Fractured Bedrock DNAPL/ Dissolved Phase Plume Conceptual Model Development at the Eastland Woolen Mill Superfund Site, Corinna, Maine

Scott Calkin, Peter Thompson, and Peter Baker, MACTEC Engineering and Consulting, Inc. and; Scott Acone, United States Army Corps of Engineers New England District and; Ed Hathaway, United States Environmental Protection Agency

Abstract

The Eastland Woolen Mill (EWM), which straddled the East Branch of the Sebecook River in Corinna, Maine, was listed on the United States Environmental Protection Agency (USEPA) National Priority List in July of 1999. The site is currently undergoing clean-up activities. The United States Army Corps of Engineers New England District is managing site activities under a cooperative interagency agreement with USEPA. Chlorinated benzenes released during EWM manufacturing processes resulted in extensive contamination to fractured meta-sedimentary bedrock underlying the Site. Chlorinated benzene dense non-aqueous phase liquids (DNAPL) have migrated vertically at the Site into underlying bedrock. A chlorinated benzene groundwater plume exists in bedrock. Under natural conditions, bedrock groundwater discharges to overburden and then to the river. This paper presents the evolution of the EWM Site fractured bedrock conceptual model and its' value in decision-making from the early stages of the remedial investigation up to the planning and implementation of Site remedial activities. Initial Site Investigation (SI) activities, including potentiometric surface mapping and groundwater sampling from existing residential wells, indicated localized bedrock groundwater contamination down gradient and cross gradient of the EWM. Several potential secondary source areas were also identified, in addition to the primary source areas beneath the EWM. The initial conceptual model developed after the SI suggested that a deep and discretely fractured bedrock system was controlling plume migration, which was expected to discharge along the river. A remedial investigation that included photo-lineament analysis, bedrock mapping, monitoring well installations, borehole geophysical logging (optical, acoustic tele-viewer, and heat-pulse flow meter), low-flow straddle packer and multi-level groundwater sampling, a groundwater pumping test, and potentiometric surface mapping was undertaken to better define contaminant distribution, fate and transport.

Key observations made from the borehole geophysical data set show the dominant set of hydraulically active fractures were along sedimentary bedding planes, which strike from E-W to NE-SW and dip 60-65 degrees to the south and southeast. The bedding plane fractures are only weakly cross connected by a smaller set of axial plane fractures and north to northwesterly trending joints, accounting for the high degree of anisotropy noted in a groundwater pumping test and cross-gradient plume alignment. The resulting average strike of combined joints and bedding plane fractures is roughly North 50° East. A pumping test conducted near the source area indicated a drawdown ellipse axis of North 43° East. The majority of the hydraulically active fractures (i.e., fractures with measurable flow under stressed conditions) in the aquifer are shallow relative to the depth of documented contamination. Hydraulically active fractures are generally within the top 130 feet of the bedrock aquifer, yet documented contamination extends nearly 300 feet deep under the former mill. A few hydraulically active fractures have been identified within the aquifer at depths down to 250 feet below the bedrock surface. Investigations were concluded to 600 feet at one location.

Groundwater sampling showed the extent of groundwater contamination was approximately four-times greater cross gradient to the southwest and northeast than in the downgradient direction that had been established by potentiometric measurements. Several residential wells were significantly impacted cross gradient (southwest) from the primary source area. Investigation of other potential sources of contamination near these wells did not identify chlorinated benzene contamination. Deep DNAPL penetration is suspected down dip along bedding plane fractures under the EWM source area. The similarity between the orientation of the aquifer anisotropy and the elongated cross gradient plume suggested that contaminated groundwater, while under a hydraulic stress, had moved preferentially, from deep within the source area, to the southwest along a narrow band of interconnected bedding plane fractures. Groundwater modeling confirmed that the high degree of anisotropy in the aquifer allowed distant domestic well pumping stresses, to pull contamination over 550 feet to the southwest along these deep, fracture pathways. Contamination in deep fractures was confirmed in the farthest wells.
Introduction

The Eastland Woolen Mill (EWM) is located in Corinna, Maine (Figure 1) and was listed on the United States Environmental Protection Agency (USEPA) National Priority List (NPL) in July of 1999. The site is undergoing investigation and clean-up activities pursuant to the National Oil and Hazardous Substances Pollution Contingency Plan (NCP). The USEPA is the lead agency at this site and work is being conducted under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), as amended by the Superfund Amendments and Reauthorization Act (SARA). The United States Army Corp of Engineers New England District (USACE-NAE) is managing site activities under a cooperative interagency agreement with USEPA.

