5, located on the north shore of the pond, in the September 1992 pumping test (CDM, 1992). A drawdown of this magnitude, more than 900 ft away from the supply wells, with much of that distance covered by surface water, indicates clearly that the production horizon responds as a semi-confined aquifer, and that the capture zone for the pumping wells is extensive. Moreover, high chloride (107 mg/L) was reported from 92-5 at the outset of this investigation; this was the *only* well in which Cl was significantly elevated at the time pumping was initiated at the production wells. Chloride in groundwater to the south (e.g., 92-1, 92-4, MNG-3 and MNG-7) is significantly lower (in the general range between 4 mg/L to 40 mg/L). In the production wells, chloride concentrations are intermediate (initially, approximately 40 and 30 mg/L for PW1 and PW2, respectively) and increase with time, to 59 and 43 mg/L. Chloride in 92-3 also increases systematically with time, suggesting that this well screen is intercepting flow from the north side of the pond to the production wells. The high-chloride, high-nitrate zone is also seen in the groundwater data from BH-1. In GF-4 (the far-field well), chloride increases slightly between 36 and 50 ft bgs, and then decreases markedly between 58 and 75 ft bgs. These trends are interpreted as indications of groundwater pulled from the Town side of the pond and groundwater discharging to the pond from the south side (from the direction of the Mass. National Guard property), respectively. The high-chloride anomaly occurs in samples where ORP was positive, consistent with the movement of oxygenated groundwater along a 'fast path' from the north side of the pond.

This stratigraphic interpretation is somewhat speculative. Nevertheless, the evidence presented in this report supports this interpretation of the general sequence of events in this area and is consistent with the region's overall Quaternary geological history.

Elevated levels of arsenic were also reported from bedrock water beneath the Town of Ayer production wells and from another, nearby, water-supply well (the "unnamed well") screened just above bedrock. In addition, the presence of arsenic-bearing sulfide minerals in the underlying bedrock has been confirmed. However, the bedrock does not appear to be the source of the arsenic detected at the supply wells, based on a number of observations in this investigation, including major-element chemistry, the lack of a correlation between dissolved iron and arsenic in the bedrock groundwater, and the thickness of the aquifer between the bottom of the producing well screens (around 60 ft bgs or 160 ft MSL) and bedrock (around 110 ft bgs or 112 ft MSL). Furthermore, the profile at GF-3A exhibits positive ORP over an interval approximately 15 ft thick below the bottom of the production well screens. This oxidizing interval would serve as a barrier to upward transport of dissolved arsenic.

6.3.2 Production Well Water Source

It appears that a significant fraction of the output of the production wells comes from the highly conductive zone between approximately 40 ft and 80 ft bgs (180 to 140 ft MSL), and the remainder is drawn from the zone immediately above. This interpretation is supported by a number of observations drawn from the groundwater chemical data:

- Piper diagram results suggest that the major-element composition of water at the production wells is consistent with mixing of ‘upper aquifer’ and ‘deep aquifer’ compositions, in a ratio that is close to 50:50.

- The compositions of the production wells, when plotted on the Piper diagrams, change with time, moving away from the point representing the shallow-aquifer composition and toward the ‘deep aquifer’ after the initial start-up in July 1998. This shift in production well composition is consistent with the expected transient associated with start-up. Immediately following initiation of pumping, the volume produced is derived from a zone local to the well, and must draw significantly from above and below the screened interval. As the longer-term head distribution becomes established with prolonged pumping, water is derived principally from a wide-reaching, predominantly radial flow, and the fraction of shallow-aquifer water produced is expected to decrease.

- Chloride concentrations in the production wells are intermediate between groundwater from the south (e.g., 92-1, 92-4, and the MNG wells) and from the north (e.g., 92-5) and increase with time, as does the chloride concentration in 92-3. These observations indicate that higher-chloride groundwater from the north side of the pond is reaching the production well screens and mixing with lower-chloride water from the south.

- Stable-isotope results show that the production wells have approximately the same isotopic signature as the other wells screened in the same interval, suggesting that their isotopic compositions are representative of the ambient aquifer. Stable-isotope data from the production wells and monitoring wells are, however, distinctly different from the pond samples. The isotopic distributions (Fig. 4-13) do not support any scenario suggesting that pond water mixes with water from any of the monitoring wells to produce the compositions observed at the pumping wells. While the isotopic composition of Grove Pond surface water may fluctuate more than the range indicated by the limited number of samples that were analyzed in this study, the production wells are isotopically similar to the bulk of the deep-aquifer water.

- The isotopic signature of the sample from GF-3B, at the top of the aquifer, is significantly heavier than either the pond or the deeper aquifer water. The water from GF-3B may reasonably be interpreted as an "end-member" composition that is representative of relatively recent rainfall. If the other wells are considered as the other isotopic end-member, one may conclude that the pond itself is the result of mixing of shallow water (close to the isotopic character of meteoric infiltration) with water from deeper within the aquifer. In addition, the pond receives contributions from direct precipitation and surface runoff, which would also carry the heavier isotopic signature .

- The stable isotope data are also consistent with the mixing of upper and lower aquifer waters in the production wells, assuming that GF-3B, from the top of the upper aquifer, is representative of the isotopic signature of that 40-ft-thick unit. The mixing ratio derived from this speculative argument is approximately 10% water from the upper part, and 90% from the lower aquifer. The discrepancy in this mixing ratio (compared to that derived from the major-element chemistry) is likely due to the lack of isotopic data from the high-arsenic groundwater at the base of the reducing zone in the upper aquifer.

- Hydraulic conductivities, inferred from slug test, grain size distributions, and specific capacity data, are one to two orders of magnitude larger in the pumping horizon than in the shallowest aquifer. The upper ~40 ft of the overburden serve as a semi-confining layer to the production zone. Extraction of water at the supply wells is therefore focused within the high-conductivity screened interval, and the head drop within this zone causes "leakage" from the overlying shallow aquifer, as well as drawing from the underlying region.

6.3.3 Arsenic Source and Pathway

No chemical or hydrologic evidence collected during this investigation indicates that the pond contributes significantly to the water produced by the pumping wells. It should be noted that the piezometer data clearly indicate a head drop across the pond-bottom sediments when the water-supply wells are pumping, and, therefore, that *some* infiltration is induced. Direct measurements by seepage meters indeed support this conclusion, showing consistent downward flow at the pond water / sediment interface, and a significant drop in the magnitude of this flux when the pumping wells are off. However, the maximum downward flux measured with the seepage meters is 0.0034 ft/d, which, when integrated over a 300-ft radius from shore, amounts to less than 1% of the well production. This is consistent with all indications from the chemistry of the system which suggest that the contribution of pond water to the production wells is negligible.

Arguments based on groundwater chemistry that point toward the upper aquifer, and not the pond or bedrock, as the source of the arsenic observed at the pumping wells, include:

- The decrease in arsenic concentrations following the initial start-up of the production wells. The decline in arsenic levels in the first three days after the wells were turned on in July 1998 is consistent with the hydrologic scenario. The vertical gradient from the shallower, reducing, high-arsenic portion of the aquifer to the production horizon would be maximum at early time, and decrease as the flow field becomes established. This would be accompanied by a decrease in arsenic at the pumping wells as the proportion of shallower aquifer water decreases. In contrast, if the arsenic produced at the supply wells originated in pore water in pond-bottom sediment, one would expect a classical "breakthrough" of increasing arsenic concentration with time. However, the opposite was observed.

- The correlation between iron and arsenic in production well water (Fig. 6-1) throughout the first 18 months following start-up (excluding the first two days, when scatter in the iron data is large, probably due to particulate or colloidal iron). This observation is also consistent with the reductive-dissolution mechanism.

- The positive correlation between dissolved iron and arsenic throughout the reducing zone in the vertical profiles of GF-3A, GF-4, and BH-1, and the correlation between iron, arsenic, and ORP (Figs. 6-2 and 6-4). The association of iron and arsenic is consistent with the 'reductive dissolution' mechanism, whereby arsenic adsorbed on ferric oxyhydroxide surfaces is liberated by dissolution of the iron phase under reducing conditions.

- The absence of any correlation between iron and arsenic in pore water in pond-bottom sediments. The mobility of both of these elements under reducing conditions (i.e., below the pond bottom, down to the redox transition zone around ~45-50 ft bgs) suggests that their association in the groundwater profiles should be equally random if their initial concentrations had arisen in the pond. The observed correlation of iron with arsenic in all three vertical profiles below the pond bottom contradicts the pond-bottom sediment source scenario.

- The decrease in arsenic in pore waters from soft-sediment cores through the pond bottom. Arsenic is present in Grove Pond bottom-sediment pore waters at levels up to 111 µg/L (Table 4-12), but pore water concentrations decreased by an order of magnitude (Table 4-13) within approximately two feet of the sediment-water interface. This rapid attenuation suggests that organic matter in pond sediments may play a significant role, either directly (through sorption or complexation) or indirectly (by facilitating sulfide formation and associated arsenic precipitation), in scavenging dissolved arsenic and other metals associated with surficial sedimentary processes.

- The increase in arsenic with depth in the vertical-profile groundwater samples. If the arsenic reaching the production wells originated from a surficial source – for example, the pond – concentrations should *decrease* with depth through the aquifer beneath the pond-bottom sediments due to attenuation (i.e., adsorption onto organic and inorganic surfaces in the overburden). In fact, the observed *increase* in arsenic with depth in upper ~40 ft of the aquifer, to levels significantly higher than those detected in pond bottom-sediment pore water, contradicts this scenario, but is consistent with the measured redox profiles.

- Mixing ratios of upper- and lower-aquifer water. Major element chemistry suggests that the composition of groundwater sampled at the production wellheads can be obtained by binary mixing of end-members composed of "shallow-aquifer" and "deep-aquifer" waters. From the Piper diagrams, a mixing ratio of approximately 45:55 shallow to deep aquifer water is estimated. Because the chemical profiles (for example, the results from GF-3A) show that the arsenic concentration increases with depth, up to 189 μg/L, this mixing ratio suggests that arsenic in the production wells should be much higher than the 20-30 μg/L usually observed. This nonconservative behavior may be due to the sorption of arsenic onto ferric oxyhydroxide surfaces formed near the redox transition near the top of the screened interval, or near or within the production well screens. In these areas, reducing water high in dissolved, ferrous iron from the upper part of the aquifer is mixed with more oxidizing groundwater drawn toward the screens. In other words, the arsenic concentrations are attenuated by sorption. It is likely that some of the iron measured in the production well water is not actually present as Fe^{+2}, the form that would be thermodynamically stable in reducing waters from 'shallow aquifer,' but in reality is colloidal ferric hydroxide that is smaller than the 0.45 μm filters used in sampling. Both of the production wells required rehabilitation during the summer of 2000 due to excessive iron fouling; this is consistent with the turbulent mixing of reducing water high in dissolved iron with more oxygenated water at the well screens.

- Fluctuations in arsenic levels. Arsenic levels have been observed to vary at the production wells, both within the time frame of this study and historically. This may reflect seasonal variations in aquifer conditions that result in hydraulic head differences, volume and timing of upper-aquifer recharge, and/or variations in the sampling schedule relative to the pumping schedule. These sources of uncertainty have not been quantified at this time.

- Arsenic distribution in overburden. Results from the soil profile sampling suggest that the solid-phase arsenic content of the upper 40 feet of overburden does not differ significantly from that of the lower part, below the redox transition zone. The observed correlations between solid-phase iron and arsenic, and between iron and other metals, support a scenario in which all of these elements were mobilized during post-depositional diagenesis of sulfide minerals derived from bedrock and their subsequent adsorption by ferric oxyhydroxides.

- Arsenic in bedrock groundwater. Elevated arsenic was identified in bedrock groundwater (up to 139 μg/L), but is not associated with dissolved iron. Moreover, in the 45-ft interval between the bottom of the extraction screens and the bedrock surface, groundwater exhibits arsenic below detection limits. These observations support the conclusion that bedrock groundwater does not contribute a significant fraction of the arsenic detected at the supply wells.

7.0 CONCLUSIONS

7.1 Key Results

From the arguments outlined in Section 6, some of the possible sources of arsenic in the Town of Ayer wells can be eliminated. The possibility of a local upgradient source (Section 6.2.2), located to the south of Grove Pond, is not supported by results obtained during this study from the wells MNG-3, MNG-7, and 92-4. The gravel-pack origin has been discounted by conversations with personnel from D. L. Maher (original installers of the production wells) and the simple mass balance calculation presented in Section 6.2.3.

Cobalt and nickel were detected in the initial groundwater sampling rounds at PW-1, and copper was detected only from the initial sampling rounds at PW-2. It is known that the bedrock from GF-1, adjacent to PW-1, contains cobaltite and pyrite, and it is likely that other sulfide phases are also present. These elements may have been mobilized along with arsenic during post-depositional diagenesis of the glacial deposits that comprise the overburden. Like arsenic, these elements are also susceptible to sorption by ferric oxyhydroxides. A possible explanation for the appearance of Cu, Co, and Ni in the initial samples is the dissolution of solid ferric oxide phases in the vicinity of the well screens by the pre-startup HCl treatment and the subsequent release of the sorbed elements. However, Cu, Co, and Ni were not detected above their respective MDLs during the remainder of the study, including the sampling in October 1998 when As values were relatively high and reproducible by independent sampling. The initial detection of certain trace metals (particularly Al, Co, Cu, and Ni) in the production well water remains unexplained, but may reflect the pre-startup well development activities and differences in well screen materials. A new stainless-steel screen was installed in PW-1, while the original silicon-bronze screen was retained in PW-2. The appearance of Al may be due to turbidity, and Co and Ni in early-time PW-1 samples may reflect the initial surging with HCl, although the absence of Cr is suspicious if the new steel screen was the source. Alternatively, it is possible that the transient appearance of these elements is indirectly related to the oxidation of sulfides in fractures immediately beneath the production wells.

The observed increase in arsenic in the production wells during October 1998, in July 1999, and in February 2000 cannot be explained by data obtained from this investigation. There is no apparent correlation of these arsenic levels with either fluctuations in production from the wells or rainfall events. The elevated arsenic concentrations that were observed during the October sampling event are apparently transient, as established by later sampling by the Town of Ayer. Moreover, available historical records show that the arsenic content in these wells has fluctuated between ~10 μg/L and 30 μg/L for years, for reasons that have not been explained.

Finally, a number of scenarios for the likely arsenic source(s) were considered and several were discounted. The deep aquifer material and/or bedrock do not appear to be candidates, in spite of the presence of elevated arsenic in bedrock groundwater. Major- and trace-element chemistry, stable isotopes, and mixing ratios do not support a significant contribution of bedrock groundwater to the production wells. In addition, the very high hydraulic conductivity of the production horizon and the large depth to bedrock (~50 ft from the bottom of the well screens), suggest that only a small fraction of the extracted water is derived from the deepest portion of the aquifer.

The previous section discussed the points in favor of a shallow-aquifer origin for the arsenic in the Town of Ayer wells. Key conclusions from this study are:

1. Arsenic observed in the Town of Ayer water supply wells is naturally-occurring and originates within the upper 40 feet of the aquifer. Within the reducing upper part of the aquifer, and also in water from the production wells, dissolved iron and arsenic are positively correlated, and both iron and arsenic are correlated with the vertical profiles of ORP (e.g., Fig. 6-4). These associations are consistent with the dissolution of ferric oxyhydroxide coatings on aquifer material and release of adsorbed arsenic under reducing conditions. Solid-phase arsenic is more or less homogeneously distributed through the overburden, and arsenic (as well as other elements) is strongly correlated with iron in the soils. Agreement between the theoretical sorbed arsenic mass, obtained with PHREEQC using the groundwater data from the profile sampling, and soil analytical results supports the conclusion that reductive dissolution of solid ferric oxyhydroxide coatings is the mechanism responsible for liberation of arsenic into solution.

2. Arsenic is observed in pore waters from pond-bottom sediments, but analyses from the soft-sediment cores showed that concentrations decrease by an order of magnitude within two feet of the sediment-water interface. In all three groundwater profiles, arsenic concentrations were below detection limits at or near the top of the aquifer. Furthermore, below the pond-bottom sediments, the concentration of arsenic in pore water increases with increasing depth within the upper 40 feet of the overburden, implying that transport is not from the surface downward. This concentration gradient is the reverse of what would be expected if Grove Pond sediments were the arsenic source.

3. The production wells are screened across the interface between the high-arsenic, low-ORP upper aquifer and the underlying, low-arsenic, oxidizing water. The groundwater profile from GF-3A shows that this interface occurs within the upper half of the production well screens (Fig. 6-4).

4. Estimates of the mixing ratio based on major-element chemistry suggest that the contributions to the production wells from the upper aquifer (upper 45 ft) and the lower aquifer (65 ft to bedrock) are approximately equal.

5. Piezometer data indicate that some induced infiltration occurs due to the pumping wells. Piezometer data indicate a measurable head drop (maximum recorded: 0.4 ft) across the pond-bottom sediment under pumping conditions. Thus, some induced infiltration clearly occurs. However, direct measurements of the infiltration flux by seepage meters indicate a small magnitude (maximum recorded: 0.0034 ft/d),

consistent with the chemical indicators of a negligible component of surface water at the supply wells.

6. Bedrock water contains elevated levels of dissolved arsenic, but the major-element chemistry does not indicate that significant quantities of water from this source reach the production wells on a direct path. The deep aquifer water is ultimately composed of bedrock water as well as overburden groundwater flowing toward the pond from the south.

7. Arsenic, iron, manganese, and other pH- and redox-sensitive elements are mobile under certain commonly occurring geochemical conditions. Sulfide minerals containing these and other elements are stable only under extremely reducing conditions, which apparently exist in the bedrock underlying the Town of Ayer wells (as evidenced by the very low groundwater ORP measurements in GF1 and GF2, and the abundant graphite observed in the bedrock core). When removed from these conditions – for example, by mechanical erosion of bedrock by glaciation, and subsequent transport and deposition – these minerals are no longer thermodynamically stable and break down through chemical processes that include oxidation and hydrolysis (e.g., in the case of pyrite, oxidation of Fe^{+2} and S^{-2}, to Fe^{+3} and SO_4^{-2}, respectively, and the hydrolysis of Fe^{+3} to $Fe(OH)_3$). When the redox potential and pH reach critical values, elements such as iron may reprecipitate as ferric oxide or oxyhydroxide coatings on the surfaces of mineral grains making up the overburden. These coatings effectively scavenge other elements, including arsenic, by complexation onto the oxide surfaces. Such associations are clearly seen in the soil analyses reported in this investigation.

8. The close-interval sampling of soil and groundwater conducted during this study yields abundant evidence of significant geochemical and hydrologic heterogeneity in the overburden. In addition, the difficulty encountered in the attempts to identify stratigraphic correlations from the geophysical logs underscores the need to consider 3-dimensional spatial relations when installing wells or sampling soil or groundwater. As the Phase I results demonstrated, wells that are screened at a particular horizon may miss a key interval entirely. A single set of groundwater or soil samples may not accurately represent the range of conditions present in the subsurface.

9. Arsenic distribution and mobility may be controlled by more than one mechanism. Results of this study and others indicate that the 'reductive dissolution' of ferric oxide coatings and subsequent release of sorbed constituents may be the process that is responsible for elevated levels of arsenic that are observed in many overburden aquifers. However, this investigation and others have also reported bedrock water that is high in arsenic but low in dissolved iron. The mechanism responsible for these observations is less well-understood and currently lacks an explanation. Nonetheless, the bedrock groundwater does not contribute significantly to the pumping wells in this particular setting.

7.2 Unresolved Questions

Although results described in this report shed new light on some of the questions surrounding the source of arsenic to the Town of Ayer wells, a number of issues have not been completely resolved.

1. Bedrock mineralogy has not been thoroughly characterized. The abundance, variety, and distribution of sulfide mineralization have not been quantified, nor has arsenic content been adequately analyzed for a representative number of bedrock samples or cores.

2. Bedrock hydrology has not been explored, particularly with respect to fracture characteristics (e.g., density, orientation, aperture, connectivity, effective hydraulic conductivity).

3. There remain ambiguities in the characterization of induced infiltration. Although the weight of evidence suggests that the pond contributes negligibly to the pumping wells, at least along pathways sufficiently fast that the pond water chemical and isotopic characteristics are retained, the very high vertical conductivities found for pond-bottom sediments are seemingly contradictory results.

4. Thermal anomalies observed in the pumping horizon intersected by GF-1 are not fully understood.

5. The influence of pumping on the observed redox profile in the groundwater, particularly the very rapid increase in ORP from ~-200 mV to ~50 mV between 43 and 50 feet bgs, is unknown. No vertical characterization was done prior to operation of the supply wells.

Finally, there remain some broader, scientific questions that bear on the evolution of the system as it is observed today. For example, this investigation does not address details of the process(es) or mechanism(s) responsible for the observed distribution of iron oxides (e.g., as surficial coatings on mineral particles), as well as the distribution of arsenic and other inorganic constituents, in the overburden. In addition, the timing of the evolution of the redox conditions, as a function of glacial movement and development of post-glacial fluvial and/or lacustrine environments, remains unexplored. Also, numerous issues pertaining to the bedrock geology and the Quaternary evolution of the overburden geomorphology are not fully understood at this time.

It was noted previously (e.g., Section 4.1.1) that background levels were established for arsenic and other metals in Devens groundwater during the 1993 Remedial Investigation (ABB-ES, 1993), and that sampling may have been conducted prior to use of the low-flow sampling protocol mandated by EPA Region I. Results in the 1993 Remedial Investigation report a background value of 10.5 µg/L for arsenic. Results from this study suggest that this value (as well as those for the other metals listed in Table D-4) should perhaps be reevaluated. The profile sampling conducted during this investigation (e.g., Fig. 6-4) revealed that dissolved arsenic in groundwater ranged from nondetectable (< 5 µg/L) to 189 µg/L, and that concentrations were dependent on the location of the well screen in the aquifer relative to the redox profile. Inasmuch as the arsenic observed throughout the aquifer appears to be naturally occurring, perhaps the use of a single, basewide "background" value for groundwater arsenic should be reconsidered, or at least qualified with respect to the redox conditions from which it was derived.

In a more general sense, perhaps the definition of "background" should also be refined, with particular attention to selection of wells appropriate for each site and all of the geochemical environments that are represented therein. Background wells are often located upgradient from sites of known contamination areas. Because such locations are frequently areas where groundwater recharge occurs, it seems possible that background data sets in general are biased toward oxidizing conditions. As results from this investigation clearly show, naturally induced reducing water may be justifiably representative of local site conditions.

Other, broader issues that are not addressed in this report include the applicability of these results to other sites, both on the Devens reservation and elsewhere. Given the information assimilated here, one can only speculate about the frequency of occurrence of the groundwater profiles observed at Grove Pond. Perhaps future studies will add to the growing arsenic literature by including soil and groundwater data obtained through close-interval, profile sampling.

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ENGINEERS AND PLANNERS

SITE LOCUS MAP

GROVE POND ARSENIC INVESTIGATION
Fort Devens
Ayer, MA

Scale: 1:25,000

Figure: 1-1

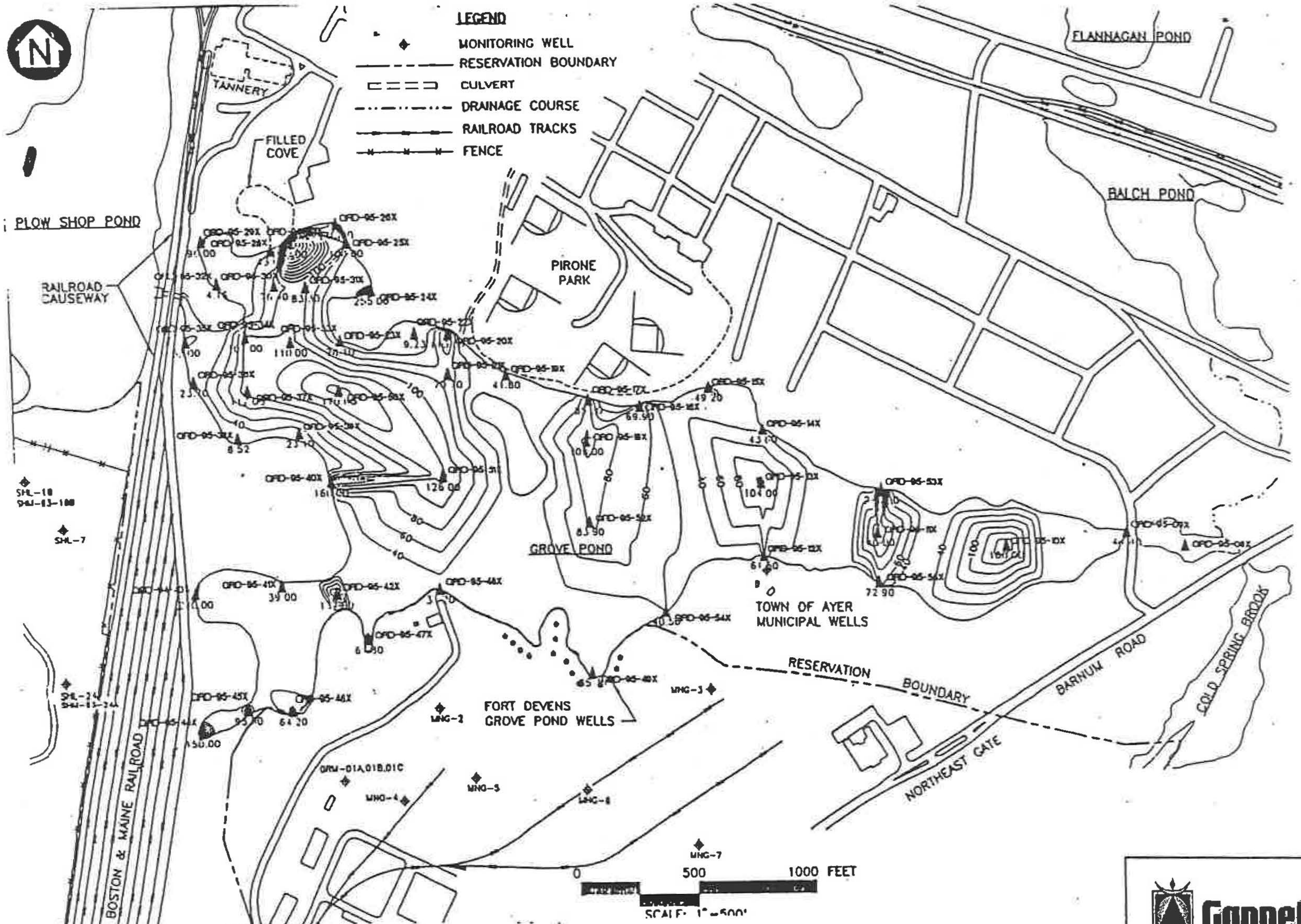

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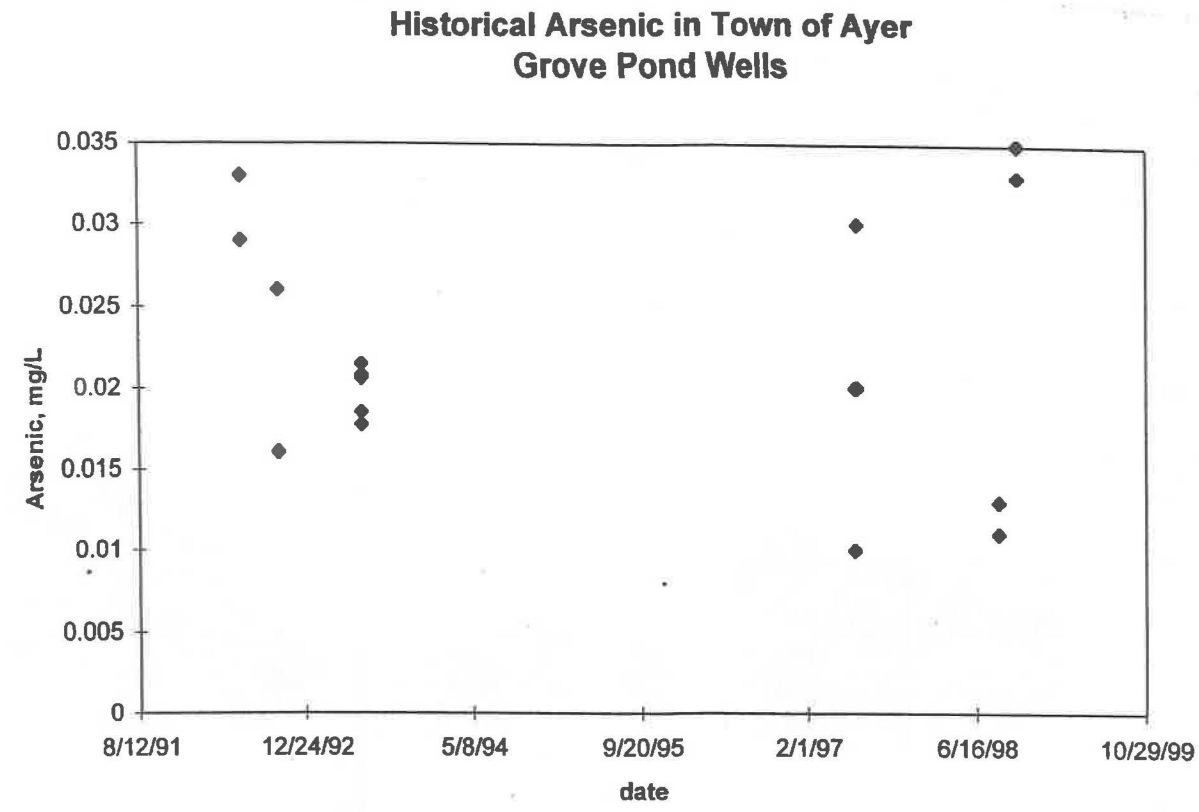
FIGURE 1~~3~~2
Bulk Sediment Arsenic Contours
Grove Pond Arsenic Investigation
Fort Devens

Note : Plan Detail from 1995 ABB Report



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Historical Arsenic Data
Grove Pond Arsenic Investigation
Fort Devens
Figure 1-#3

Old Well Locations - Phase I

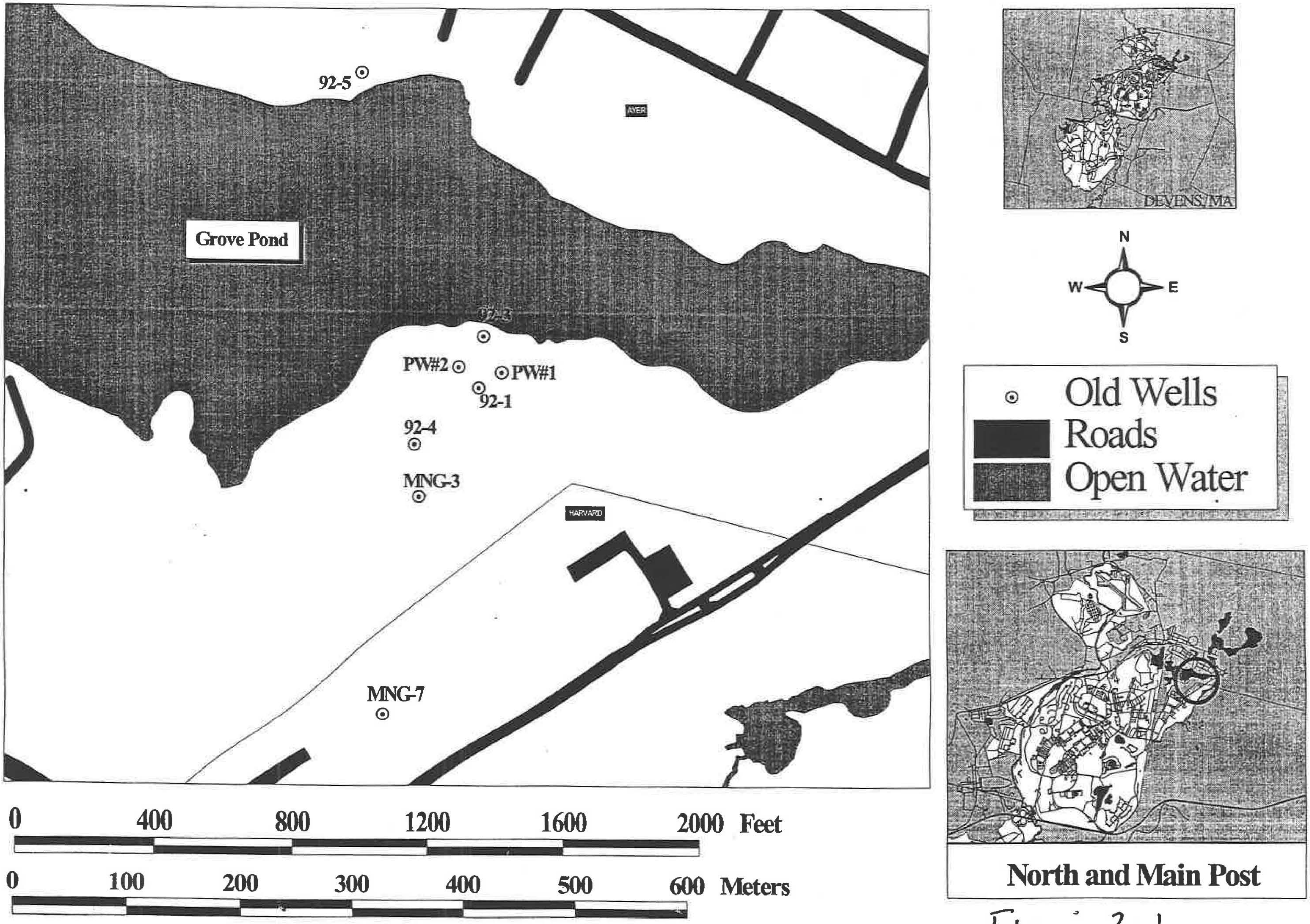
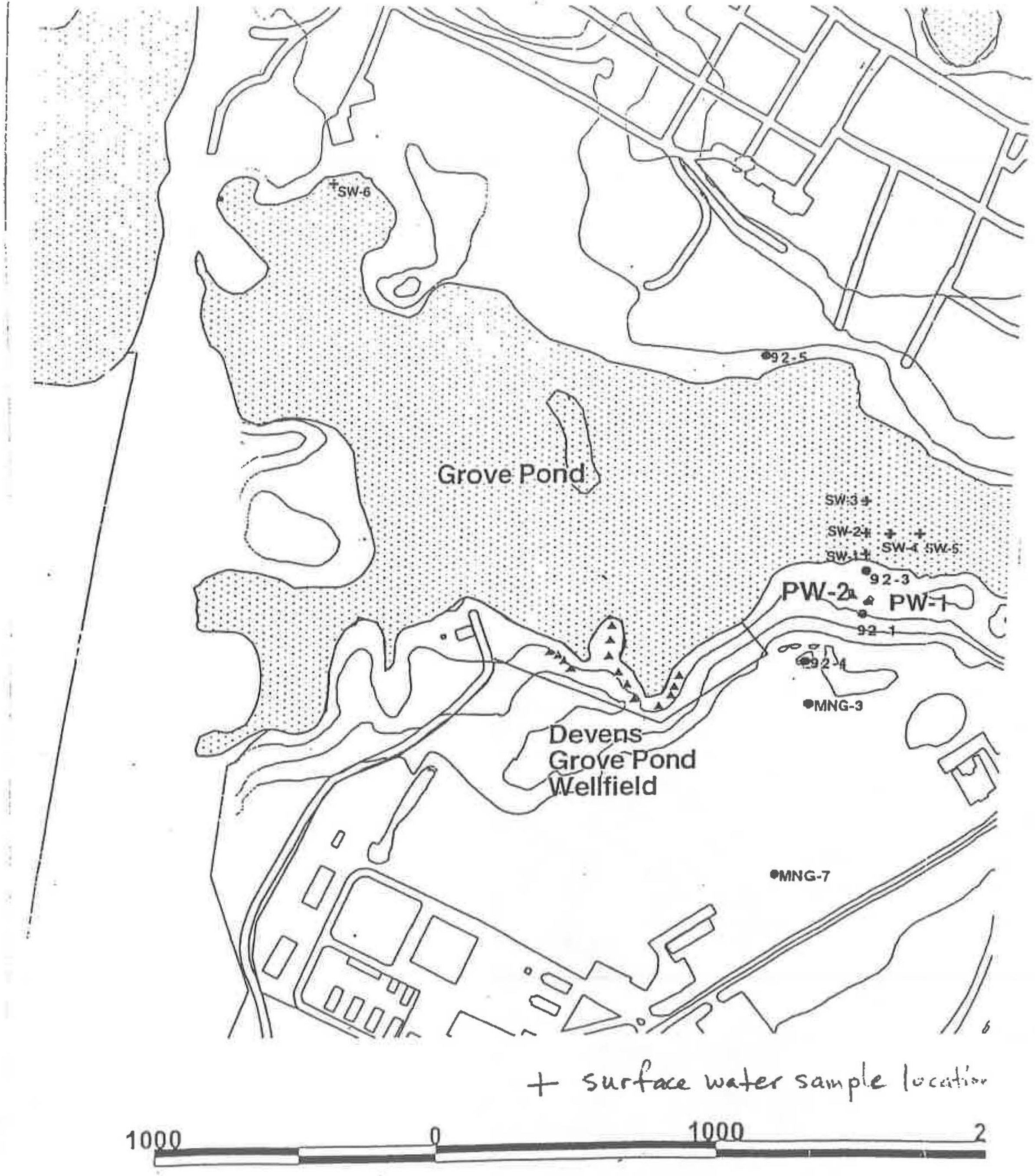


Figure 2-1



+ surface water sample location

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FIGURE 2-2
Surface Water Sample Locations
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New Well Locations - Phase II

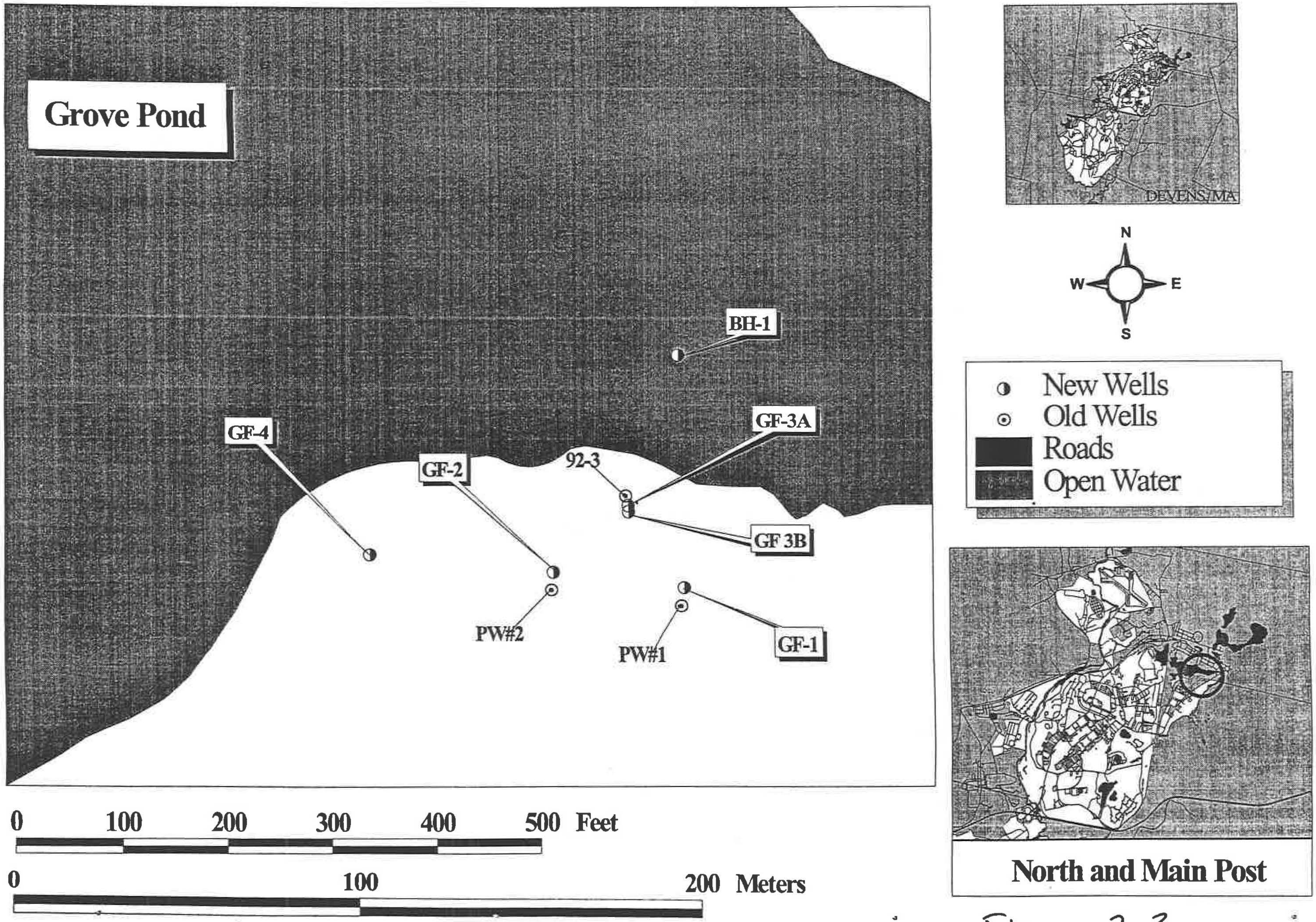

Figure 2-3

Sediment Sample Location

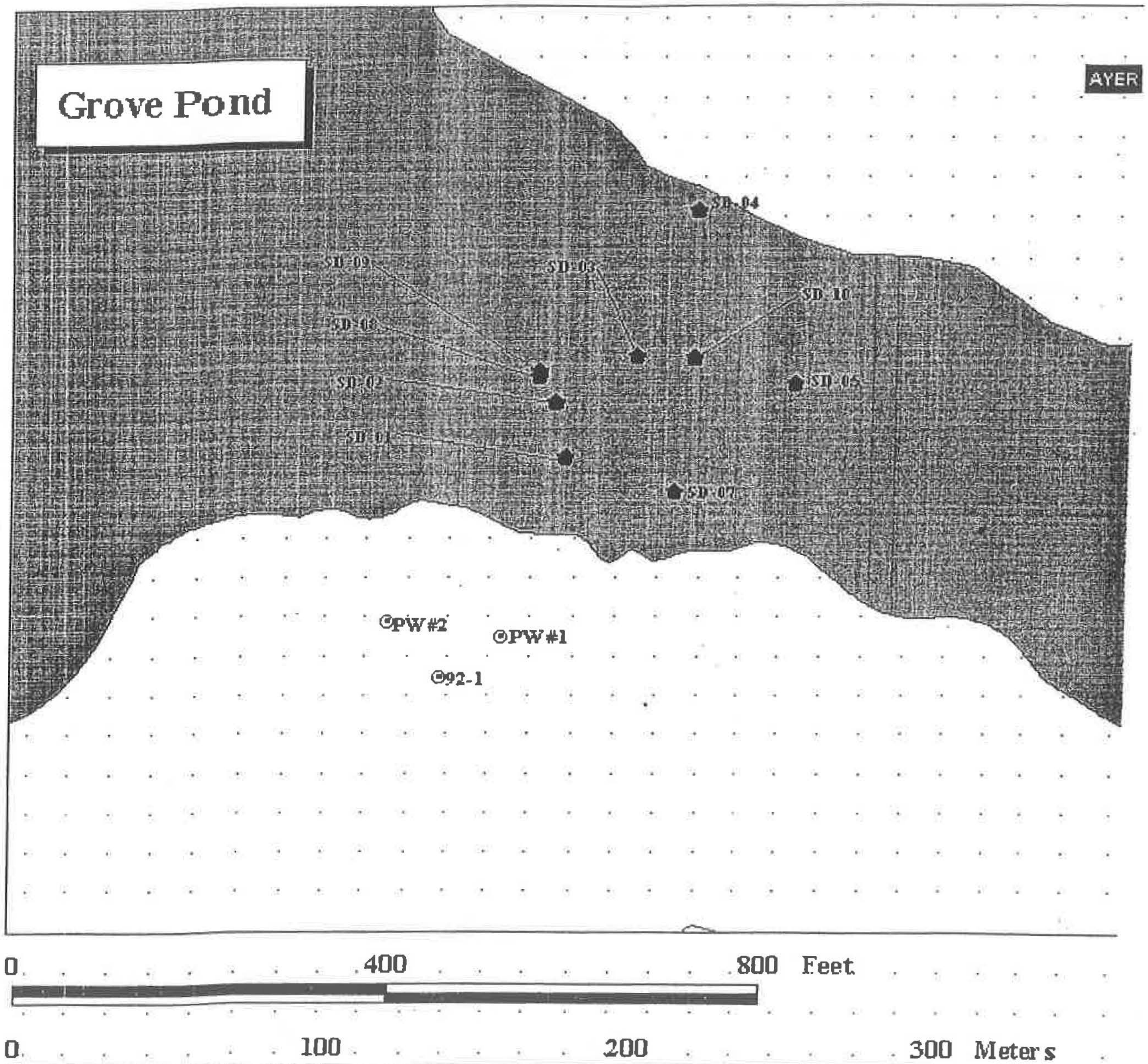

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FIGURE 2.~~3~~4
Sediment Sample Locations
Grove Pond Arsenic Investigation
Fort Devens

Soft Core Sample Location

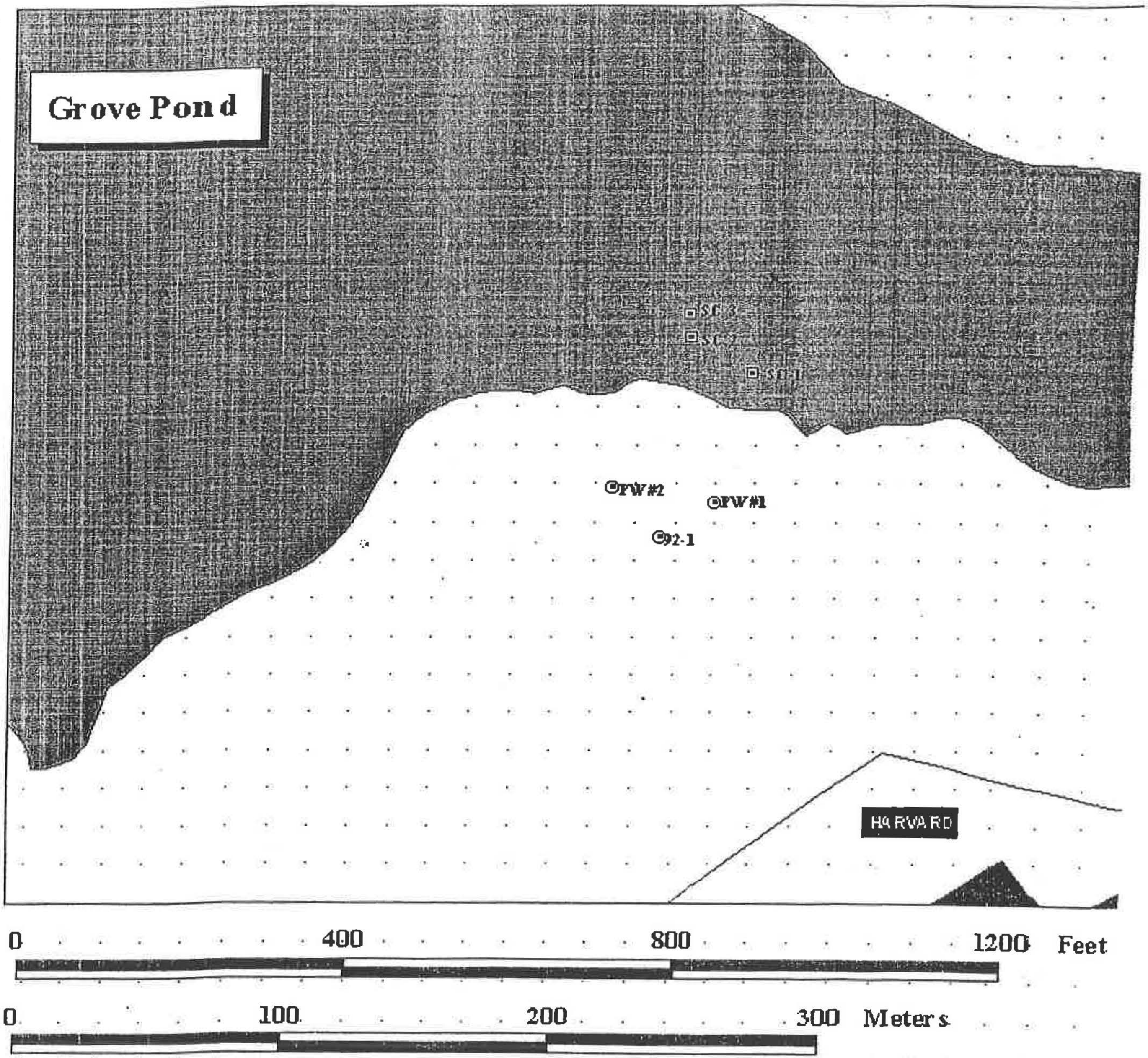

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FIGURE 2-~~4~~5
Soft Core Sample Locations
Grove Pond Arsenic Investigation
Fort Devens

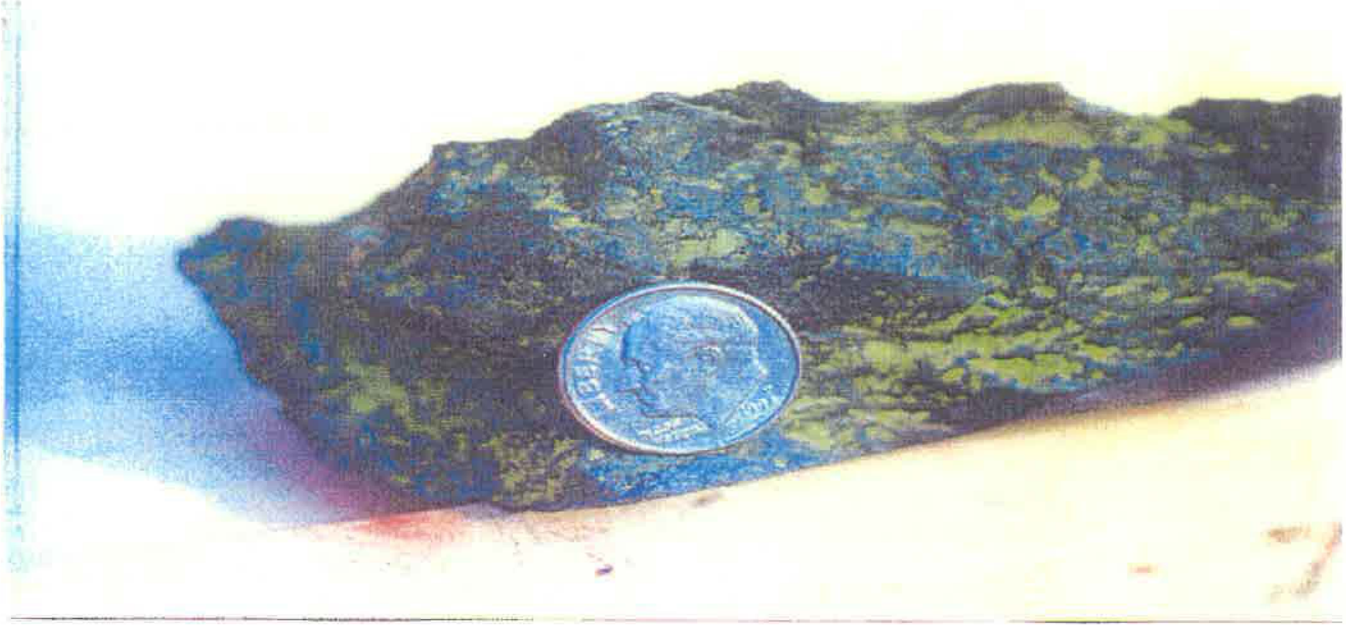

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FIGURE 2-6
Rock Core GF-1
Grove Pond Arsenic Investigation
Fort Devens

Seepage Meter Locations

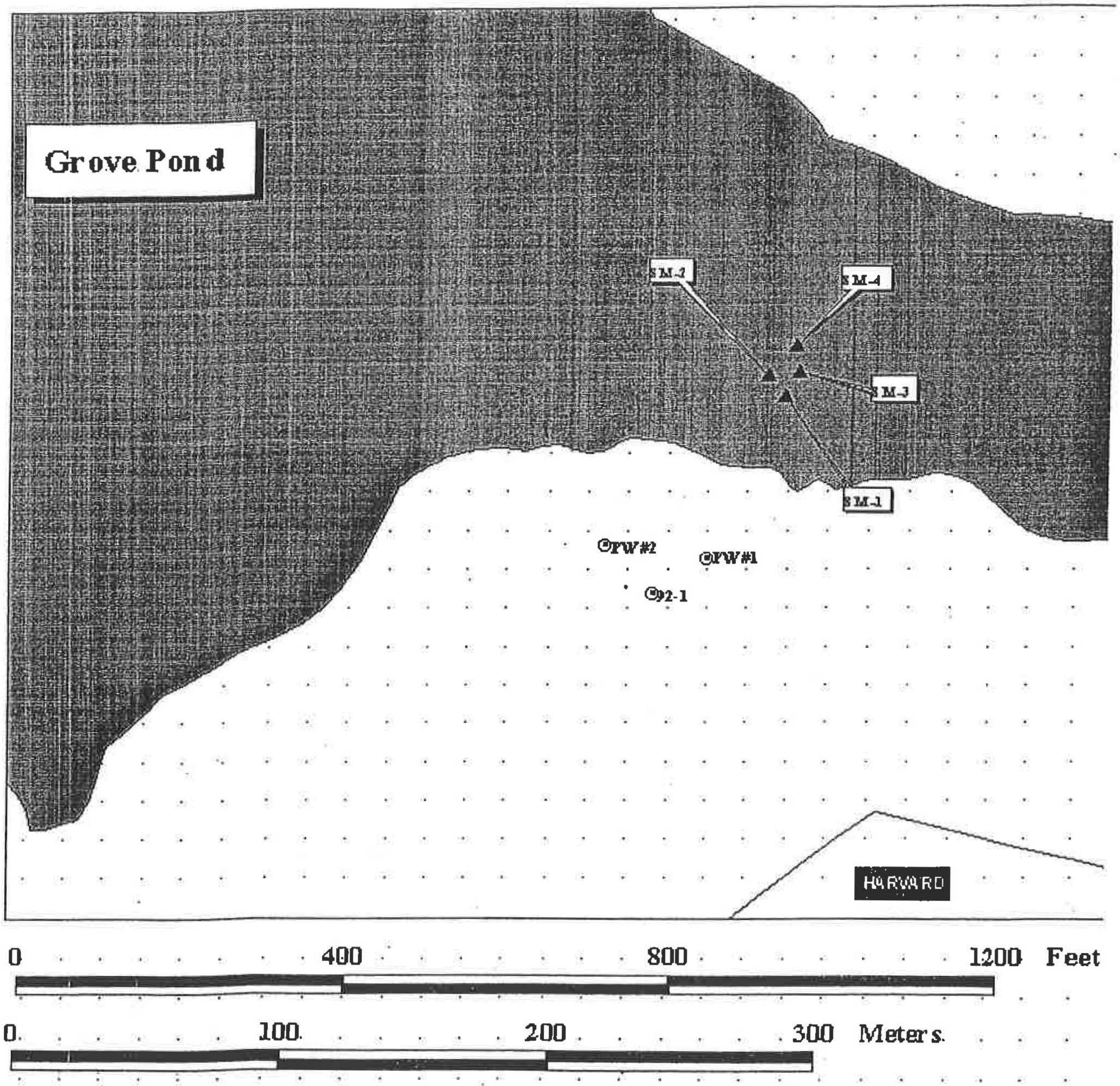

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FIGURE 2-7
Seepage Meter Locations
Grove Pond Arsenic Investigation
Fort Devens

Note: uncorrected field GPS fixes

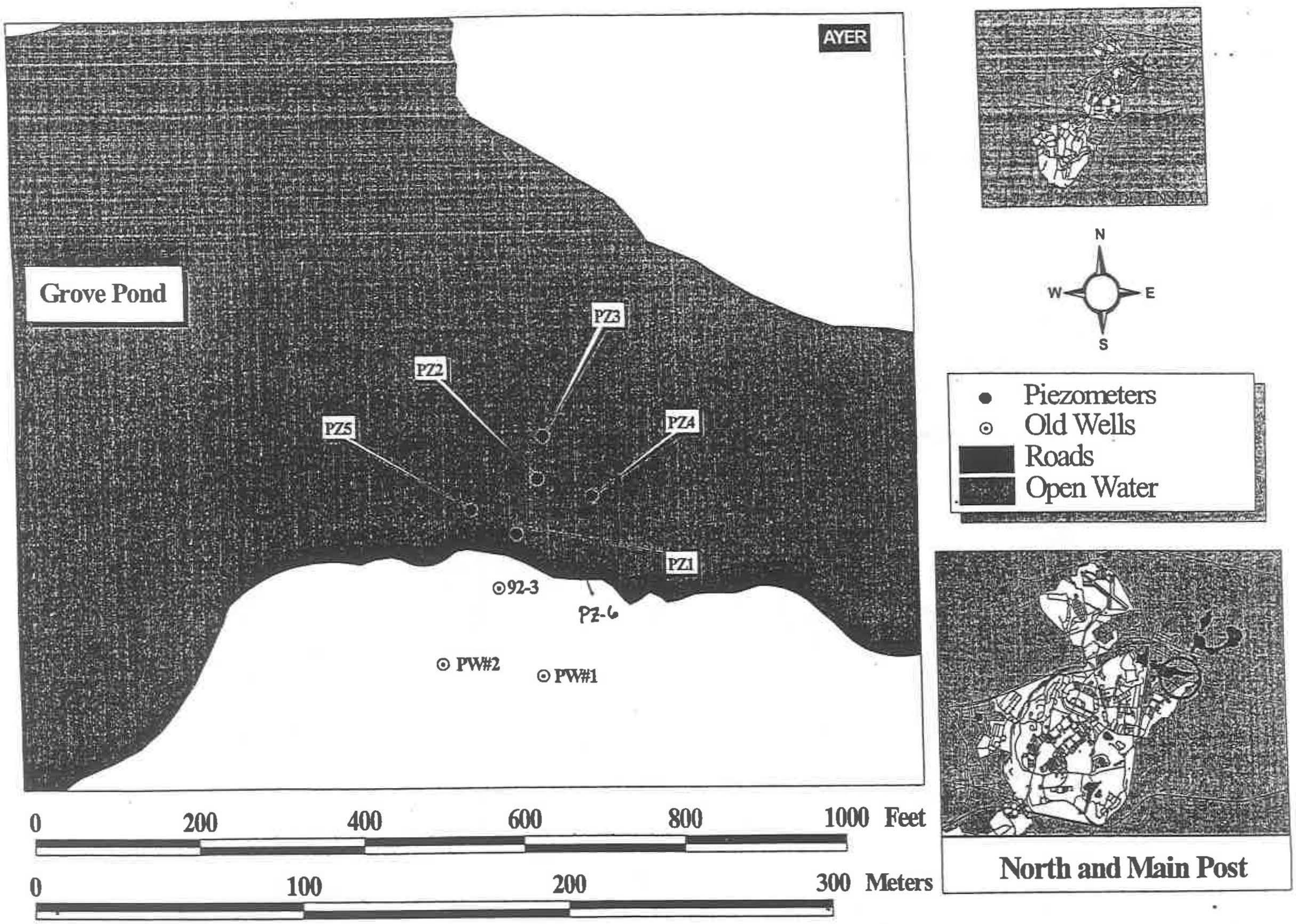

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FIGURE 2-8
Piezometer Locations
Grove Pond Arsenic Investigation
Fort Devens

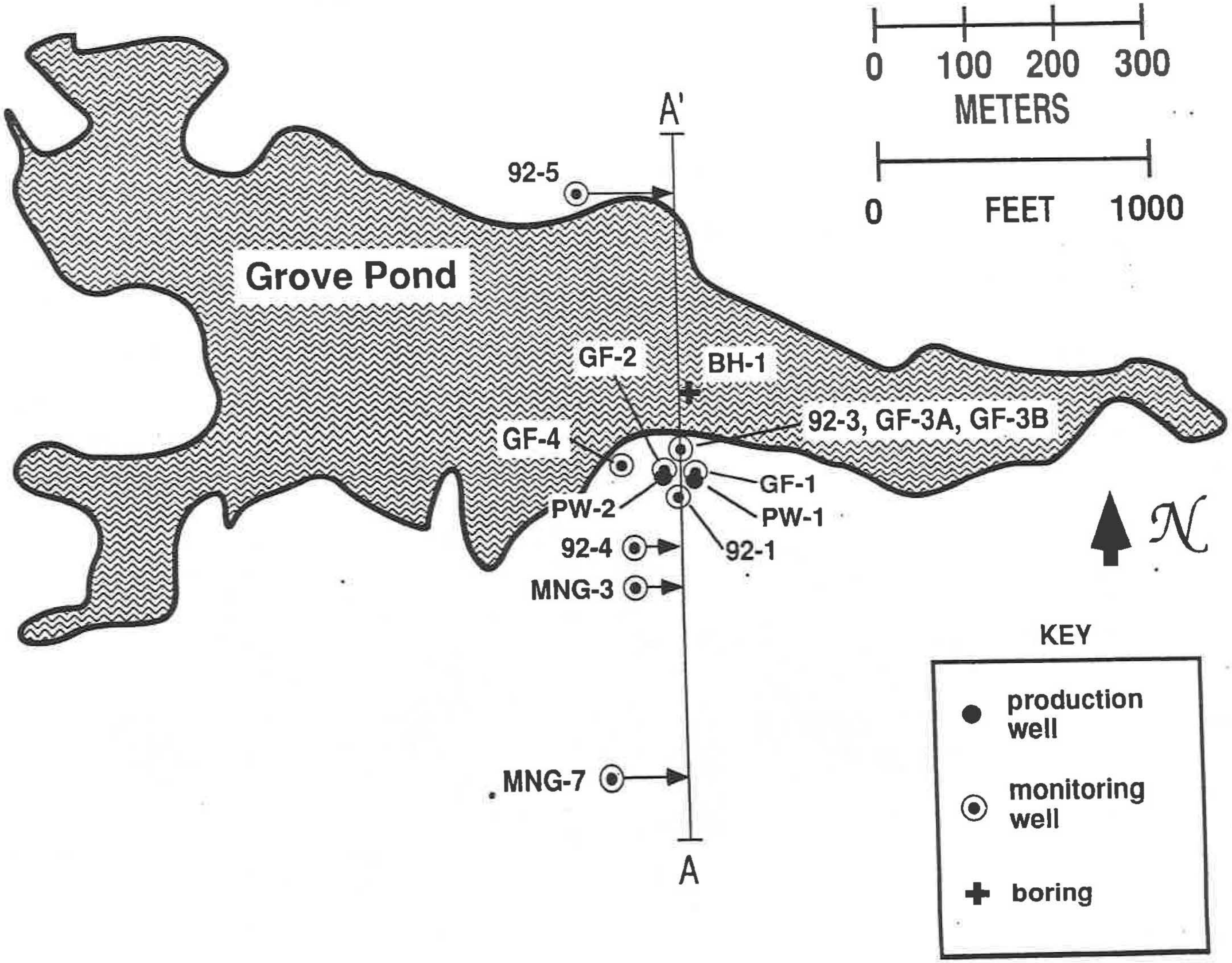

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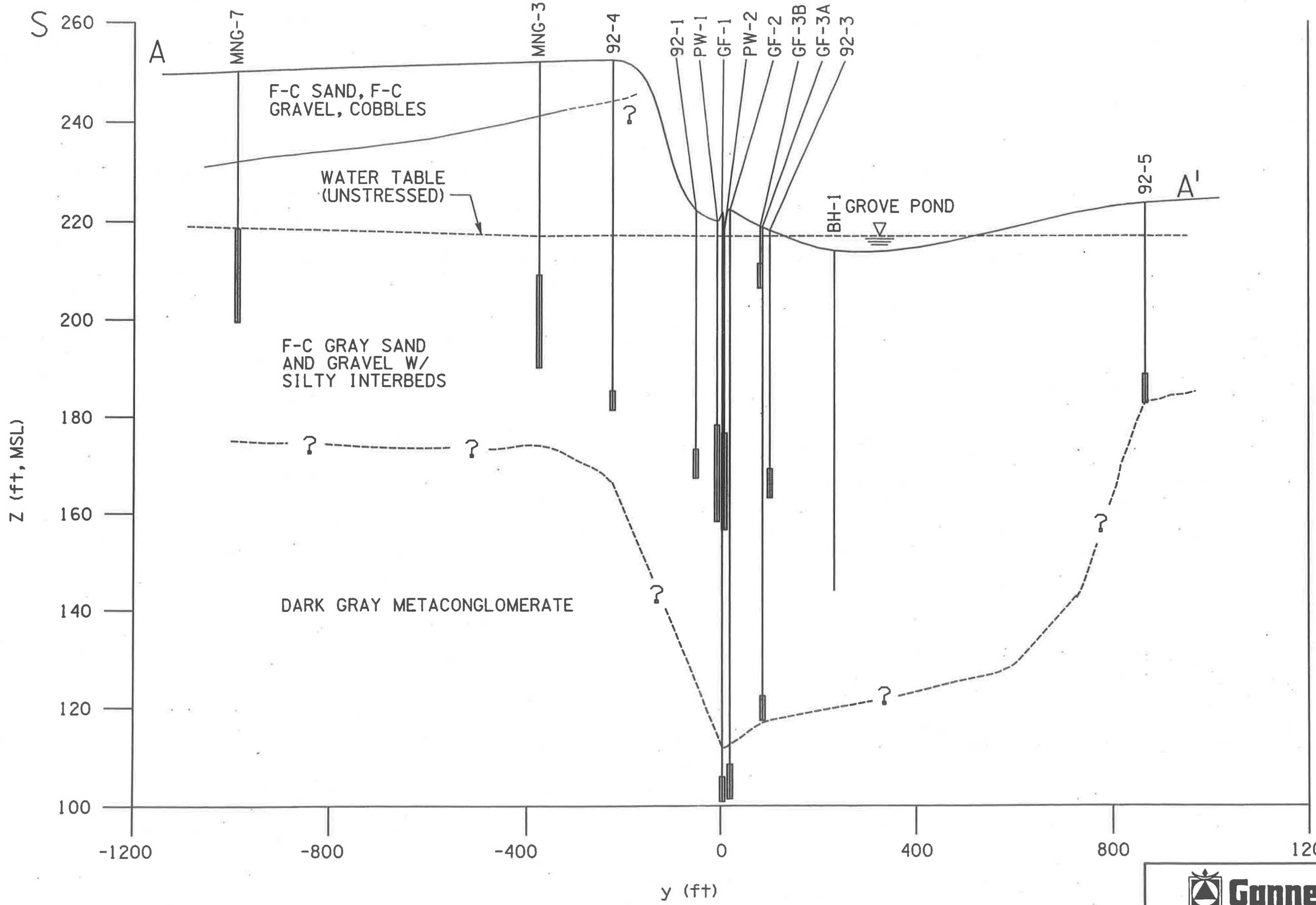
FIGURE 3-1
Location of N-S Cross Section
Grove Pond Arsenic Investigation
Fort Devens



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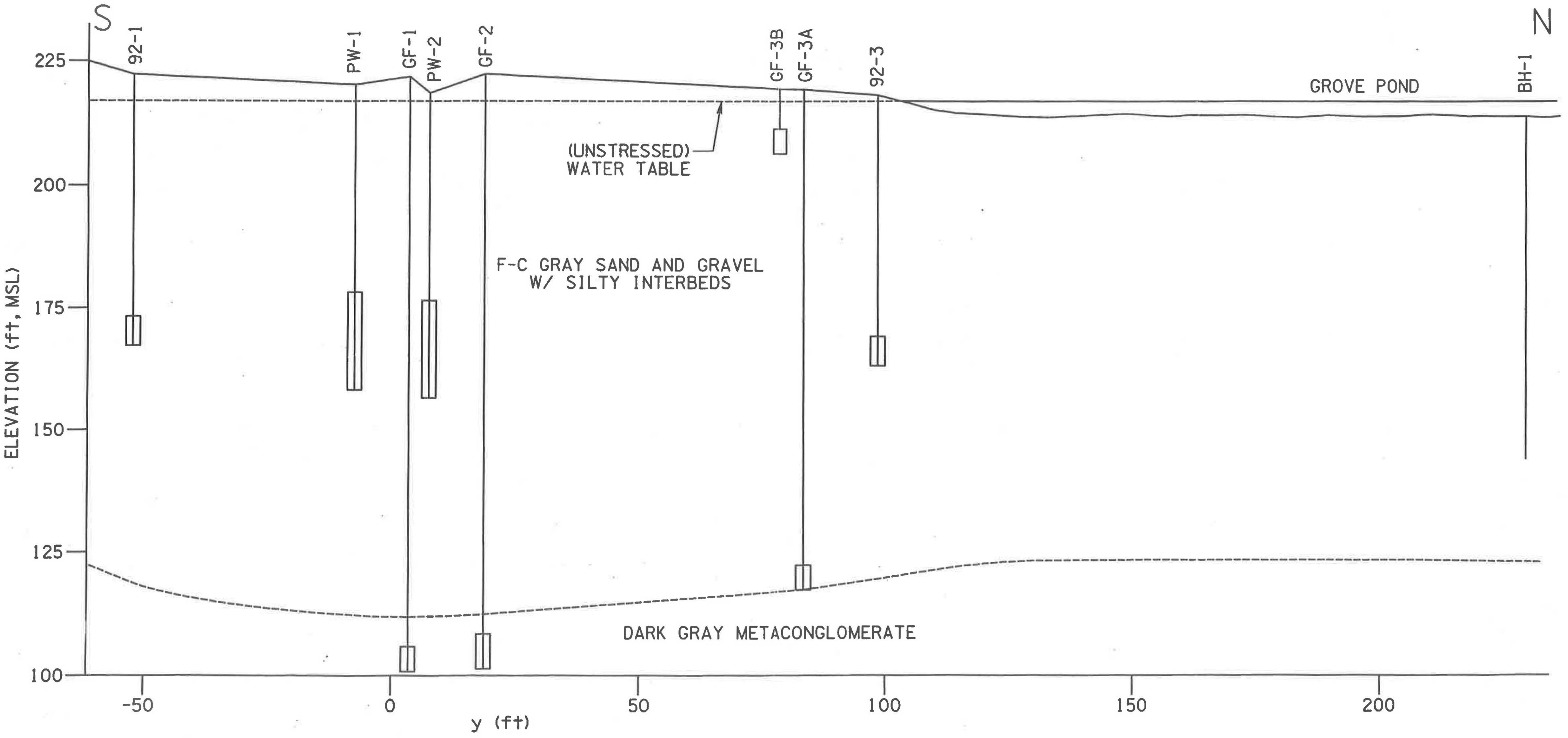
N-S CROSS SECTION THROUGH STUDY AREA

GROVE POND ARSENIC INVESTIGATION
FORT DEVENS

FIGURE 3-~~1~~2

FILE: J:\31204\SK2.DGN
DATE: 18-Oct-00 11:55



NOTE:
NO VERTICAL EXAGGERATION

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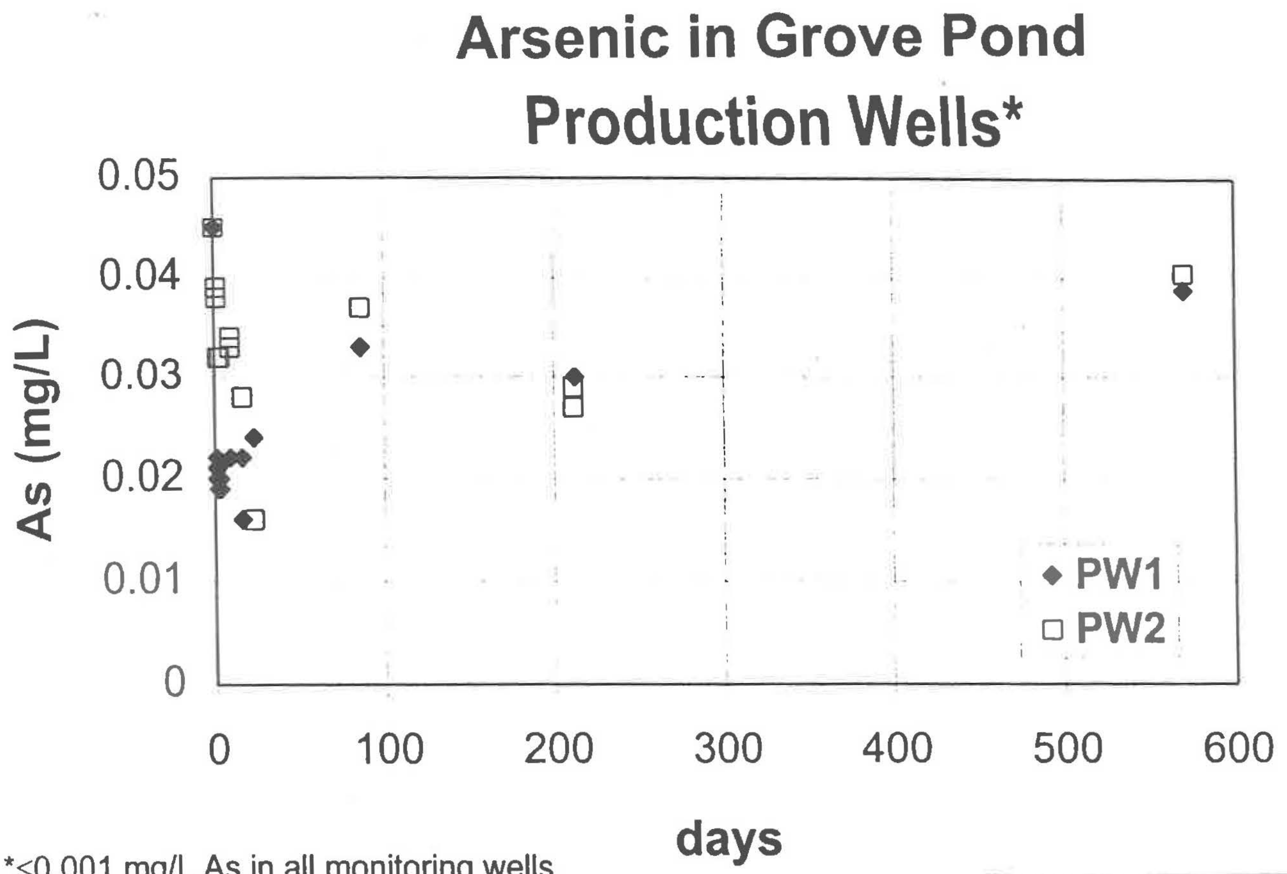
N-S CROSS SECTION NEAR PRODUCTION WELLS

GROVE POND ARSENIC INVESTIGATION
FORT DEVENS

FIGURE 3-~~2~~ 3

F1... \312 ... 1.DG..
DATE: 18-Oct-00 10:56



*≤0.001 mg/L As in all monitoring wells

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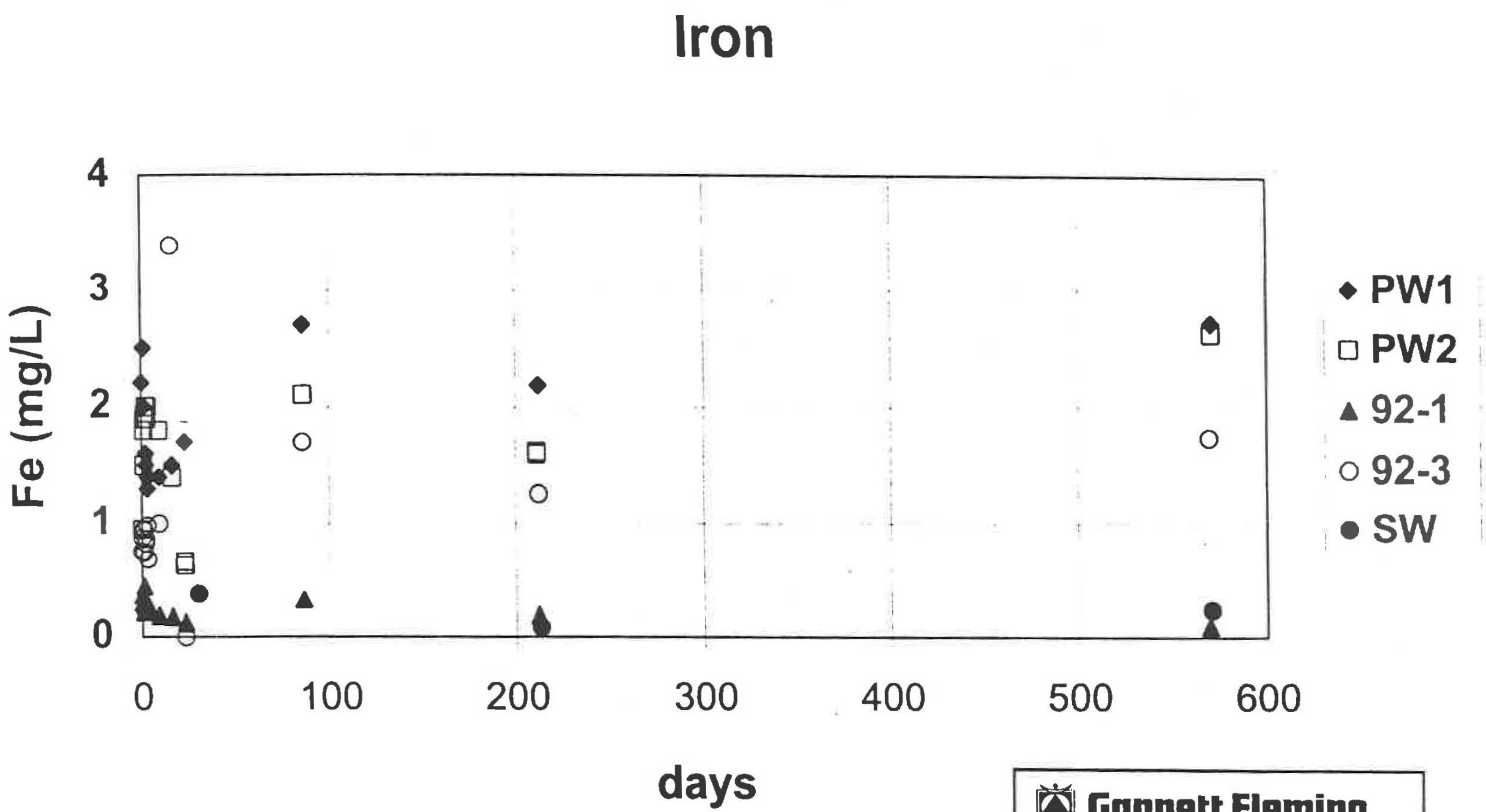
Arsenic in Prodcution Wells
Grove Pond Arsenic Investigation
Fort Devens
Figure 4-1



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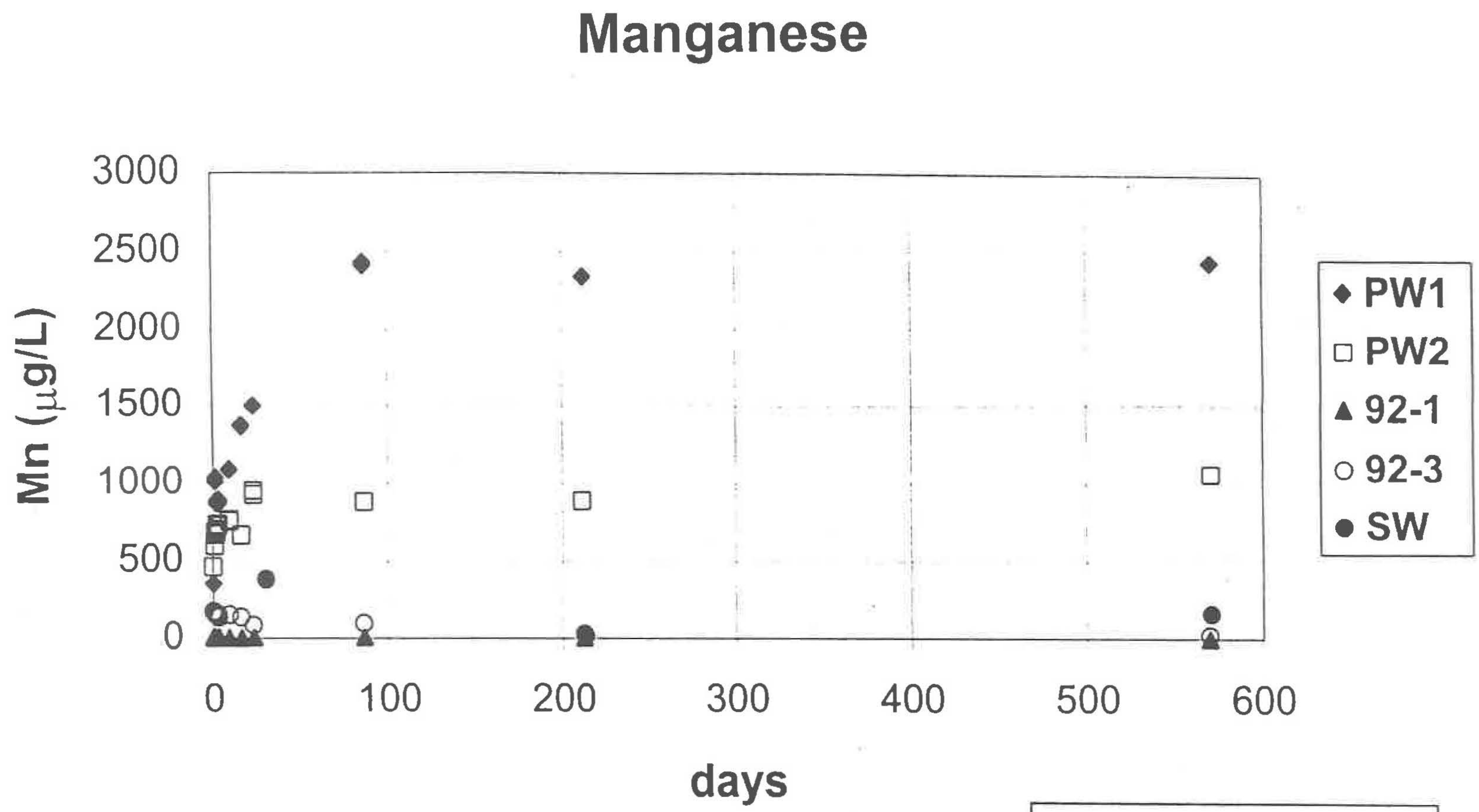
Iron
Grove Pond Arsenic Investigation
Fort Devens
Figure 4-2



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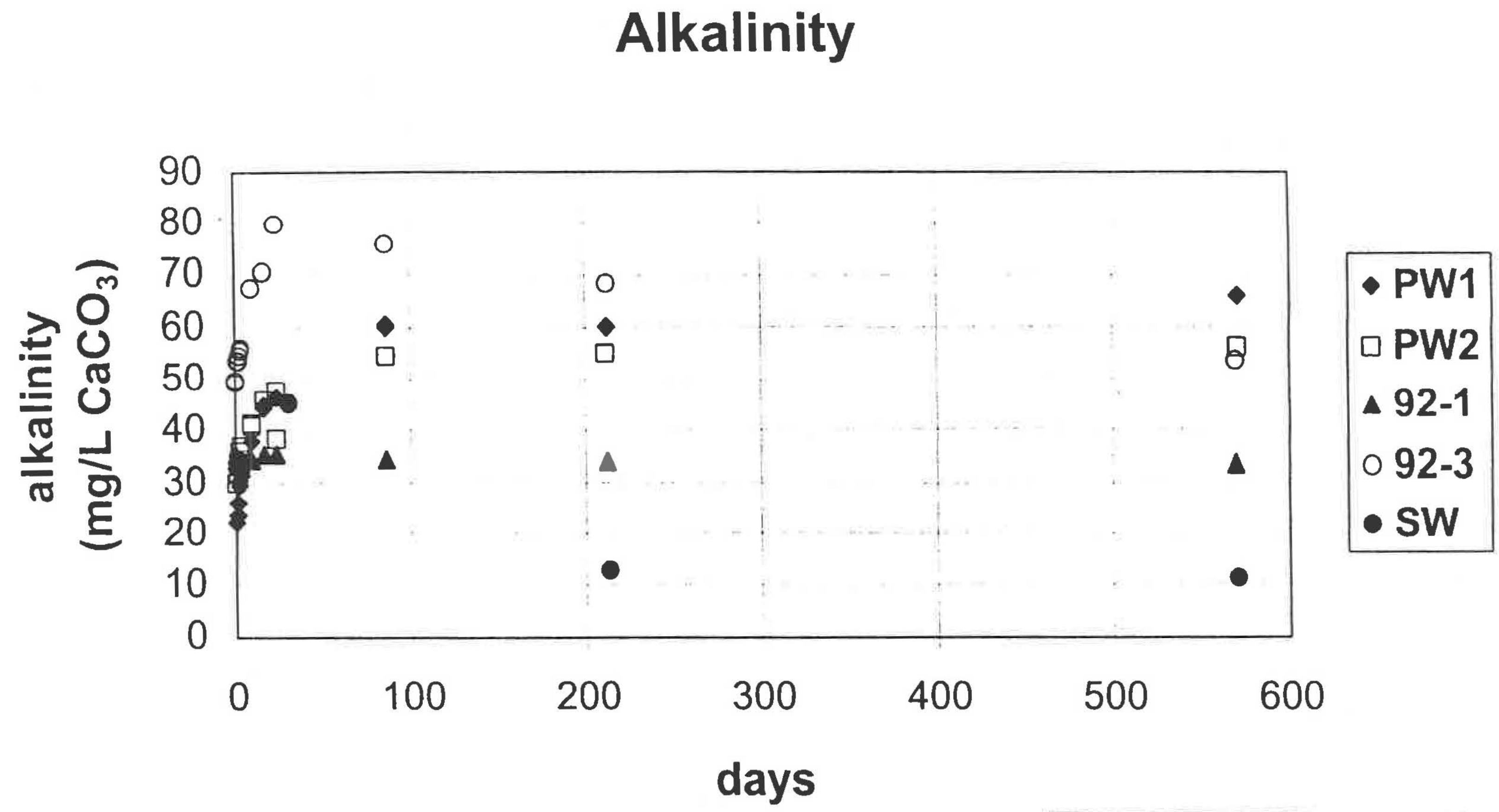
Maganese
Grove Pond Arsenic Investigation
Fort Devens
Figure 4-3



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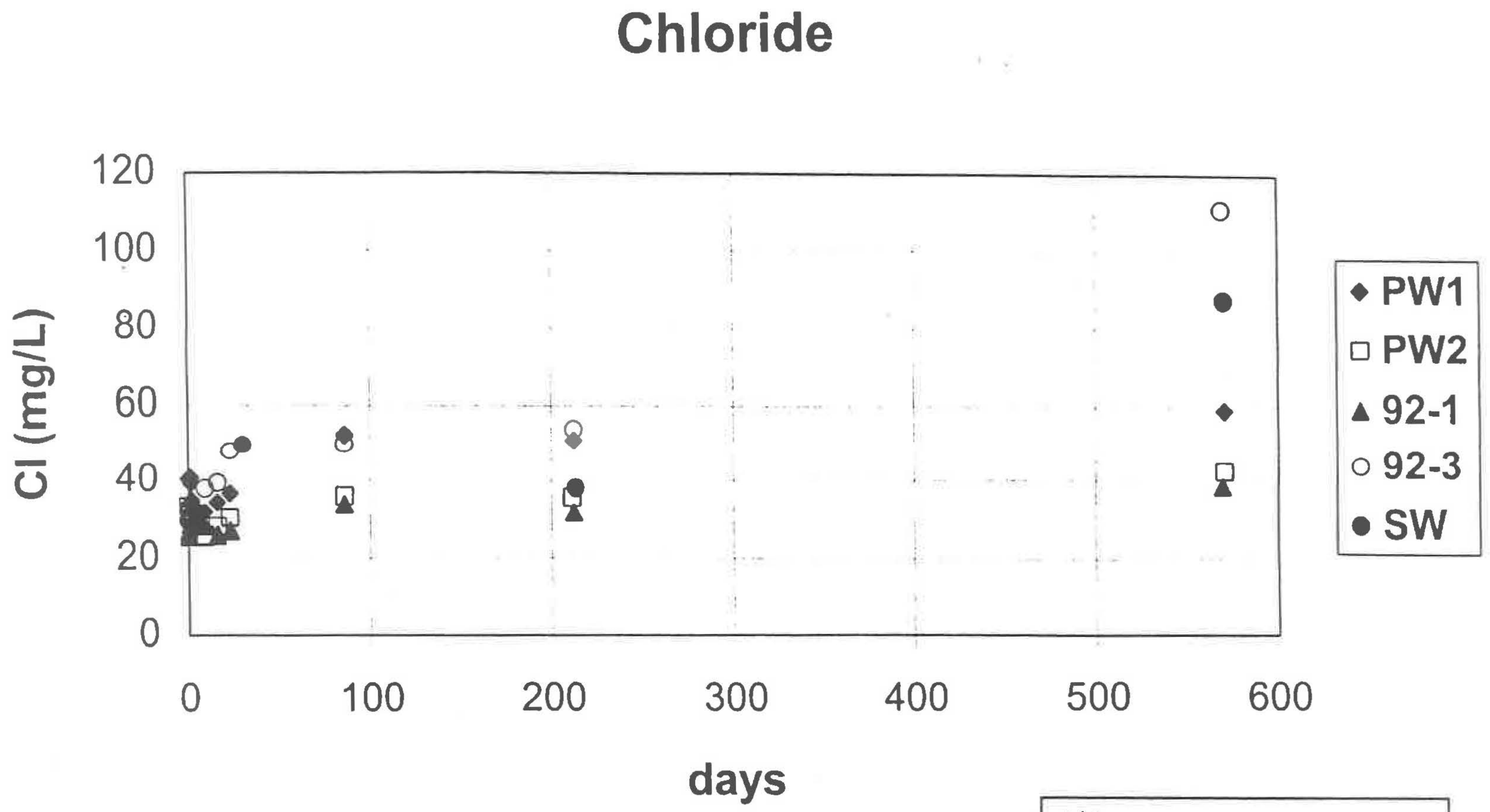
Alkalinity, as mg/L $CaCO_3$ Grove Pond Arsenic Investigation
Fort Devens
Figure 4-4



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Chloride
Grove Pond Arsenic Investigation
Fort Devens
Figure 4-5