The Eastland Woolen Mill (EWM) manufactured wool and blended woven fabrics from 1912 to 1996 when it underwent bankruptcy. EWM conducted business within a complex of connected buildings clustered around former Mill Pond impoundment formed by dam (Middle Dam) on the East Branch of the Sebasticook River (EBSR). Operations included two adjacent areas (Building 14, and an Underground Storage Tank (UST) Area) located immediately east of the main building complex, as well as several other smaller properties located around town. The locations of study areas are shown in Figure 2.

EWM operations resulted in discharges of process wastewater containing residual dye by-products containing Dye Aid. The primary chemical constituents of Dye Aid included chlorinated benzene compounds. The process waste discharge occurred from the dye kettles and washing operations and resulted in extensive contamination of soils under the EWM complex, the underlying bedrock, and river sediments.

Chlorinated benzene dense non-aqueous phase liquids (DNAPL) are present at the Site and have penetrated into underlying bedrock. A groundwater plume with high concentrations of chlorinated benzene compounds exists in overburden groundwater and bedrock groundwater to depth in excess of 300 feet below ground surface immediately under the source. The bedrock plume extends approximately 400 feet downgradient from the EWM Source Area. As a result of the strong discharge conditions at the site, the bedrock plume originating at the EWM Source Area rapidly discharges to overburden and surface waters, and appears to be in a stable configuration with respect to downgradient persistence.

The conceptual model that was developed indicates that the bedrock groundwater system responds in a strongly anisotropic manner to groundwater pumping stresses due to the dominance of a bedding plane fracture network. This high degree of anisotropy allowed distant pumping stresses, aligned parallel to the source area along the direction of bedding plane fractures to pull shallow bedrock groundwater downward and deep groundwater outward from the EWM source area. Contaminated groundwater was pulled approximately 550 feet to the southwest along narrow fracture pathways by pumping from water supply wells in the Sunshine Village Apartments complex, without impacting several overlying shallow bedrock wells. To the northeast, chlorinated benzene contamination migrated to bedrock groundwater supply wells adjacent to an underground storage tank area where chemical releases resulted in considerable contamination of the overburden groundwater system. The source of bedrock groundwater contamination in this area is believed to have resulted from pumping stresses imposed on the contaminated region of overburden groundwater, resulting in downward gradients and migration of contaminants from overburden to bedrock. Based upon numerical simulations it is likely that the origin of bedrock groundwater contamination northeast of the Site was a not result of lateral migration from the EWM source area where DNAPL is present.
FIGURE 2
LOCATION OF EWM SOURCE AREAS

LEGEND

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<td>POTENTIAL SOURCE AREAS</td>
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<td></td>
<td>AREAS SUBJECT TO EARLY CLEANUP</td>
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<td>FEASIBILITY STUDY OPERABLE UNITS</td>
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SCALE: 1"=750'
Conceptual Model Development

A site-specific conceptual model was developed for the former EWM site after evaluating geologic maps, watershed drainage patterns, topographic maps, photo-lineaments, fracture patterns in limited bedrock outcrops and any existing groundwater information. The conceptual model, in combination with the location of the suspected source areas, was used as a basis for locating bedrock explorations and allows a thoughtful analysis of possible remediation strategies.

Bedrock underlying Corinna and this portion of central Maine consists of metamorphosed siltstones (the Waterville Formation) contained within a south easterly dipping flank of a regional scale anticline. Bedding typically is moderately to steeply dipping, ranging from 40 degrees to near vertical. Bedding plane, axial plane and cross-cutting fractures are also present in outcrop exposure behind the former EWM. Downtown Corinna is located in the East Branch of the Sebasticook River valley. In the vicinity of the Site, the river valley does not appear to be structurally controlled or underlain by an identifiable fault structure. Based on the evaluation of the existing information the following objectives were developed to further refine the conceptual model:

- Characterize the complex structure and composition of the fractured bedrock aquifer
- Measure the stratigraphic thickness and compositional continuity in the glacial till overburden
- Conduct fracture analysis, develop a comprehensive conceptual model of the fracture network, assess the vertical extent of the productive aquifer and dominant hydraulic characteristics of productive water bearing fractures and controls on chlorinated solvent migration.
- Measure field water quality/hydrophysical parameters of the borehole fluids.
- Measure vertical flow between and at fracture zones under ambient and stressed condition