GROUNDWATER ARSENIC

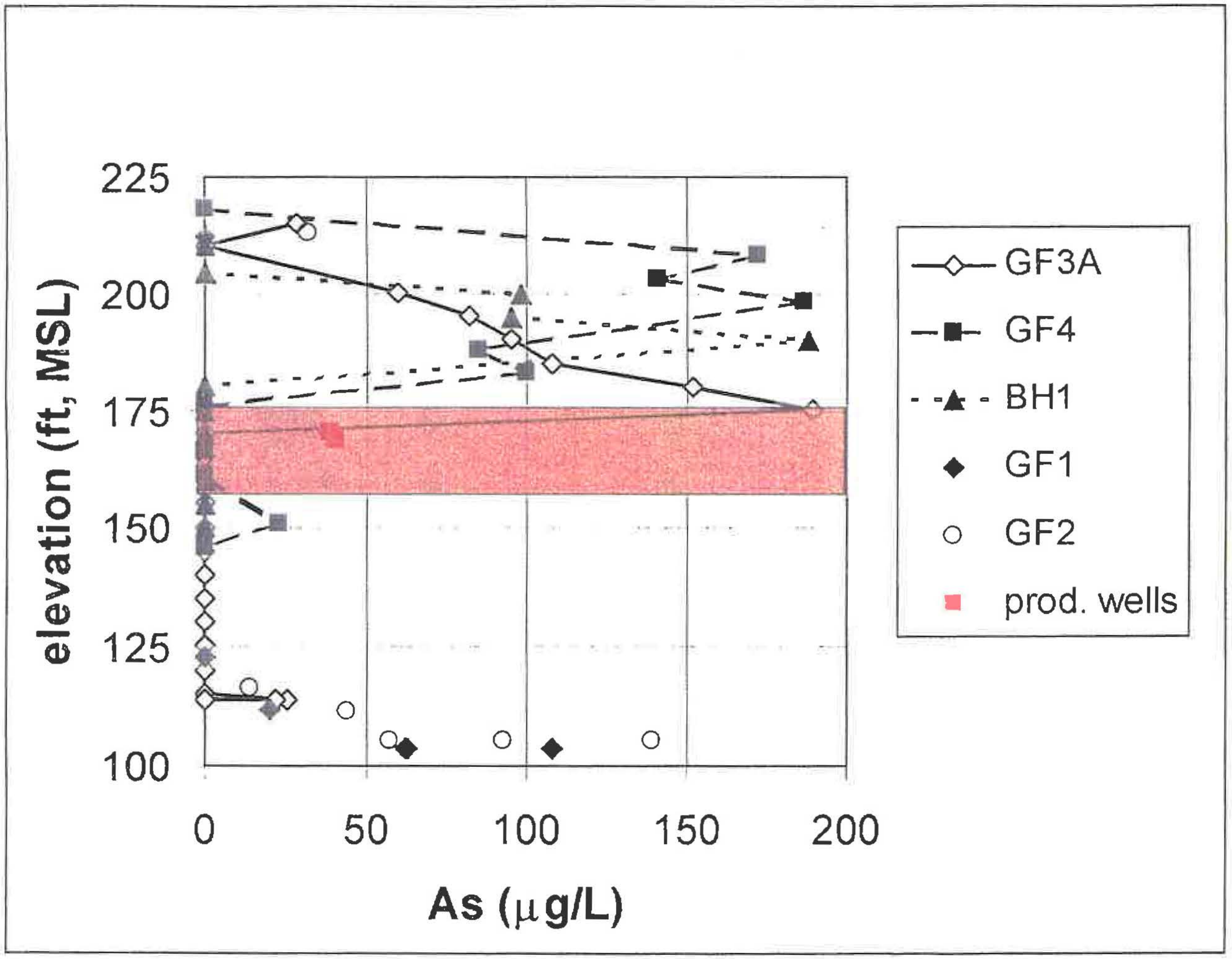

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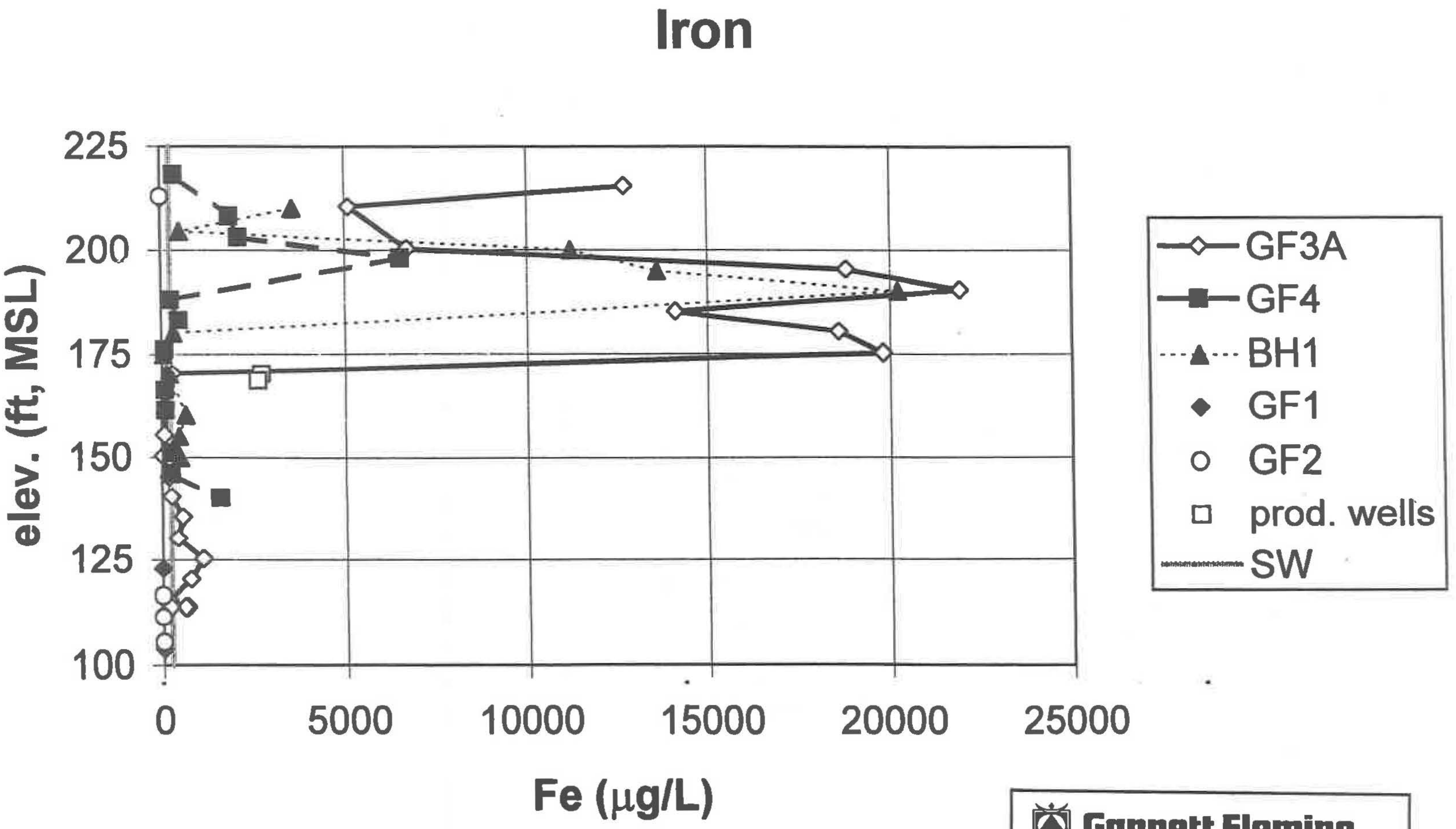
FIGURE 4-6
Groundwater Arsenic
Grove Pond Arsenic Investigation
Fort Devens



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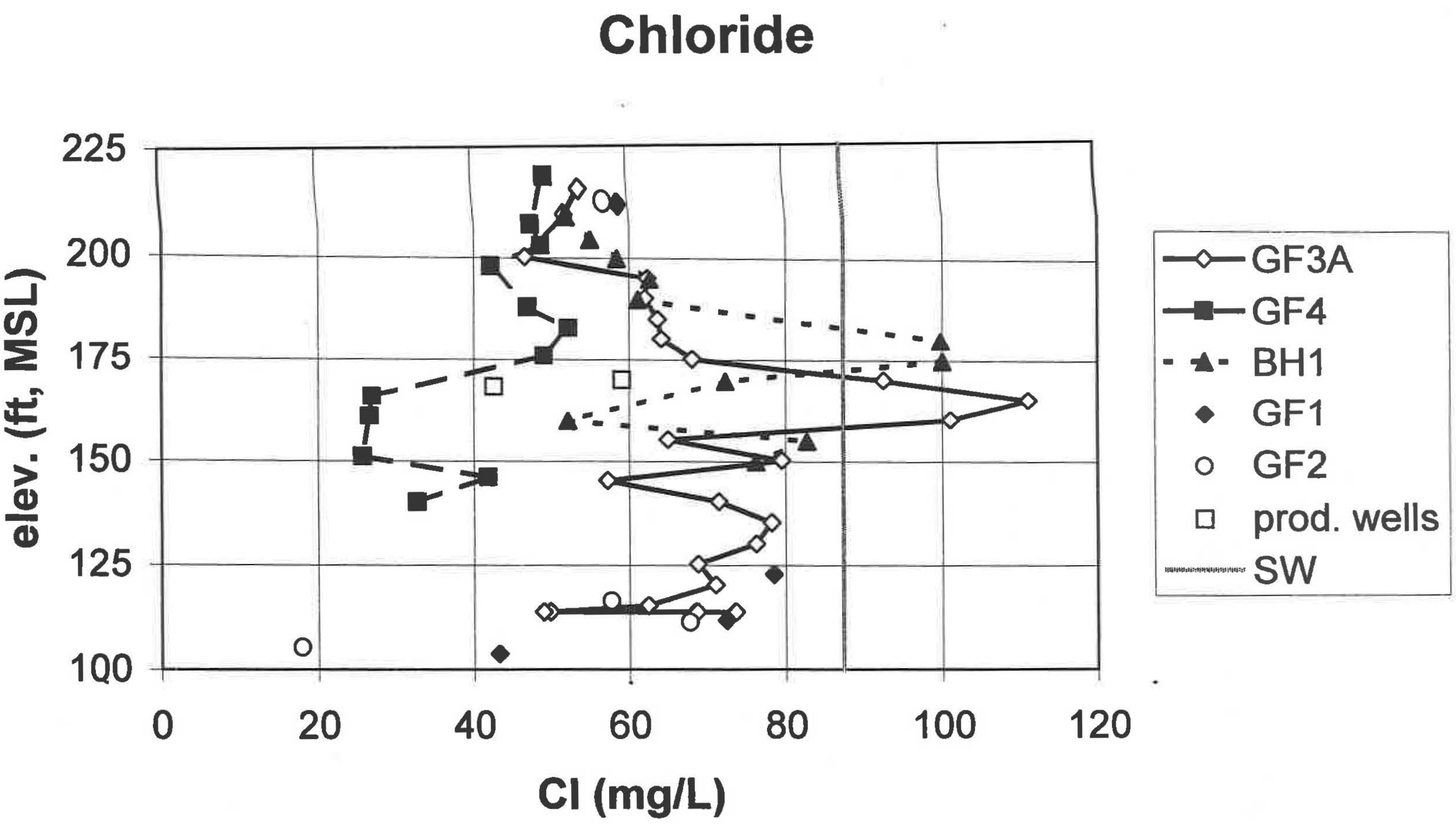
Iron Profiles
Grove Pond Arsenic Investigation
Fort Devens
Figure 4-7



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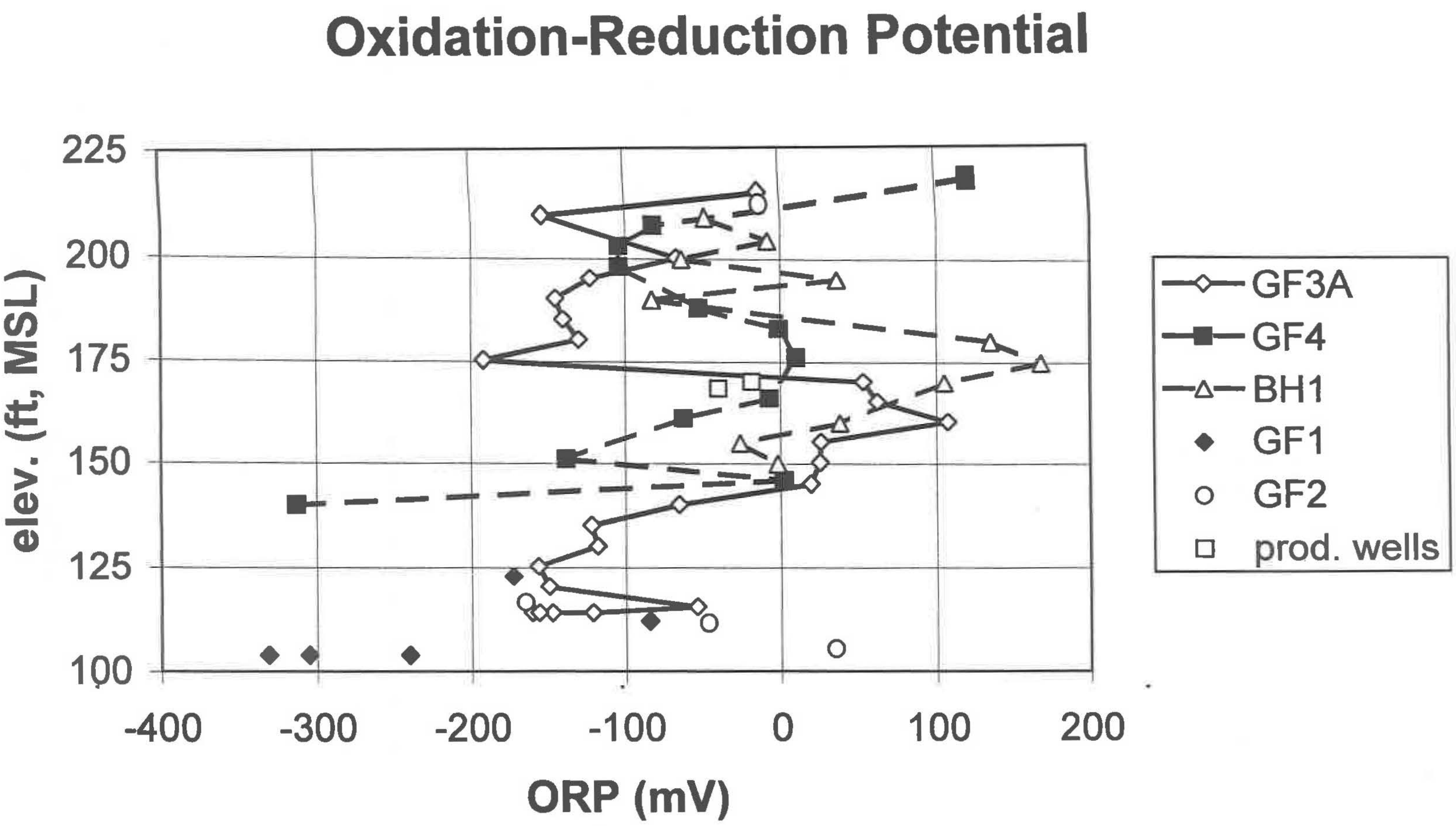
Chloride Profiles
Grove Pond Arsenic Investigation
Fort Devens
Figure 4-8



Oxidation-Reduction Potential

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ORP Profiles
Grove Pond Arsenic Investigation
Fort Devens
Figure 4-9

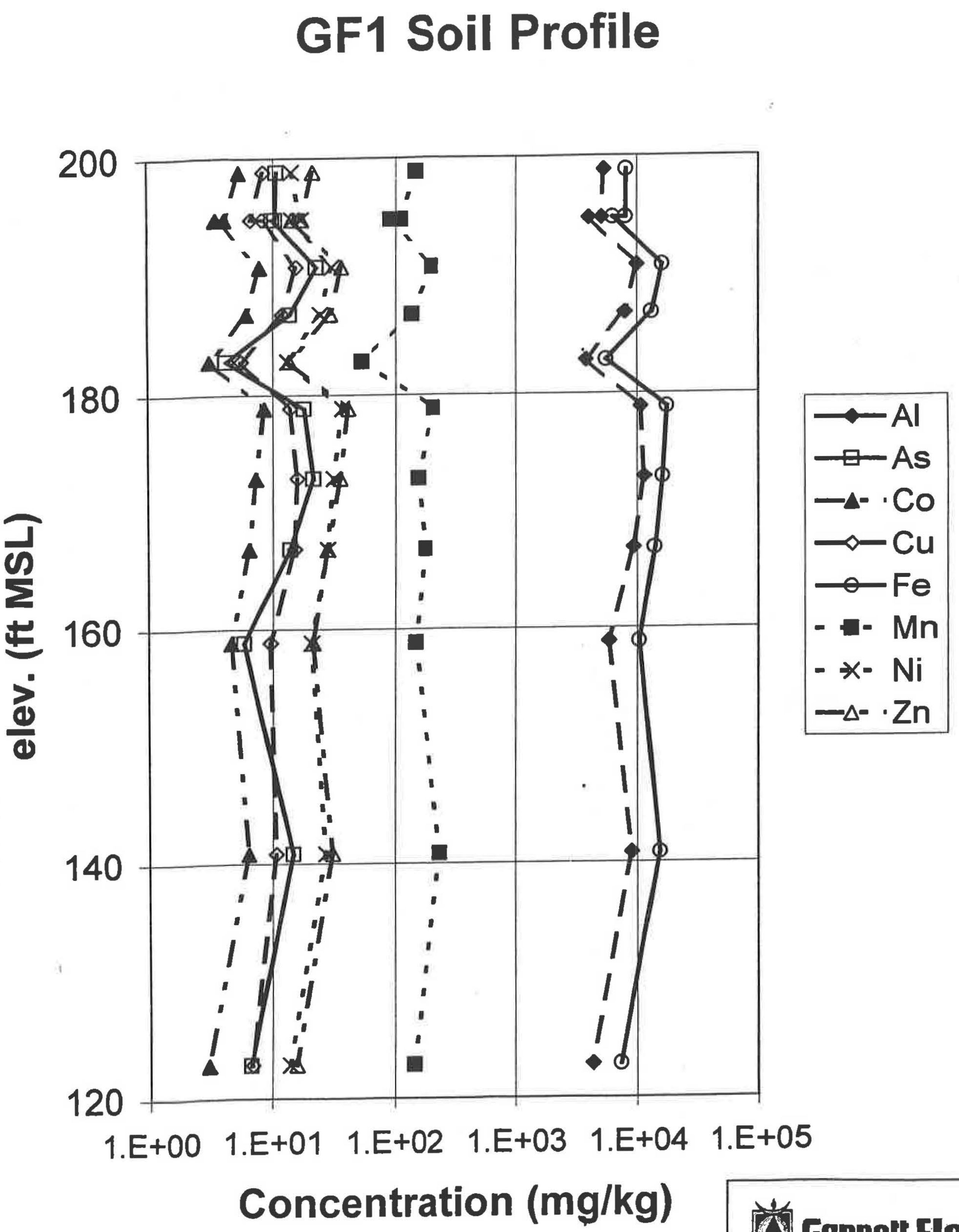

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FIGURE 4-10
GF-1 Soil Profile
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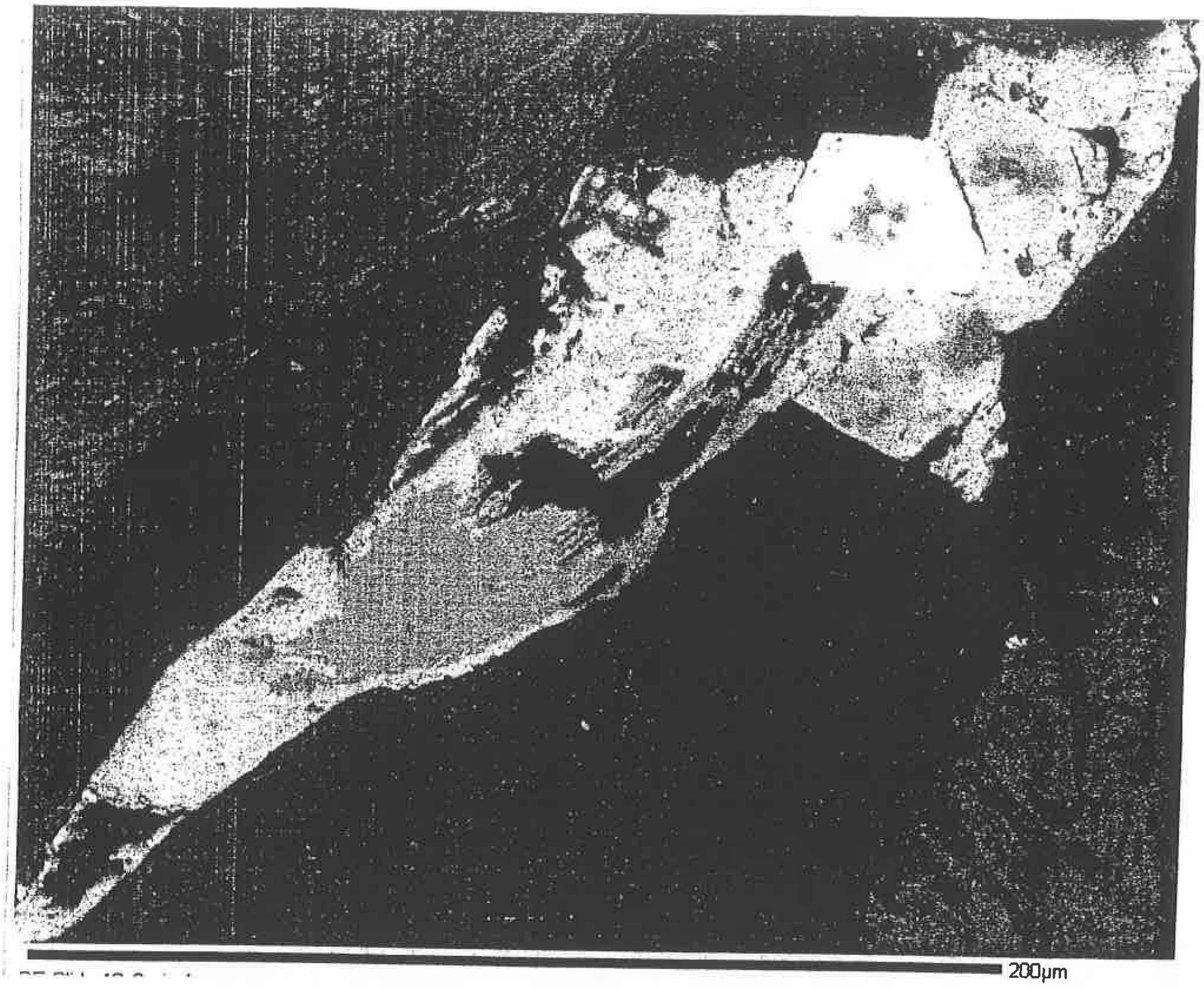

Backscattered electron image showing pyrite (FeS_2) and cobaltite ($CoAsS$; upper right) in Grove Pond bedrock. Scale bar = 200 µm.

Compositions by Electron Microprobe*

	Element Weight Percent (avg.)					
	Fe	Ni	Co	Cu	S	As
FeS_2	45.05	0.56	0.03	0.02	55.25	0.03
$CoAsS$	6.90	7.22	20.42	0.21	21.70	46.63

*Probe analyses and electron micrographs courtesy of Prof. R. Hon, Boston College Geology and Geophysics Department

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FIGURE 4-11

Grove Pond Arsenic Investigation
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Fe Slide 12 Grain 1

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FIGURE 4-12 (a)
Fe Element Map
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S Slide 12 Grain 1

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FIGURE 4-12 (b)
"S" Element Map
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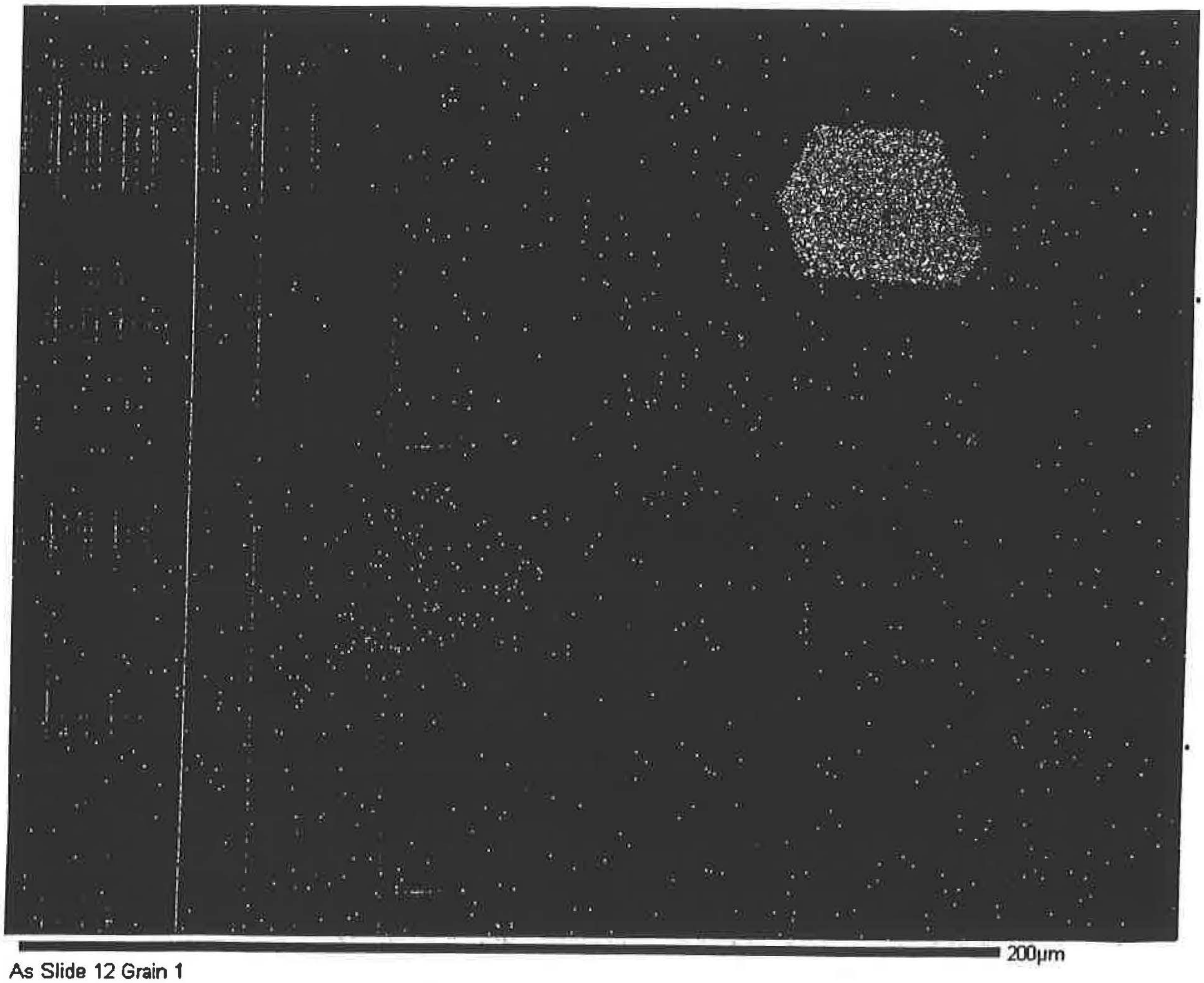

As Slide 12 Grain 1

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FIGURE 4-12 (c)
As Element Map
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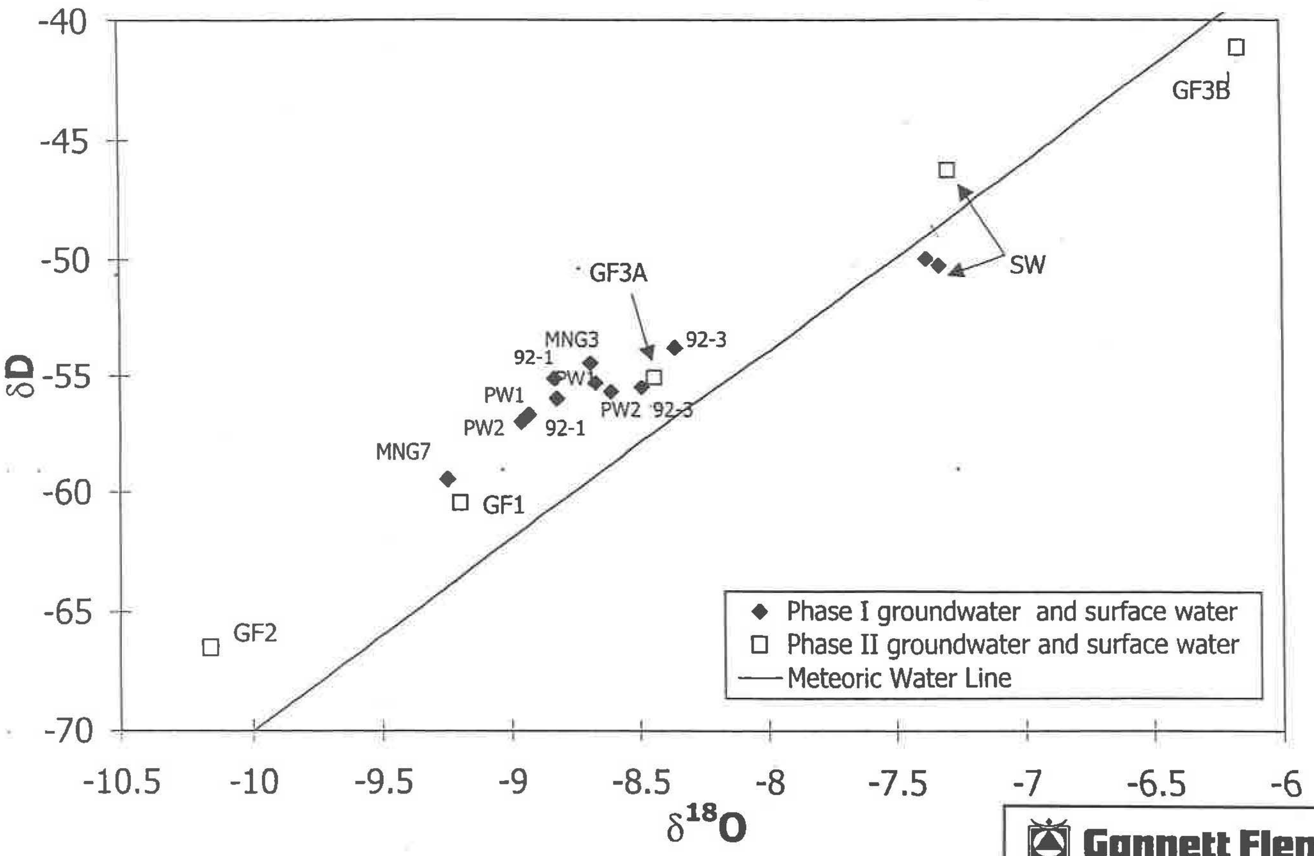
Grove Pond Isotope Data



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Grove Pond Isotope Data
Grove Pond Arsenic Investigation
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Figure 4-13

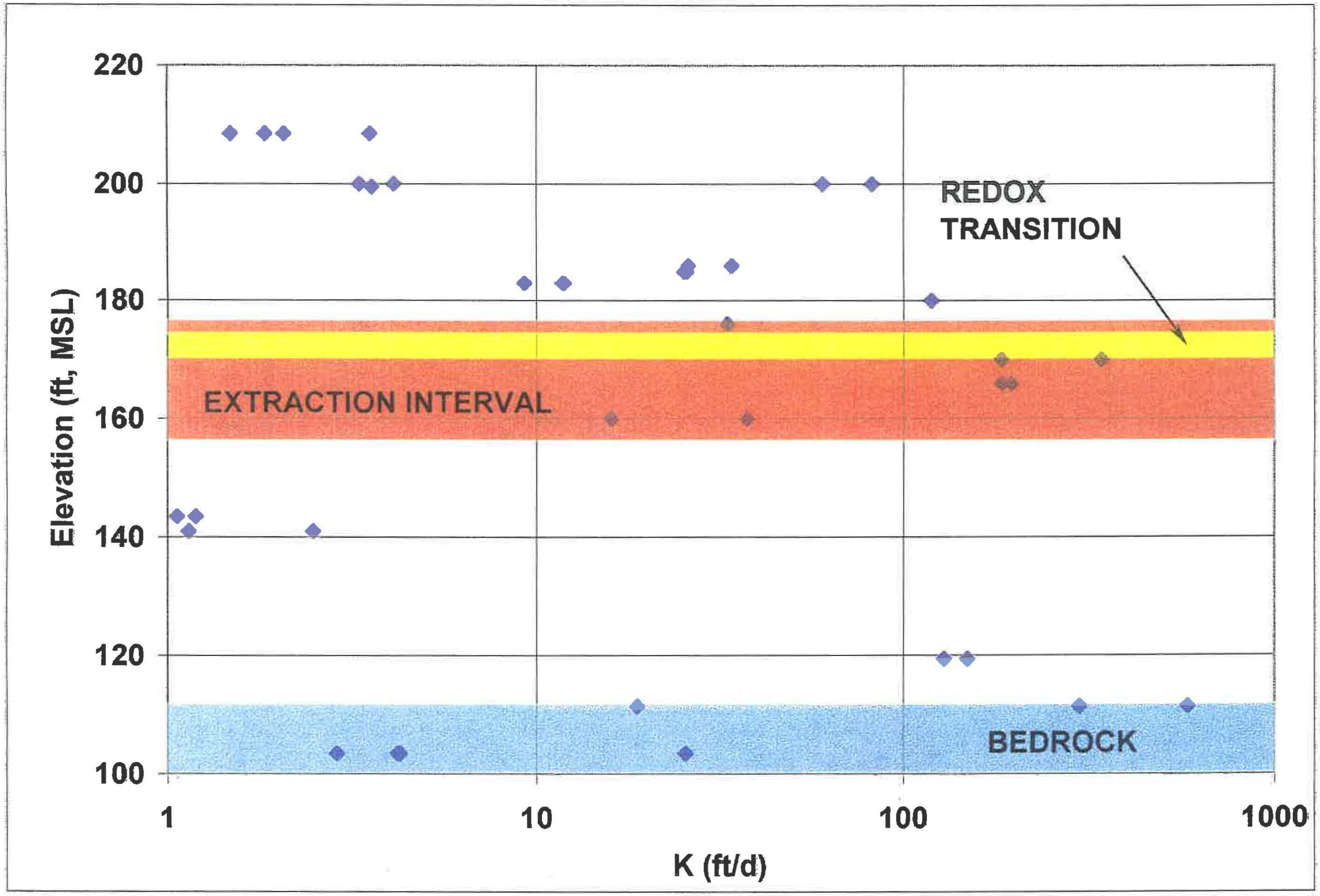

Figure 4-14
Hydraulic Conductivity from Slug Tests
Grove Pond Arsenic Investigation

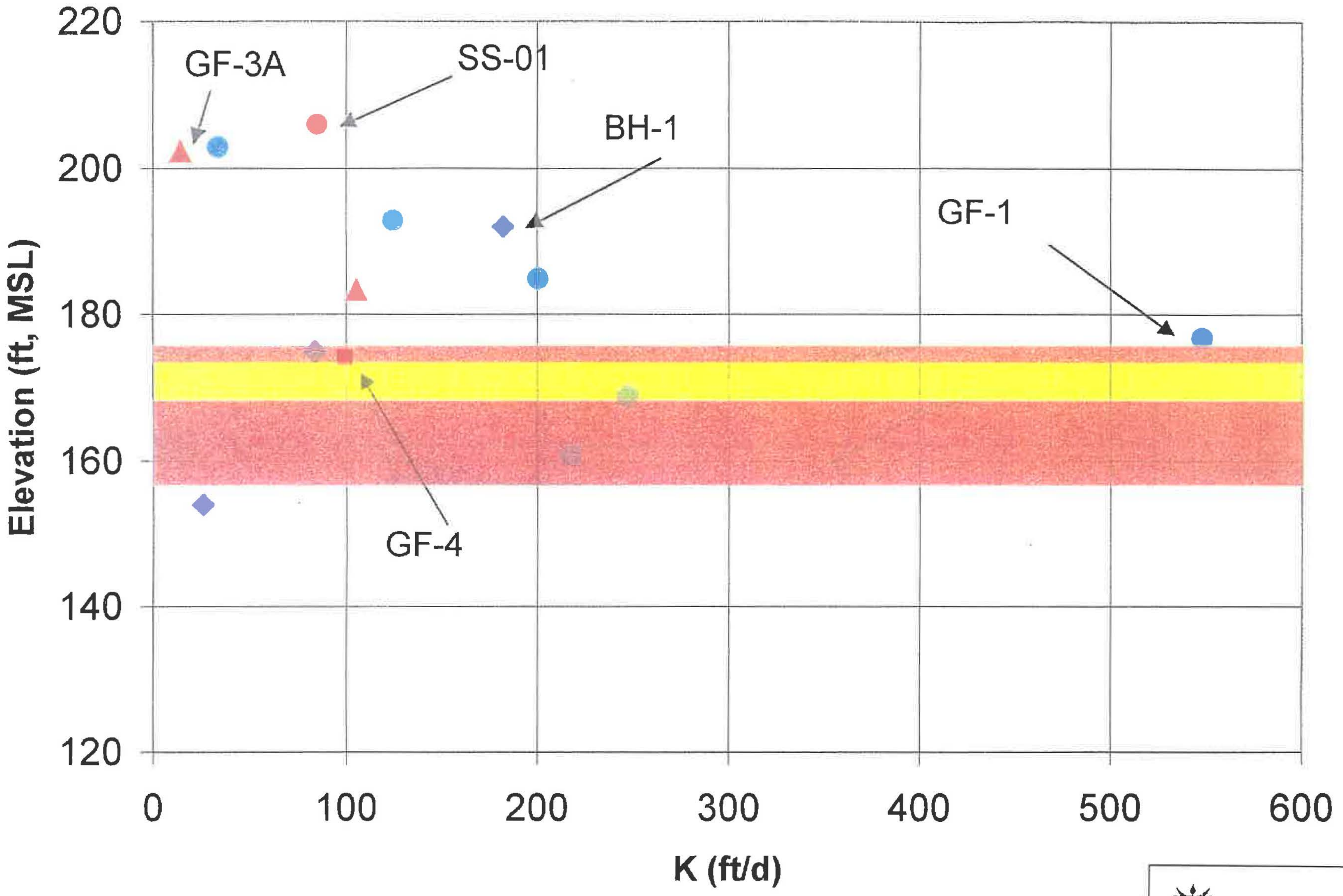

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FIGURE 4-15
Hydraulic Conductivity From Grain Size
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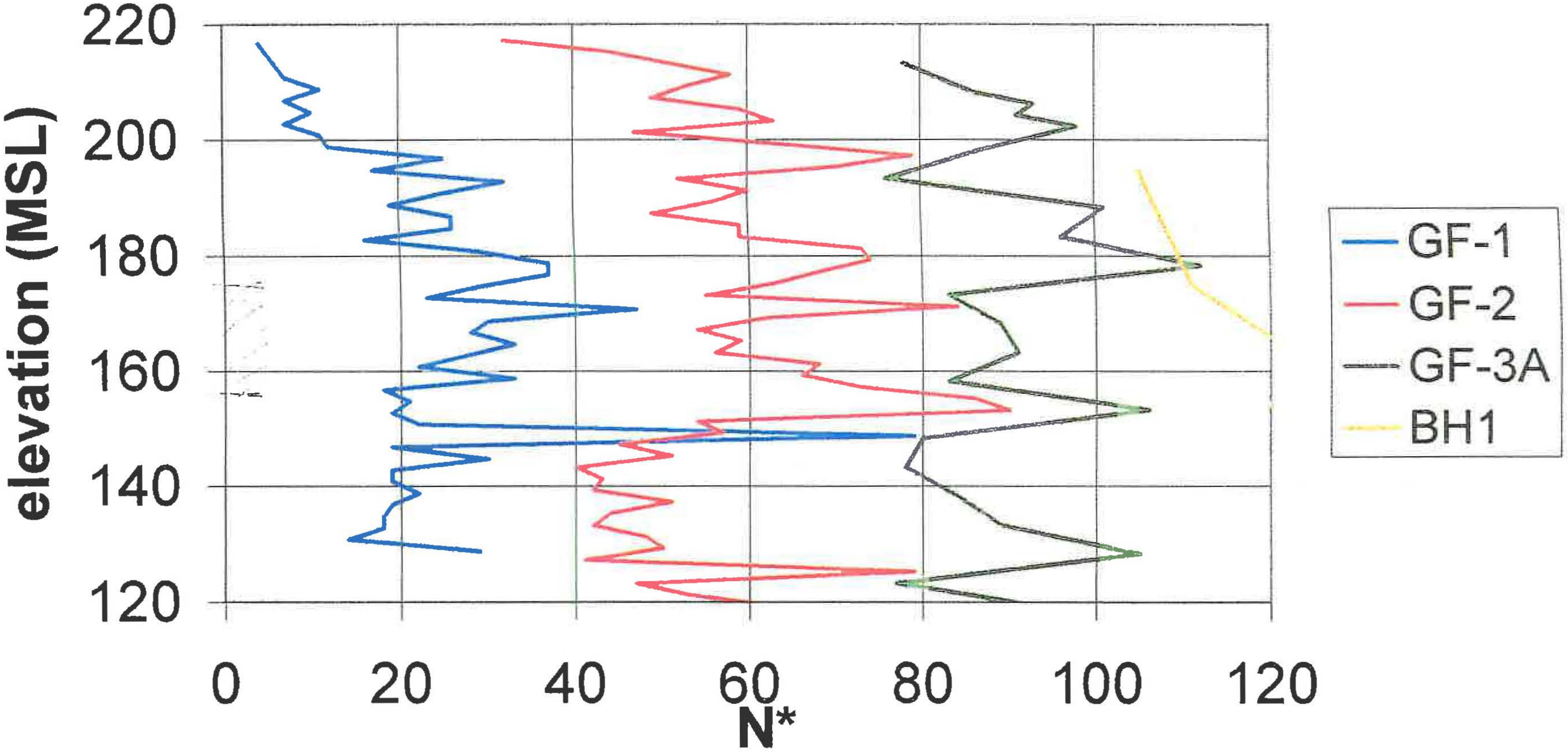
Stratigraphy from Blow Counts



*shifted for graphic presentation

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FIGURE 4-16
Stratigraphy from Blow Counts
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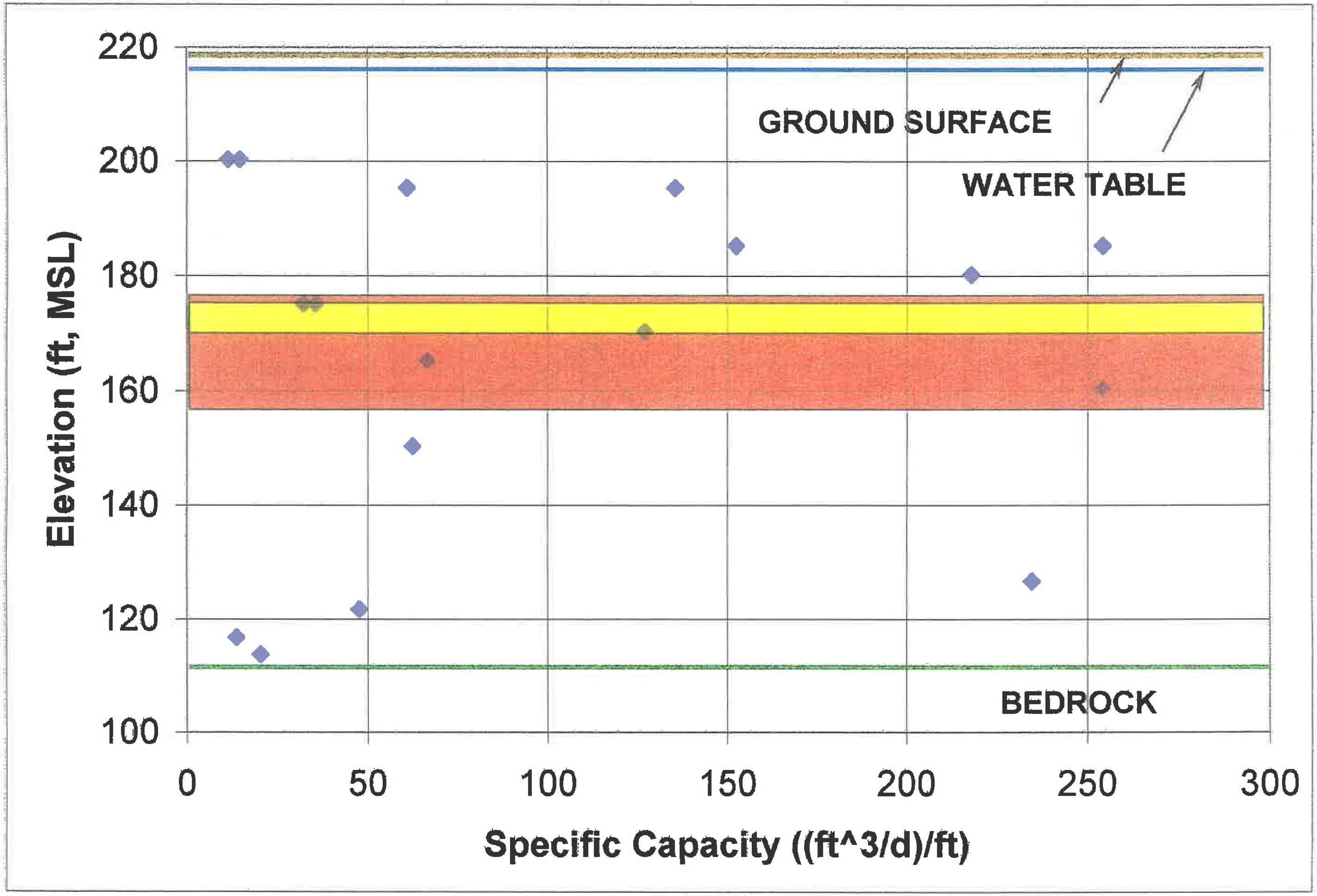
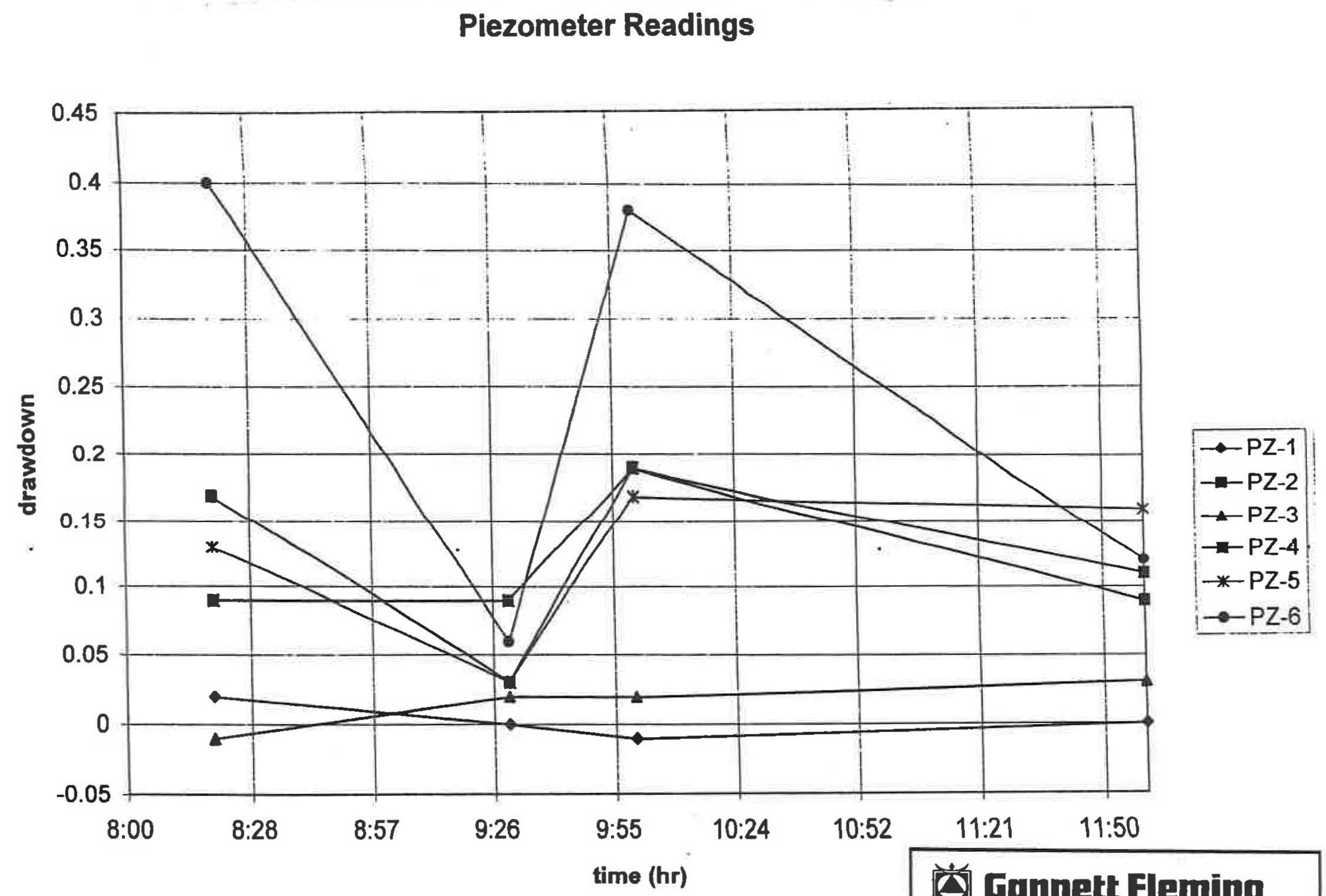


Figure 4-17
Specific Capacity, GF-3A
Grove Pond Arsenic Investigation



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Piezometer Readings
Grove Pond Arsenic Investigation
Fort Devens
Figure 4-18

PIEZOMETER ARRAY

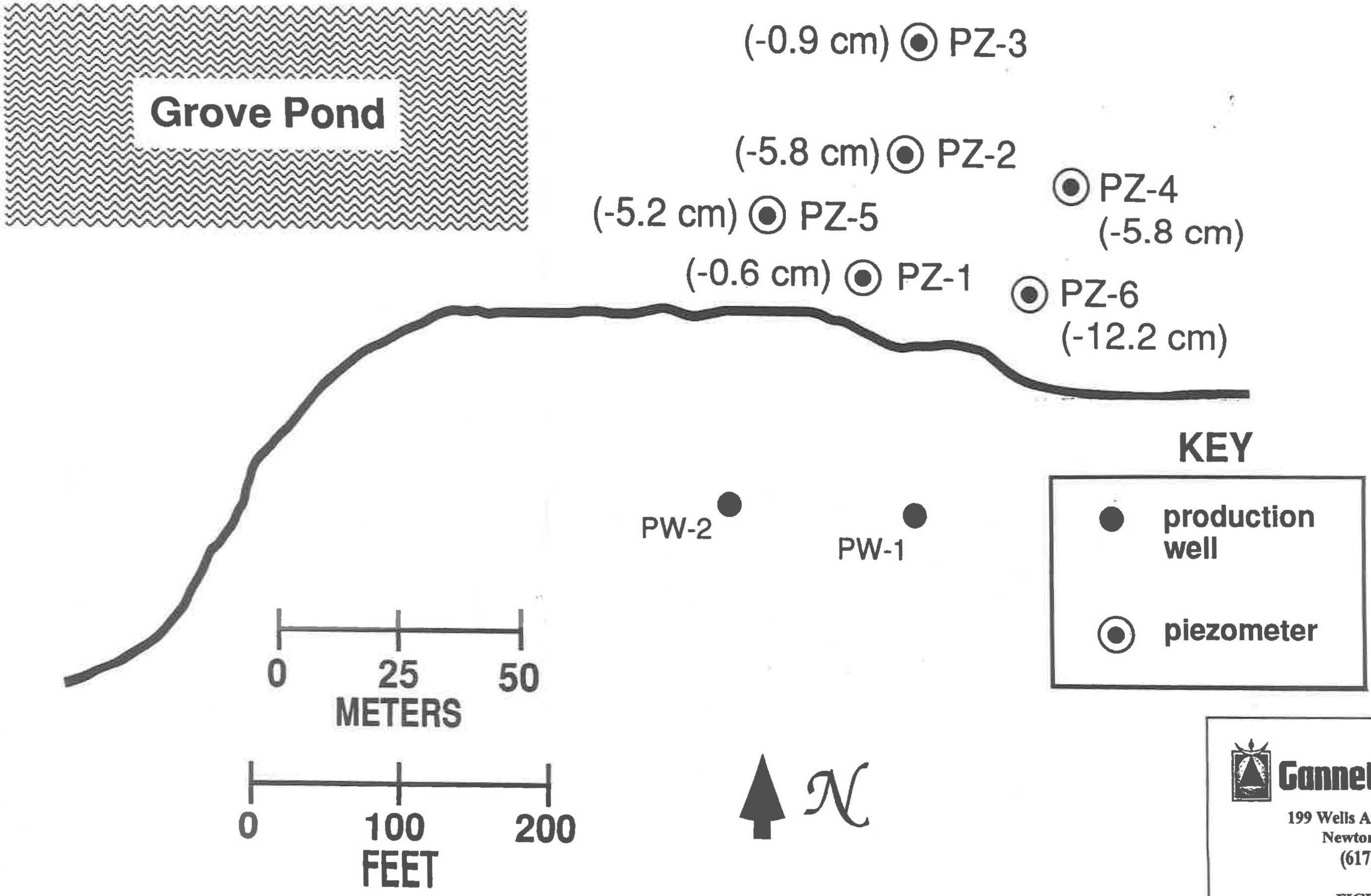

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FIGURE 4-~~18~~ 19
Maximum Drawdowns Piezometer Array
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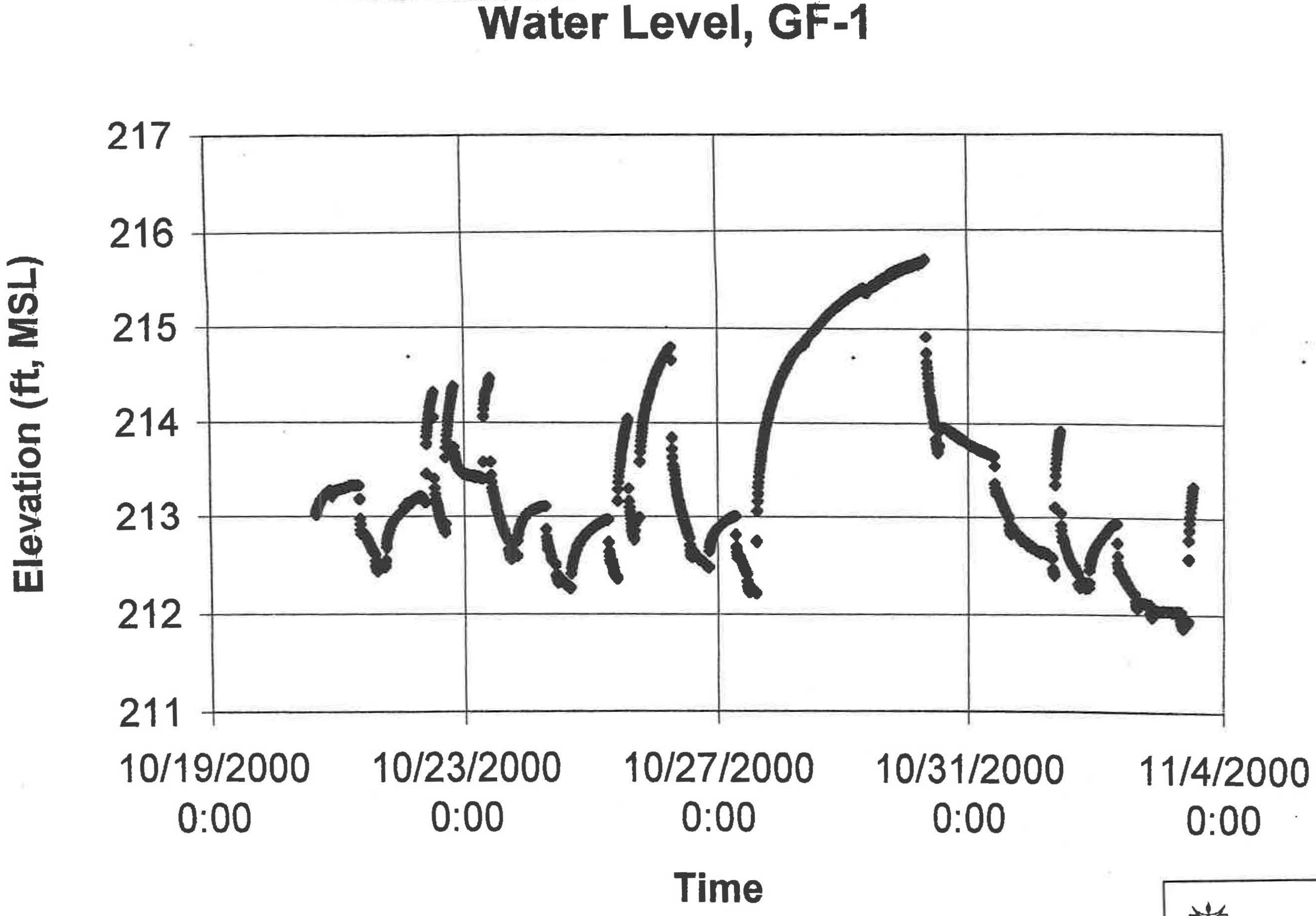

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FIGURE 4-~~19~~ 20
Water Level - GF-1
Grove Pond Arsenic Investigation
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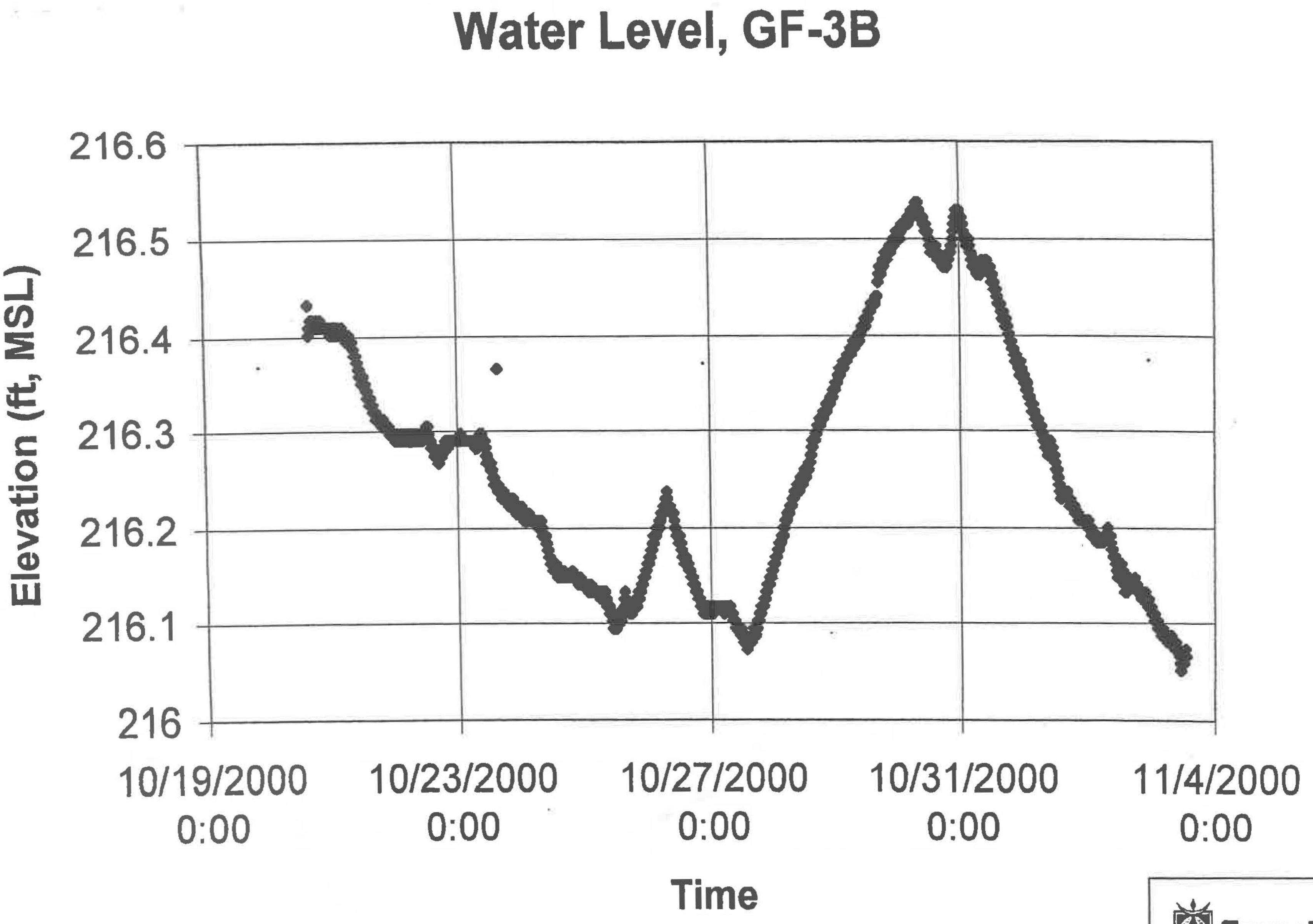

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FIGURE 4-~~20~~ 21
Water Level - GF-3B
Grove Pond Arsenic Investigation
Fort Devens

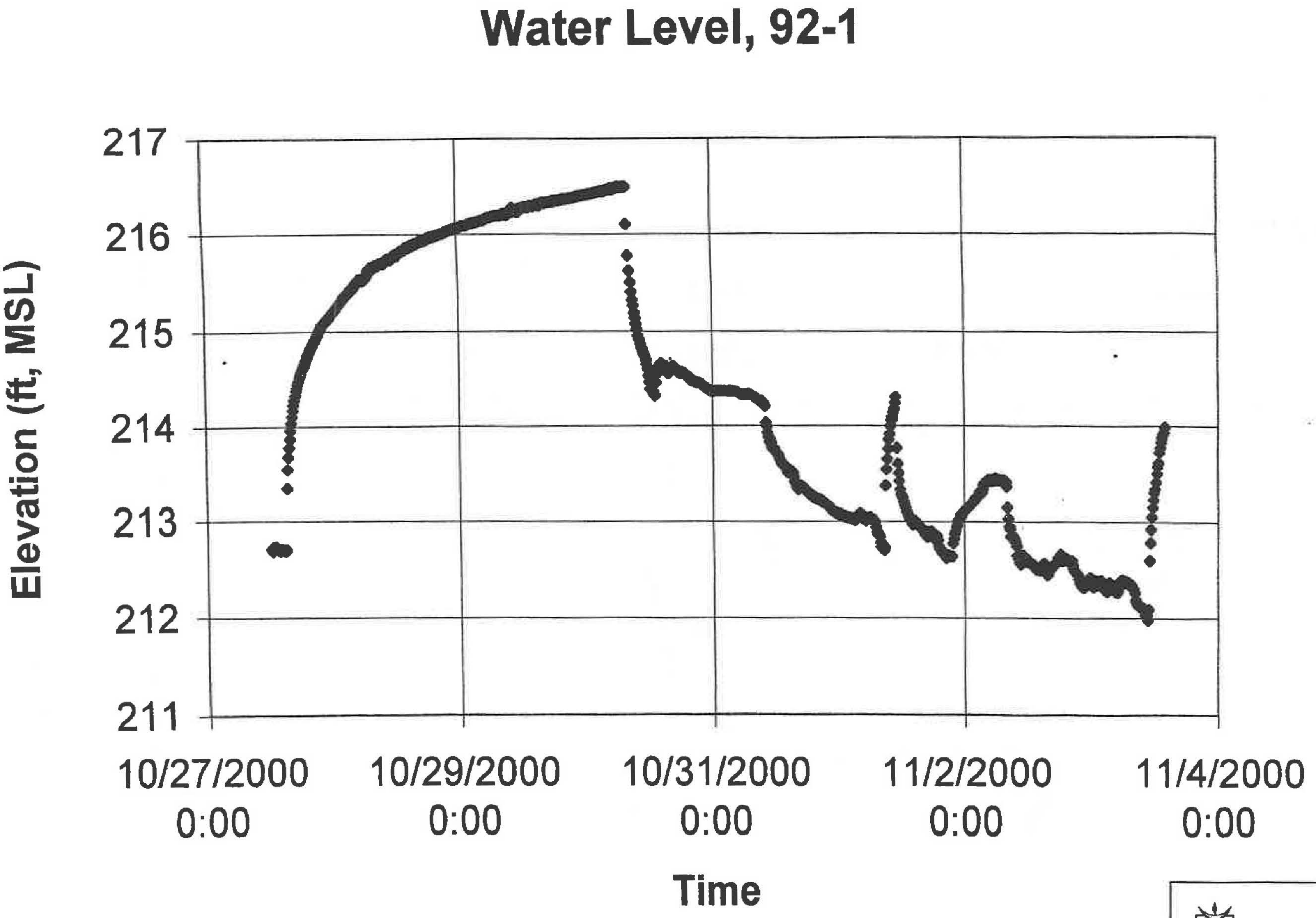

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FIGURE 4-~~21~~ 22
Water Level - 92-1
Grove Pond Arsenic Investigation
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Water Level, GF-1

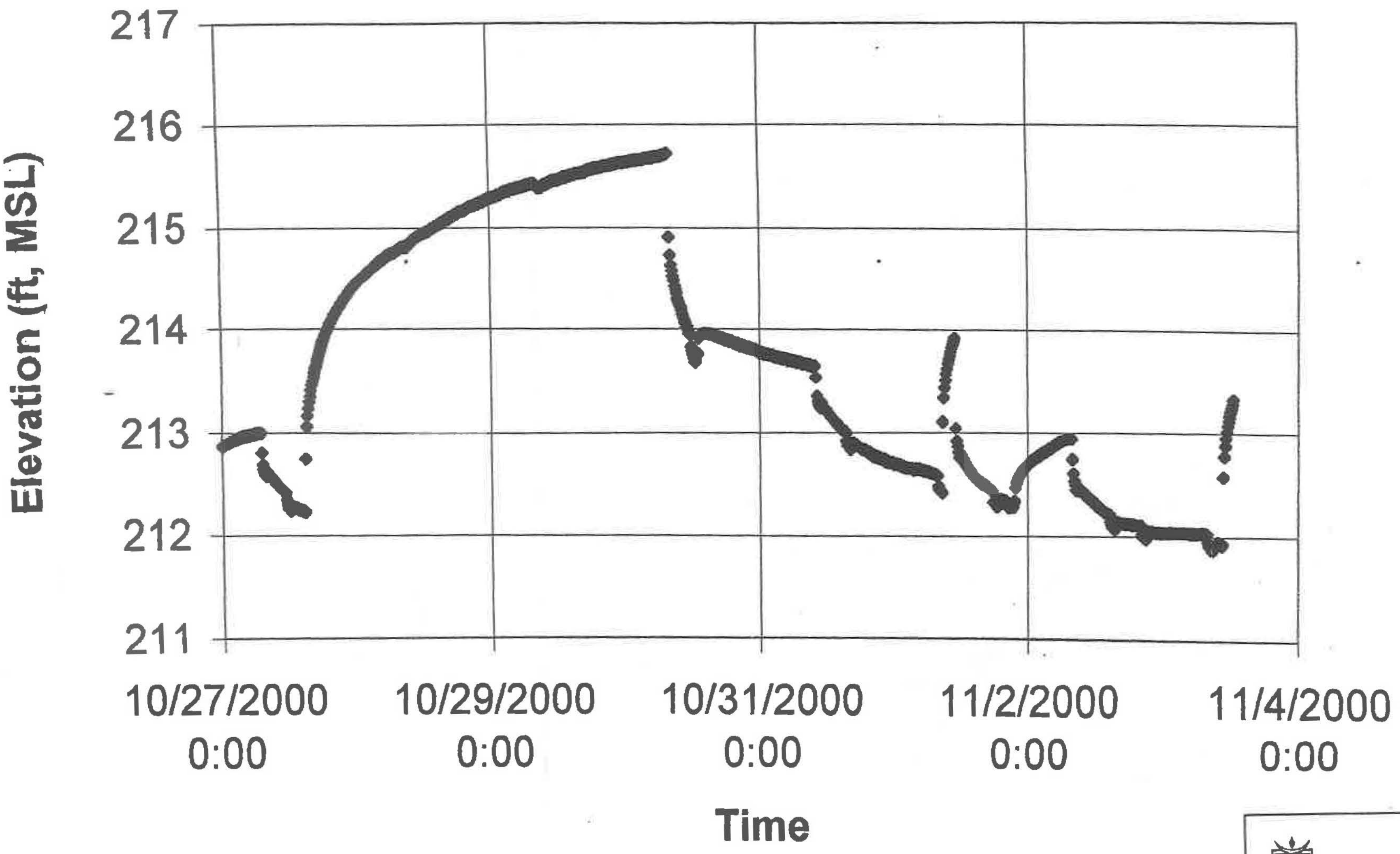

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FIGURE 4-~~22~~ 23
Water Level - GF-1
Grove Pond Arsenic Investigation
Fort Devens

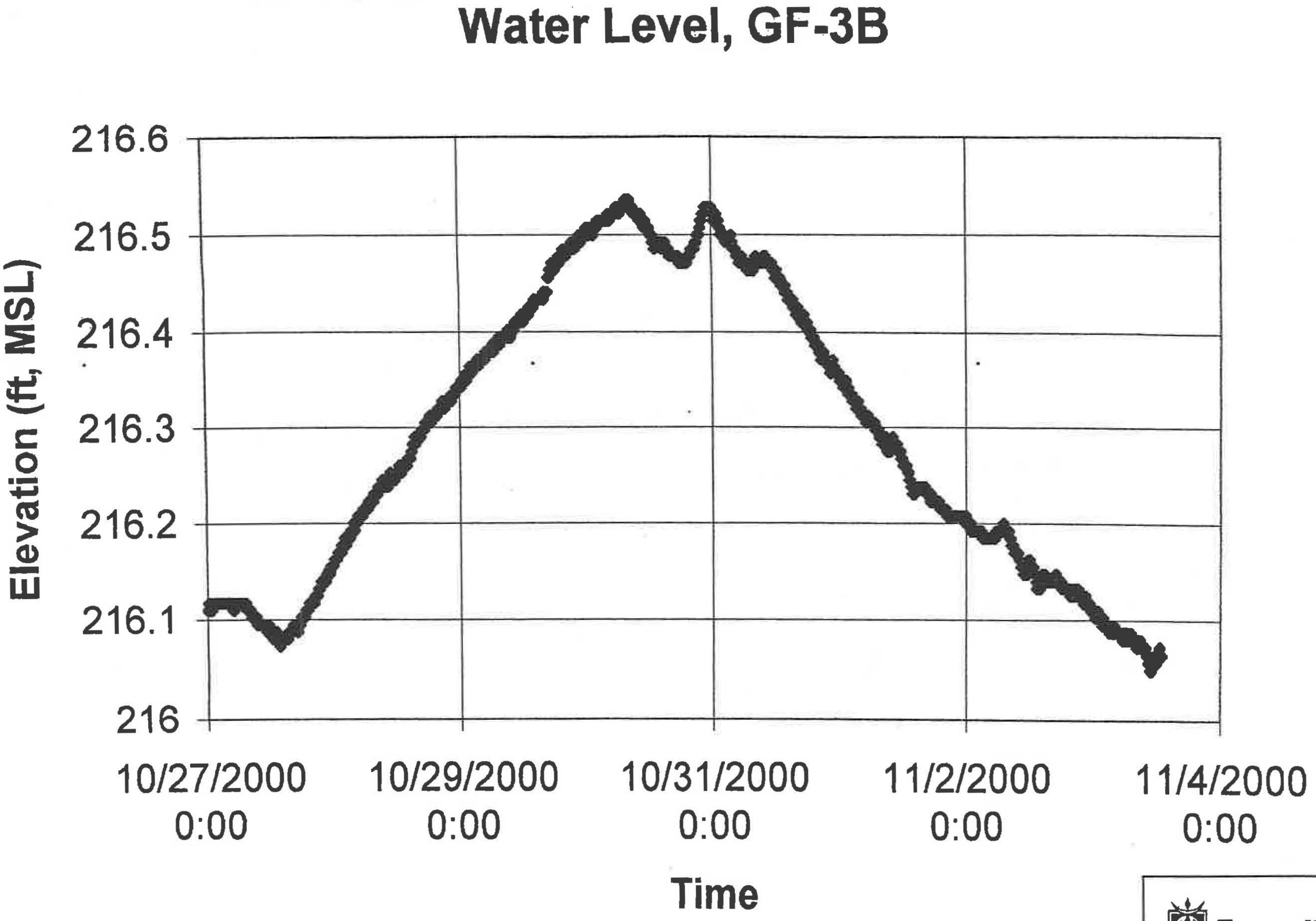

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FIGURE 4-~~23~~ 24
Water Level - GF-3B
Grove Pond Arsenic Investigation
Fort Devens

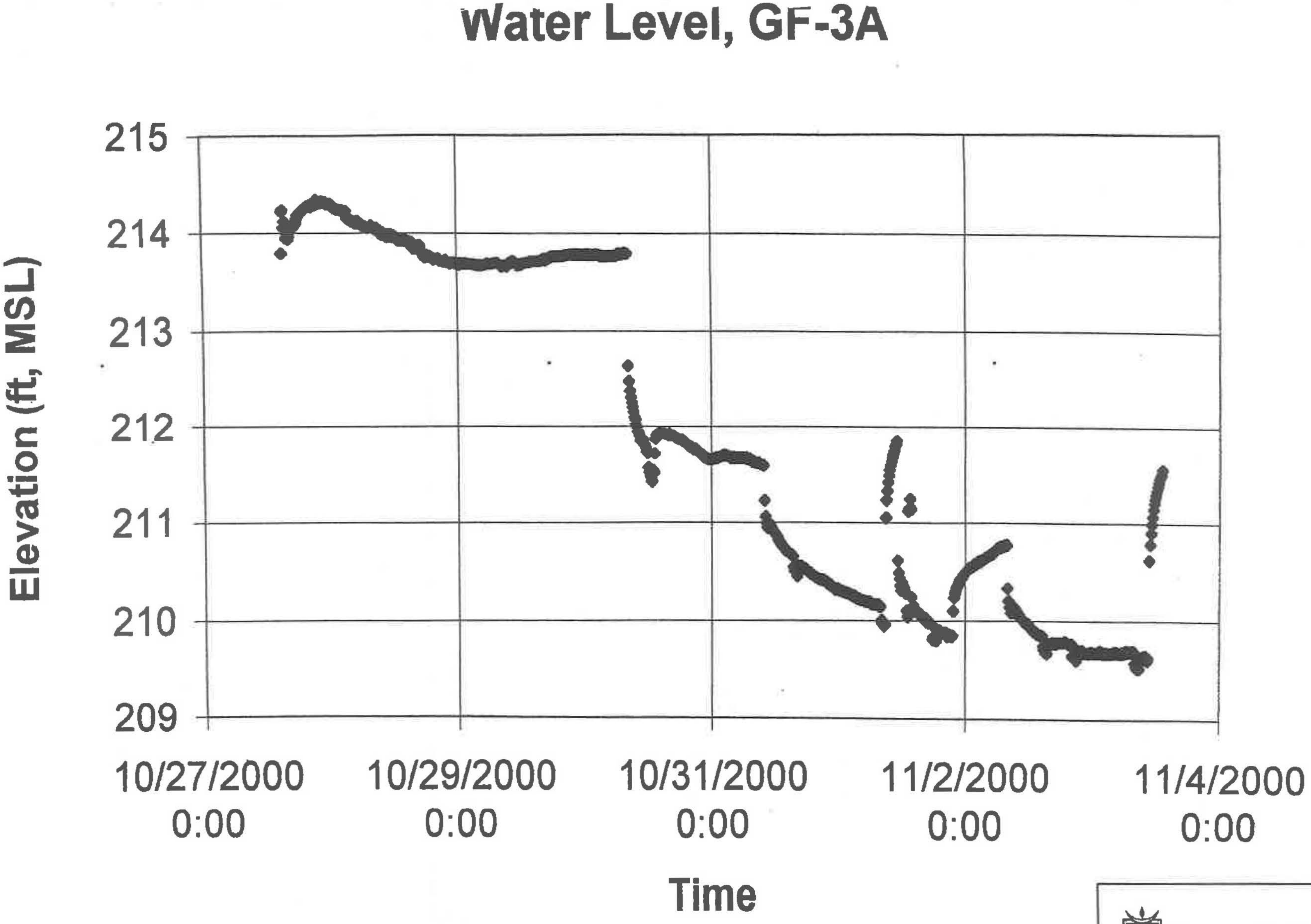

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FIGURE 4-~~24~~ 25
Water Level, GF-3A
Grove Pond Arsenic Investigation
Fort Devens

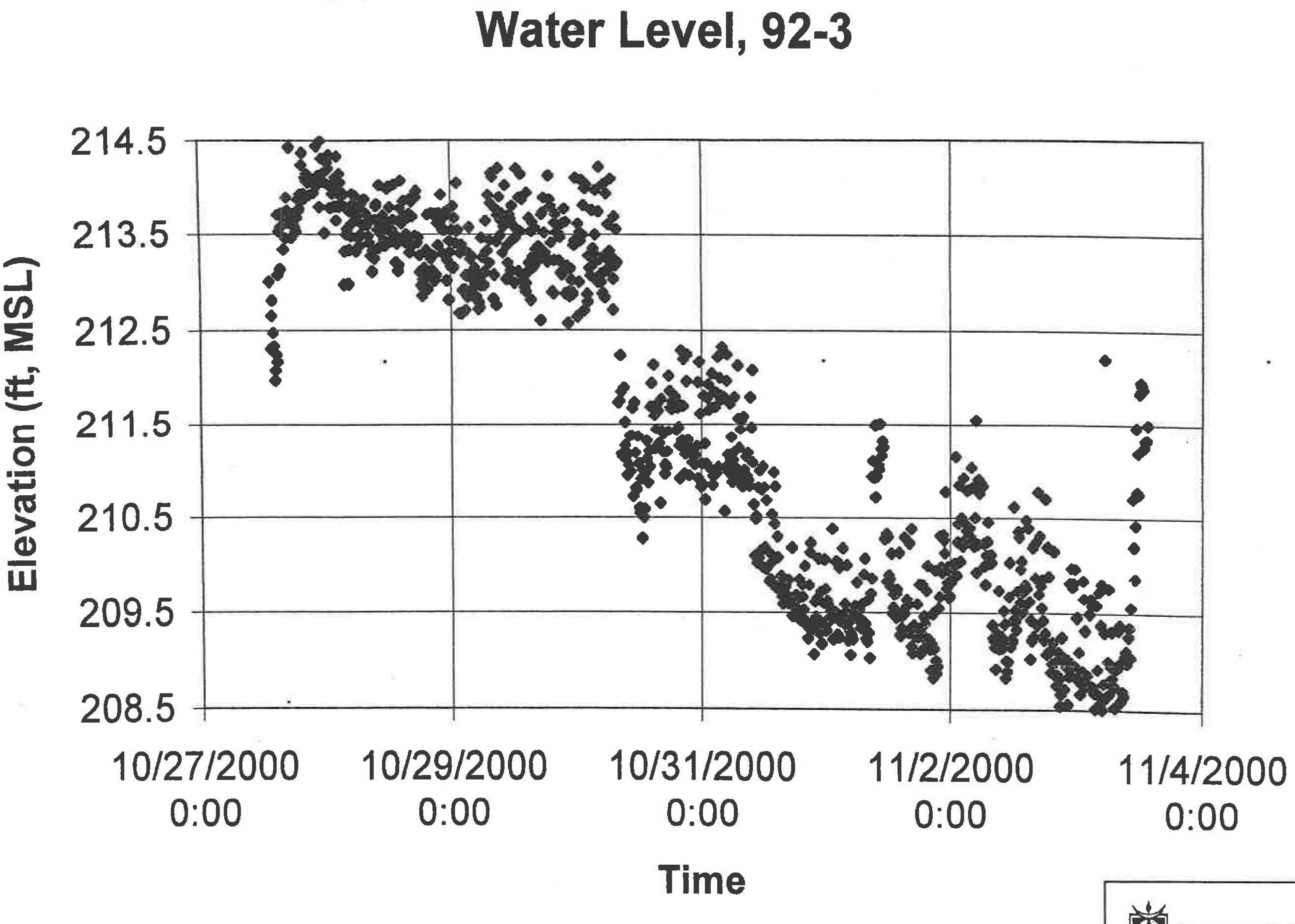

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FIGURE 4-~~25~~ 26
Water Level, 92-3
Grove Pond Arsenic Investigation
Fort Devens

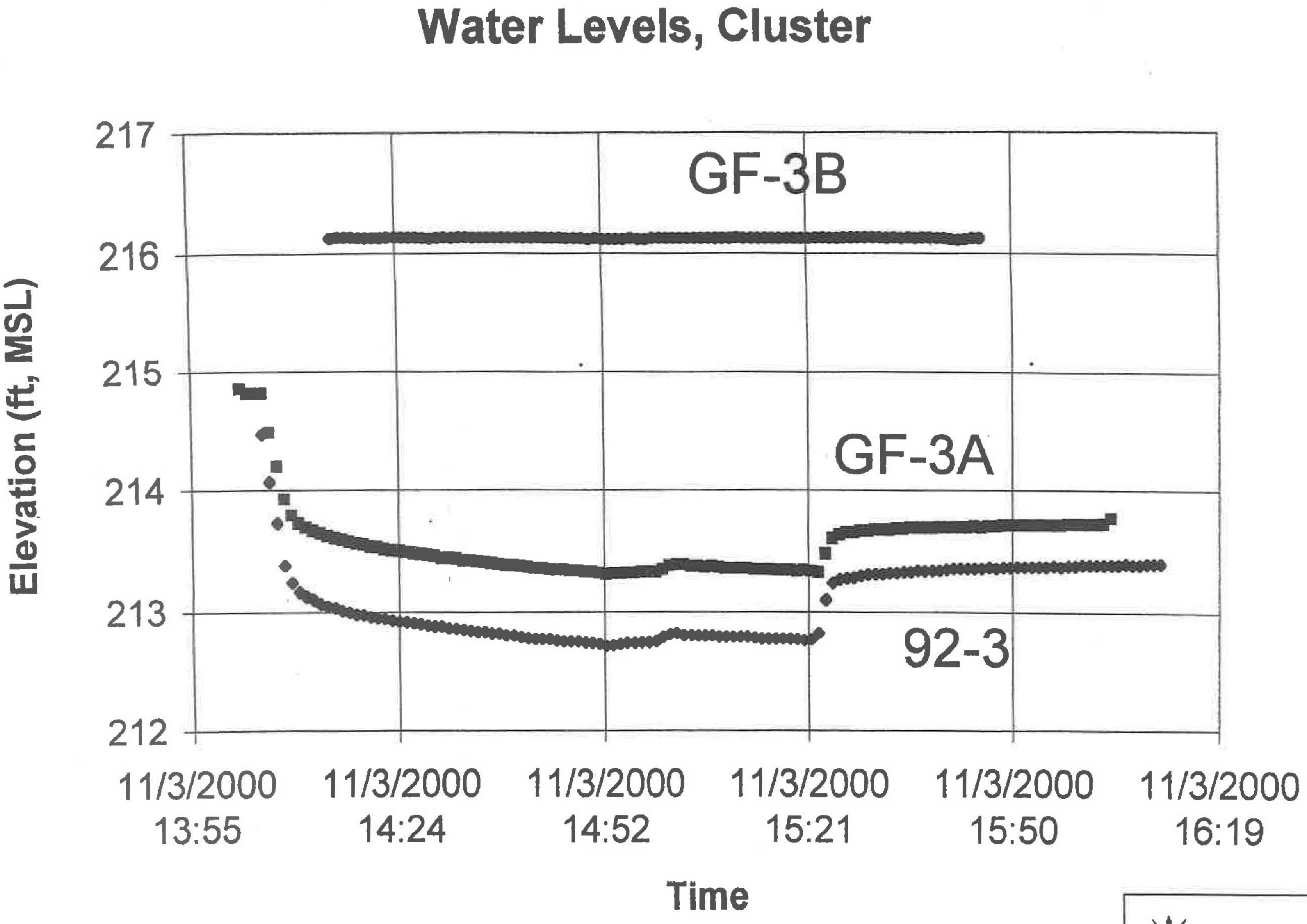

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FIGURE 4-~~26~~27
Water Levels, Cluster
Grove Pond Arsenic Investigation
Fort Devens

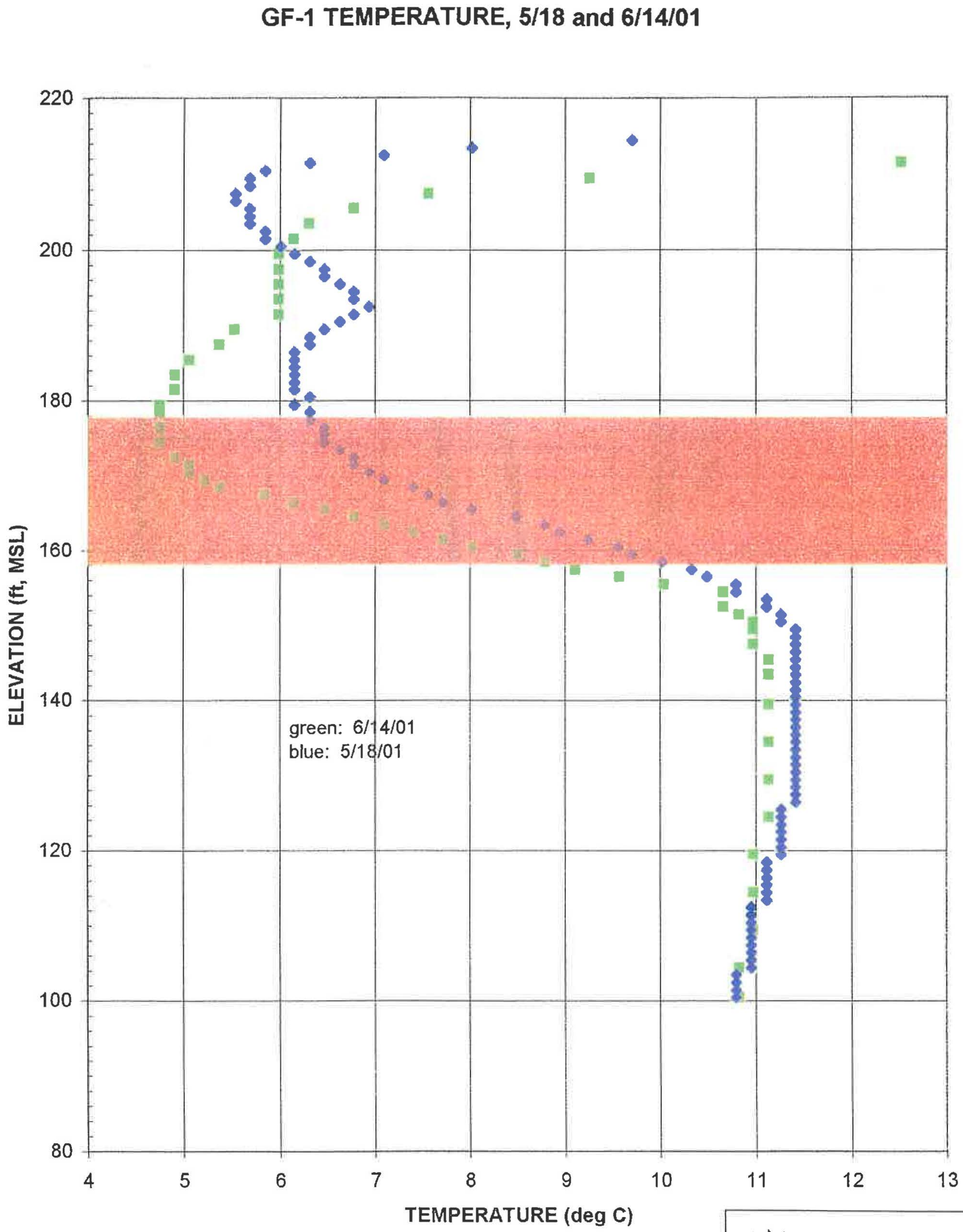

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FIGURE 4-~~27~~ 28
GF-1 Temperature, 5/18 and 6/14/01
Grove Pond Arsenic Investigation
Fort Devens

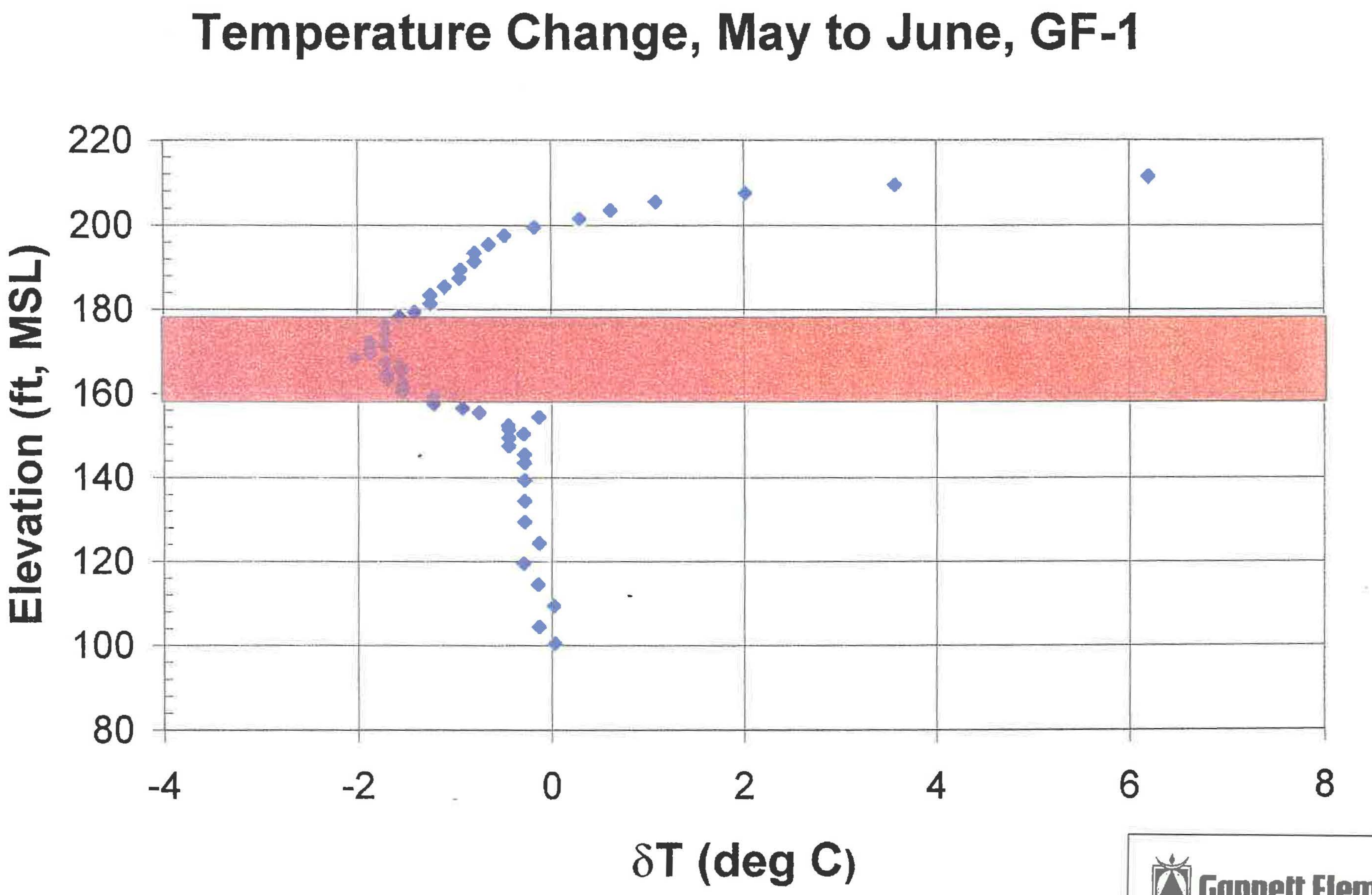

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FIGURE 4-~~28~~ 29
Temperature Change – May to June GF-1
Grove Pond Arsenic Investigation
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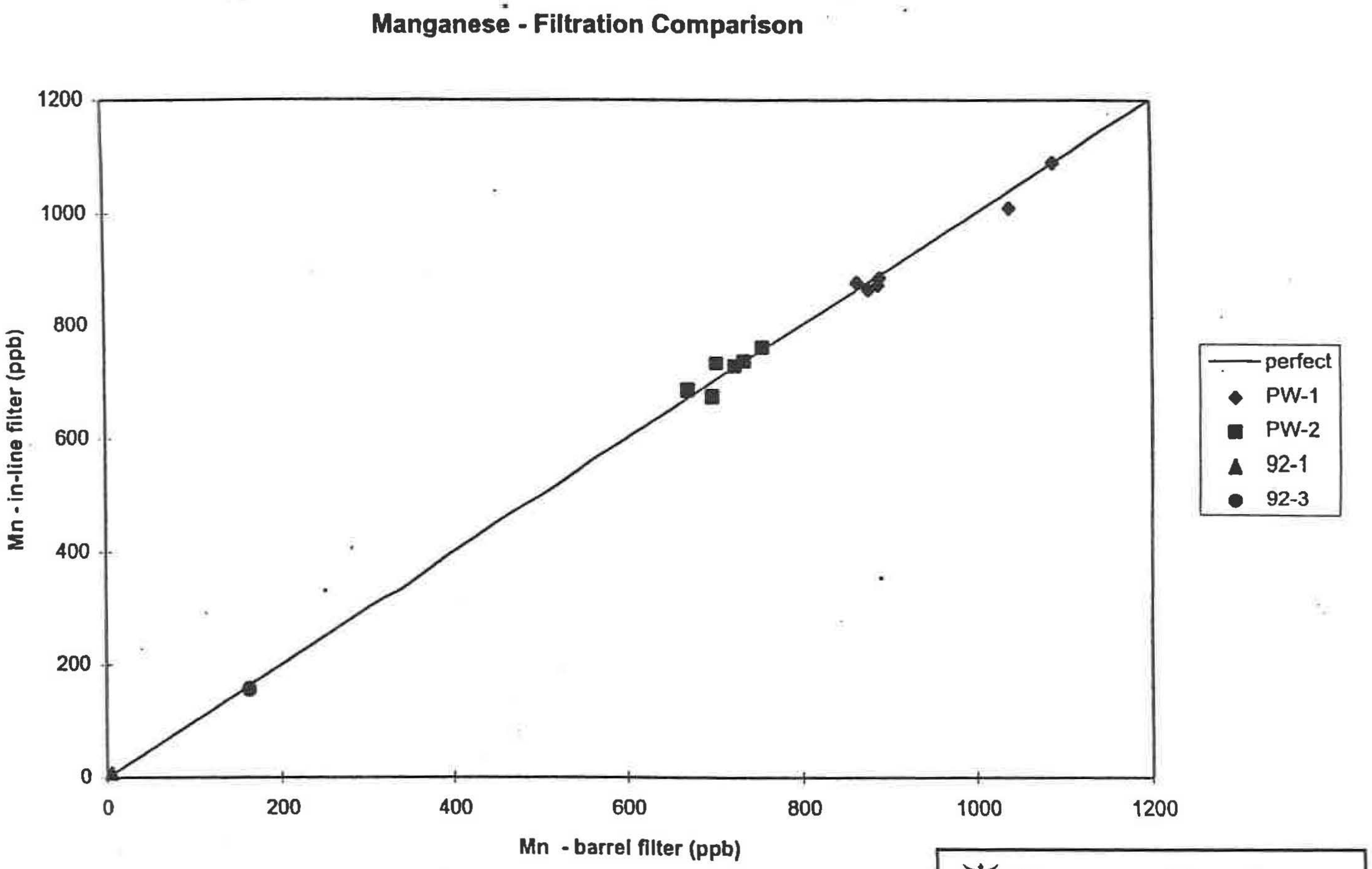