Bedrock Borings

The distribution of contaminants was initially evaluated by drilling several bedrock borings down gradient and along strike of primary fracture sets. Depth of borings was based on early estimates of the vertical plume dimension, proximity to the source and discharge area, and the nature of the suspected contaminants. (i.e. dissolved versus DNAPL, or a mixture of both). Bedrock borings have been completed using air-hammer, diamond bit coring, and roto-sonic methods. Air-hammer drilling methods were used for deep investigations and the boreholes were logged geophysical methods to characterize the fracture network. Bedrock cuttings were logged at one-foot intervals and changes in groundwater returns observed to identify lithologic and structural variations and the presence of water-bearing fractures. Water bearing fractures and fracture zones are indicated by changes in drilling rate, mineralogy and secondary alteration. These included the presence of iron oxides, clayey gouge, weathered rock matrix, slickensided rock surfaces and in cases, an increase in chlorite. Once drilling was completed, the borehole was developed using airlift methods until water returns were clear.

Geophysical Logging

Borehole geophysical logging was completed in selected residential water supply wells and in all bedrock boreholes to determine depth and orientation of water-bearing fractures. The standard suite of logs included caliper, temperature, fluid resistivity, single point resistance (SPR), and spontaneous potential (SP). Caliper is used to identify changes in borehole diameter, temperature gradients induced by groundwater movement, and electrically conductive zones. Caliper and resistivity measurements are susceptible to borehole diameter variations caused by breakouts, and therefore cannot be solely relied upon to identify water-bearing zones. However, caliper deviations observed in the bedrock underlying Corinna generally indicate the presence of fractures. Optical Televiewer or Acoustic Televiewer (ATV) tools were used to identify bedding features and fractures. These downhole imaging logs are interpreted for obvious fractures. The on-site geophysicist evaluated the borehole images and standard log suite to identify selected zones for Heat Pulse Flow Meter (HPFM). The HPFM testing was completed under non-pumping or ambient conditions and stressed conditions depending on flow regime of the borehole. Each zone was tested first under ambient (i.e., steady state) conditions to determine whether vertical flow cells exist within the borehole. The HPFM tool was run a second time under pumping conditions to identify other water-bearing zones that may not be apparent under ambient flow. A small submersible pump was placed near the bottom of the casing. The well was pumped at a low rate
(usually more than 1 gallon per minute) while the HPFM logging is repeated for each zone. The rate was adjusted to maximize discharge but minimize drawdown. Measurements were taken above and below each selected fracture.

**Hydraulic Testing and Groundwater Packer Sampling**

Hydraulic testing and sampling were conducted in a three-part process: 1) hydraulic tests were conducted on each zone, 2) each water-bearing zone was packer sampled and 3) selected zones were retrofitted with permanent sampling apparatus. Fracture zones were isolated using pneumatically inflated packers. A static packer test was conducted by taking water level measurements within and above the sample zone. Measurements were continued until the water levels reach equilibrium. By using the same reference, vertical hydraulic gradients were estimated for the selected zones. Once the water levels stabilized, a submersible or bladder pump was lowered into the riser pipe of the packer assembly and a short-term, low stress specific capacity test was conducted. After completing the specific capacity test, a bladder pump was used to collect a low-flow groundwater sample from the isolated zone for chemical analysis.

**Borehole Retrofits**

Vertical hydraulic gradients near the river are strongly upward. The boreholes in these discharge areas were left as open boreholes, completed as monitoring wells or retrofitted with multiport sampling devices. Depending on the size of the borehole drilled, nested monitoring wells or multiport sampling devices (e.g., FLUTE liners) were installed to monitor selected zones. The multilevel sampling devices also provide a means to accurately measure the vertical hydraulic gradients between the various zones. An advantage of the FLUTE liner system is that the liner can be removed from the wells, if desired, thus preserving the large investment represented by the borehole for additional uses (i.e., future location for treatment injection or extraction).

**Chemical Analysis**

During the remedial investigation an on-site laboratory data was used for to analyze groundwater samples for target volatile organic compounds, which included chlorinated benzene compounds, trichloroethylene, tetrachloroethylene, and benzene. The on-site analysis provided for rapid assessment of chemical concentrations in the bedrock aquifer. This data allowed frequent re-assessment of the conceptual model during the progress of the investigation and presented opportunities optimize and adjust planned bedrock boring locations.

In addition to groundwater samples, rock samples from air-hammered boreholes and roto-sonic cored boreholes have also been collected and prepared for extraction by methanol and VOC analysis. This purpose of these methanol extracted rock chip (MERC) samples is to assess the fracture specific differences in contamination levels and assess the extent of diffusion of contaminants from fracture margins into weathered and unweathered rock matrix. High concentrations of contaminants in the rock matrix surrounding fractures provide an ongoing source of contamination that may significantly effect the selection or performance of a remedial alternatives for the site. These approaches help provide a fracture specific means of assessing matrix diffusion affects.