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Manganese Filtration Comparision
Grove Pond Arsenic Investigation
Fort Devens
Figure 4-~~29~~ 30

PIPER DIAGRAMS

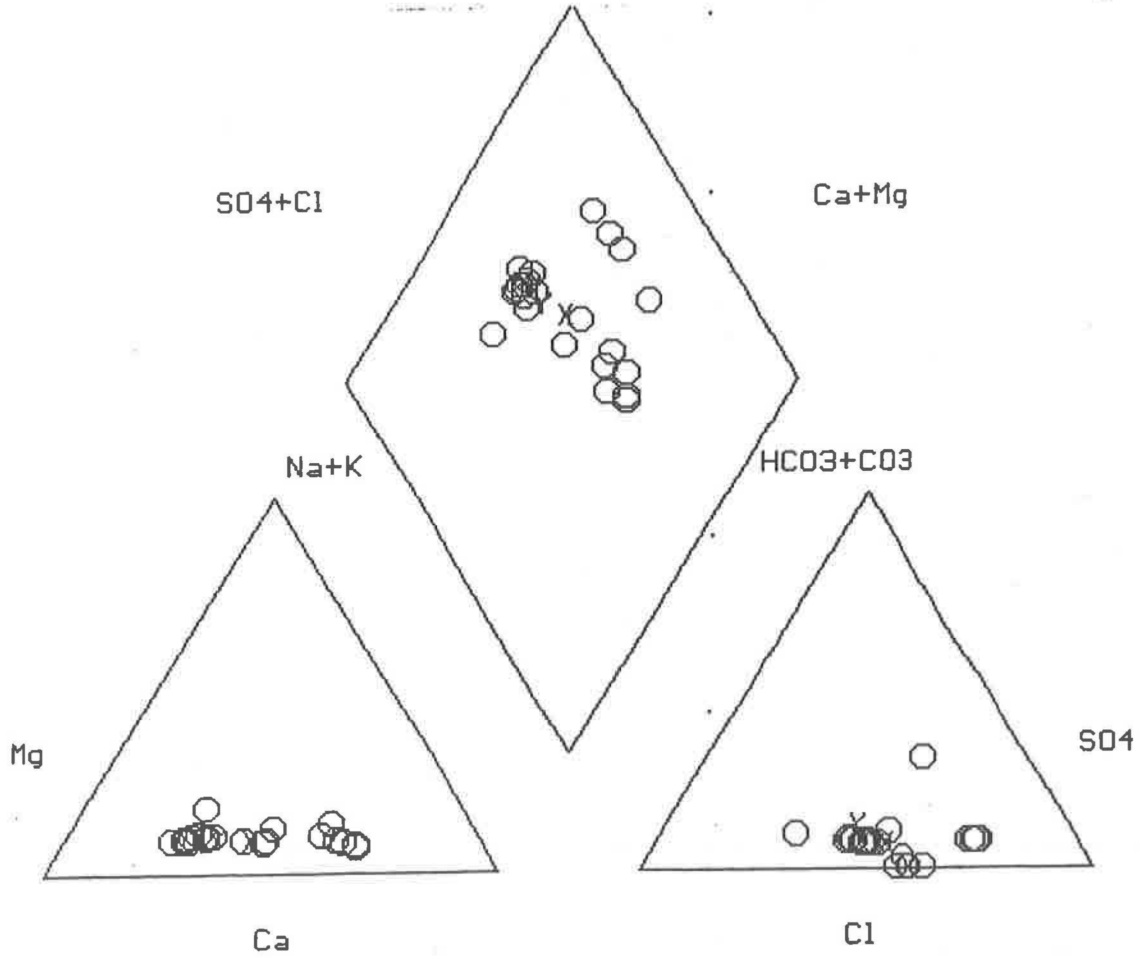

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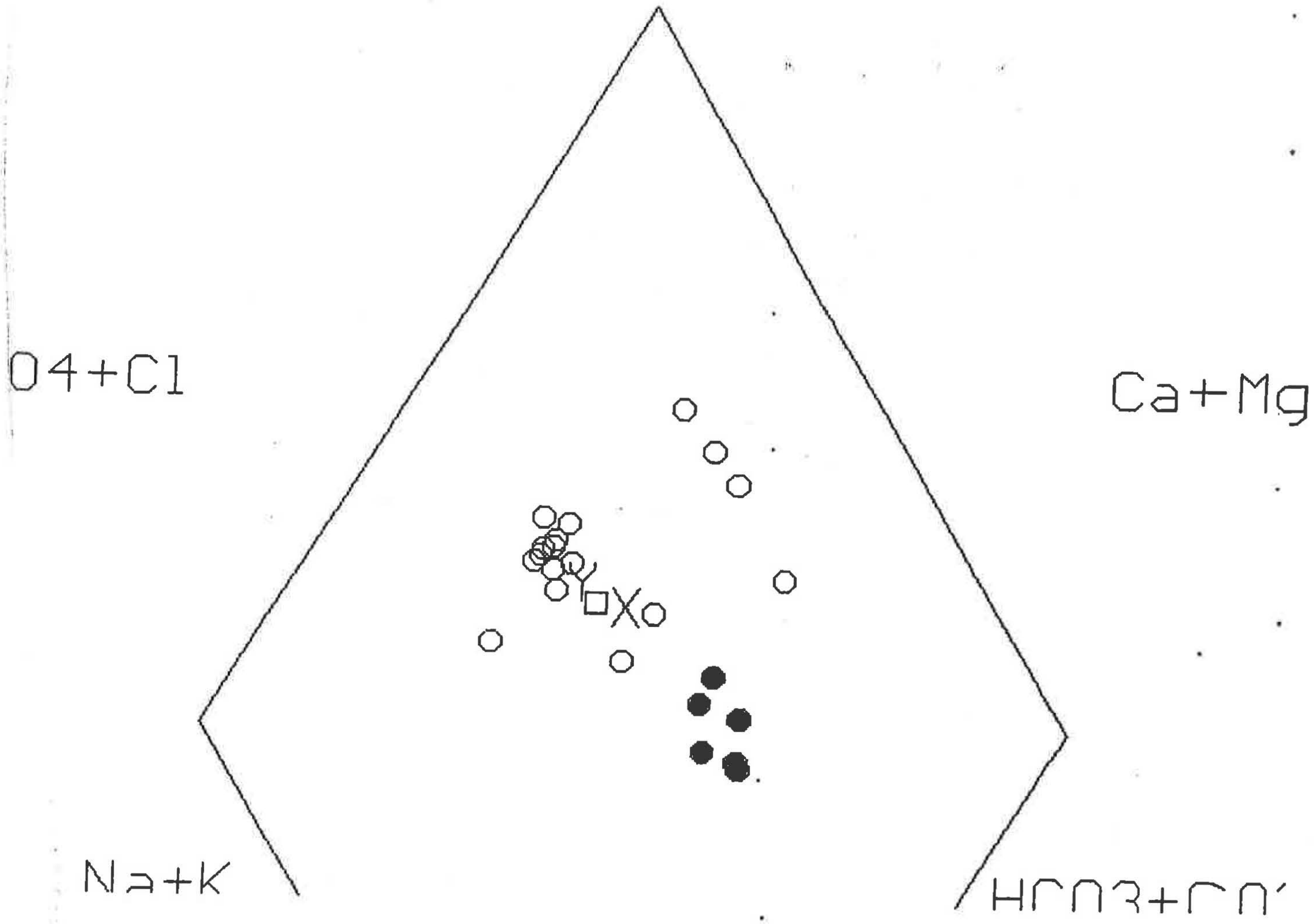
FIGURE 5-1
Piper Diagrams
Grove Pond Arsenic Investigation
Fort Devens



X, Y = **production wells PW1 and PW2, respectively**

□ = **mixture (45% upper aquifer, 55% lower aquifer)**

○ = groundwater

● = groundwater with arsenic

w = **surface water**

B = **bedrock water**

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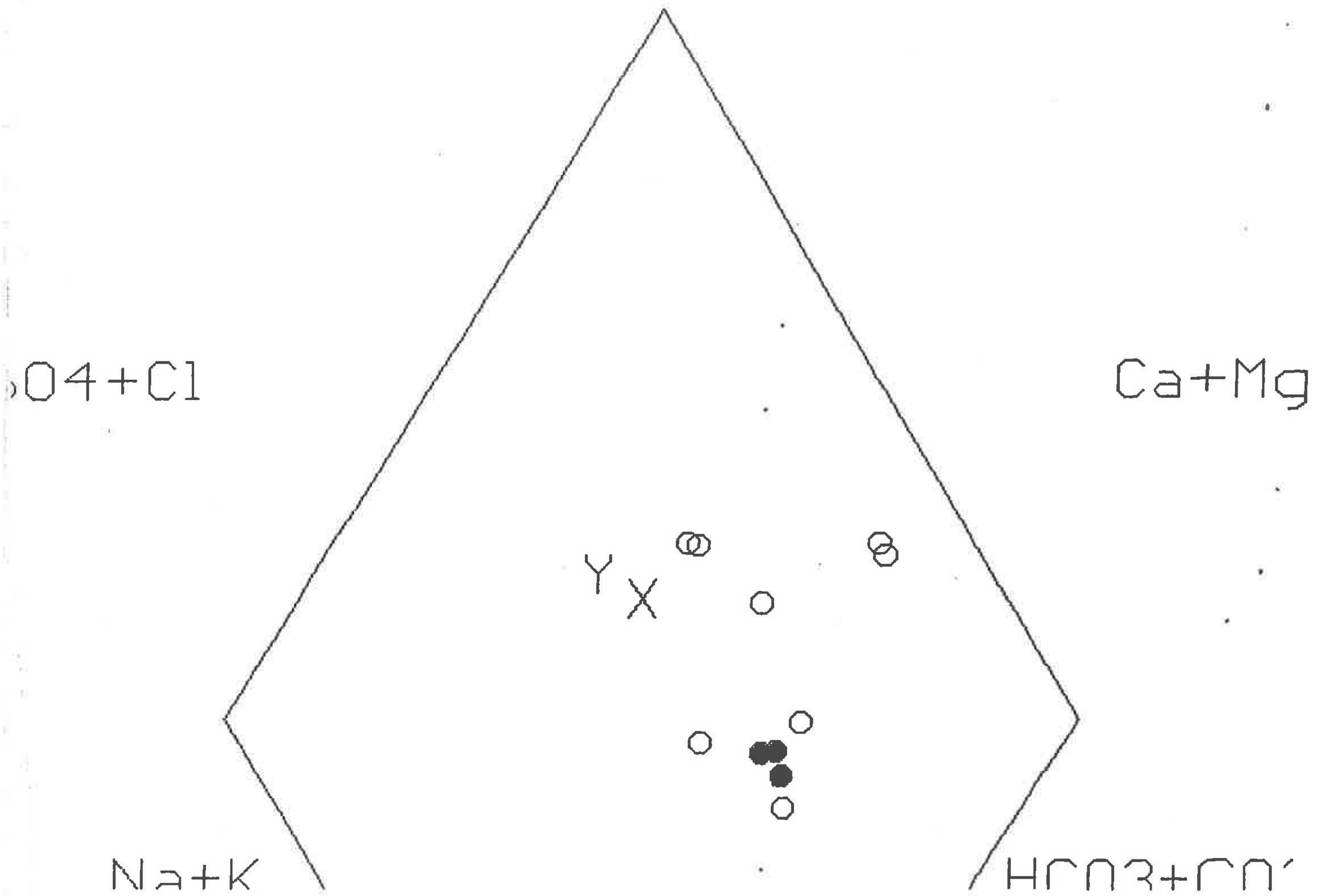
FIGURE 5-2
Piper Diagram – GF-3A
Grove Pond Arsenic Investigation
Fort Devens



X, Y = production wells PW1 and PW2, respectively

□ = mixture (45% upper aquifer, 55% lower aquifer)

○ = groundwater

● = groundwater with arsenic

w = surface water

B = bedrock water

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FIGURE 5-3
Piper Diagram – BH-1 (in-pond borehole)
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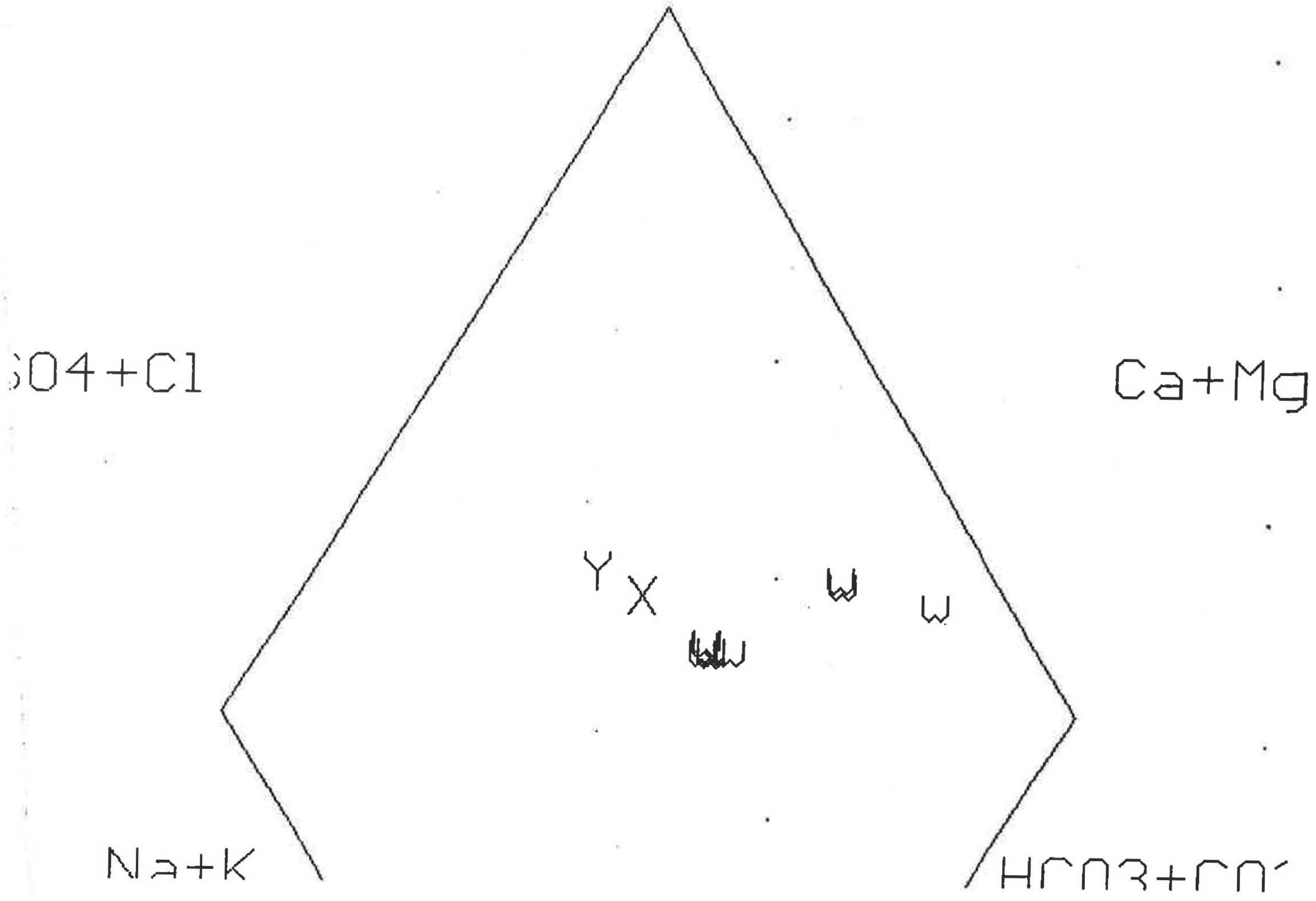
Fort Devens



X, Y = production wells PW1 and PW2, respectively

□ = mixture (45% upper aquifer, 55% lower aquifer)

O = groundwater

● = groundwater with arsenic

w = surface water

B = bedrock water

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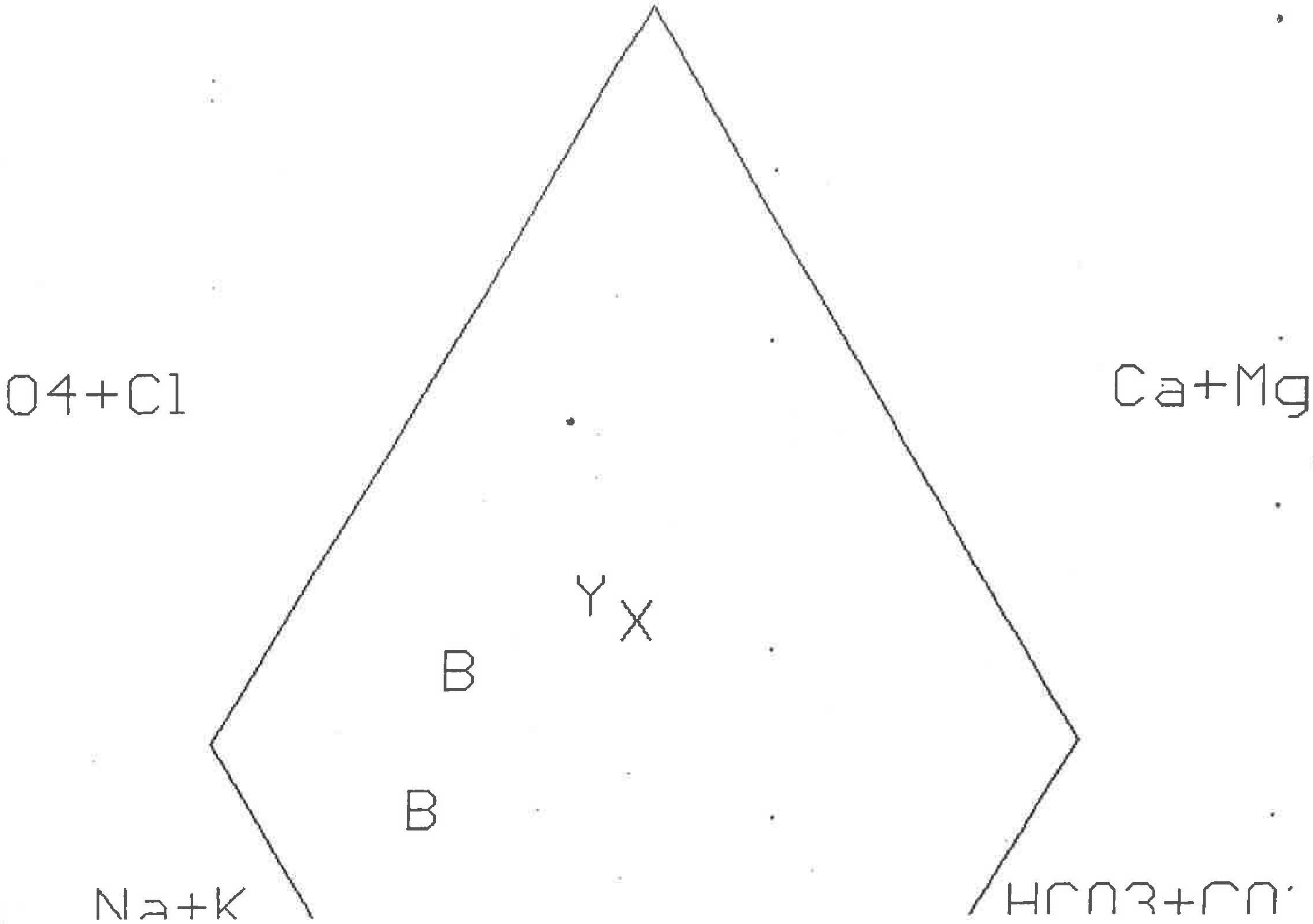
FIGURE 5-4
Piper Diagram – Surface Water
Grove Pond Arsenic Investigation
Fort Devens



X, Y = production wells PW1 and PW2, respectively
□ = mixture (45% upper aquifer, 55% lower aquifer)
O = groundwater
● = groundwater with arsenic
w = surface water
B = bedrock water

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FIGURE 5-5
Piper Diagram - Bedrock Wells
Grove Pond Arsenic Investigation
Fort Devens

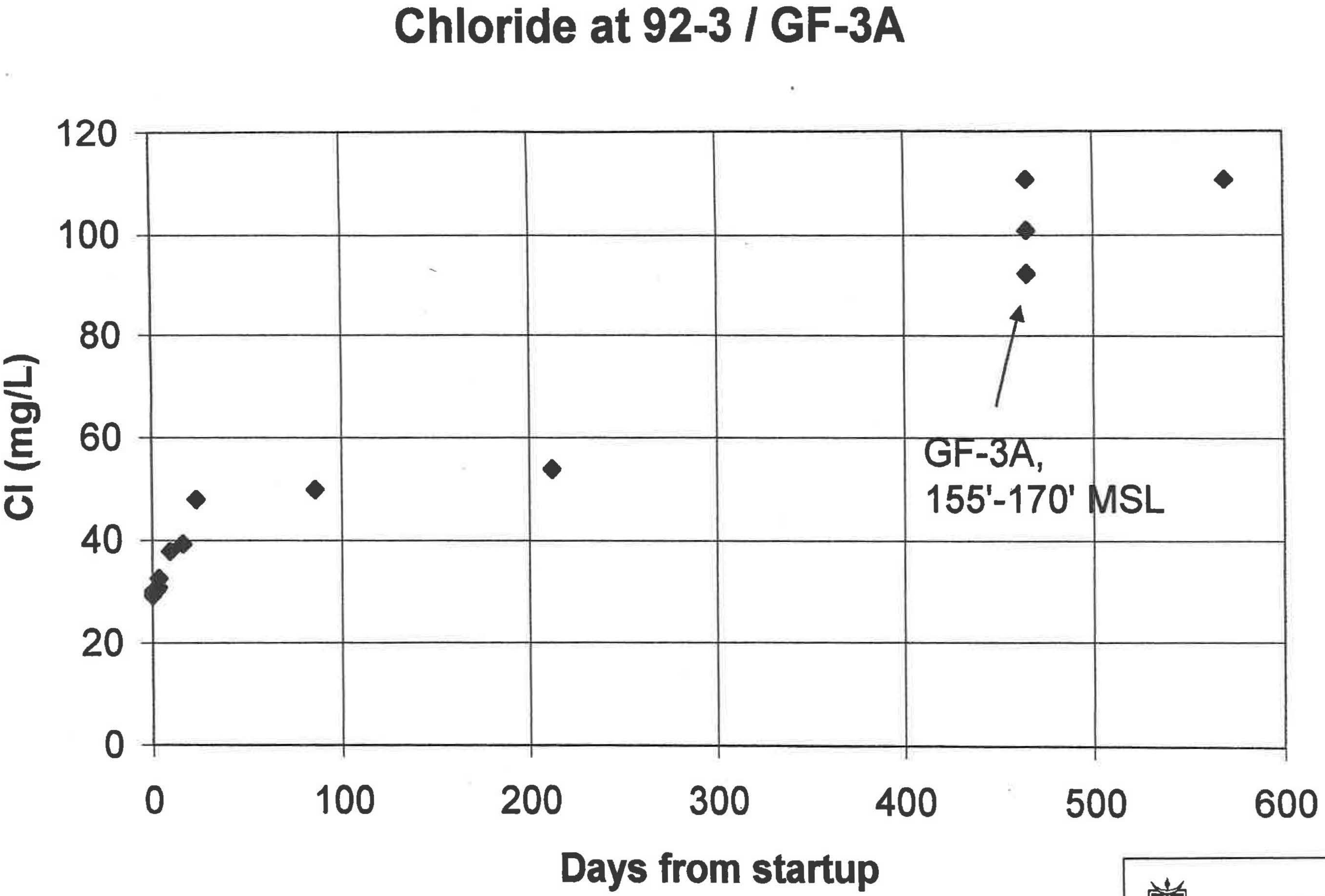

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FIGURE 5-6
Chloride at 92-3/GF-3A
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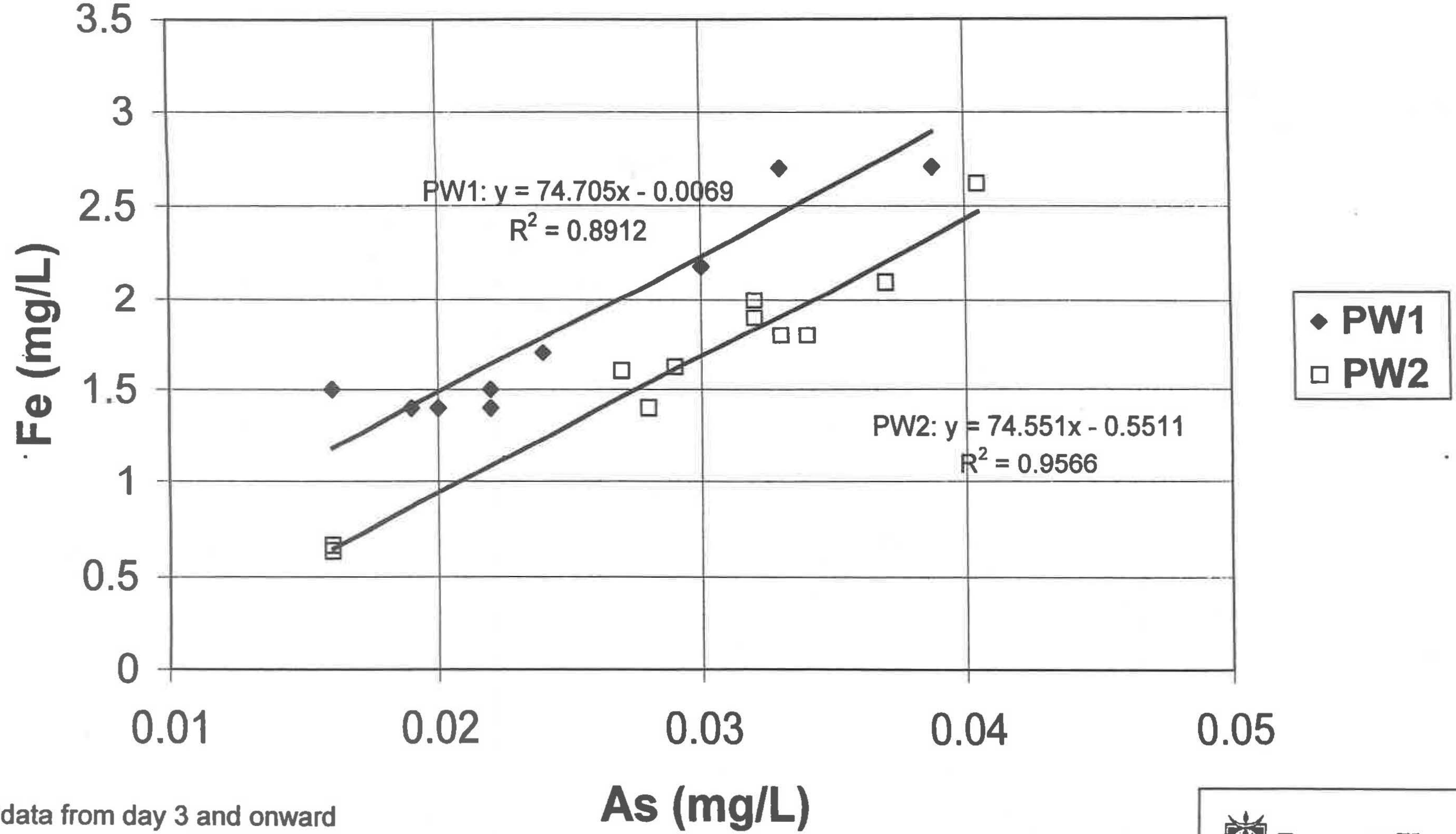
Iron and Arsenic in Production Wells*



*data from day 3 and onward

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FIGURE –6-1
Iron and Arsenic in Production Wells
Grove Pond Arsenic Investigation
Fort Devens

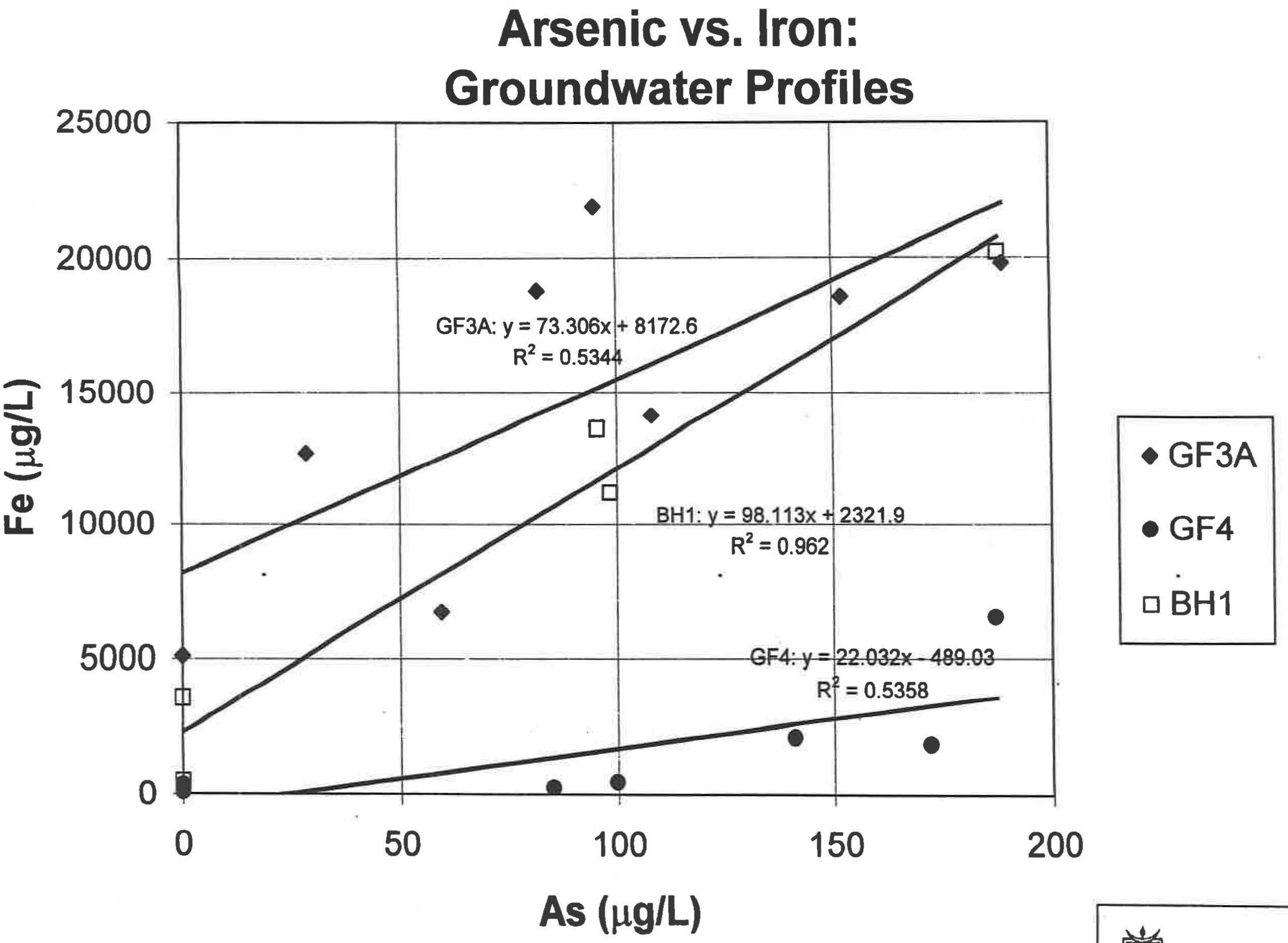

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FIGURE –6-2
Arsenic vs. Iron – Groundwater Profiles
Grove Pond Arsenic Investigation
Fort Devens

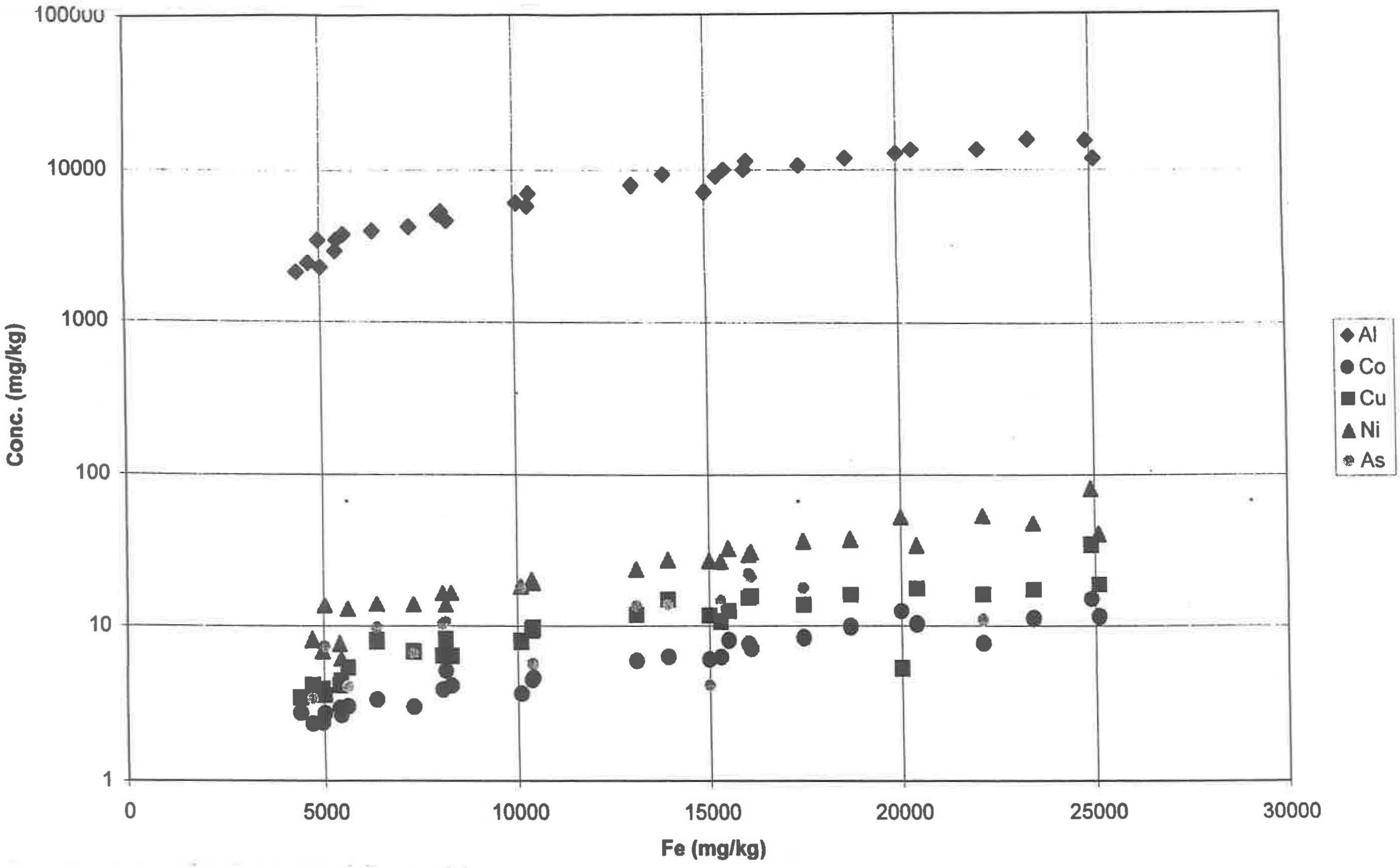

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FIGURE 6-~~A~~-3
Soil Fe, Other Metals
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Fort Devens

Groundwater Iron, Arsenic, and ORP: GF3A

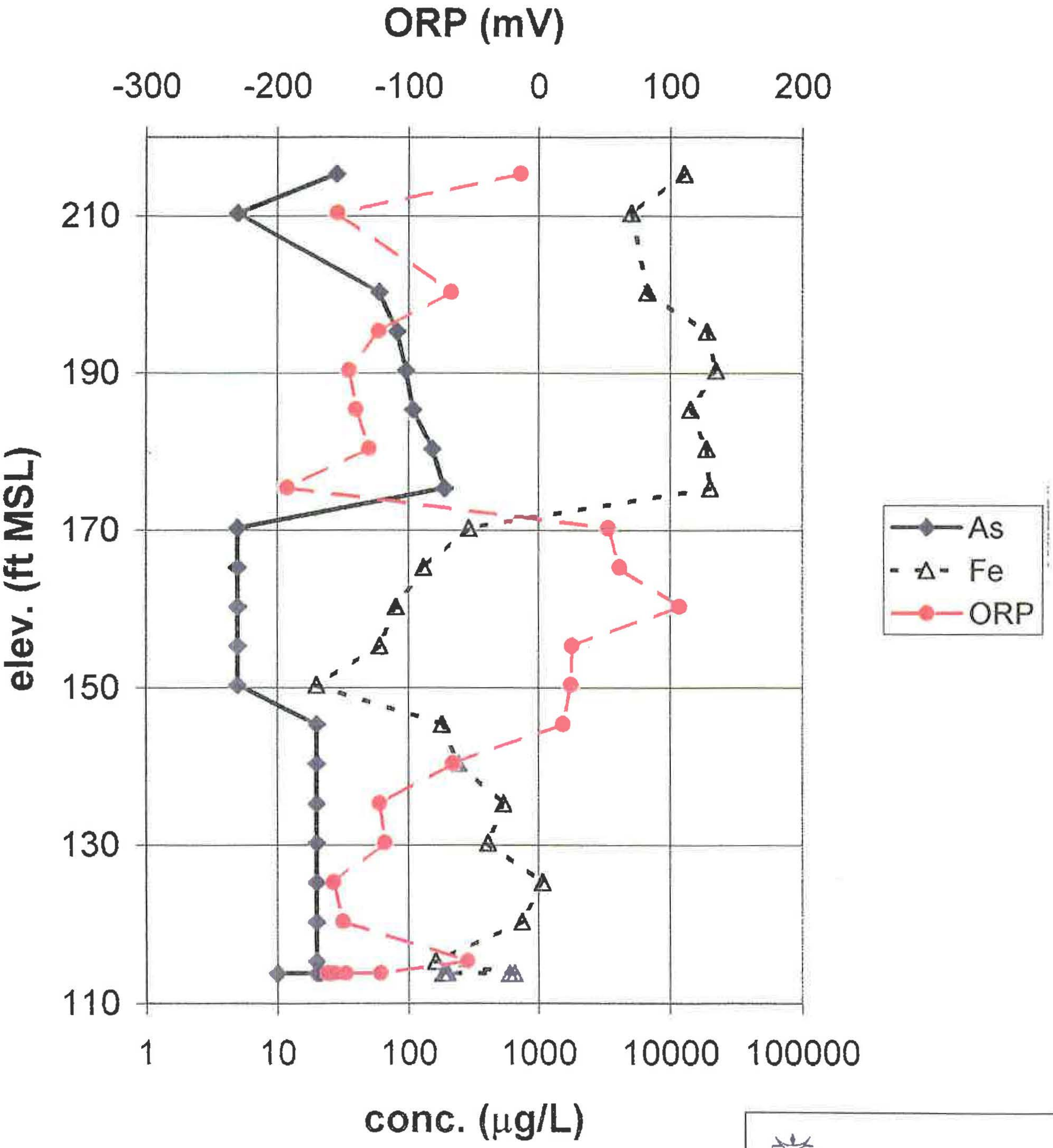

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FIGURE 6-~~3~~ 4
Groundwater Iron, Arsenic and ORP: GF-3A
Grove Pond Arsenic Investigation
Fort Devens

Table 2-1
SAMPLE LOCATIONS (all media)
Grove Pond Arsenic Investigation, Fort Devens

			NAD 27			N latitude			W longitude			
	location		Northing	Easting		deg	min	sec	deg	min	sec	Notes
pre-existing wells	MNG-7		564337	577656		42	32	55.099	71	34	58.500	[1]
	MNG-3		564950	577766		42	33	1.155	71	34	57.039	
	92-4		565101.5	577753.1		42	33	2.651	71	34	57.213	
	92-1		565272.2	577943.3		42	33	4.340	71	34	54.674	
	PW-1		565317.1	578010.4		42	33	4.784	71	34	53.778	
	PW-2		565332.2	577890.1		42	33	4.932	71	34	55.385	
	92-3		565423.2	577956.7		42	33	5.832	71	34	54.497	
	92-5		566192	577601		42	33	13.422	71	34	59.259	
new wells/borings	GF-1		565334.8	578012.7		42	33	4.958	71	34	53.747	[2]
	GF-2		565349.7	577886.4		42	33	5.106	71	34	55.435	
	GF-3A		565413.9	577959.4		42	33	5.739	71	34	54.460	
	GF-3B		565408.1	577959.8		42	33	5.682	71	34	54.455	
	GF-4		565367	577710.6		42	33	5.277	71	34	57.784	
	BH-1		565557.8	578007.4		42	33	7.160	71	34	53.819	
piezometers	PZ-1		565488.4	577979.1		42	33	6.475	71	34	54.197	[2]
	PZ-2		565557.8	578007.4		42	33	7.160	71	34	53.819	
	PZ-3		565610.2	578014.9		42	33	7.678	71	34	53.718	
	PZ-4		565536.5	578074.5		42	33	6.950	71	34	52.922	
	PZ-5		565519.2	577923.5		42	33	6.780	71	34	54.940	
	PZ-6		565479.9	578054.1		42	33	6.391	71	34	53.194	
soft-sediment cores	SC-1		565480.9	578054.1		42	33	6.401	71	34	53.194	[3]
	SC-2		565526.4	577988		42	33	6.851	71	34	54.078	
	SC-3		565556	577976.2		42	33	7.142	71	34	54.236	

seepage meters	SM-1		565518.8	578103.1		42	33	6.775	71	34	52.540	[4]
	SM-2		565545.6	578083.6		42	33	7.040	71	34	52.800	
	SM-3		565543.1	578121.8		42	33	7.015	71	34	52.290	
	SM-4		565584.1	578119.5		42	33	7.420	71	34	52.320	
surface water	SW-1		565463.2	577956.6		42	33	6.226	71	34	54.498	[5]
	SW-2		565538.2	577956.5		42	33	6.967	71	34	54.498	
	SW-3		565653.3	577956.4		42	33	8.103	71	34	54.500	
	SW-4		565538.3	578031.5		42	33	6.968	71	34	53.496	
	SW-5		565538.4	578131.5		42	33	6.969	71	34	52.160	
	SW-6		566871.8	576164		42	33	20.134	71	35	18.450	
sediment	SD-1		565518.8	578072.7		42	33	6.776	71	34	52.946	[6]
	SD-2		565581.1	578060.3		42	33	7.390	71	34	53.112	
	SD-3		565631.7	578147.1		42	33	7.890	71	34	51.952	
	SD-4		565792.5	578212.3		42	33	9.478	71	34	51.081	
	SD-5		565601.8	578320.6		42	33	7.595	71	34	49.633	
	SD-6		566871.8	576164		42	33	20.134	71	35	18.450	
	SD-7		565481.2	578191.2		42	33	6.404	71	34	51.363	
	SD-8		565608.4	578044.6		42	33	7.660	71	34	53.322	
	SD-9		565614.3	578117.9		42	33	7.718	71	34	52.342	
	SD-10		565630.2	578208.8		42	33	7.875	71	34	51.127	

[1] NAD 27 coordinates based on survey (CDM, 1993); latitude/longitude conversion courtesy of U. S. Army BRAC office

[2] locations fixed by GPS, courtesy of U. S. Army BRAC office, reported in NAD 27; latitude/longitude conversion approximate

[3] locations estimated from approximate distances to nearest piezometer

[4] locations fixed by GPS, courtesy of USEPA; reported as latitude/longitude (uncorrected); NAD 27 conversion approximate

[5] locations fixed by chain and compass, referenced to MW 92-3; latitude/longitude conversion approximate

[6] locations fixed by GPS, courtesy of USEPA ESAT personnel

Table 2-2
Well Elevation Data
Grove Pond Arsenic Investigation, Fort Devens

		elevation (ft, MSL)					depth (ft bgs)		
	location	ground surface	top of screen	bottom of screen	bedrock or refusal	top of riser	top of screen	bottom of screen	screen length (ft)
pre-existing wells	MNG-7	250.11	218.46	199.46		250.11	31.65	50.65	19
	MNG-3	252.02	209.11	190.11	174.02	254.55	42.91	61.91	19
	92-4	252.35	185.35	181.35	166.35	255.36	67	71	4
	92-1	222.25	173.25	167.25		224.15	49	55	6
	PW-1	220.24	178.24	158.24			42	62	20
	PW-2	218.55	176.55	156.55			42	62	20
	92-3	218.18	169.18	163.18		220.19	49	55	6
	92-5	223.67	188.67	182.67	182.67	224.67	35	41	6
new wells/borings	GF-1	221.84	105.84	100.84	111.84	224.45	116	121	5
	GF-2	222.38	108.38	101.38	112.38	224.07	114	121	7
	GF-3A	219.32	122.32	117.32	117.32	221.47	97	102	5
	GF-3B	219.41	211.41	206.41		221.43	8	13	5
	GF-4	225.09	146.09	141.09	140.09	226.73	79	84	5
	BH-1	214 [1]		144 [2]					

[1] approximate pond-bottom elevation

[2] elevation of bottom of boring

TABLE 2-3
Summary of Sampling Schedule
Grove Pond Arsenic Investigation
Fort Devens

	Month 1								Month 3
	Week 1				Week 2	Week 3	Week 4	Week 5	
Sample Location	Day 1	Day 2	Day 3	Day 4					
PW1	7/27: 2:25 pm	7/28: 1:20 pm*, 5:25 pm	7/29: 10:45 am, 4:20 pm	7/30: 11:05 am, 4:20 pm	8/5: 1:10 pm	8/12: 12:35 pm*	8/19: 10:20 am		10/21: 12:30 pm*
PW2	7/27: 2:01 pm	7/28: 1:15 pm, 5:20 pm	7/29: 9:50 am, 3:15 pm	7/30: 10:20 am, 5:00 pm	8/5: 2:50 pm*	8/12: 2:45 pm	8/19: 11:10 am*		10/21: 11:50 am
92-1	7/27: 1:30 pm, 2:50 pm	7/28: 11:59 am, 6:20 pm	7/29: 12:20 pm, 5:15 pm	7/30: 3:25 pm, 6:50 pm	8/5: 2:20 pm	8/12: 2:00 pm	8/19: 1:25 pm		10/21: 10:30 am
92-3	7/27: 11:10 am, 2:35 pm	7/28: 2:25 pm, 7:12 pm	7/29: 11:52 am, 3:45 pm	7/30: 12:25 pm, 6:00 pm	8/5: 4:05 pm	8/12: 11:30 am	8/19: 12:25 pm		10/21: 9:05 am
MNG3						8/13: 9:45 am			10/20: 1:20 pm*
MNG7								8/26: 11:40 am	10/20: 11:50 am
92-4								8/27: 11:00 am	10/20: 3:00 pm
92-5									10/22: 10:45 am*
Surface Water Samples (6)								8/26: 2:30-4:30 pm*	

Note: * A field duplicate was taken immediately following this event.

Table 2-4

Descriptive Log for Soft-Sediment Cores

Grove Pond Arsenic Investigation, Fort Devens

SC-1			
sub-section	depth interval (ft)		sampled for
1	0-0.4	black, organic, decayed aquatic plant matter	bulk sediment chemistry
1	0.4-0.8	black, organic, decayed aquatic plant matter	pore water chemistry
1	0.8-1.2	gray, silty sand with some organic matter	hydraulic conductivity
1	1.2-1.65	sand, some silt	pore water chemistry
2	1.65-2.25	disturbed material ("wash")	
2	2.25-2.65	sand, some organics, lighter color	bulk sediment chemistry
2	2.65-2.95	coarse sand and gravel	hydraulic conductivity
2	2.95-3.25	coarse sand and gravel	pore water chemistry
3	3.25-3.85	disturbed material ("wash")	
3	3.85-4.25	coarse sand, some gravel	bulk sediment chemistry
3	4.25-4.65	coarse sand and gravel, iron oxide visible	pore water chemistry
3	4.65-5.10	very coarse sand and gravel	bulk sediment chemistry

SC-2			
sub-section	depth interval (ft)		sampled for
1	0-0.35	black, organic, decayed aquatic plant matter	bulk sediment chemistry
1	0.35-0.7	gray, silty sand with some organic matter	pore water chemistry
2	0.7-1.1	gray, silty sand with some organic matter	hydraulic conductivity
2	1.1-1.4	gray to brown, silty sand	bulk sediment chemistry
2	1.4-1.7	gray-brown silty sand, increasing sand fraction	pore water chemistry
2	1.7-2.0	gray-brown coarse sand with silt; some Fe oxidation	bulk sediment chemistry
2	2.0-2.35	dense, gray sand with silt and gravel; some Fe oxide	pore water chemistry

SC-3			
sub-section	depth interval (ft)		sampled for
1	0-0.3	black, organic, decayed aquatic plant matter	bulk sediment chemistry
1	0.3-0.6	black, organic, decayed aquatic plant matter	pore water chemistry
1	0.6-1.0	organics grading downward to gray silt	hydraulic conductivity
2	1.0-1.85	disturbed material ("wash")	
2	1.85-2.15	gray-brown sand, some black organics	bulk sediment chemistry
2	2.15-2.45	gray-brown sand	pore water chemistry

Table 3-1
Monthly Rainfall, Worcester Municipal Airport
Grove Pond Arsenic Investigation
Fort Devens

Month	average rainfall*	1998	1999	2000
January	3.43	5.65	7.22	3.64
February	3.11	4.49	3.54	3.44
March	3.71	5.53	5.04	4.28
April	3.65	3.37	0.96	6.34
May	3.35	5.07	3.54	3.7
June	3.48	10.3	1.15	6.05
July	3.61	3.11	3.54	5.08
August	3.50	2.52	2.4	2.76
September	3.63	2.31	9.73	3.61
October	3.61	5.48	4.16	2.59
November	3.90	2.15	2.87	3.88
December	3.60	1.55	2.21	4.7
Total annual	**42.57**	**51.53**	**46.36**	**50.07**

*Average is for period 1895 to 2000.
Units = inches of rainfall

Table 4-1

PHASE I INORGANIC DATA (unfiltered groundwater)

Grove Pond Arsenic Investigation, Fort Devens

well ID	sample date	days	Ag	Al	As (mg/L)	Ba	Be	Ca (mg/L)	Cd	Co	Cr	Cu	Fe (mg/L)
PW1GW001	7/26/98	0.1	1.5U	115	0.045	8.3	0.50U	12.7	1.5U	4	3.0U	1.8	2.8
PW1GW002	7/27/98	1.1	1.5U	346	0.023	18.7	0.50U	15.3	1.5U	4.4	3.0U	2	2.6
PW1GW003*	7/27/98	1.1	1.5U	349	0.024	18.9	0.50U	15.1	1.5U	4.2	3.0U	2	2.5
PW1GW004	7/27/98	1.3	1.5U	330	0.022	18.5	0.50U	15.6	1.5U	3.8	3.0U	1.9	2.2
PW1GW005	7/28/98	2.0	1.5U	122	0.022	11.8	0.50U	15.3	1.5U	2.4	3.0U	1.5U	1.6
PW1GW006	7/28/98	2.2	1.5U	64	0.021	8.9	0.50U	15.3	1.5U	1.7	3.0U	1.5U	1.5
PW1GW007	7/29/98	3.0	1.5U	36.6	0.020	7.9	0.50U	15.6	1.5U	1.5	3.0U	1.5U	1.4
PW1GW008	7/29/98	3.2	1.5U	34.9	0.020	7.8	0.50U	16	1.5U	1.6	3.0U	1.5U	1.4
PW1GW009	8/4/98	9.1	3.0U	10.0U	0.022	7.7	0.50U	17.6	1.5U	1.5U	3.0U	1.5U	1.4
PW1GW0010	8/11/98	16.1	3.0U	14.9	0.022	9.1	0.50U	20.6	1.5U	1.5U	3.0U	1.5U	1.6
PW1GW0011*	8/11/98	16.1	3.0U	10.0U	0.022	9.7	0.50U	20.6	1.5U	1.5U	3.0U	1.5U	1.6
PW1GW0012	8/18/98	23.0	3.0U	15.4	0.024	12.1	0.50U	22.2	1.5U	1.5U	3.0U	4	1.8
PW1GW0013	10/20/98	86.1	1.5U	5.0U	0.034	14.4	1.0U	30.3	1.5U	1.5U	1.5U	1.5U	2.7
PW1GW0014*	10/20/98	86.1	1.5U	5.0U	0.033	14.6	1.0U	30.4	1.5U	1.5U	1.5U	1.5U	2.8
PW1GW015	2/23/99	212.1	6.0U	100U	0.030	13.5	2.0U	29.1	3.0U	3.0U	3.0U	3.0U	2.19
PW2GW001	7/26/98	0.1	1.5U	10.0U	0.047	11	0.50U	19.3	1.5U	1.5	3.0U	22	0.93
PW2GW002	7/27/98	1.1	1.5U	10.0U	0.037	11.7	0.50U	19.4	1.5U	1.5U	3.0U	11.9	1.4
PW2GW003	7/27/98	1.3	1.5U	10.0U	0.037	13	0.50U	19.3	1.5U	1.5U	3.0U	7	1.9
PW2GW004	7/28/98	1.9	1.5U	10.0U	0.033	13.2	0.50U	19.7	1.5U	1.5U	3.0U	6.5	1.9
PW2GW005	7/28/98	2.2	1.5U	10	0.032	14.1	0.50U	20	1.5U	1.5U	3.0U	4.4	2
PW2GW006	7/29/98	3.0	1.5U	10.0U	0.032	14.1	0.50U	20.2	1.5U	1.5U	3.0U	3.2	2
PW2GW007	7/29/98	3.2	1.5U	10.0U	0.031	14.2	0.50U	20.4	1.5U	1.5U	3.0U	2.6	2
PW2GW008	8/4/98	9.2	3.0U	10.0U	0.035	15.2	0.50U	20.7	1.5U	1.5U	3.0U	1.5U	1.9
PW2GW009*	8/4/98	9.2	3.0U	10.0U	0.034	15.4	0.50U	20.3	1.5U	1.5U	3.0U	1.5U	1.9
PW2GW0010	8/11/98	16.1	3.0U	10.0U	0.028	14.7	0.50U	23.5	1.5U	1.5U	3.0U	1.5U	1.5
PW2GW0011	8/18/98	23.0	3.0U	10.0U	0.02	12.8	0.50U	23.7	1.5U	1.5U	3.0U	1.5U	1.7
PW2GW0012*	8/18/98	23.0	3.0U	10.0U	0.02	13.6	0.50U	24	1.5U	1.5U	3.0U	1.5U	1.6
PW2GW0013	10/20/98	86.0	1.5U	5.0U	0.037	19.2	1.0U	28.5	1.5U	1.5U	1.5U	1.5U	2.1
PW2GW014	2/22/99	211.1	6.0U	100U	0.029	17.2	2.0U	27.7	3.0U	3.0U	3.0U	5	1.62
PW2GW015	2/22/99	211.1	6.0U	100U	0.029	17	2.0U	28.3	3.0U	3.0U	3.0U	3.0U	1.67
921GW001	7/26/98	0.1	3.0U	10.0U	0.001U	6.2	0.50U	18.2	1.5U	1.5U	3.0U	1.5U	0.35
921GW002	7/26/98	0.2	1.5U	10.0U	0.001U	6.4	0.50U	18.7	1.5U	1.5U	3.0U	1.5U	0.28
921GW003	7/27/98	1.0	1.5U	10.0U	0.001	6.8	0.50U	19.9	1.5U	1.5U	3.0U	1.5U	0.24
921GW004	7/27/98	1.3	1.5U	10.0U	0.001U	6.8	0.50U	19.7	1.5U	1.5U	3.0U	1.5U	0.39
921GW005	7/28/98	2.0	1.5U	10.0U	0.001U	6.9	0.50U	20	1.5U	1.5U	3.0U	1.5U	0.37
921GW006	7/28/98	2.3	1.5U	10.0U	0.001U	6.8	0.50U	19.8	1.5U	1.5U	3.0U	1.5U	0.32
921GW007	7/29/98	3.2	1.5U	10.0U	0.001U	6.9	0.50U	20.6	1.5U	1.5U	3.0U	1.5U	0.313
921GW008	7/29/98	3.3	1.5U	10.0U	0.001U	6.8	0.50U	20.2	1.5U	1.5U	3.0U	1.5U	0.28
921GW009	8/4/98	9.1	3.0U	10.0U	0.001U	6.6	0.50U	20	1.5U	1.5U	3.0U	1.5U	0.26
921GW010	8/11/98	16.1	3.0U	10.0U	0.001U	6.2	0.50U	18.8	1.5U	1.5U	3.0U	1.5U	0.3
921GW011	8/18/98	23.1	3.0U	10.0U	0.001U	6.8	0.50U	20.5	1.5U	1.5U	3.0U	1.5U	0.6
921GW012	10/20/98	86.0	1.5U	5.0U	0.001U	8.1	1.0U	23.8	1.5U	1.5U	1.5U	1.5U	1.8
921GW013	2/23/99	212.0	6.0U	100U	0.001U	7.2	2.0U	22	3.0U	3.0U	3.0U	3.0U	0.986

Table 4-1
PHASE I INORGANIC DATA (unfiltered groundwater)
Grove Pond Arsenic Investigation, Fort Devens

well ID	sample date	days	Ag	Al	As (mg/L)	Ba	Be	Ca (mg/L)	Cd	Co	Cr	Cu	Fe (mg/L)
923GW001	7/26/98	0.0	1.5U	10.0U	0.001U	7.8	0.50U	19.1	1.5U	1.5U	3.0U	1.5U	1
923GW002	7/26/98	0.1	1.5U	10.0U	0.001	7.9	0.50U	18.7	1.5U	1.5U	3.0U	1.5U	0.84
923GW003	7/27/98	1.1	1.5U	10.0U	0.001U	8.5	0.50U	20.1	1.5U	1.5U	3.0U	1.5U	1.4
923GW004	7/27/98	1.3	1.5U	10.0U	0.001U	8.3	0.50U	19.9	1.5U	1.5U	3.0U	1.5U	0.74
923GW005	7/28/98	2.0	1.5U	10.0U	0.001U	8.3	0.50U	20.3	1.5U	1.5U	3.0U	1.5U	0.8
923GW006	7/28/98	2.2	1.5U	10.0U	0.001U	8.5	0.50U	20.5	1.5U	1.5U	3.0U	1.5U	0.77
923GW007	7/29/98	3.1	1.5U	10.0U	0.001U	8.6	0.50U	21.9	1.5U	1.5U	3.0U	1.5U	0.84
923GW008	7/29/98	3.3	1.5U	10.0U	0.001U	8.5	0.50U	21.8	1.5U	1.5U	3.0U	1.5U	0.67
923GW009	8/4/98	9.2	3.0U	10.0U	0.001U	11.3	0.50U	28.3	1.5U	1.5U	3.0U	1.5U	1.2
923GW010	8/11/98	16.0	3.0U	10.0U	0.001U	11	0.50U	29.2	1.5U	1.5U	3.0U	1.5U	2.4
923GW011	8/18/98	23.1	3.0U	10.0U	0.001U	12.5	0.50U	38.3	1.5U	1.5U	3.0U	1.5U	2.4
923GW012	10/20/98	85.9	1.5U	5.0U	0.001U	13.6	1.0U	37.6	1.5U	1.5U	1.5U	1.5U	1.6
923GW013	2/23/99	212.1	6.0U	100U	0.001U	13.8	2.0U	35.4	3.0U	3.0U	3.0U	3.0U	1.3
MNG3GW001	8/12/98	16.9	3.0U	10.0U	0.001	17.7	0.50U	39.2	1.5U	1.5U	3.0U	1.5U	.02U
MNG3GW002	10/19/98	85.1	1.5U	65.2	0.001	13.7	1.0U	28.5	1.5U	3	4.1	1.5U	0.16
MNG3GW003*	10/19/98	85.1	1.5U	65.4	0.002	13.9	1.0U	28.7	1.5U	1.7	3.1	1.5U	0.15
MNG3GW004	2/22/99	211.1	6.0U	100U	0.001	12.3	2.0U	25.5	3.0U	3.0U	3.0U	3.0U	0.0274
MNG7GW001	8/25/98	30.0	3.0U	515	0.002	4.4	0.50U	6.5	1.5U	1.5U	3.0U	1.5U	0.71
MNG7GW002	10/19/98	85.0	1.5U	7510	0.002	39.1	1.0U	6.5	1.5U	6.9	62.1	9.6	7.5
MNG7GW003	2/22/99	211.0	6.0U	1700	0.001U	8.7	2.0U	5.6	3.0U	3.0U	10.0U	3.3	1.82
92-4GW001	8/26/98	31.0	3.0U	256	0.004	8.4	0.50U	25.3	1.5U	2	4.3	41.4	16.5
92-4GW002	10/19/98	85.2	1.5U	124	0.002	8.4	1.0U	28	1.5U	1.6	5	1.5U	2.1
924GW003	2/24/99	212.9	6.0U	365	0.002	9.4	2.0U	22.2	3.0U	3.0U	5.0U	3.0U	1.54
925GW001	10/21/98	87.0	1.5U	126	0.001	21.4	1.0U	37	1.5U	1.5U	5.0U	3.0U	6.3
925GW002*	10/21/98	87.0	1.5U	8.9	0.001	17.8	1.0U	46.6	1.5U	1.5U	1.5U	1.5U	2.3
SW001	8/25/98	30.1	3.0U	176	0.005	14.2	0.50U	20.5	1.5U	1.5U	3.0U	1.5U	1.1
SW002	8/25/98	30.2	3.0U	24.4	0.004	9	0.50U	20.1	1.5U	1.5U	3.0U	1.5U	0.56
SW003	8/25/98	30.2	3.0U	21.3	0.003	7.7	0.50U	20	1.5U	1.5U	3.0U	1.5U	0.36
SW004	8/25/98	30.2	3.0U	32	0.009	18.5	0.50U	20.3	1.5U	1.5U	3.0U	1.5U	2
SW005	8/25/98	30.2	3.0U	43.1	0.006	11	0.50U	20	1.5U	1.5U	3.0U	1.5U	0.88
SW006	8/25/98	30.2	3.0U	122	0.010	22.3	0.50U	30.5	1.5U	1.5U	31.5	3.4	1.8
SW007*	8/25/98	30.2	3.0U	57.5	0.009	20.5	0.50U	30.3	1.5U	1.5U	18.3	1.8	1.5
SW008	2/24/99	213.0	6.0U	100U	0.001	7.6	2.0U	8.8	3.0U	3.0U	3.0U	3.0U	0.12

Table 4-1
PHASE I INORGANIC DATA (unfiltered groundwater)
Grove Pond Arsenic Investigation, Fort Devens

well ID	sample date	Hg	K (mg/L)	Mg (mg/L)	Mn	Na (mg/L)	Ni	Pb	Sb	Se	Tl	V	Zn
PW1GW001	7/26/98	0.5U	2.5	2.1	553	22.4	10	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW002	7/27/98	0.5U	2.5	2.3	1060	18.1	9.4	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW003*	7/27/98	0.5U	2.5	2.3	1060	18.1	8.4	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW004	7/27/98	0.5U	2.5	2.2	1080	18.1	7.2	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW005	7/28/98	0.51	2.4	2.1	926	17.9	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW006	7/28/98	0.5U	2.4	2	918	18	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW007	7/29/98	0.5U	2.4	2	920	18.8	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW008	7/29/98	0.5U	2.4	2	932	18.1	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW009	8/4/98	0.5U	2.5	2.2	1130	18.1	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW0010	8/11/98	0.5U	2.6	2.4	1380	18.6	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW0011*	8/11/98	0.5U	2.6	2.4	1380	18.8	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW0012	8/18/98	0.9	2.7	2.6	1510	19.2	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW0013	10/20/98	0.2U	3.2	3.5	2370	23.9	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	1.8
PW1GW0014*	10/20/98	0.2U	3.3	3.6	2380	24.7	6.0U	5.0U	5.0U	10.0U	20.0U	1.5U	2.1
PW1GW015	2/23/99	N/A	3.1	3.5	2340	24.9	6.0U	10.0U	20.0U	10.0U	20.0U	6.0U	6.0U
PW2GW001	7/26/98	0.5U	2.7	2.5	484	15.4	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW002	7/27/98	0.5U	2.6	2.5	573	14.4	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW003	7/27/98	0.5U	2.5	2.5	672	14.2	6.3	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW004	7/28/98	0.5U	2.5	2.5	705	14.2	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW005	7/28/98	0.5U	2.5	2.5	736	13.7	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW006	7/29/98	0.5U	2.6	2.5	756	14.3	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW007	7/29/98	0.5U	2.5	2.5	765	13.8	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW008	8/4/98	0.5U	2.6	2.5	783	13.4	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW009*	8/4/98	0.5U	2.6	2.5	787	13.5	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW0010	8/11/98	0.5U	2.7	2.7	676	13.9	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW0011	8/18/98	0.5U	2.9	2.7	881	15.7	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW0012*	8/18/98	0.5U	2.9	2.8	760	15	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW0013	10/20/98	0.2U	3.1	3.3	872	17.4	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	1.5U
PW2GW014	2/22/99	N/A	3.1	3.3	873	17.8	6.0U	10.0U	20.0U	10.0U	20.0U	6.0U	6.0U
PW2GW015	2/22/99	N/A	3	3.2	893	17.1	6.0U	10.0U	20.0U	10.0U	20.0U	6.0U	18.6
921GW001	7/26/98	0.5U	2.3	2.1	9.7	14.2	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW002	7/26/98	0.5U	2.3	2.2	8.2	14.2	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW003	7/27/98	0.5U	2.4	2.3	6.8	14	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW004	7/27/98	0.5U	2.4	2.2	5.1	14.3	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW005	7/28/98	0.5U	2.4	2.3	8.1	14.6	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW006	7/28/98	0.5U	2.4	2.3	5.6	14.5	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW007	7/29/98	0.5U	2.4	2.4	7.9	14.1	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW008	7/29/98	0.5U	2.4	2.3	7.4	14.6	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW009	8/4/98	0.5U	2.5	2.4	5.6	13.8	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW010	8/11/98	0.5U	2.4	2.2	7.2	13.3	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW011	8/18/98	0.5U	2.5	2.4	7.4	13.2	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW012	10/20/98	0.20U	2.8	2.8	10.9	15.1	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	11
921GW013	2/23/99	N/A	2.7	2.6	7	14.9	6.0U	10.0U	20.0U	10.0U	20.0U	6.0U	6.0U

Table 4-1
PHASE I INORGANIC DATA (unfiltered groundwater)
Grove Pond Arsenic Investigation, Fort Devens

well ID	sample date	Hg	K (mg/L)	Mg (mg/L)	Mn	Na (mg/L)	Ni	Pb	Sb	Se	Tl	V	Zn
923GW001	7/26/98	0.5U	2.9	1.9	188	21.3	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW002	7/26/98	0.5U	3	1.9	189	22	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW003	7/27/98	0.5U	3	2	192	21.4	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW004	7/27/98	0.5U	3	2	166	22.4	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW005	7/28/98	0.5U	3	2	165	22.5	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW006	7/28/98	0.5U	3	2	160	21.9	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW007	7/29/98	0.5U	3	2.2	151	22.5	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW008	7/29/98	0.5U	3.1	2.2	146	22.3	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW009	8/4/98	0.5U	3.6	2.9	153	24.2	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW010	8/11/98	0.5U	3.7	3	115	24.5	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW011	8/18/98	0.5U	3.8	3.7	101	25.2	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW012	10/20/98	0.2U	4.1	3.8	97.2	26.4	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	50.2
923GW013	2/23/99	N/A	4	3.8	30.7	26.2	6.0U	10.0U	20.0U	10.0U	20.0U	6.0U	6.0U
MNG3GW001	8/12/98	0.5U	3.5	3.4	1.0U	23.1	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
MNG3GW002	10/19/98	0.2U	3.3	2.7	18	19.2	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	20.7
MNG3GW003*	10/19/98	0.2U	3.3	2.8	17.4	19.4	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	29.3
MNG3GW004	2/22/99	N/A	3.1	2.6	2.2	18.3	6.0U	10.0U	20.0U	10.0U	20.0U	6.0U	8.8
MNG7GW001	8/25/98	0.2U	0.97	0.83	20	3.3	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
MNG7GW002	10/19/98	0.2U	2.4	2.2	129	4.3	43.9	10.0U	5.0U	10.0U	40.0U	8.8	41.3
MNG7GW003	2/22/99	N/A	2.0U	0.95	32	3.6	6.0U	10.0U	20.0U	10.0U	20.0U	6.0U	6.0U
92-4GW001	8/26/98	0.2U	3.4	2.9	107	9.6	15.9	7.7	5.0U	10.0U	40.0U	1.5U	289
92-4GW002	10/19/98	0.2U	3.7	3.3	22.1	11.9	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	607
924GW003	2/24/99	N/A	3.3	2.8	13	11.2	6.0U	10.0U	20.0U	10.0U	20.0U	6.0U	279
925GW001	10/21/98	0.2U	3.4	4.1	46.4	42.8	6.0U	5.0U	5.0U	20.0U	40.0U	1.5U	76
925GW002*	10/21/98	0.2U	3.5	4.7	41.3	44.9	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	64.3
SW001	8/25/98	0.5U	1.4	3.1	453	26.2	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	17.1
SW002	8/25/98	0.5U	1.3	3	262	27	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
SW003	8/25/98	0.5U	1.5	3	164	29.5	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
SW004	8/25/98	0.5U	1.6	3.1	1040	26.8	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
SW005	8/25/98	0.5U	1.6	3.2	459	28.5	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
SW006	8/25/98	0.5U	1.8	3.3	389	43.1	6.0U	7.1	5.0U	10.0U	40.0U	1.5U	12.0U
SW007*	8/25/98	0.5U	1.8	3.3	343	43.2	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
SW008	2/24/99	N/A	2.0U	1.7	18.2	22.4	6.0U	10.0U	20.0U	10.0U	20.0U	6.0U	6.0U

µg/L except where noted

* duplicate (of the previous sample)

U = not detected above the reporting limit

J = approximate

N/A = not analyzed

Arsenic analyses courtesy of MADEP laboratory; all other analyses courtesy of EPA laboratory

Table 4-2

PHASE I INORGANIC DATA (filtered groundwater)

Grove Pond Arsenic Investigation, Fort Devens

well ID	sample date	days	Ag	Al	As (mg/L)	Ba	Be	Ca (mg/L)	Cd	Co	Cr	Cu	Fe (mg/L)
PW1GW001F	7/26/98	0.1	3.0U	68	0.045	6.7	0.50U	12.3	1.5U	2.5	3.0U	1.5U	2.2
PW1GW002F	7/27/98	1.1	3.0U	53.8	0.021	18.4	0.50U	14.5	3.0U	4.3	3.0U	1.5U	2.5
PW1GW003F*	7/27/98	1.1	3.0U	10.0U	0.022	18.7	0.50U	14.7	3.0U	4.3	3.0U	1.5U	2.5
PW1GW004F	7/27/98	1.3	3.0U	10.0U	0.020	18.2	0.50U	14.9	3.0U	1.5U	3.0U	1.5U	2
PW1GW004FX	7/27/98	1.3	1.5U	29.8		16.9	0.50U	15.1	1.5U	3.9	3.0U	1.5U	2
PW1GW005F	7/28/98	2.0	3.0U	85	0.021	11.3	0.50U	14.4	3.0U	2.3	3.0U	1.5U	1.6
PW1GW005FX	7/28/98	2.0	3.0U	50.8		11.5	0.50U	14.5	1.5U	2.4	3.0U	1.5U	1.6
PW1GW006F	7/28/98	2.2	1.5U	50.2	0.019	8.7	0.50U	15.2	1.5U	1.7	3.0U	1.5U	1.5
PW1GW006FX	7/28/98	2.2	3.0U	36.5		8.9	0.50U	14.7	3.0U	1.5U	3.0U	1.5U	1.5
PW1GW007F	7/29/98	3.0	3.0U	30.6	0.020	7.9	0.50U	15.1	1.5U	1.5U	3.0U	1.5U	1.4
PW1GW007FX	7/29/98	3.0	3.0U	23.4		7.7	0.50U	14.7	1.5U	1.6	3.0U	1.5U	1.3
PW1GW008F	7/29/98	3.2	3.0U	30.7	0.019	7.9	0.50U	15.1	1.5U	1.5U	3.0U	1.5U	1.4
PW1GW008FX	7/29/98	3.2	3.0U	24.4		7.9	0.50U	15.3	1.5U	1.6	3.0U	1.5U	1.4
PW1GW009F	8/4/98	9.1	1.5U	10.0U	0.022	8	0.50U	17.1	1.5U	1.5U	3.0U	1.5U	1.4
PW1GW009FX	8/4/98	9.1	1.5U	10.0U		8.1	0.50U	16.8	1.5U	1.5U	3.0U	1.5U	1.4
PW1GW010F	8/11/98	16.1	1.5U	10.0U	0.022	9.6	0.50U	19.9	1.5U	1.5U	3.0U	1.5U	1.5
PW1GW011F*	8/11/98	16.1	1.5U	10.0U	0.016	9.7	0.50U	19.9	1.5U	1.5U	3.0U	1.5U	1.5
PW1GW012F	8/18/98	23.0	3.0U	10.0U	0.024	9.8	0.50U	21.5	3.0U	1.5U	3.0U	1.5U	1.7
PW1GW013F	10/20/98	86.1	1.5U	5.0U	0.033	14.6	1.0U	30.8	1.5U	1.5U	1.5U	1.5U	2.7
PW1GW014F*	10/20/98	86.1	1.5U	5.0U	0.033	14.8	1.0U	30.7	1.5U	1.5U	1.5U	1.5U	2.7
PW1GW015F	2/23/99	212.1	6.0U	100U	0.03	13.4	2.0U	29.1	3.0U	3.0U	3.0U	3.0U	2.18
PW1W1	2/17/00	571.1	1.5U	10.0U	0.0388	155	0.50U	27.4	1.5U	1.5U	1.5U	1.5U	2.71
PW2GW001F	7/26/98	0.1	3.0U	10.0U	0.045	10.9	0.50U	18.2	1.5U	1.5U	3.0U	17.3	0.95
PW2GW002F	7/27/98	1.1	1.5U	10.0U	0.039	12.1	0.50U	19.2	1.5U	1.5	3.0U	9.6	1.5
PW2GW003F	7/27/98	1.3	1.5U	10.0U	0.038	13.2	0.50U	19.2	1.5U	1.6	3.0U	6.2	1.8
PW2GW003FX	7/27/98	1.3	1.5U	10.0U		13.4	0.50U	19.6	1.5U	1.7	3.0U	6	1.9
PW2GW004F	7/28/98	1.9	1.5U	10.0U	0.032	13.2	0.50U	19.5	1.5U	1.5	3.0U	5.1	1.9
PW2GW004FX	7/28/98	1.9	3.0U	10.0U		13.4	0.50U	18.7	1.5U	1.5U	3.0U	4.9	1.9
PW2GW005F	7/28/98	2.2	3.0U	10.0U	0.032	14	0.50U	19.1	3.0U	1.5U	3.0U	3.7	2
PW2GW005FX	7/28/98	2.2	1.5U	10.0U		13.9	0.50U	19.7	1.5U	1.5U	3.0U	3.2	2
PW2GW006F	7/29/98	3.0	3.0U	10.0U	0.032	14.3	0.50U	19.6	1.5U	1.5U	3.0U	2.9	1.9
PW2GW006FX	7/29/98	3.0	3.0U	10.0U		14.3	0.50U	19.3	3.0U	1.5U	3.0U	2.5	2
PW2GW007F	7/29/98	3.2	3.0U	10.0U	0.032	14.4	0.50U	19.4	1.5U	1.5U	3.0U	2.2	2
PW2GW007FX	7/29/98	3.2	3.0U	10.0U		14.5	0.50U	19.6	1.5U	1.5U	3.0U	2.4	2
PW2GW008F	8/4/98	9.2	1.5U	10.0U	0.033	16.1	0.50U	19.5	1.5U	1.5U	3.0U	1.5U	1.8
PW2GW008FX	8/4/98	9.2	1.5U	10.0U		16.2	0.50U	20	1.5U	1.5U	3.0U	1.5U	1.8
PW2GW009F*	8/4/98	9.2	1.5U	10.0U	0.034	16	0.50U	19.7	1.5U	1.5U	3.0U	1.5U	1.8
PW2GW010F	8/11/98	16.1	1.5U	10.0U	0.028	15.6	0.50U	22.9	1.5U	1.5U	3.0U	1.5U	1.4
PW2GW011F	8/18/98	23.0	3.0U	10.0U	0.016	12.1	0.50U	22.7	3.0U	1.5U	3.0U	1.5U	0.63
PW2GW012F*	8/18/98	23.0	3.0U	10.0U	0.016	12	0.50U	22.7	3.0U	1.5U	3.0U	1.5U	0.66
PW2GW013F	10/20/98	86.0	1.5U	5.0U	0.037	19.4	1.0U	28.6	1.5U	1.5U	1.5U	1.5U	2.1
PW2GW014F	2/22/99	211.1	6.0U	100U	0.027	17.1	2.0U	27.9	3.0U	3.0U	3.0U	3.0U	1.6
PW2GW015F*	2/22/99	211.1	6.0U	100U	0.029	16.8	2.0U	28.2	3.0U	3.0U	3.0U	3.0U	1.62
PW2W1	2/17/00	571.1	1.5U	10.0U	0.0405	86	0.50U	25.1	1.5U	1.5U	1.5U	1.5U	2.62

Table 4-2
PHASE I INORGANIC DATA (filtered groundwater)
Grove Pond Arsenic Investigation, Fort Devens

well ID	sample date	days	Ag	Al	As (mg/L)	Ba	Be	Ca (mg/L)	Cd	Co	Cr	Cu	Fe (mg/L)
921GW001F	7/26/98	0.1	3.0U	10.0U	0.001U	6.3	0.50U	17.7	3.0U	1.5U	3.0U	1.5U	0.36
921GW002F	7/26/98	0.2	3.0U	10.0U	0.001U	6.9	0.50U	18.2	1.5U	1.5U	3.0U	1.5U	0.29
921GW003F	7/27/98	1.0	3.0U	10.0U	0.001U	6.8	0.50U	18.7	1.5U	1.5U	3.0U	1.5U	0.22
921GW004F	7/27/98	1.3	3.0U	10.0U	0.001U	7.1	0.50U	18.9	1.5U	1.5U	3.0U	1.5U	0.27
921GW004FX	7/27/98	1.3	1.5U	10.0U		6.7	0.50U	19.6	1.5U	1.5U	3.0U	1.5U	0.44
921GW005F	7/28/98	2.0	1.5U	10.0U	0.001U	6.8	0.50U	19.8	1.5U	1.5U	3.0U	1.5U	0.31
921GW006F	7/28/98	2.3	3.0U	10.0U	0.001U	7	0.50U	19.3	3.0U	1.5U	3.0U	1.5U	0.25
921GW007F	7/29/98	3.2	3.0U	10.0U	0.001U	7.2	0.50U	20.2	1.5U	1.5U	3.0U	1.5U	0.26
921GW008F	7/29/98	3.3	3.0U	10.0U	0.001U	6.9	0.50U	19.8	1.5U	1.5U	3.0U	1.5U	0.25
921GW009F	8/4/98	9.1	1.5U	10.0U	0.001U	6.9	0.50U	19.6	1.5U	1.5U	3.0U	1.5U	0.18
921GW010F	8/11/98	16.1	1.5U	10.0U	0.001U	6.6	0.50U	18.1	1.5U	1.5U	3.0U	1.5U	0.17
921GW011F	8/18/98	23.1	3.0U	10.0U	0.001U	6.8	0.50U	19.9	3.0U	1.5U	3.0U	1.5U	0.12
921GW012F	10/20/98	86.0	1.5U	5.0U	0.001U	7.8	1.0U	23.7	1.5U	1.5U	1.5U	1.5U	0.32
921GW013F	2/23/99	212.0	6.0U	100U	0.001U	7.3	2.0U	22.6	3.0U	3.0U	3.0U	3.0U	0.185
921W2	2/16/00	570.1	1.5U	10.0U	10.0U	128	0.50U	20.8	1.5U	1.5U	1.5U	1.5U	0.096
923GW001F	7/26/98	0.0	3.0U	10.0U	0.001U	7.9	0.50U	18.4	3.0U	1.5U	3.0U	1.5U	0.75
923GW002F	7/26/98	0.1	3.0U	10.0U	0.001U	8	0.50U	18	3.0U	1.5U	3.0U	1.5U	0.87
923GW003F	7/27/98	1.1	1.5U	10.0U	0.001U	8.4	0.50U	20	1.5U	1.5U	3.0U	1.5U	0.94
923GW004F	7/27/98	1.3	1.5U	10.0U	0.001U	8.3	0.50U	19.9	1.5U	1.5U	3.0U	1.5U	0.74
923GW004FX	7/27/98	1.3	3.0U	10.0U		8.4	0.50U	19.2	1.5U	1.5U	3.0U	1.5U	0.95
923GW005F	7/28/98	2.0	3.0U	10.0U	0.001U	8.7	0.50U	19.5	3.0U	1.5U	3.0U	1.5U	0.82
923GW006F	7/28/98	2.2	3.0U	10.0U	0.001U	8.5	0.50U	19.4	3.0U	1.5U	3.0U	1.5U	0.86
923GW007F	7/29/98	3.1	3.0U	10.0U	0.001U	8.7	0.50U	20.4	3.0U	1.5U	3.0U	1.5U	0.98
923GW008F	7/29/98	3.3	3.0U	10.0U	0.001U	8.6	0.50U	20.5	1.5U	1.5U	3.0U	1.5U	0.68
923GW009F	8/4/98	9.2	1.5U	10.0U	0.001U	11.5	0.50U	28.3	1.5U	1.5U	3.0U	1.5U	1
923GW010F	8/11/98	16.0	1.5U	10.0U	0.001U	11.5	0.50U	38.2	1.5U	1.5U	3.0U	1.5U	3.4
923GW011F	8/18/98	23.1	3.0U	10.0U	0.001U	12	0.50U	37	3.0U	1.5U	3.0U	1.5U	.02U
923GW012F	10/20/98	85.9	1.5U	5.0U	0.001U	13.5	1.0U	38.4	1.5U	1.5U	1.5U	1.5U	1.7
923GW013F	2/23/99	212.1	6.0U	100U	0.001U	14.1	2.0U	35.6	3.0U	3.0U	3.0U	3.0U	1.26
923W2	2/16/00	570.0	1.5U	10.0U	10.0U	36.2	0.50U	43.8	1.5U	1.5U	1.5U	1.5U	1.74
MNG3GW001F	8/12/98	16.9	1.5U	10.0U	0.002	18.7	0.50U	38.6	1.5U	1.5U	3.0U	1.5U	.02U
MNG3GW002F	10/19/98	85.1	1.5U	5.0U	0.001	13.4	1.0U	28.4	1.5U	1.5U	1.8	1.5U	0.01
MNG3GW003F*	10/19/98	85.1	1.5U	5.0U	0.001	13.4	1.0U	28.8	1.5U	1.5U	1.5U	1.5U	0.01U
MNG3GW004F	2/22/99	211.1	6.0U	100U	0.001	11.8	2.0U	24.8	3.0U	3.0U	3.0U	3.0U	0.02U
MNG7GW001F	8/25/98	30.0	1.5U	10.0U	0.001U	1.5U	0.50U	6	1.5U	1.5U	3.0U	1.5U	.02U
MNG7GW002F	10/19/98	85.0	1.5U	5.0U	0.001	1.5U	1.0U	6.1	1.5U	2.1	1.5U	1.5U	0.04
MNG7GW003F	2/22/99	211.0	6.0U	100U	0.001U	3.0U	2.0U	5.8	3.0U	3.0U	3.0U	3.0U	0.02U
924GW001F	8/26/98	31.0	3.0U	10.0U	0.002	6.3	0.50U	22.8	3.0U	1.5U	3.0U	1.5U	0.13
924GW002F	10/19/98	85.2	1.5U	5.0U	0.002	7.3	1.0U	26.9	1.5U	1.5U	1.5U	1.5U	0.37
924GW003F	2/24/99	212.9	6.0U	100U	0.002	8	2.0U	25	3.0U	3.0U	3.0U	3.0U	0.0768
925GW001F	10/21/98	87.0	1.5U	5.0U	0.001U	17.9	1.0U	46.5	1.5U	1.5U	1.5U	1.5U	1.8
925GW002F*	10/21/98	87.0	1.5U	5.0U	0.001	17.9	1.0U	47	1.5U	1.5U	1.5U	1.5U	2

Table 4-2

PHASE I INORGANIC DATA (filtered groundwater)

Grove Pond Arsenic Investigation, Fort Devens

well ID	sample date	days	Ag	Al	As (mg/L)	Ba	Be	Ca (mg/L)	Cd	Co	Cr	Cu	Fe (mg/L)
SW001F	8/25/98	30.1	3.0U	10.0U	0.004	11.8	0.50U	18.7	3.0U	1.5U	3.0U	1.5U	0.33
SW002F	8/25/98	30.2	3.0U	10.0U	0.002	7.2	0.50U	18.4	3.0U	1.5U	3.0U	1.5U	0.16
SW003F	8/25/98	30.2	3.0U	10.0U	0.003	7.4	0.50U	18.5	3.0U	1.5U	3.0U	1.5U	0.17
SW004F	8/25/98	30.2	3.0U	10.0U	0.005	11.3	0.50U	18.8	3.0U	1.5U	3.0U	1.5U	0.4
SW005F	8/25/98	30.2	3.0U	10.0U	0.007	14	0.50U	19.1	3.0U	1.5U	3.0U	1.5U	0.8
SW006F	8/25/98	30.2	3.0U	10.0U	0.008	18.4	0.50U	28	3.0U	1.5U	3.0U	1.5U	0.28
SW007F*	8/25/98	30.2	3.0U	10.0U	0.009	17.7	0.50U	28	3.0U	1.5U	3.0U	1.5U	0.2
SW008	2/24/99	213.0	6.0U	100U	0.001	7.5	2.0U	8.8	3.0U	3.0U	3.0U	3.0U	0.0776
SW1	2/17/00	570.5	1.5U	34.6	10.0U	13.2	0.50U	10.1	1.5U	1.5U	1.5U	1.5U	236

Table 4-2

PHASE I INORGANIC DATA (filtered groundwater)

Grove Pond Arsenic Investigation, Fort Devens

well ID	sample date	Hg	K (mg/L)	Mg (mg/L)	Mn	Na (mg/L)	Ni	Pb	Sb	Se	Tl	V	Zn
PW1GW001F	7/26/98	0.5U	2.6	2.2	355	22.4	6.6	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW002F	7/27/98	0.5U	2.8	2.2	1010	19	9.2	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW003F*	7/27/98	0.5U	2.7	2.2	1030	19	7.7	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW004F	7/27/98	0.5U	2.6	2.2	1040	18.9	8.5	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW004FX	7/27/98	0.5U	2.4	2.1	1010	18.8	7	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW005F	7/28/98	0.5U	2.6	2	864	21.2	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW005FX	7/28/98	0.5U	2.5	2.1	876	18	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW006F	7/28/98	0.5U	2.3	2	888	18.7	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW006FX	7/28/98	0.5U	2.6	2	872	18.2	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW007F	7/29/98	0.5U	2.6	2	877	19	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW007FX	7/29/98	0.5U	2.5	2	864	18.4	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW008F	7/29/98	0.5U	2.6	2.1	890	19.5	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.5
PW1GW008FX	7/29/98	0.5U	2.5	2	885	18.3	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW009F	8/4/98	0.5U	2.5	2.2	1090	19	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW009FX	8/4/98	0.5U	2.6	2.2	1090	19.5	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW010F	8/11/98	0.5U	2.7	2.4	1370	19.6	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW011F*	8/11/98	0.5U	2.7	2.4	1360	19.6	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW012F	8/18/98	0.5U	2.7	2.7	1500	19.8	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW1GW013F	10/20/98	0.2U	3.3	3.6	2410	24.5	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	1.7
PW1GW014F*	10/20/98	0.2U	3.3	3.7	2430	25.1	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	1.8
PW1GW015F	2/23/99		3.1	3.5	2340	25.1	6.0U	10.0U	20.0U	10.0U	20.0U	6.0U	6.0U
PW1W1	2/17/00		3.3	3.7	2430	27.9	6.0U	5.0U	5.0U	10UJ	100UJ	1.5U	50.1
PW2GW001F	7/26/98	0.5U	2.8	2.5	464	15.5	6.2	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW002F	7/27/98	0.5U	2.6	2.5	599	15.6	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW003F	7/27/98	0.5U	2.6	2.5	670	14.8	6.5	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW003FX	7/27/98	0.5U	2.6	2.5	684	14.6	6.1	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW004F	7/28/98	0.5U	2.6	2.5	698	14.7	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW004FX	7/28/98	0.5U	2.6	2.5	673	13.8	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW005F	7/28/98	0.5U	2.7	2.5	703	14.5	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW005FX	7/28/98	0.5U	2.5	2.5	731	14.2	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW006F	7/29/98	0.5U	2.8	2.5	724	14.1	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW006FX	7/29/98	0.5U	2.7	2.5	726	14.1	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW007F	7/29/98	0.5U	2.7	2.5	734	13.9	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW007FX	7/29/98	0.5U	2.7	2.5	735	14	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW008F	8/4/98	0.5U	2.7	2.5	755	14.2	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW008FX	8/4/98	0.5U	2.6	2.5	760	14.2	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW009F*	8/4/98	0.5U	2.7	2.5	764	14.4	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW010F	8/11/98	0.5U	2.8	2.7	666	14.6	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW011F	8/18/98	0.5U	2.9	2.8	927	16.6	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW012F*	8/18/98	0.5U	3	2.8	954	16.9	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
PW2GW013F	10/20/98	0.2U	3.1	3.4	879	17.5	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	1.5U
PW2GW014F	2/22/99		3	3.2	886	17.4	6.0U	10.0U	20.0U	10.0U	20.0U	6.0U	6.3
PW2GW015F*	2/22/99		2.9	3.2	886	17	6.0U	10.0U	20.0U	10.0U	20.0U	6.0U	6.0U
PW2W1	2/17/00		3	3.2	1070	20.1	6.0U	5.0U	5.0U	10UJ	100UJ	1.5U	28.1

Table 4-2
PHASE I INORGANIC DATA (filtered groundwater)
Grove Pond Arsenic Investigation, Fort Devens

well ID	sample date	Hg	K (mg/L)	Mg (mg/L)	Mn	Na (mg/L)	Ni	Pb	Sb	Se	Tl	V	Zn
921GW001F	7/26/98	0.5U	2.5	2.2	13.1	14.5	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW002F	7/26/98	0.5U	2.5	2.1	7.1	14	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW003F	7/27/98	0.5U	2.5	2.3	6.8	14.5	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW004F	7/27/98	0.5U	2.5	2.3	5.5	14.6	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW004FX	7/27/98	0.5U	2.4	2.2	7.8	14.5	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW005F	7/28/98	0.5U	2.4	2.3	8.5	14.8	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW006F	7/28/98	0.5U	2.6	2.3	6.8	14.4	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW007F	7/29/98	0.5U	2.6	2.4	11.1	14.4	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW008F	7/29/98	0.5U	2.6	2.4	7.1	14.4	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW009F	8/4/98	0.5U	2.6	2.4	5.9	14.4	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW010F	8/11/98	0.5U	2.5	2.2	5.9	14	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW011F	8/18/98	0.5U	2.6	2.4	7.1	13.6	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
921GW012F	10/20/98	0.20U	2.8	2.8	10.1	15	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	52.4
921GW013F	2/23/99		2.8	2.6	8	14.6	6.0U	10.0U	20.0U	10.0U	20.0U	6.0U	6.0U
921W2	2/16/00		2.7	2.7	6	16	6.0U	5.0U	5.0U	10UJ	100UJ	1.5U	45.2
923GW001F	7/26/98	0.5U	3.2	1.9	176	22.6	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW002F	7/26/98	0.5U	3.2	1.9	179	21.9	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW003F	7/27/98	0.5U	3	2	175	22.9	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW004F	7/27/98	0.5U	3	2	163	23.5	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW004FX	7/27/98	0.5U	3.1	2	156	21.7	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW005F	7/28/98	0.5U	3.3	2	160	22.4	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW006F	7/28/98	0.5U	3.2	2	153	22.2	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW007F	7/29/98	0.5U	3.3	2.1	156	22.8	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW008F	7/29/98	0.5U	3.2	2.2	139	22.5	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW009F	8/4/98	0.5U	3.6	2.8	157	26.1	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW010F	8/11/98	0.5U	3.8	3	142	25.3	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW011F	8/18/98	0.5U	4	3.8	88.2	26.3	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
923GW012F	10/20/98	0.2U	4.1	3.8	103	26.2	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	106
923GW013F	2/23/99		4	3.7	32.6	25.6	6.0U	10.0U	20.0U	10.0U	20.0U	6.0U	6.0U
923W2	2/16/00		5	5.3	25.7	35.8	6.0U	5.0U	5.0U	10UJ	100UJ	1.5U	7.1
MNG3GW001F	8/12/98	0.5U	3.8	3.5	1.0U	24.4	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	14.4
MNG3GW002F	10/19/98	0.2U	3.3	2.8	1.8	19.6	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	84.3
MNG3GW003F*	10/19/98	0.2U	3.3	2.8	5.0U	19.5	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	25.7
MNG3GW004F	2/22/99		3	2.6	2.0U	18.8	6.0U	10.0U	20.0U	10.0U	20.0U	6.0U	6.0U
MNG7GW001F	8/25/98	0.2U	0.81	0.63	1.0U	3.6	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
MNG7GW002F	10/19/98	0.2U	0.9	0.67	3.6	3.5	10.0U	5.0U	5.0U	10.0U	40.0U	1.5U	59.1
MNG7GW003F	2/22/99		2.0U	0.65	5.3	3.5	6.0U	10.0U	20.0U	10.0U	20.0U	6.0U	6.0U
924GW001F	8/26/98	0.2U	3.5	2.8	16.1	10.2	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	84.1
924GW002F	10/19/98	0.2U	3.7	3.2	15.7	12.1	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	248
924GW003F	2/24/99		3.4	3	3.8	11.6	6.0U	10.0U	20.0U	10.0U	20.0U	6.0U	118
925GW001F	10/21/98	0.2U	3.6	4.7	42	44.8	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	98
925GW002F*	10/21/98	0.2U	3.6	4.8	42.2	45	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	86.2

Table 4-2
PHASE I INORGANIC DATA (filtered groundwater)
Grove Pond Arsenic Investigation, Fort Devens

well ID	sample date	Hg	K (mg/L)	Mg (mg/L)	Mn	Na (mg/L)	Ni	Pb	Sb	Se	Tl	V	Zn
SW001F	8/25/98	0.5U	1.4	3	383	27.4	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
SW002F	8/25/98	0.5U	1.4	3.1	118	28.8	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
SW003F	8/25/98	0.5U	1.6	3	142	31.6	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
SW004F	8/25/98	0.5U	1.5	3.1	484	28.1	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
SW005F	8/25/98	0.5U	1.7	3.1	801	29.9	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
SW006F	8/25/98	0.5U	1.9	3.3	280	45.4	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
SW007F*	8/25/98	0.5U	1.9	3.3	249	45.1	6.0U	5.0U	5.0U	10.0U	40.0U	1.5U	12.0U
SW008	2/24/99	N/A	2.0U	1.7	18	22.1	6.0U	10.0U	20.0U	10.0U	20.0U	6.0U	6.0U
SW1	2/17/00	N/A	1.8	2.3	166	46.9	6.0U	5.0U	5.0U	10UJ	100UJ	1.5U	10.1

µg/L except where noted

* duplicate (of the previous sample)

U = not detected above the reporting limit

J = approximate

N/A = not analyzed

FX = in-line filters; PW1-10F, PW2-9F, and all subsequent samples from PW1 and PW2 are in-line filters

Arsenic analyses courtesy of MADEP laboratory; all other analyses courtesy of EPA laboratory

Table 4-3

Phase I Anions and Alkalinity

Grove Pond Arsenic Investigation, Fort Devens

well ID	sample date	days	alkalinity†	Cl	SO_4	Br	NO_3/NO_2	F	o-PO_4
PW1GW001	7/26/98	0.1	22.2	40.4	11.3	ND	1.66		
PW1GW002	7/27/98	1.1	23.7	40.7	11.1	ND	2.81		
PW1GW003	7/27/98	1.1	23.7	40.5	11.1	ND	3.13		
PW1GW004	7/27/98	1.3	26.1	39.2	11.1	ND	3.19		
PW1GW005	7/28/98	2.0	29.6	34.8	11.1	ND	2.43		
PW1GW006	7/28/98	2.2	30.6	33.4	11.1	ND	2.06		
PW1GW007	7/29/98	3.0	32	32.7	11.2	ND	2.54		
PW1GW008	7/29/98	3.2	32.5	32.4	11.2	ND	2.5		
PW1GW009	8/4/98	9.1	37.9	31.7	10.7	ND	2.47		
PW1GW010	8/11/98	16.1	44.8	34.2	10.8	ND	2.35		
PW1GW011	8/11/98	16.1	44.3	34.2	10.8	ND	2.26		
PW1GW012	8/18/98	23.0	46.3	36.6	11.1	ND	1.59		
PW1GW013	10/20/98	86.1	60.1	52.1	11.3	ND	0.57*		
PW1GW014	10/20/98	86.1	60.6	52.5	11.3	ND	0.59*		
PW1GW015	2/23/99	212.1	60.1	51	10.7	ND	0.47*		
PW1W1	2/17/00	570.5	66	59.1	8.7	ND	0.34*	ND	ND
PW2GW001	7/26/98	0.1	30.1	33.2	14.4	ND	1.99		
PW2GW002	7/27/98	1.1	32	31.9	14.9	ND	0.91		
PW2GW003	7/27/98	1.3	34	31	15.3	ND	3.52		
PW2GW004	7/28/98	1.9	34.5	30.1	15.1	ND	2.47		
PW2GW005	7/28/98	2.2	36	29.5	15.1	ND	2.26		
PW2GW006	7/29/98	3.0	36	28.7	15.1	ND	2.52		
PW2GW007	7/29/98	3.2	37	28.7	15.2	ND	2.37		
PW2GW008	8/4/98	9.2	41.4	25.7	14.4	ND	2.21		
PW2GW009	8/4/98	9.2	40.9	25.5	14.4	ND	1.62		
PW2GW010	8/11/98	16.1	45.8	28	14.7	ND	2.76		
PW2GW011	8/18/98	23.0	47.8	30.2	14.2	ND	2.39		
PW2GW012	8/18/98	23.0	38.4	30.3	14.1	ND	1.87		
PW2GW013	10/20/98	86.0	54.7	35.9	14.7	ND	0.61*		
PW2GW014	2/22/99	211.1	55.2	35.5	15.2	ND	0.62*		
PW2GW015	2/22/99	211.1	55.2	35.5	15.2	ND	0.62*		
PW2W1	2/17/00	570.5	56.2	42.6	13.3	ND	0.61*	ND	ND
921GW001	7/26/98	0.1	35.5	25.6	11.8	ND	4.17		
921GW002	7/26/98	0.2	34.5	26.7	12	ND	4.32		
921GW003	7/27/98	1.0	35	28.1	12.4	ND	5.18		
921GW004	7/27/98	1.3	34	28.7	12.5	ND	5.21		
921GW005	7/28/98	2.0	34	29.8	12.6	ND	4.79		
921GW006	7/28/98	2.3	33.5	29.8	12.7	ND	5.61		
921GW007	7/29/98	3.2	34.5	30.1	12.9	ND	5.55		
921GW008	7/29/98	3.3	33	29.9	12.8	ND	5.67		
921GW009	8/4/98	9.1	34.5	28	12.4	ND	5.11		
921GW010	8/11/98	16.1	35.5	25.8	11.2	ND	4.51		
921GW011	8/18/98	23.1	35.5	26.8	12.2	ND	4.1		
921GW012	10/20/98	86.0	34.5	33.8	14.1	ND	1.50*		
921GW013	2/23/99	212.0	34	31.6	14.6	ND	1.59*		
921W2	2/16/00	569.5	33.5	38.5	15.4	ND	1.9*	ND	ND
923GW001	7/26/98	0.0	49.3	29.2	13.6	ND	ND		
923GW002	7/26/98	0.1	49.8	29.9	14.2	ND	ND		
923GW003	7/27/98	1.1	53.7	30.1	13.8	ND	ND		
923GW004	7/27/98	1.3	53.7	30.1	14	ND	0.32		
923GW005	7/28/98	2.0	53.7	30.1	14.1	ND	0.21		
923GW006	7/28/98	2.2	54.7	30.2	14.2	ND	ND		
923GW007	7/29/98	3.1	55.7	30.7	14.3	ND	ND		
923GW008	7/29/98	3.3	56.2	32.5	14.8	ND	~0.05		
923GW009	8/4/98	9.2	67.5	37.9	14.6	ND	0.11		
923GW010	8/11/98	16.0	70.5	39.4	14.9	ND	ND		
923GW011	8/18/98	23.1	79.8	48	16.1	ND	ND		
923GW012	10/20/98	85.9	75.9	49.9	17.1	~0.05	0.02*		
923GW013	2/23/99	212.1	68.5	53.9	77.2**	~0.05	0.35*		
923W2	2/16/00	569.5	53.7	111	16	ND	1.8*	ND	ND

Table 4-3
Phase I Anions and Alkalinity
Grove Pond Arsenic Investigation, Fort Devens

well ID	sample date	days	alkalinity	Cl	SO_4	Br	NO_3/NO_2	F	o-PO_4
MNG3GW001	8/12/98	16.9	28.6	69.2	17.8	ND	16.4		
MNG3GW002	10/19/98	85.1	42.4	37.2	17.3	ND	2.48*		
MNG3GW003	10/19/98	85.1	41.4	37.3	17.4	ND	2.50*		
MNG3GW004	2/22/99	211.1	41.4	32.7	19.4	ND	1.97*		
MNG7GW001	8/25/98	30.0	7.4	4.36	8.94	ND	6.31		
MNG7GW002	10/19/98	85.0	7.9	4.01	8.74	ND	1.34*		
MNG7GW003	2/22/99	211.0	5.9	4.26	8.95	ND	1.23*		
924GW001	8/26/98	31.0	47.8	20.1	15.2	ND	10.6		
924GW002	10/19/98	85.2	42.9	29.2	15.2	ND	1.55*		
924GW003	2/24/99	212.9	42.9	25.9	22.6	ND	1.28*		
925GW001	10/21/98	87.0	62.1	107	18.7	~0.06	1.47*		
925GW002	10/21/98	87.0	62.2	106	37.8	~0.06	1.51*		
SW001	8/25/98	30.1	44.3	47.2	7.9	ND	ND		
SW002	8/25/98	30.2	44.8	49.1	7.31	ND	ND		
SW003	8/25/98	30.2	43.9	53.4	7.36	ND	ND		
SW004	8/25/98	30.2	46.8	48.8	6.81	ND	0.13		
SW005	8/25/98	30.2	46.3	50.1	7.48	ND	ND		
SW006	8/25/98	30.2	72.9	71.3	3.47	ND	ND		
SW007	8/25/98	30.2	72.4	70.6	3.32	ND	~0.06		
SW008	2/24/99	213.0	12.8	38	9.34	ND	0.07*		
SW1	2/17/00	570.5	11.3	87.3	10.5	ND	0.3*	ND	ND

† Alkalinity in mg/L $CaCO_3$; all other analyses in mg/L

~Estimated value below calibration range

*NO3/NO2 reported as N

**Lab value is 77.2; could be 17.2?

Table 4-4
Phase I Field Water-Quality Parameters
Grove Pond Arsenic Investigation, Fort Devens

sample ID	sample date	days	pH	Temp.	DO (mg/L)	cond.µmhos/cm	ORP (mV)
PW1GW001	7/26/98	0.1	6.47	12.73	3.57	205	
PW1GW002	7/27/98	1.1	6.68	15.72	3.58	210	
PW1GW003	7/27/98	1.1	6.68	15.72	3.58	210	
PW1GW004	7/27/98	1.3	6.75	13.28	4.10	213	
PW1GW005	7/28/98	2.0	6.91	13.80	3.00	198	
PW1GW006	7/28/98	2.2	7.09	12.28	1.40	188	
PW1GW007	7/29/98	3.0	7.14	15.00	3.78	190	
PW1GW008	7/29/98	3.2	6.38	10.61	5.48	194	64
PW1GW009	8/4/98	9.1	6.62	10.38	6.91	148	61
PW1GW0010	8/11/98	16.1	6.81	10.40	0.59	163	19
PW1GW0011	8/11/98	16.1	6.81	10.40	0.59	163	19
PW1GW0012	8/18/98	23.0	6.64	10.52	1.01	172	129
PW1GW0013	10/20/98	86.1	6.60	10.85	3.01	285	
PW1GW0014	10/20/98	86.1	6.60	10.85	3.01	285	
PW1GW0015	2/23/99	212.1	6.86	11.22	5.91	231	28
PW1W1	2/17/00	571.1	6.91	11.45	0.84	205	-15
PW2GW001	7/26/98	0.1	6.39	13.17	1.73	208	
PW2GW002	7/27/98	1.1	6.93	14.15	2.93	204	
PW2GW003	7/27/98	1.3	6.89	12.73	2.67	194	
PW2GW004	7/28/98	1.9	7.00	13.83	2.23	206	
PW2GW005	7/28/98	2.2	7.12	12.46	1.88	204	
PW2GW006	7/29/98	3.0	7.09	13.68	2.48	189	
PW2GW007	7/29/98	3.2	6.59	11.35	4.07	202	21
PW2GW008	8/4/98	9.2	6.84	10.91	4.57	145	33
PW2GW009	8/4/98	9.2	6.84	10.91	4.57	145	33
PW2GW0010	8/11/98	16.1	7.04	12.87	0.63	166	3
PW2GW0011	8/18/98	23.0	6.90	20.56*	0.46	202	55
PW2GW0012	8/18/98	23.0	6.90	20.56*	0.46	202	55
PW2GW0013	10/20/98	86.0	6.76	11.48	1.74	235	
PW2GW0014	2/22/99	211.1	6.44	11.32	11.48	193	83
PW2GW0015	2/22/99	211.1	6.44	11.32	11.48	194	83
PW2W1	2/17/00	571.1	7.10	11.89	0.16	135	-40
92-1GW001	7/26/98	0.1	6.59	13.60	5.55	186	
92-1GW002	7/26/98	0.2	6.92	12.27	4.73	202	
92-1GW003	7/27/98	1.0	7.02	13.05	5.38	216	
92-1GW004	7/27/98	1.3	6.88	11.93	5.67	205	
92-1GW005	7/28/98	2.0	7.27	12.90	1.85	194	
92-1GW006	7/28/98	2.3	7.07	11.82	4.85	189	
92-1GW007	7/29/98	3.2	6.71	10.20	8.50	195	95
92-1GW008	7/29/98	3.3	6.68	10.18	8.28	195	85
92-1GW009	8/4/98	9.1	6.93	10.19	16.85	139	
92-1GW0010	8/11/98	16.1	7.18	10.22	1.29	131	67
92-1GW0011	8/18/98	23.1	7.32	10.90	2.90	133	79
92-1GW0012	10/20/98	86.0	6.77	10.80	5.28	199	
92-1GW0013	2/23/99	212.0	6.88	11.13	8.68	158	89
92-1W2	2/16/00	570.1	6.85	12.02	0.15	171	52
92-3GW001	7/26/98	0.0	7.38	13.50	0.50		
92-3GW002	7/26/98	0.1	6.71	12.90	2.50		
92-3GW003	7/27/98	1.1	6.02	12.30	0.43	238	
92-3GW004	7/27/98	1.3	7.02	11.60	0.60	229	
92-3GW005	7/28/98	2.0	7.12	12.70	0.20	205	
92-3GW006	7/28/98	2.2	6.87	11.85	0.43	202	
92-3GW007	7/29/98	3.1	7.70	11.94	0.74	225	
92-3GW008	7/29/98	3.3	6.65	10.57	0.14	231	-9
92-3GW009	8/4/98	9.2	7.07	10.66	0.58	198	
92-3GW0010	8/11/98	16.0	7.19	11.14	-0.05	223	
92-3GW0011	8/18/98	23.1	7.22	10.98	0.74	249	-145
92-3GW0012	10/20/98	85.9	6.75	11.00	0.78	307	
92-3GW0013	2/23/99	212.1	7.11	11.42	2.07	250	-46
92-3W2	2/16/00	570.0	6.62	11.67	0.00	364	0

Table 4-4

Phase I Field Water-Quality Parameters

Grove Pond Arsenic Investigation, Fort Devens

sample ID	sample date	days	pH	Temp.	DO (mg/L)	cond.µmhos/cm	ORP (mV)
MNG3GW001	8/12/98	16.9	6.99	12.12	2.20	269	310
MNG3GW002	10/19/98	85.1	6.70	12.00	5.60	240	
MNG3GW003	10/19/98	85.1	6.70	12.00	5.60	240	
MNG3GW004	2/22/99	211.1	6.45	11.97	8.51	185	234
MNG7GW001	8/25/98	30.0	6.16	11.75	0.97	44	
MNG7GW002	10/19/98	85.0	6.01	13.60	8.01	507	
MNG7GW003	2/22/99	211.0	6.23	12.16	10.83	44	222
92-4GW001	8/26/98	31.0	7.29	11.26	0.86	142	12
92-4GW002	10/19/98	85.2	7.42	11.20	3.18	200	
92-4GW003	2/24/99	212.9	7.19	11.09	5.96	155	-50
92-5GW001	10/21/98		6.58	11.00	1.02	440	
SW1	8/25/98	30.1	6.62	23.08	0.17	244	39
SW2	8/25/98	30.2	6.80	23.00	0.68	244	7.9/21 rising
SW3	8/25/98	30.2	6.79	22.80	0.53	257	89
SW4	8/25/98	30.2	6.71	22.35	0.14	245	8
SW5	8/25/98	30.2	6.83	23.15	0.65	253	49
SW6	8/25/98	30.2	6.97	24.18	2.16	370	2
SW7	8/25/98	30.2	6.97	24.18	2.16	370	2
SW8	2/24/99	213.0	6.87	1.34	0.02	98	164
SW1	2/17/00	571.0	8.61	0.17	0.02	177	43
*possible reporting error							

Table 4-5

Phase II Inorganic Data (groundwater)

Grove Pond Arsenic Investigation, Fort Devens

sample ID	screen Interval (ft bgs)	elevation (ft MSL)	date	Ag	Al	As	Ba	Be	Ca (mg/L)	Cd	Co	Cr	Cu	Fe
GF1GW01	8.5-10.5	212.34	10/14/99	30.0U	50.0U	5.0U	182.0	0.50U	13.8	1.5U	1.5U	1.5U	2.1	92.2
GF1GW02	98-100	122.84	10/19/99	30.0U	50.0U	5.0U	170.0	0.50U	47.6	1.5U	1.5U	1.5U	1.5U	1160
GF1GW03	110	111.84	10/20/99	30.0U	50.0U	19.8	71.9	0.50U	56.1	1.5U	1.5U	1.5U	1.5U	1010
GF1GW04	115-120	103.84	11/9/99	30.0U	131	61.9	30.0	0.50U	72.0	1.5U	1.5U	3.0U	1.5U	18.8
GF1GW05 (dup)	115-120	103.84	11/9/99	30.0U	79.9	62.7	68.3	0.50U	74.5	1.5U	1.5U	3.0U	1.5U	10.0U
GF1GW06	115-120	103.84	2/15/00	1.5U	48.8	108	42.4	0.50U	54.0	1.5U	1.5U	1.5U	1.5U	44.5
GF2GW01	8.5-10.5	212.88	10/21/99	30.0U	50.0U	32	121.0	0.50U	17.2	1.5U	6.5	1.5U	1.5U	2840
GF2GW02	106	116.38	10/27/99	3.0U	40.0U	13.9	183.0	0.50U	30.6	3.0U	1.5U	3.0U	3.0U	3000
GF2GW03	111	111.38	10/28/99	3.0U	40.0U	43.7	148.0	0.50U	3.6	3.0U	1.6	3.0U	3.0U	1650
GF2GW04	114-121	105.38	11/15/99	3.0U	136	57	151.0	0.50U	14.3	1.5U	1.5U	3.0U	7.5	178
GF2GW05 (dup)	114-121	105.38	11/15/99	3.0U	168	92.8	73.4	0.50U	19.5	1.5U	1.5U	3.0U	5	228
GF2GW06	114-121	105.38	2/17/00	1.5U	37.5	139	234.0	0.50U	45.0	1.5U	1.5U	1.5U	1.5U	20.0U
GF3AGW01-3-5	3-5	215.32	11/1/99	3.0U	107	28.4	202.0	0.50U	15.7	3.0U	3.6	3.0U	5.8	12700
GF3AGW02-8-10	8-10	210.32	11/1/99	3.0U	40.0U	5.0U	171.0	0.50U	21.8	3.0U	10.2	3.0U	7	5100
GF3AGW03-18-20	18-20	200.32	11/2/99	3.0U	40.0U	59.4	278.0	0.50U	11.4	3.0U	7.4	3.0U	3.0U	6700
GF3AGW04-23-25	23-25	195.32	11/2/99	3.0U	42	81.8	206.0	0.50U	16.4	3.0U	1.5U	3.0U	3.0U	18800
GF3AGW05-28-30	28-30	190.32	11/2/99	3.0U	40.0U	95.1	308.0	0.50U	15.8	3.0U	2.3	3.0U	3.0U	21900
GF3AGW06-33-35	33-35	185.32	11/2/99	3.0U	90.6	108	462.0	0.50U	15.3	3.0U	2.5	3.0U	3.0U	14100
GF3AGW07-38-40	38-40	180.32	11/2/99	3.0U	40.0U	152	78.7	0.50U	14.2	3.0U	1.5U	3.0U	3.0U	18600
GF3AGW08-43-45	43-45	175.32	11/3/99	3.0U	40.1	189	151.0	0.50U	15.6	3.0U	1.5U	3.0U	3.0U	19800
GF3AGW09-48-50	48-50	170.32	11/3/99	3.0U	40.0U	5.0U	37.7	0.50U	2.9	3.0U	1.6	3.0U	3.0U	290
GF3AGW10-53-55	53-55	165.32	11/3/99	3.0U	40.0U	5.0U	102.0	0.50U	50.0	3.0U	1.6	3.0U	3.0U	130
GF3AGW11-58-60	58-60	160.32	11/3/99	3.0U	40.0U	5.0U	55.6	0.50U	3.8	3.0U	1.5U	3.0U	3.0U	80
GF3AGW12-63-65	63-65	155.32	11/3/99	3.0U	40.0U	5.0U	14.1	0.50U	4.9	3.0U	1.5U	3.0U	3.0U	60
GF3AGW13-68-70	68-70	150.32	11/4/99	3.0U	40.0U	5.0U	33.6	0.50U	52.7	3.0U	1.5U	3.0U	3.0U	20
GF3AGW14-73-75	73-75	145.32	11/4/99	3.0U	65.5	20.0U	268.0	0.50U	37.2	1.5U	2	3.0U	6.1	180
GF3AGW15-78-80	78-80	140.32	11/5/99	3.0U	40.0U	20.0U	143.0	0.50U	54.4	1.5U	1.5U	3.0U	1.5U	242
GF3AGW16-83-85	83-85	135.32	11/5/99	3.0U	40.0U	20.0U	105.0	0.50U	64.4	1.5U	1.5U	3.0U	1.5U	535
GF3AGW17-88-90	88-90	130.32	11/5/99	3.0U	40.0U	20.0U	197.0	0.50U	64.2	1.5U	1.5U	3.0U	1.5U	407
GF3AGW18-93-95	93-95	125.32	11/8/99	3.0U	40.0U	20.0U	77.8	0.50U	62.2	1.5U	1.5U	3.0U	1.5U	1080
GF3AGW19-98-100	98-100	120.32	11/8/99	3.0U	40.0U	20.0U	171.0	0.50U	64.3	1.5U	1.5U	3.0U	1.5U	747
GF3AGW20-103-105	97-102	115.32	11/8/99	3.0U	40.0U	20.0U	179.0	0.50U	53.8	1.5U	1.5U	3.0U	1.5U	161
GF3AGW21-104-107	97-102	113.82	11/9/99	3.0U	40.0U	25.4	18.3	0.50U	56.2	1.5U	1.5U	3.0U	1.5U	652
GF3AGW22 (dup)	97-102	113.82	11/9/99	3.0U	40.0U	21.4	24.7	0.50U	55.9	1.5U	1.5U	3.0U	1.5U	596
GF3AGW23-103	97-102	113.82	11/16/99	3.0U	40.0U	20.0U	63.0	0.50U	63.6	1.5U	1.5U	3.0U	1.5U	183
GF3AGW24-103 (dup)	97-102	113.82	11/16/99	3.0U	40.0U	20.0U	34.7	0.50U	63.8	1.5U	1.5U	3.0U	1.5U	184
GF3AGW25	97-102	113.82	2/16/00	1.5U	10.0U	10.0U	289.0	0.50U	53.9	1.5U	1.5U	1.5U	1.5U	197
GF3AGW26	97-102	113.82	2/16/00	1.5U	10.0U	10.0U	43.9	0.50U	54.7	1.5U	1.5U	1.5U	1.5U	199
GF3BW01	9-11	209.41	11/16/99	3.0U	40.0U	44.7	59.5	0.50U	15.9	1.5U	3.2	3.0U	3.5	15000
GF3BW02	9-11	209.41	2/16/00	1.5U	10.0U	27.9	118.0	0.50U	11.0	1.5U	1.9	1.5U	38.5	12900
GF4GW01	11-13	218.09	11/10/99	3.0U	371	20.0U	308.0	0.50U	27.8	1.5U	2.8	3.0U	1.5U	368
GF4GW02	16-18	208.09	11/10/99	3.0U	40.0U	172	64.9	0.50U	24.4	1.7	2.5	3.0U	1.5U	1860
GF4GW03	21-23	203.09	11/10/99	3.0U	40.0U	141	59.1	0.50U	23.5	1.7	1.5	3.0U	10.4	2100
GF4GW04	26-28	198.09	11/10/99	3.0U	41.4	187	50.4	0.50U	35.1	2.2	1.5U	3.0U	1.5U	6520
GF4GW05	36-38	188.09	11/10/99	3.0U	40.0U	85	220.0	0.50U	32.3	1.5U	1.5U	3.0U	1.5U	256
GF4GW06	41-43	183.09	11/11/99	3.0U	40.0U	99.8	231.0	0.50U	32.4	1.5U	1.5U	3.0U	1.5U	471

Table 4-5
Phase II Inorganic Data (groundwater)
Grove Pond Arsenic Investigation, Fort Devens

sample ID	screen interval (ft bgs)	elevation (ft MSL)	date	Ag	Al	As	Ba	Be	Ca (mg/L)	Cd	Co	Cr	Cu	Fe
GF4GW07	48-50	176.09	11/11/99	3.0U	40.0U	20.0U	139.0	0.50U	35.3	1.5U	2.4	3.0U	1.5U	89.6
GF4GW08	58-60	166.09	11/11/99	3.0U	43.6	20.0U	169.0	0.50U	37.0	1.5U	1.5U	3.0U	1.5U	95
GF4GW09	63-65	161.09	11/11/99	3.0U	40.0U	20.0U	56.7	0.50U	38.1	1.5U	1.5U	3.0U	1.5U	112
GF4GW10	73-75	151.09	11/11/99	3.0U	40.0U	22.9	170.0	0.50U	42.3	1.5U	1.5U	3.0U	1.5U	250
GF4GW11	78-80	146.09	11/12/99	3.0U	132	20.0U	124.0	0.50U	35.8	1.5U	1.5U	3.0U	1.5U	251
GF4	85	140.09	11/30/99	3.0U	1440	20.0U	221.0	0.50U	29.1	1.5U	1.5U	3.0U	4.8	1570
BH1GW01 6-8	6-8	210	11/19/99	3.0U	87.2	20.0U	332.0	0.5U	17.5	1.5U	1.5U	3.0U	1.5U	3570
BH1GW02 11-14	11-13	204.5	11/22/99	3.0U	40.0U	20.0U	25.3	0.5U	11.0	1.5U	1.5U	3.0U	1.5U	499
BH1GW03 16-18	16-18	200	11/22/99	3.0U	71.6	98.4	211.0	0.5U	15.0	1.5U	1.5U	3.0U	1.5U	11200
BH1GW04 21-23	21-23	195	11/22/99	3.0U	73.8	95.4	270.0	0.5U	14.0	1.5U	1.5U	3.0U	1.5U	13600
BH1GW05 26-28	26-28	190	11/22/99	3.0U	66	188	112.0	0.5U	14.0	1.5U	1.5U	3.0U	1.5U	20200
BH1GW06 36-38	36-38	180	11/23/99	3.0U	40.0U	20.0U	87.4	0.5U	21.5	1.5U	1.5U	3.0U	1.5U	318
BH1GW07 41-43	41-43	175	11/23/99	3.0U	40.0U	20.0U	87.8	0.5U	21.4	1.5U	1.5U	3.0U	1.5U	52.2
BH1GW08 46-48	46-48	170	11/23/99	3.0U	97.9	20.0U	213.0	0.5U	16.4	1.5U	2.2	3.0U	2.2	214
BH1GW09 56-58	56-58	160	11/24/99	3.0U	40.0U	20.0U	91.3	0.5U	19.8	1.5U	1.5U	3.0U	1.5U	656
BH1GW10 61-63	61-63	155	11/29/99	3.0U	40.0U	20.0U	279.0	0.5U	40.2	1.5U	1.5U	3.0U	1.5U	470
BH1GW11 66-68	66-68	150	11/29/99	3.0U	40.0U	20.0U	106.0	0.5U	38.5	1.5U	2	3.0U	1.5U	491

Table 4-5

Phase II Inorganic Data (groundwater)

Grove Pond Arsenic Investigation, Fort Devens

sample ID	screen interval (ft bgs)	elevation (ft MSL)	date	K (mg/L)	Mg (mg/L)	Mn	Na (mg/L)	Ni	Pb	Sb	Se	Tl	V	Zn
GF1GW01	8.5-10.5	212.34	10/14/99	4.8	1.4	81.8	37.4	3.0U	10.0U	40.0U	20.0U	10.0U	1.5U	83.1
GF1GW02	98-100	122.84	10/19/99	5.1	5.9	5020	30.0	5.0U	10.0U	40.0U	20.0U	10.0U	1.5U	229
GF1GW03	110	111.84	10/20/99	4.8	10.3	883	28.8	3.0U	10.0U	40.0U	20.0U	10.0U	1.5U	12.0U
GF1GW04	115-120	103.84	11/9/99	4.5	11.4	326	25.6	6.0U	10.0U	20.0U	20.0U	10.0U	1.5U	12.0U
GF1GW05 (dup)	115-120	103.84	11/9/99	4.4	11.5	353	26.0	6.0U	10.0U	20.0U	20.0U	10.0U	1.5U	12.0U
GF1GW06	115-120	103.84	2/15/00	3.6	12.4	564	23.7	6.0U	5.0U	5.0U	10.0UJ	100UJ	1.5U	11.4
GF2GW01	8.5-10.5	212.88	10/21/99	3.5	2.1	931	31.3	3.0U	10.0U	40.0U	20.0U	10.0U	1.5U	31
GF2GW02	106	116.38	10/27/99	4.6	3.7	676	25.8	14.9	5.0U	5.0U	20.0U	40.0U	1.5U	127
GF2GW03	111	111.38	10/28/99	4.7	4.1	969	25.0	14	5.0U	5.0U	20.0U	40.0U	1.5U	58.9
GF2GW04	114-121	105.38	11/15/99	20.2	7.3	4.4	41.3	6.0U	5.0U	5.0U	20.0U	40.0U	1.5U	12.0U
GF2GW05 (dup)	114-121	105.38	11/15/99	17.2	8.8	19.4	44.8	6.0U	5.0U	5.0U	20.0U	40.0U	1.5U	12.0U
GF2GW06	114-121	105.38	2/17/00	3.6	10.5	489	26.9	6.0U	5.0U	5.0U	10.0UJ	100UJ	1.5U	4.2
GF3AGW01-3-5	3-5	215.32	11/1/99	2.3	3.9	1090	30.7	45.2	5.0U	5.0U	20.0U	40.0U	1.5U	428
GF3AGW02-8-10	8-10	210.32	11/1/99	4.2	3.6	1530	22.7	28.7	5.5	5.0U	20.0U	40.0U	1.5U	298
GF3AGW03-18-20	18-20	200.32	11/2/99	1.9	2	4090	20.3	6.0U	5.0U	5.0U	20.0U	40.0U	1.5U	670
GF3AGW04-23-25	23-25	195.32	11/2/99	3	2.7	1550	33.9	6.0U	5.0U	5.0U	20.0U	40.0U	1.5U	197
GF3AGW05-28-30	28-30	190.32	11/2/99	2.7	2.8	1370	27.7	6.0U	5.0U	5.0U	20.0U	40.0U	1.5U	219
GF3AGW06-33-35	33-35	185.32	11/2/99	3.3	2.5	1440	33.8	6.0U	5.0U	5.0U	20.0U	40.0U	1.5U	275
GF3AGW07-38-40	38-40	180.32	11/2/99	3	2.2	1510	35.2	7.0U	5.0U	5.0U	20.0U	40.0U	1.5U	77.4
GF3AGW08-43-45	43-45	175.32	11/3/99	3.4	2.2	1890	39.2	6.0U	5.0U	5.0U	20.0U	40.0U	1.5U	37.4
GF3AGW09-48-50	48-50	170.32	11/3/99	5.1	3.6	351	34.4	8.8	10.4	5.0U	20.0U	40.0U	1.5U	13.2
GF3AGW10-53-55	53-55	165.32	11/3/99	5.2	5.2	210	29.5	6.0U	18.9	5.0U	20.0U	40.0U	1.5U	32.5
GF3AGW11-58-60	58-60	160.32	11/3/99	5.3	4.3	26.2	33.8	6.0U	11.4	5.0U	20.0U	40.0U	1.5U	24.8
GF3AGW12-63-65	63-65	155.32	11/3/99	4.6	4.2	42	19.6	6.0U	10.0U	5.0U	20.0U	40.0U	1.5U	12.0U
GF3AGW13-68-70	68-70	150.32	11/4/99	5.7	4.9	435	23.2	6.0U	7.7	5.0U	20.0U	40.0U	1.5U	12.0U
GF3AGW14-73-75	73-75	145.32	11/4/99	6.2	4	839	36.0	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	93.5
GF3AGW15-78-80	78-80	140.32	11/5/99	6.3	5.2	1190	28.4	7	10.0U	20.0U	10.0U	20.0U	1.5U	26.9
GF3AGW16-83-85	83-85	135.32	11/5/99	6.4	5.4	1510	27.9	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	12.0U
GF3AGW17-88-90	88-90	130.32	11/5/99	6.6	5.4	969	28.1	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	67.1
GF3AGW18-93-95	93-95	125.32	11/8/99	6.1	5.4	394	26.0	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	12.0U
GF3AGW19-98-100	98-100	120.32	11/8/99	5.9	5.3	233	26.5	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	47.7
GF3AGW20-103-105	97-102	115.32	11/8/99	7.2	5.4	379	28.1	10.1	10.0U	20.0U	10.0U	20.0U	1.5U	45.1
GF3AGW21-104-107	97-102	113.82	11/9/99	3.7	10.7	711	29.5	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	12.0U
GF3AGW22 (dup)	97-102	113.82	11/9/99	3.9	10.4	695	29.3	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	12.0U
GF3AGW23-103	97-102	113.82	11/16/99	5.8	5.6	291	26.3	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	12.0U
GF3AGW24-103 (dup)	97-102	113.82	11/16/99	5.8	5.7	291	26.3	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	12.0U
GF3AGW25	97-102	113.82	2/16/00	5.1	5.8	298	26.7	6.0U	5.0U	5.0U	10UJ	100UJ	1.5U	86.5
GF3AGW26	97-102	113.82	2/16/00	5.5	5.8	300	26.5	6.0U	5.0U	5.0U	10UJ	100UJ	1.5U	4.6
GF3BW01	9-11	209.41	11/16/99	2.3	2.9	1270	29.4	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	13.5
GF3BW02	9-11	209.41	2/16/00	1.6	2.3	719	21.6	6.0U	5.0U	5.0U	10UJ	100UJ	1.5U	44.1
GF4GW01	11-13	218.09	11/10/99	4.6	4.6	745	29.8	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	170
GF4GW02	16-18	208.09	11/10/99	3.7	2.9	2720	28.4	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	30.4
GF4GW03	21-23	203.09	11/10/99	4	2.6	2820	29.3	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	17.3
GF4GW04	26-28	198.09	11/10/99	3.6	4.1	2550	20.4	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	17.1
GF4GW05	36-38	188.09	11/10/99	2.9	3.6	2670	30.4	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	279
GF4GW06	41-43	183.09	11/11/99	2.8	3.5	2570	29.2	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	371

Table 4-5
Phase II Inorganic Data (groundwater)
Grove Pond Arsenic Investigation, Fort Devens

sample ID	screen interval (ft bgs)	elevation (ft MSL)	date	K (mg/L)	Mg (mg/L)	Mn	Na (mg/L)	NI	Pb	Sb	Se	Tl	V	Zn
GF4GW07	48-50	176.09	11/11/99	3.3	3.8	2740	25.6	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	260
GF4GW08	58-60	166.09	11/11/99	3.2	4	331	17.5	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	135
GF4GW09	63-65	161.09	11/11/99	3	4.1	153	17.2	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	129
GF4GW10	73-75	151.09	11/11/99	3.1	5	257	16.0	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	147
GF4GW11	78-80	146.09	11/12/99	5.7	4.2	545	23.6	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	54.1
GF4	85	140.09	11/30/99	5.6	3.7	110	24.3	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	12.0U
BH1GW01 6-8	6-8	210	11/19/99	2.8	2.8	1670	33.0	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	611
BH1GW02 11-14	11-13	204.5	11/22/99	4.2	1.2	431	36.3	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	11600
BH1GW03 16-18	16-18	200	11/22/99	2.9	2.1	1560	38.7	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	891
BH1GW04 21-23	21-23	195	11/22/99	3.8	2	1140	38.3	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	3970
BH1GW05 26-28	26-28	190	11/22/99	4.6	2	1520	42.9	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	453
BH1GW06 36-38	36-38	180	11/23/99	4.9	2.5	366	50.0	9	10.0U	20.0U	10.0U	20.0U	1.5U	810
BH1GW07 41-43	41-43	175	11/23/99	4.3	2.5	125	54.3	7.6	10.0U	20.0U	10.0U	20.0U	1.5U	909
BH1GW08 46-48	46-48	170	11/23/99	3.9	2.4	440	47.5	6.9	10.0U	20.0U	10.0U	20.0U	1.5U	1490
BH1GW09 56-58	56-58	160	11/24/99	2.8	2.5	107	31.5	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	47
BH1GW10 61-63	61-63	155	11/29/99	4	4.1	110	38.9	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	109
BH1GW11 66-68	66-68	150	11/29/99	3.9	3.9	159	34.7	6.0U	10.0U	20.0U	10.0U	20.0U	1.5U	39.2

U = not detected above the reporting limit

J = approximate

Phase II inorganics data from EPA Lab

(data in µg/L unless otherwise noted)

Table 4-6

Phase II Anions and Alkalinity

Grove Pond Arsenic Investigation, Fort Devens

sample ID	screen interval (ft bgs)	elevation (ft MSL)	date	F	Cl	NO_2/NO_3	Br	o-PO_4	SO_4	alkalinity†
GF1GW01	8.5-10.5	212.34	10/14/99	ND	58.7	ND	ND	ND	9.2	37.6
GF1GW02	98-100	122.84	10/19/99	ND	78.5	ND	ND	ND	9.3	119
GF1GW03	110	111.84	10/20/99	ND	72.4	ND	ND	ND	14.9	150
GF1GW04	115-120	103.84	11/9/99	0.15	43.2	ND	ND	ND	26.3	169
GF1GW05 (dup)	115-120	103.84	11/9/99	0.14	42.4	ND	ND	ND	31.1	84.8
GF1GW06	115-120	103.84	2/15/00	0.14	42.6	ND	ND	ND	31.2	87.2
GF2GW01	8.5-10.5	212.88	10/21/99	ND	56.9	ND	ND	ND	4.55	41.4
GF2GW02	106	116.38	10/27/99	ND	57.7	0.05	ND	ND	11.8	74.4
GF2GW03	111	111.38	10/28/99	ND	67.7	0.12	ND	ND	12.2	76.9
GF2GW04	114-121	105.38	11/15/99	0.15	17.9	ND	ND	ND	21.5	182
GF2GW05 (dup)	114-121	105.38	11/15/99	0.1	8.3	ND	ND	ND	24.5	120
GF2GW06	114-121	105.38	2/17/00	ND	9.1	ND	ND	ND	24.4	122
GF3AGW01-3-5	3-5	215.32	11/1/99	ND	53.8	ND	ND	ND	44.2	35.5
GF3AGW02-8-10	8-10	210.32	11/1/99	ND	51.7	0.07	ND	ND	13.9	58.6
GF3AGW03-18-20	18-20	200.32	11/2/99	ND	46.5	ND	ND	ND	3.2	47.3
GF3AGW04-23-25	23-25	195.32	11/2/99	ND	62.3	ND	ND	ND	0.57	68
GF3AGW05-28-30	28-30	190.32	11/2/99	ND	62	ND	ND	ND	0.52	52.2
GF3AGW06-33-35	33-35	185.32	11/2/99	ND	63.6	ND	ND	ND	0.48	53.2
GF3AGW07-38-40	38-40	180.32	11/2/99	ND	64.1	ND	ND	ND	1.1	61.6
GF3AGW08-43-45	43-45	175.32	11/3/99	ND	68	ND	ND	ND	1.3	66.5
GF3AGW09-48-50	48-50	170.32	11/3/99	ND	92.4	0.9	ND	ND	13.4	40.4
GF3AGW10-53-55	53-55	165.32	11/3/99	ND	111	1.5	ND	ND	16.8	52.7
GF3AGW11-58-60	58-60	160.32	11/3/99	ND	101	1.7	ND	ND	14.6	45.8
GF3AGW12-63-65	63-65	155.32	11/3/99	ND	64.9	0.05	ND	ND	14.8	94.1
GF3AGW13-68-70	68-70	150.32	11/4/99	ND	79.5	0.07	ND	ND	15.3	102
GF3AGW14-73-75	73-75	145.32	11/4/99	ND	57.2	0.27	ND	ND	11.9	82.3
GF3AGW15-78-80	78-80	140.32	11/5/99	ND	71.4	0.09	ND	ND	15.2	101
GF3AGW16-83-85	83-85	135.32	11/5/99	ND	78.2	0.12	ND	ND	16	112
GF3AGW17-88-90	88-90	130.32	11/5/99	ND	76.2	0.09	ND	ND	15.9	112
GF3AGW18-93-95	93-95	125.32	11/8/99	ND	68.7	0.2	ND	ND	16	112
GF3AGW19-98-100	98-100	120.32	11/8/99	ND	71	0.38	ND	ND	16.3	113
GF3AGW20-103-105	97-102	115.32	11/8/99	ND	62.4	0.05	ND	ND	15.6	105
GF3AGW21-104-107	97-102	113.82	11/9/99	0.1	49.8	0.13	ND	ND	20.2	143
GF3AGW22 (dup)	97-102	113.82	11/9/99	ND	48.9	0.92	ND	ND	19.7	144
GF3AGW23-103	97-102	113.82	11/16/99	ND	68.4	0.1	ND	ND	16.2	117
GF3AGW24-103 (dup)	97-102	113.82	11/16/99	ND	68.6	0.24	ND	ND	16.8	117
GF3AGW25	97-102	113.82	2/16/00	ND	73.5	0.07	ND	ND	17.3	118
GF3AGW26	97-102	113.82	2/16/00	ND	73.6	ND	ND	ND	17.1	118
GF3BW01	9-11	209.41	11/16/99	ND	52.8	0.24	ND	ND	16.4	45.3
GF3BW02	9-11	209.41	2/16/00	ND	47.4	ND	ND	ND	0.9	31.5

Table 4-6
Phase II Anions and Alkalinity
Grove Pond Arsenic Investigation, Fort Devens

sample ID	screen interval (ft bgs)	elevation (ft MSL)	date	F	Cl	NO_2/NO_3	Br	o-PO_4	SO_4	alkalinity†
GF4GW01	11-13	218.09	11/10/99	ND	49.4	ND	ND	ND	11.6	61.6
GF4GW02	16-18	208.09	11/10/99	ND	47.3	ND	ND	ND	5.6	62.1
GF4GW03	21-23	203.09	11/10/99	ND	48.6	ND	ND	ND	7.7	62.6
GF4GW04	26-28	198.09	11/10/99	ND	42.2	0.15	ND	ND	8.8	78.3
GF4GW05	36-38	188.09	11/10/99	ND	46.9	0.22	ND	ND	8.5	79.8
GF4GW06	41-43	183.09	11/11/99	ND	52.2	0.2	ND	ND	5.7	80.3
GF4GW07	48-50	176.09	11/11/99	ND	49	ND	ND	ND	8	81.3
GF4GW08	58-60	166.09	11/11/99	ND	26.8	ND	ND	ND	23.9	78.8
GF4GW09	63-65	161.09	11/11/99	ND	26.5	0.11	ND	ND	24.3	81.8
GF4GW10	73-75	151.09	11/11/99	ND	25.6	0.7	ND	ND	21.9	97.6
GF4GW11	78-80	146.09	11/12/99	ND	41.8	0.1	ND	ND	14.4	77.9
GF4	85	140.09	11/30/99	ND	32.6	0.1	ND	ND	19.4	61.6
BH1GW01 6-8	6-8	210	11/19/99	ND	51.9	ND	ND	ND	0.22	62.1
BH1GW02 11-14	11-13	204.5	11/22/99	ND	55	0.08	ND	ND	4	55.7
BH1GW03 16-18	16-18	200	11/22/99	ND	58.4	0.15	ND	ND	0.15	53.7
BH1GW04 21-23	21-23	195	11/22/99	ND	62.6	0.07	ND	ND	1.5	54.2
BH1GW05 26-28	26-28	190	11/22/99	ND	61.1	0.12	ND	ND	0.92	54.7
BH1GW06 36-38	36-38	180	11/23/99	ND	99.8	1.5	ND	ND	14.3	20.2
BH1GW07 41-43	41-43	175	11/23/99	ND	100	3.2	ND	ND	13.9	20.2
BH1GW08 46-48	46-48	170	11/23/99	ND	72.3	1.2	ND	ND	12	56.2
BH1GW09 56-58	56-58	160	11/24/99	ND	52.1	0.42	ND	ND	11.2	35.5
BH1GW10 61-63	61-63	155	11/29/99	ND	82.7	0.96	ND	ND	12.3	63.1
BH1GW11 66-68	66-68	150	11/29/99	ND	76.2	0.35	ND	ND	11.9	61.6
		reporting limits		0.1	0.5	0.03/0.023	0.1	0.033	0.1	

† Alkalinity in mg/L $CaCO_3$; all other analyses in mg/L

Table 4-7
Phase II Field Water-Quality Parameters
Grove Pond Arsenic Investigation, Fort Devens

sample ID	screen interval (ft bgs)	elevation (ft MSL)	date	pH	temp.	DO (mg/L)	Cond. (mS/m)	ORP (mV)	turbidity	TDS (g/L)
GF1GW01	8.5-10.5	212.34	10/14/99	5.50	18.0	0.4	29	-401	2	0.19
GF1GW02	98-100	122.84	10/19/99	6.48	11.7	0.3	50	-173	150	0.32
GF1GW03	110	111.84	10/20/99	7.30	11.6	0.4	55	-85	200	0.35
GF1GW04	115-120	103.84	11/9/99	9.76	11.4	0.4	46	-331	116	0.3
GF1GW05 (dup)	115-120	103.84	11/9/99	8.73	11.2	0.1	335	-305	1	0.3
GF1GW06	115-120	103.84	2/15/00	8.73	11.4	0.3	145	-241	106	n.r
GF2GW01	8.5-10.5	212.88	10/21/99	5.53	18.0	0.3	31	-13	14	0.23
GF2GW02	106	116.38	10/27/99	7.47	15.2	0.4	38	-165	200	0.25
GF2GW03	111	111.38	10/28/99	7.26	14.1	2.3	42	-47	990	0.27
GF2GW04	114-121	105.38	11/15/99	8.28	11.7	0.0	250	35	190	n.r.
GF2GW05 (dup)	114-121	105.38	11/15/99	9.30	13.7	1.4	38	-230	20	0.25
GF2GW06	114-121	105.38	2/17/00	9.30	13.7	1.4	38	-230	20	0.25
GF3AGW01-3-5	3-5	215.32	11/1/99	6.30	14.2	4.8	37	-14	990	0.24
GF3AGW02-8-10	8-10	210.32	11/1/99	7.98	16.8	8.5	35	-154	990	0.24
GF3AGW03-18-20	18-20	200.32	11/2/99	6.31	13.0	0.3	26	-68	356	0.17
GF3AGW04-23-25	23-25	195.32	11/2/99	6.72	12.2	0.4	40	-123	85	0.26
GF3AGW05-28-30	28-30	190.32	11/2/99	6.99	12.5	0.7	54	-145	160	0.38
GF3AGW06-33-35	33-35	185.32	11/2/99	7.00	14.4	0.3	41	-140	990+	0.27
GF3AGW07-38-40	38-40	180.32	11/2/99	7.01	14.0	0.4	63	-130	0	0.43
GF3AGW08-43-45	43-45	175.32	11/3/99	6.84	13.0	0.4	40	-192	541	0.26
GF3AGW09-48-50	48-50	170.32	11/3/99	6.34	12.7	0.6	43	53	60	0.28
GF3AGW10-53-55	53-55	165.32	11/3/99	6.46	12.8	0.4	54	62	140	0.34
GF3AGW11-58-60	58-60	160.32	11/3/99	6.00	14.1	1.7	48	107	5	0.31
GF3AGW12-63-65	63-65	155.32	11/3/99	6.82	12.2	0.4	43	26	44	0.28
GF3AGW13-68-70	68-70	150.32	11/4/99	7.22	11.0	0.8	50	25	424	0.32
GF3AGW14-73-75	73-75	145.32	11/4/99	7.96	12.3	6.3	40	19	330	0.26
GF3AGW15-78-80	78-80	140.32	11/5/99	7.35	10.9	1.4	46	-66	990+	0.30
GF3AGW16-83-85	83-85	135.32	11/5/99	7.26	11.2	0.3	52	-122	40	0.33
GF3AGW17-88-90	88-90	130.32	11/5/99	7.26	11.3	0.3	58	-118	67	0.38
GF3AGW18-93-95	93-95	125.32	11/8/99	7.36	10.8	0.3	50	-157	83	0.32
GF3AGW19-98-100	98-100	120.32	11/8/99	7.53	10.9	0.3	69	-150	16	0.47
GF3AGW20-103-105	97-102	115.32	11/8/99	7.72	11.2	3.6	46	-55	330	0.30
GF3AGW21-104-107	97-102	113.82	11/9/99	7.18	10.6	0.7	47	-121	990	0.31
GF3AGW22 (dup)	97-102	113.82	11/9/99	7.18	10.6	0.7	47	-121	990	0.31
GF3AGW23-103	97-102	113.82	11/16/99	7.57	11.0	0.4	49	-161	1	0.32
GF3AGW24-103 (dup)	97-102	113.82	11/16/99	7.57	11.0	0.4	49	-161	1	0.32
GF3AGW25	97-102	113.82	2/16/00	7.70	10.9	0.5	48	-148	330	n.r.
GF3AGW26	97-102	113.82	2/16/00	7.70	11.0	0.4	49	-156	110	n.r.
GF3BW01	9-11	209.41	11/16/99	6.30	12.9	1.5	32	-71	1	0.21
GF3BW02	9-11	209.41	2/16/00	6.40	8.2	0.0	162	-31	1	n.r.
GF4GW01	11-13	218.09	11/10/99	7.22	17.1	6.6	31	121	990+	0.2
GF4GW02	16-18	208.09	11/10/99	6.92	17.5	0.5	32	-82	69.7	0.21
GF4GW03	21-23	203.09	11/10/99	7.05	16.8	0.4	32	-104	80.3	0.21
GF4GW04	26-28	198.09	11/10/99	6.81	15.3	0.6	34	-104	400	0.22
GF4GW05	36-38	188.09	11/10/99	7.08	14.2	0.4	37	-53	52.3	0.24
GF4GW06	41-43	183.09	11/11/99	6.15	12.8	0.6	35	-1	227	0.23
GF4GW07	48-50	176.09	11/11/99	6.60	12.1	1	34	10	110	0.22
GF4GW08	58-60	166.09	11/11/99	7.02	11.5	0.6	30	-7	69.8	0.2
GF4GW09	63-65	161.09	11/11/99	7.31	11.4	0.5	30	-63	64.7	0.2
GF4GW10	73-75	151.09	11/11/99	7.72	11.6	0.6	32	-138	315	0.21
GF4GW11	78-80	146.09	11/12/99	7.61	11.5	7.2	34	2	990+	0.22
GF4	85	140.09	11/30/99	9.42	13.1	0.4	21	-313	990+	0.13

Table 4-7

Phase II Field Water-Quality Parameters

Grove Pond Arsenic Investigation, Fort Devens

sample ID	screen interval (ft bgs)	elevation (ft MSL)	date	pH	temp.	DO (mg/L)	Cond. (mS/m)	ORP (mV)	turbidity	TDS (g/L)
BH1GW01 6-8	6-8	210	11/19/99	6.35	15.1	0.4	31	-49	5	0.2
BH1GW02 11-14	11-13	204.5	11/22/99	6.68	12.2	4.4	24	-8	12	0.16
BH1GW03 16-18	16-18	200	11/22/99	6.28	15.3	0.6	35	-64	108	0.23
BH1GW04 21-23	21-23	195	11/22/99	6.81	16.7	8.2	27	36	990+	0.17
BH1GW05 26-28	26-28	190	11/22/99	6.48	14.5	1.7	38	-83	90	0.25
BH1GW06 36-38	36-38	180	11/23/99	5.80	12.6	2.6	43	135	49	0.28
BH1GW07 41-43	41-43	175	11/23/99	5.87	12.8	9.2	43	168	69	0.28
BH1GW08 46-48	46-48	170	11/23/99	7.50	16.0	11.2	31	105	990+	0.2
BH1GW09 56-58	56-58	160	11/24/99	6.48	13.4	15.3	28	38	16	0.18
BH1GW10 61-63	61-63	155	11/29/99	6.44	11.0	1.8	44	-26	90	0.29
BH1GW11 66-68	66-68	150	11/29/99	6.73	11.2	3.2	41	-2	330	0.26
n.r. = not reported										

Table 4-8
Metals in Soil Profile Samples
Grove Pond Arsenic Investigation, Fort Devens

ta from EPA laboratory												
Sample	**Elevation**	**Ag**	**Al**	**As**	**Ba**	**Be**	**Ca**	**Cd**	**Co**	**Cr**	**Cu**	**Fe**
GF3A-6-8	212.32	1.5U	3480	20.0U	9.6	0.50U	452	2UJ	2.4	7.6	4	4970
GF3A 16-18	202.32	3.0U	3490	10.0U	16.2	0.50U	689	1.5U	2.7	6.9	4.5	5440
GF3A 20-22	198.32	3.0U	2140	10.0U	9.9	0.50U	409	1.5U	2.8	5.1	3.5	4410
GF3A 25-27	193.32	3.0U	2950	10.0U	14.8	0.50U	774	1.5U	3	7.2	4.2	5410
GF3A 30-32	188.32	3.0U	10000	15UJ	59.2	0.50U	1060	1.5U	8.2	37.8	12.5	15500
GF3A 35-37	183.32	3.0U	12000	30UJ	66.2	0.50U	1550	1.5U	9.9	47	16	18700
GF3A 40-42	178.32	3.0U	4670	10.0U	21	0.50U	681	1.5U	4.2	19	6.5	8310
GF3A 50-52	168.32	3.0U	13600	25UJ	63.7	0.50U	2230	1.5U	10.3	51.4	17.6	20400
GF3A 55-57	163.32	3.0U	15600	45UJ	92.7	0.50U	3130	1.5U	14.9	66.4	34.2	24900
GF3A 60-62	158.32	3.0U	15900	30.0U	92.1	0.56	2910	1.5U	11.1	72.2	17.2	23400
GF3A 65-67	153.32	3.0U	11900	100UJ	55.2	0.50U	2390	1.5U	11.4	46.9	18.6	25100
GF3A-100-102	118.32	1.5U	12900	20.0U	28.8	0.50U	2160	2UJ	12.4	63.2	5.4	20000
GF2-10-12	211.38	1.5U	21600	20.0U	135	0.8	2410	2UJ	15.4	84.5	25.1	26100
GF2-106-108	115.38	1.5U	4590	20.0U	18	0.50U	2550	2UJ	3.4	18.5	4.9	8010
GF4-13-15	211.09	1.5U	17400	20.0U	109	0.50U	3480	2UJ	11.2	55.8	19.4	21400
R.L.		3	10	10	1.5	0.5	20	1.5	1.5	1.5	1.5	10
GF1-S17-40-42	180.84	ND	13600	10.9	60	ND	3260	ND	7.8	80.4	16.1	22100
F1-S32-70-72	150.84	ND	7140	4.2	31.9	ND	1590	ND	6.2	32.2	11.7	15000
R.L.		0.5	10	2	1.5	0.5	10	0.5	0.5	3	3	10
Sample	**Elevation**	**K**	**Mg**	**Mn**	**Na**	**Ni**	**Pb**	**Sb**	**Se**	**Tl**	**V**	**Zn**
GF3A-6-8	212.32	1000U	1220	48.6	100U	7	20.0U	10UJ	10.0U	20.0U	5.2	11.6
GF3A 16-18	202.32	1000U	1300	88.9	1000U	6.3	5.0U	10UJ	10.0U	20.0U	5.5	18
GF3A 20-22	198.32	1000U	952	50.8	1000U	0	5.0U	10UJ	10.0U	20.0U	3.9	19.8
GF3A 25-27	193.32	1000U	1420	60.1	1000U	7.8	5.0U	10UJ	10.0U	20.0U	5.6	14.8
GF3A 30-32	188.32	3890	7490	173	1000U	32.8	5.0U	10UJ	10.0U	20.0U	26.4	33.2
GF3A 35-37	183.32	3940	9170	220	1000U	37.5	6.3	10.0U	10.0U	20.0U	30	39.5
GF3A 40-42	178.32	1070	3170	82.5	1000U	16.7	5.0U	10.0U	10.0U	20.0U	10.7	17.8
GF3A 50-52	168.32	5060	9920	386	1000U	34.1	7.1	10.0U	10.0U	20.0U	32.1	41.6
GF3A 55-57	163.32	5280	11300	1330	1000U	80.8	16.8	10UJ	10.0U	20.0U	35.4	54.9
GF3A 60-62	158.32	5320	11400	955	1000U	47.4	10.3	10.0U	10.0U	20.0U	36.7	51.1
GF3A 65-67	153.32	3780	8620	488	1000U	40.5	9.6	10.0U	10.0U	20.0U	29.1	40.7
GF3A-100-102	118.32	4943	11200	336	100U	52.2	20.0U	10UJ	10.0U	20.0U	23.9	45.5
GF2-10-12	211.38	6921	12300	453	491	53.7	20.0U	10UJ	10.0U	20.0U	45.8	46.3
GF2-106-108	115.38	1360	3300	111	100U	13.8	20.0U	10UJ	10.0U	20.0U	11	14.5
GF4-13-15	211.09	6660	10300	398	278	42	20.0U	10UJ	10.0U	20.0U	38.7	42
R.L.		1000	20	1	1000	6	10	10	10	20	1.5	3
F1-S17-40-42	180.84	4510	10600	358	ND	53.4	6.2	ND	ND	ND	35.8	44.4
GF1-S32-70-72	150.84	2040	5330	268	ND	27.4	6.9	ND	ND	ND	18.1	27.2
R.L.		500	10	1	500	6	2	5	2.5	0.5	6	3
ta from New England Testing Laboratory (NETL)												
ample	**Elevation**	**Al**	**As**	**Co**	**Cu**	**Fe**	**Mn**	**Ni**	**Zn**			
GF1-22-24	198.84	5352.62	10.58	5.23	8.26	8161.18	145.33	13.97	20.94			
GF1-26-28	194.84	5144.62	10.32	3.95	6.53	8084.4	109.35	16.74	16.96			
F1-26-28 dup	194.84	3997.59	9.77	3.39	8.1	6377.21	90.32	14.13	14.1			
GF1-30-32	190.84	9966.88	22.41	7.78	15.36	16027.03	200.79	29.86	36.12			
GF1-34-36	186.84	7956.07	13.58	6.08	11.84	13101.97	135.76	24.1	29.28			
GF1-38-40	182.84	3792.45	4.13	3.07	5.47	5620.15	53.13	13.05	13.53			
GF1-42-44	178.84	10659.6	17.84	8.49	13.72	17468.74	207.1	36.5	41.18			
GF1-48-50	172.84	11426.4	21.29	7.27	15.78	16094.4	154.71	31.09	35.48			
GF1-54-56	166.84	9328.32	13.81	6.43	15	13928.39	178.38	27.69	27.84			
GF1-62-64	158.84	5831.01	5.8	4.57	9.47	10370.11	147.77	20.59	21.17			
GF1-80-82	140.84	9005.08	14.74	6.41	10.68	15301.38	237.04	27.06	30.8			
GF1-98-100	122.84	4260.41	6.77	3.05	6.95	7333.16	144.11	14.06	15.94			
GF3A-45-47	173.32	6104.43	17.99	3.72	8.06	10090.3	104.77	18.57	21.1			
GF3A-70-72	148.32	6979.87	5.82	4.71	9.75	10403.16	134.41	19.58	21.51			
BH1-18-20	198	2459.32	3.45	2.37	4.21	4712.55	46.15	8.24	13.79			
BH1-50-52	166	2308.47	7.48	2.76	3.62	5022.95	397.64	13.81	13.76			
R.L.		3.25--3.89	0.32–0.39	0.32–0.39	1.30-1.56	3.25-3.89	0.32--0.39	0.32--0.39	1.30-1.56			
tes:												
ta in mg/kg, dry weight												
Elevation in MSL												
L. = reporting limit												

Table 4-9
Total Organic Carbon Results, GF-3A
Grove Pond Arsenic Investigation, Fort Devens

Lab ID	**Sample ID**	**elev.** **ft MSL**	**TOC** **mg/kg dry wt**	**R.L.**
AA05693	3A 16-18	202.32	610UJ	610
AA05692	3A 20-22	198.32	650UJ	650
AA05696	3A 25-27	193.32	740UJ	740
AA05694	3A 30-32	188.32	720J	570
AA95701	3A 35-37	183.32	1050J	760
AA05698	3A 40-42	178.32	720UJ	720
AA05700	3A 50-52	168.32	720UJ	720
AA05695	3A 55-57	163.32	2210J	720
AA05697	3A 60-62	158.32	1170J	680
AA05699	3A 65-67	153.32	780J	570
AA03191	SS01	surface	572	450
AA03192	SS02	surface	496	460

*Note: samples were inappropriate for TOC determination because they were composed mostly of stones, pebbles, stone fragments, and coarse sand. Preparation of representative 15 to 25 mg aliquots was difficult to achieve. Also, samples were submitted more than four months beyond required hold time (because these samples were submitted in lieu of samples sent in for metals analysis on which requested detection limits were not met).

Table 4-10
Phase II Pond Sediment Results
Grove Pond Arsenic Investigation, Fort Devens

Field ID	Ag	Al	As	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe
SD-01	4.2U	5150	25.0U	34.2	0.71U	3650	10J	6	94.1	16.4	5780
SD-02	10.8U	11100	110U	92.5	1.8U	8680	51J	31	284	52.8	22200
SD-03	9.0U	12800	90.0U	97	1.5U	6300	8J	23.4	284	33.3	20200
SD-04	11.0U	11300	80.0U	86.1	1.8U	6320	7J	18.8	153	33.6	15300
SD-05	11.6U	11400	100U	81.6	1.9U	6130	13J	24.7	198	37.2	20100
SD-06	10.2U	9240	120U	99.5	1.7U	11700	7J	8.3	5610	124	24300
SD-07	6.0U	6030	45.0U	44.4	1.0U	4370	4J	6.8	482	21.6	8720
SD-08	12.4U	10300	120U	85.8	2.1U	6960	24J	28.4	1000	81.1	21800
SD-09	4.4U	8090	35.0U	43.6	0.73U	3130	12J	8.3	219	17.7	8860
SD-10	9.9U	11700	90.0U	82.1	1.7U	5610	22J	24.1	213	37.9	18000
GP-55*	6.2U	11500	125U	96.8	1.2	6380	49J	33	340	52.6	24500
R. L.	N/A	10	10-20	1.5	N/A	20	1.5	1.5	1.5	1.5	10

Field ID	K	Mg	Mn	Na	Ni	Pb	Sb	Se	Tl	V	Zn
SD-01	1420U	831	237	1420U	14	75.8	14UJ	14.2U	28.3U	17.9	137
SD-02	3590U	2470	1020	3590U	50.4	235	36UJ	35.9U	71.7U	38.4	532
SD-03	3010U	2640	1270	3010U	26	114	30UJ	30.1U	60.2U	26.7	229
SD-04	3660U	2220	1080	3660U	24.3	123	37UJ	36.6U	73.2U	27.1	257
SD-05	3870U	2490	857	3870U	30.1	147	39UJ	38.7U	77.4U	30.4	332
SD-06	3420U	3060	284	3420U	27.5	277	34UJ	34.2U	68.3U	40.4	369
SD-07	2010U	1020	595	2010U	14.2	80.5	20UJ	20.1U	40.1U	14.1	106
SD-08	4120U	2170	1060	4120U	43	221	41UJ	41.2U	82.4U	34.2	431
SD-09	1460U	1250	622	1460U	16.9	79.8	15UJ	14.6U	29.2U	16.5	133
SD-10	3300U	2670	870	3300U	35.8	223	33UJ	33.0U	65.9U	31.5	354
GP-55*	2080U	2560	1090	2080U	51.9	251	21UJ	20.8U	41.7U	39.7	512
R. L.	100	20	1-2	100	6	10	10	10	N/A	3	3

all data in mg/kg dry wt

N/A = not on PAL

U = not detected above the reporting limit

J = approximate

*GP-55 is field duplicate of SD-02

3 elements reported that were not on PAL; 6 elements did not meet promised reporting limit

Table 4-11

Phase II Inorganic Data (pore water, unfiltered)

Grove Pond Arsenic Investigation, Fort Devens

Field ID	Ag	As	Al	Ba	Be	Ca (mg/L)	Cd	Co	Cr	Cu	Fe
SD-01	1.5U	57.6	2110	41.2	0.5U	19.3	14.3	2.2	37.3	42.1	4070
SD-02	1.5U	104	1380	58	0.5U	16.3	18.2	2.4	40.2	31.6	4250
GP-55	1.5U	107	1430	56.7	0.5U	16.7	15.7	2.5	41.9	30	3430
SD-03	1.5U	134	2920	73.5	0.5U	17.4	4.4	4.8	99	50.4	4970
SD-04	1.5U	69.4	1020	56.1	0.5U	20.3	2.1	1.9	16.6	17.5	5000
SD-05	1.5U	138	1090	41.4	0.5U	16.2	4.1	2.2	24.2	19.2	2220
SD-06	1.5U	38.2	250	65.1	0.5U	87.8	1.5U	1.5U	176	16.2	1480
SD-07	1.5U	112	551	28	0.5U	11	1.8	1.5U	44.2	18.5	1740
SD-08	1.5U	118	1690	67.8	0.5U	25.1	9.9	2.8	196	36.3	4020
SD-09	1.5U	113	980	47.8	0.5U	15	5.7	1.9	22.5	27.6	2610
SD-10	1.5U	121	1300	48.5	0.5U	13.8	7.6	2	42.3	33.5	2530
PRB	1.5U	5.0U	10.0U	3.0U	0.5U	10.0U	1.5U	1.5U	1.5U	6.0U	20.0U
EB	1.5U	5.0U	33.3	3.0U	0.5U	0.21	1.5U	1.5U	1.5U	6.0U	64.5
91-004*	1.5U	25.0U	10.0U	2.3	0.5U	0.01	1.5U	5.4	950	8.1	65300

Field ID	K (mg/L)	Mg (mg/L)	Mn	Na (mg/L)	Ni	Pb	Sb	Se	Tl	V	Zn
SD-01	3.3	2.9	1060	31.8	10.0U	81.9	5.0U	10.0U	20.0U	6.8	64.4
SD-02	2.1	2.7	2480	28.3	10.2	63.9	5.0U	10.0U	20.0U	5.6	59.1
GP-55	2.2	2.8	2300	29.5	7.8	76.6	5.0U	10.0U	20.0U	5.2	47.7
SD-03	3.8	2.6	3010	35.1	7.9	57.5	5.0U	10.0U	20.0U	5.2	43.4
SD-04	4.8	3.3	3240	37.2	6.0U	26.7	5.0U	10.0U	20.0U	1.7	30.0U
SD-05	1.8	2.8	1830	28	6.0U	35.6	5.0U	10.0U	20.0U	3.3	30.0U
SD-06	1.6	4.7	538	73.4	6.0U	24.5	5.0U	10.0U	20.0U	2.8	40.0U
SD-07	3.8	1.6	774	30.7	6.0U	20.0U	5.0U	10.0U	20.0U	3.9	30.0U
SD-08	3.2	3.9	3150	32.7	7.1	57.4	5.0U	10.0U	20.0U	4.6	43.8
SD-09	4.8	2.2	1690	34.5	6.0U	35.6	5.0U	10.0U	20.0U	5.9	27
SD-10	4.8	2.1	1590	35.5	7.0U	41.3	5.0U	10.0U	20.0U	6	57.4
PRB	1.0U	0.01U	1.0U	1.0U	6.0U	20.0U	5.0U	10.0U	20.0U	1.5U	30.0U
EB	1.0U	11.2	7.6	1.0U	6.0U	20.0U	5.0U	10.0U	20.0U	1.5U	46
91-004*	1.0U	0.02	8.1	1.0U	1400	81	5.0U	10.0U	20.0U	1.5U	12.7

Notes:

*performance evaluation sample

GP-55 is field duplicate of SD-02

Results in µg/L unless otherwise noted

Pore water from surface sediment samples collected with ESAT personnel

Table 4-12
Phase II Inorganic Data (pore water, filtered)
Grove Pond Arsenic Investigation, Fort Devens

Field ID	Ag	As	Al	Ba	Be	Ca (mg/L)	Cd	Co	Cr	Cu	Fe
SD-01	1.5U	37.9	539	213	0.5U	17.3	3.9	1.5U	8.6	17.5	1050
SD-02	1.5U	90.8	461	415	0.5U	15.6	7.4	1.5U	13.8	12.4	1290
GP-55	1.5U	73.5	324	216	0.5U	15.2	4.3	1.5U	9.8	11.3	752
SD-03	1.5U	105	732	550	0.5U	16.2	2.1	2	23.9	19.2	1410
SD-04	1.5U	56.8	208	162	0.5U	19.4	1.5U	1.5U	4.1	6.0U	3230
SD-05	1.5U	111	226	155	0.5U	15.2	2.0U	1.5U	7.1	6.3	535
SD-06	1.5U	35.9	30.6	148	0.5U	87.8	1.5U	1.5U	30.4	5	243
SD-07	1.5U	88.9	265	137	0.5U	10.5	1.5U	1.5U	24	12.1	759
SD-08	1.5U	79.2	294	273	0.5U	24	2.4	1.5U	34.9	11	789
SD-09	1.5U	78.9	437	267	0.5U	13.8	3	1.5U	12.7	18.9	1040
SD-10	1.5U	89.9	593	189	0.5U	13.4	4.2	1.5U	22.4	18	960
PRB	1.5U	5.0U	10.0U	4.4	0.5U	0.09	1.5U	1.5U	1.5U	6.0U	20.0U

Field ID	K (mg/L)	Mg (mg/L)	Mn	Na (mg/L)	Ni	Pb	Sb	Se	Tl	V	Zn
SD-01	3.2	2.7	922	32.2	6.0U	25.2	5.0U	10.0U	20.0U	2.1	117
SD-02	2.2	2.6	2310	30.2	6.0U	25	5.0U	10.0U	20.0U	1.7	230
GP-55	2.1	2.6	1770	29.3	6.0U	20.0U	5.0U	10.0U	20.0U	1.5U	109
SD-03	4	2460	2710	38.8	6.0U	20.0U	5.0U	10.0U	20.0U	1.5U	284
SD-04	4.7	3.1	3040	36.6	6.0U	20.0U	5.0U	10.0U	20.0U	1.5U	71.6
SD-05	2	2650	1690	28.1	6.0U	20.0U	5.0U	10.0U	20.0U	1.5U	74.8
SD-06	1.6	4.8	510	76.3	6.0U	20.0U	5.0U	10.0U	20.0U	1.5U	45.2
SD-07	3.8	1.6	191	31.6	6.0U	20.0U	5.0U	10.0U	20.0U	2.1	183
SD-08	3.3	3.8	2950	33.7	6.0U	20.0U	5.0U	10.0U	20.0U	1.5U	125
SD-09	4.9	2.1	229	35.7	6.0U	20.0U	5.0U	10.0U	20.0U	2.4	120
SD-10	4.7	2	536	35.4	6.0U	20.0U	5.0U	10.0U	20.0U	2.4	370
PRB	1.0U	0.01	1.0U	1.0U	6.0U	20.0U	5.0U	10.0U	20.0U	1.5U	30.0U

Notes:

*performance evaluation sample

GP-55 is field duplicate of SD-02

Results in µg/L unless otherwise noted

Pore water from surface sediment samples collected with ESAT personnel

Table 4-13
Phase II Inorganic Data (pore water, soft-sediment core)
Grove Pond Arsenic Investigation, Fort Devens

sample ID	Ag	As	Al	Ba	Be	Ca (mg/L)	Cd	Co	Cr	Cu	Fe	
2SC1	0.2U	4.7	167	163	0.20U	316	0.20U	2.8	0.50U	0.77	135	
2SC2	0.45	7	280	155	0.20U	155	0.45	3.4	0.50U	0.95	56.3	
3SC3	0.92	11.1	331	130	0.20U	298	0.92	14.2	0.74	1.1	289	
R. L.	0.2	2	2	0.5	0.2	0.1	0.2	0.2	0.5	0.2	20	
sample ID	**K (mg/L**	**Mg (mg/L)**	**Mn**	**Na (mg/L)**	**Ni**	**Pb**	**Sb**	**Se**	**Tl**	**V**	**Zn**	**pH**
2SC1	N/A	43.7	21.4	N/A	9.4	0.22	1.1	2.5U	0.22	0.98	7.2	6.44
2SC2	N/A	18.1	8.1	N/A	5.2	0.57	0.42	2.5U	0.05U	0.6	11.7	5.48
3SC3	N/A	34.9	25.2	N/A	14.1	1.1	0.57	2.5U	0.12	1	90.6	5.11
R. L.		0.04	0.0002		0.2	0.05	0.2	2.5	0.05	0.5	0.2	

Notes:

R. L. = reporting limit

N/A = not analyzed

Results in µg/L unless otherwise noted

Samples were taken by Gannett Fleming from pond-sediment cores

Only three samples yielded enough water for analysis.

Table 4-14
Phase II Inorganic Data (soft-sediment core)
Grove Pond Arsenic Investigation, Fort Devens

Sample	Ag	Al	As	Ba	Be	Ca	Cd	Co	Cr	Cu	Fe
1SC1	6.0U	10100	50.0U	93.4	1.3	10300	8.8	12.1	64.9	19.3	12600
4 C1	6.0U	4600	20.0U	10.8	0.50U	633	1.5U	3.0U	10.8	3.0U	6040
6 C1	6.0U	4660	20.0U	7.4	0.50U	400	1.5U	3.4	10.9	4.6	7230
8SC1	6.0U	5030	20.0U	13.8	0.50U	973	1.5U	5	11.7	6.3	7720
1SC2	6.0U	10700	90.0U	88.1	1.2	6820	53.1	23.7	184	43.5	19300
C2	6.0U	5720	20.0U	19.8	0.50U	1110	1.5U	3.0U	10.2	3.0U	5020
C2	6.0U	4210	20.0U	15.3	0.50U	1050	1.5U	3.0U	9.5	3.0U	4700
1SC3	6.0U	11500	90.0U	82	0.95	6280	15.8	24.9	167	39.1	18800
3SC3	6.0U	5980	20.0U	22.8	0.50U	1120	1.5U	5.3	14	5.1	6830
E S03	6.0U	2390	10.0U	16.6	0.50U	414	1.5U	3	7.1	3.8	5500
SS01	1.5U	3230	19.6U	7.9	0.49U	312	3UJ	2.3	7.6	4.2	5400
SS02	1.5U	6190	20.0U	24.4	0.50U	7760	3UJ	4.8	22.4	6.8	10600

Sample	K	Mg	Mn	Na	Ni	Pb	Sb	Se	Tl	V	Zn	pH
1 C1	1000U	1520	1280	1000U	24.6	53.1	10.0U	20.0U	20.0U	16.1	159	5.5
C1	1000U	1690	76.7	1000U	12.6	20.0U	10.0U	20.0U	20.0U	5.7	17.6	6
6SC1	1000U	2190	64.7	1000U	15.2	20.0U	10.0U	20.0U	20.0U	5.5	20.7	6.8
8SC1	1000U	2220	85.1	1000U	15	20.0U	10.0U	20.0U	20.0U	8	25.2	6.7
C2	1000U	2320	1180	1000U	46.5	185	10.0U	20.0U	20.0U	32.8	398	5.4
C2	1000U	1520	72.8	1000U	10.9	20.0U	10.0U	20.0U	20.0U	6	17.6	6.1
5SC2	1000U	1310	60.5	1000U	10.6	20.0U	10.0U	20.0U	20.0U	5.1	16.5	6.8
1SC3	1000U	2470	965	1000U	40.1	127	10.0U	20.0U	20.0U	25.7	363	5.5
C3	1000U	2050	91.7	1000U	21.3	20.0U	10.0U	20.0U	20.0U	6.7	25.5	6.7
BHS03	433	1190	362J	100U	14.4	20.0U	5.0U	20.0U	20.0U	6.0U	14.5	7.4
SS01	425	1310	83.6	98U	7.4	19.6U	19.6UJ	9.8U	9.8U	5.9U	22.6	7.72
02	1820	4690	254	162	18.2	20.0U	20.0UJ	10.0U	20.0U	14.5	22.2	8.06

Notes:

L. = reporting limit

N/A = not analyzed

Results in mg/kg dry wt.

Table 4-15
Whole-Rock Analysis (bedrock core)
Grove Pond Arsenic Investigation, Fort Devens

element	units	GF1 C-2 1.0	GF2 C-2 1.58	Method
Al	%	8.59	5.83	ICP16
Al	%	8.695	5.682	ICP40
Ca	%	0.24	0.12	ICP16
Ca	%	0.24	0.126	ICP40
Fe	%	4.65	7.44	ICP16
Fe	%	4.33	6.89	ICP40
K	%	2.56	1.05	ICP16
K	%	2.33	0.97	ICP40
Mg	%	1.09	1	ICP16
Mg	%	1.065	1.04	ICP40
Na	%	0.72	0.37	ICP16
Na	%	0.705	0.365	ICP40
P	%	0.06	0.05	ICP16
P	%	0.05	0.035	ICP40
Si	%	33.6	37.8	ICP16
Ti	%	0.46	0.39	ICP16
Ti	%	0.173	0.322	ICP40
As	ppm	24.8	11.2	As hyd
Ba	ppm	438	211	ICP16
Ba	ppm	433	223	ICP40
Be	ppm	3	<1	ICP40
Ce	ppm	77	80	ICP40
Co	ppm	12	13	ICP40
Cr	ppm	138	185	ICP16
Cr	ppm	92	101	ICP40
Cu	ppm	<2	61	ICP40
Ga	ppm	29	25	ICP40
La	ppm	38	39	ICP40
Li	ppm	75	82	ICP40
Mn	ppm	120	494	ICP16
Mn	ppm	113	483	ICP40
Mo	ppm	9	7	ICP40
Nb	ppm	15	11	ICP16
Nb	ppm	9	14	ICP40
Nd	ppm	29	40	ICP40
Ni	ppm	57	53	ICP40
Pb	ppm	38	16	ICP40
Sc	ppm	16	14	ICP40
Sr	ppm	55	24	ICP16
Sr	ppm	53	25	ICP40
Th	ppm	15	9	ICP40
V	ppm	107	103	ICP40
Y	ppm	22	22	ICP16
Y	ppm	9	8	ICP40
Yb	ppm	1	1	ICP40
Zn	ppm	79	100	ICP40
Zr	ppm	235	236	ICP16
S	%	0.09	0.19	total S

Analyses courtesy of the US Geological Survey

Table 4-16

Stable Isotope Data (groundwater and surface water)

Grove Pond Arsenic Investigation, Fort Devens

Sample	Sample date	δD	$\delta^{18}O$
PW-1	8/18/98	-56.8	-8.93
PW-1	10/20/98	-55.4	-8.67
PW-2	8/11/98	-57.1	-8.96
PW-2	10/20/98	-55.8	-8.61
92-1	8/18/98	-56.1	-8.82
	10/20/98	-55.2	-8.83
92-3	8/18/98	-55.6	-8.49
	10/20/98	-53.8	-8.36
MNG3	8/12/98	-54.5	-8.69
MNG7	8/25/98	-59.5	-9.25
SW-1	8/25/98	-50	-7.38
SW-3	8/25/98	-50.3	-7.33
SW1	2/17/00	-46.27	-7.29
GF1GW06	2/15/00	-60.49	-9.2
GF2GW06	2/17/00	-66.52	-10.16
GF3AGW25	2/16/00	-55.15	-8.44
GF3BGW02	2/16/00	-41.14	-6.16
Notes:			
Results in parts per mil			
Isotope analyses courtesy of the US Geological Survey			

TABLE 4-~~18~~ 17
Slug Test Results

well/boring	interval bgs	interval elev., MSL	date	type	logged by	rising / falling	K cm/s	K ft/d
92-1	49-55	167-173	5/18/2001	MW	hand	falling	1.21E-01	343
						rising	6.49E-02	184
92-3	49-55	163-169	11/17/1999	MW		falling	6.53E-02	185
						rising	6.91E-02	196
92-4	67-71	181-185	6/14/2001	MW	hand	falling	4.16E-03	11.8
					hand	falling	3.27E-03	9.28
					hand	falling	4.20E-03	11.9
92-5	35-41	183-189	7/15/1998	MW	hand	rising	1.20E-02	34
EX-2			7/15/1998	MW	hand	falling	9.14E-03	25.9
MNG-3	43-62	190-209	7/15/1998	MW	hand	rising	1.26E-03	3.57
MNG-7	32-51	199-218	7/15/1998	MW	hand	falling	1.24E-03	3.52
						rising	7.27E-04	2.06
GF-1	98-100	122-124	10/19/1999	DP		falling	7.13E-01	2020
						rising	5.36E-01	1520
	110-111	111-112	10/20/1999	O		falling	2.07E-01	586
						rising	1.06E-01	300
	116-121	101-106	10/26/1999	MW		falling	1.50E-03	4.24
						rising	1.48E-03	4.19
			11/9/1999	MW		falling	1.01E-03	2.86
			11/17/1999	MW		falling		
						rising	9.00E-03	25.5
GF-2	106	116	10/27/1999	O		falling		
						rising		
	110-111	111-112	10/28/1999	O		falling	6.63E-03	18.8
						rising		
GF-3A	18-20	199-201	11/2/1999	DP		falling	1.16E-03	3.3
						rising	1.45E-03	4.1
	33-35	184-186	11/2/1999	DP		falling	9.07E-03	25.7
						rising	8.93E-03	25.3
	107	112	11/9/1999	O		falling		
						rising		
	97-102	117-122	11/17/1999	MW		falling	5.26E-02	149
						rising	4.55E-02	129
GF-3B	8-13	206-211	11/17/1999	MW		falling	5.22E-04	1.48
						rising	6.46E-04	1.83
GF-4	48-50	175-177	11/11/1999	DP		falling	1.17E-02	33.1
						rising	1.17E-02	33.2
	83-85	140-142	11/12/1999	DP		falling	8.71E-04	2.47
						rising	4.02E-04	1.14
	79-84	141-146	6/14/2001	MW	hand	falling	4.20E-04	1.19
						rising	3.74E-04	1.06
BH-1	16-18	199-201	11/22/1999	DP		falling	2.12E-02	60.2
						rising	2.90E-02	82.2
	36-38	179-181	11/23/1999	DP		falling	4.20E-02	119
						rising	4.20E-02	119
	56-58	159-161	11/24/1999	DP		falling	1.32E-02	37.5
						rising	5.64E-03	16

Table 4-18
Grain Size Analytical Results
Grove Pond Arsenic Investigation, Fort Devens

		gravel	coarse sand	medium sand	fine sand	silt & clay
	depth	sieve #4	sieve #10	sieve #40	sieve #200	
Field ID	interval	4.75 mm	2 mm	0.425 mm	0.075 mm	<0.075 mm
BHS01	21-23 ft	0	0	62.4	33.9	3.7
BHS02	38-40 ft	0	0.2	45.4	46.8	7.6
BHS04	59-61 ft	0	0.1	16.5	66.3	17.1

		coarse sand		medium sand		fine sand	
	depth	sieve#10	sieve #20	sieve #40	sieve #60	sieve #140	
Field ID	interval	2.0 mm	0.850 mm	0.425 mm	0.250 mm	0.106 mm	<0.106 mm
GF4	50-52	1.2	25.2	22.1	13.3	13.1	25.1
GF-3B	35-37	1.7	25.3	22.5	13.1	13.1	24.4
SS01	10-12	3.1	7.6	28.3	38.8	16.5	6.3
GF-3A	16-18	1.1	1.5	2.8	7.3	44.4	42.9
GF-IS-6	18-20	0.1	0.3	5.8	31.8	55.3	6.7
GF-IS-11	28-30	0.3	27.6	25.1	13.7	16.7	16.8
GF-IS-15	36-38	0	28.5	45.4	17.8	6.5	1.8
GF-IS-19	44-46	38.6	17	11.6	7.8	14.3	10.7
GF-IS-23	52-54	0.6	43	22.2	10.6	12.5	11.1
GF-IS-27	60-62	0.2	35.3	36.1	13	11	4.4

Grain size measurements courtesy of EPA Lab Biology Section

TABLE 4-19
Hydraulic Conductivity From Grain Size

		d_50	K (ft/day) (Shepherd)	depth ft, bgs	surface elevation ft, MSL	sample elevation ft, MSL
BHS01		0.5782	182.2390144	-22	214	192
BHS02		0.361	83.77209893	-39	214	175
BHS03		0.1774	25.94095614	-60	214	154
GF4	50-52	0.4003	99.34562297	-51	225.09	174.09
GF-3A	35-37	0.4146	105.2690867	-36	219.32	183.32
SS01	10-12	0.3638	84.84689623	-11	217	206
GF-3A	16-18	0.1216	13.91082581	-17	219.32	202.32
GF-IS-6	18-20	0.2075	33.59637193	-19	221.84	202.84
GF-IS-11	28-30	0.4592	124.5993035	-29	221.84	192.84
GF-IS-15	36-38	0.6125	200.4183892	-37	221.84	184.84
GF-IS-19	44-46	1.1268	547.9738034	-45	221.84	176.84
GF-IS-23	52-54	0.696	247.4672653	-53	221.84	168.84
GF-IS-27	60-62	0.6434	217.3733293	-61	221.84	160.84

TABLE 4-20
Specific Capacity Data
GF-3A

depth interval	midpt	sec/L	Q (ft^3/day)	dh (ft)	spec. cap. Q/dh	elev ft (MSL)
18-20	-19	30	101.664	9	11.296	200.32
18-20	-19	60	50.832	3.5	14.52343	200.32
23-25	-24	25	121.9968	2	60.9984	195.32
23-25	-24	45	67.776	0.5	135.552	195.32
33-35	-34	40	76.248	0.5	152.496	185.32
33-35	-34	120	25.416	0.1	254.16	185.32
38-40	-39	35	87.140571	0.4	217.8514	180.32
43-45	-44	50	60.9984	1.9	32.10442	175.32
43-45	-44	22	138.63273	3.9	35.54685	175.32
48-50	-49	15	203.328	1.6	127.08	170.32
53-55	-54	17	179.40706	2.7	66.44706	165.32
58-60	-59	10	304.992	1.2	254.16	160.32
68-70	-69	8	381.24	6.1	62.49836	150.32
92-93	-92.5	5	609.984	2.6	234.6092	126.82
97-98	-97.5	5	609.984	12.8	47.655	121.82
102-103	-102.5	5	609.984	44.8	13.61571	116.82
104-107	-105.5	5	609.984	30	20.3328	113.82

TABLE 4-21
Piezometer Data

Date	Approx. Time	Piezo ID	Stick-up (ft)	Depth to Water (ft)	Drawdown (ft)
11/23/99	10:00	PZ-1	2.06	2.05	-0.01
11/23/99	10:00	PZ-2	3.71	3.9	0.19
11/23/99	10:00	PZ-3	2.03	2.05	0.02
11/23/99	10:00	PZ-4	2.21	2.4	0.19
11/23/99	10:00	PZ-5	2.08	2.25	0.17
11/23/99	10:00	PZ-6	2.02	2.4	0.38
11/24/99	8:20	PZ-1	2.06	2.08	0.02
11/24/99	8:20	PZ-2	3.71	3.88	0.17
11/24/99	8:20	PZ-3	2.03	2.02	-0.01
11/24/99	8:20	PZ-4	2.21	2.3	0.09
11/24/99	8:20	PZ-5	2.08	2.21	0.13
11/24/99	8:20	PZ-6	2.02	2.42	0.4
11/29/99	9:30	PZ-1	1.92	1.92	0
11/29/99	9:30	PZ-2	3.58	3.61	0.03
11/29/99	9:30	PZ-3	1.88	1.9	0.02
11/29/99	9:30	PZ-4	2.05	2.14	0.09
11/29/99	9:30	PZ-5	1.92	1.95	0.03
11/29/99	9:30	PZ-6	1.86	1.92	0.06
11/29/99	12:00	PZ-1	1.91	1.91	0
11/29/99	12:00	PZ-2	3.56	3.65	0.09
11/29/99	12:00	PZ-3	1.89	1.92	0.03
11/29/99	12:00	PZ-4	2.07	2.18	0.11
11/29/99	12:00	PZ-5	1.92	2.08	0.16
11/29/99	12:00	PZ-6	1.88	2	0.12

TABLE 4-22
Seepage Meter Results

Run #1 SM no.	valve open	valve closed	final volume (ml)	elapsed hours	elapsed days	elapsed seconds	flux cm/s	flux ft/day
1	10/20/0014:09	10/23/00 12:55	1000	70.7566667	2.948194	254724	0	0
2	10/20/00 14:15	10/23/00 14:03	175	71.8	2.991667	258480	1.19073E-06	0.003375
3	10/20/00 14:11	10/23/00 13:30	660	71.3166667	2.971528	256740	4.94052E-07	0.0014
4	10/20/00 14:12	10/23/00 13:46	175	71.5666667	2.981944	257640	1.19462E-06	0.003386
Run #2 SM no.	valve open	valve closed	final volume (ml)	elapsed hours	elapsed days	elapsed seconds	flux cm/s	flux ft/day
1	pulled for repair							
2	10/23/00 14:27	10/27/00 16:00	150	97.55	4.064583	351180	9.02977E-07	0.00256
3	10/20/00 14:25	10/27/00 15:42	165	97.2833333	4.053472	350220	8.89473E-07	0.002521
4	10/23/00 14:26	10/27/00 15:49	550	97.3833333	4.057639	350580	4.78865E-07	0.001357
Run #3 SM no.	valve open	valve closed	final volume (ml)	elapsed hours	elapsed days	elasped seconds	flux cm/s	flux ft/day
	(EDT)	(EST)						
1	10/27/00 16:09	10/30/00 11:35	1000	67.4333333	2.809722	242760	0	0
2	10/27/00 16:06	10/30/00 11:40	260	67.5666667	2.815278	243240	1.13497E-06	0.003217
3	10/27/00 16:08	10/30/00 11:37	930	67.4833333	2.811806	242940	1.07495E-07	0.000305
4	10/27/00 16:07	10/30/00 11:38	970	67.5166667	2.813194	243060	4.60463E-08	0.000131
Run #4 SM no.	valve open	valve closed	final volume (ml)	elapsed hours	elapsed days	elasped seconds	flux cm/s	flux ft/day
1	10/30/00 12:05	11/3/00 14:54	380	98.8167	4.117363	355740.1	6.50199E-07	0.001843
2	10/30/00 12:14	11/3/00 14:58	160	98.7333	4.113888	355439.9	8.81659E-07	0.002499
3	10/30/00 12:08	11/3/00 15:02	960	98.9	4.120833	356040	4.1913E-08	0.000119
4	10/30/00 12:10	11/3/00 15:07	955	98.95	4.122917	356220	4.71283E-08	0.000134