**Site Characterization Findings and Conceptual Model Development**

The geomorphology of the Corinna area is dominated east and west by two gentle north-south trending ridges with a broad intervening river floodplain, in which the ESBR meanders. Within the valley, bedrock is overlain by glacial deposits, composed principally of heterogeneous mixtures of sand, silt, gravel and cobbles (till), inter-layered with fluvo-glacial sediments (laminated, fine silty sands). The thickness of these overburden deposits across the site varies from ten to greater than forty feet. Bedrock is comprised of a moderately dipping sequence of sedimentary rock dominated by slightly calcareous meta-siltstone, and shaley siltstone. Bedrock has well-developed foliation and fracture patterns that parallel compositional layering or bedding.

Groundwater occurs in the overburden and in the bedrock. Throughout the central portion of the site, underlying the river, the overburden appears to consists of a lower and upper till unit with a narrow intervening sequence of thinly bedded, fine silty sand which contains thin wispy lenses of carbonaceous material. Based on
results of a pumping test the bedrock groundwater appears confined, and is hydraulically connected to the lower till groundwater unit. The upper till groundwater unit and surface water system do not appear to have an appreciable hydraulic connection to the underlying bedrock or deeper till groundwater unit.

**Synoptic Groundwater Elevation Measurements**

Two synoptic rounds of groundwater elevation measurement were conducted. The first round occurred in September, several weeks after the 1999 field program had mobilized. This synoptic round did not have the advantage of the additional wells that were installed during the 1999 field program, but was adequate to verify the large-scale conceptual groundwater flow patterns. The second synoptic round occurred on November 30, 1999, several days before the permanent shut-down of the Sunshine Village bedrock water supply system. In creating the bedrock potentiometric maps, care was been taken to consider the depths of screened well intervals, the presence of vertical gradients in bedrock, and the effects that open boreholes have on averaging of vertical head differences across the formation by artificially connecting fracture networks.

Figure 3 presents the interpretation of bedrock potentiometric surface from the November 30, 1999 synoptic data. This figure indicates three areas of groundwater depression associated with pumping of residential wells and clusters of residential wells. The deepest and most persistent pumping cone of depression is on the western side of the EBSR, and is associated with the Sunshine Village well system, which reportedly pumped in excess of several thousand gallons per day. The lateral movement of groundwater is from the surrounding topographic highs outside the figure boundary, toward the river system, and toward specific residential wells. The predominance and magnitude of the Sunshine Village pumping well cone of depression, on the left side of Figure 3 suggests it was capable of capturing a portion of groundwater system immediately south of the EWM source area. This explains the persistence and the magnitude of chlorobenzene contamination in those wells, and wells along that flow path. The pumping stress from the Sunshine Village Production Well No. 1 is transmitted by both deep and shallow fractures.

Groundwater pumping stresses to the east of the site are of smaller magnitude and more variable. Some of the locations are rental properties, serving from one to three apartments. Their affect on contaminant migration is far less than the long-term, persistent and deep drawdown from the Sunshine Village wells.

This figure also shows several well pairs south of the EWM source area surrounding the river. The bedrock potentiometric surfaces adjacent to the river at these locations are well above the river surface, and, in several instances, are well above ground surface. The head difference between bedrock relative and the river water surface varies seasonally. Bedrock heads were often one to four feet above the river surface, and in several wells farther down river, greater than 10 feet. Moving laterally from the river, groundwater potentials reverse and show downward gradients from shallow to deeper bedrock. These downward potentials increase in response to pumping stresses. The flows in the river are highly variable and can fluctuate from less than ten to several hundred cubic feet per second over the course of several days before and after a normal rain event.
Bedrock Structure and Fractured Flow Conditions

Borehole geophysical data pertaining to bedrock structure has been compiled and represented in three principal figures to show the relationship between fracture orientation and the hydraulics of groundwater flow under stressed borehole conditions. Figure 4 presents section though the lateral extent of the groundwater plume (along bedrock strike) along the section line A-A’ indicated in Figure 3. This figure shows the location of packer sample intervals that represent some of the water bearing fractures within the bedrock. Wells without packer samples are existing residential or former residential wells that could not be packer sampled, or had not been at the time this figure was created in 2000. This figure provides a view of some of the initial data that was used in the early stages of development of the site conceptual model.

Figure 5 presents an interpretation of the bedrock surface south of the EWM, and also the strike and dip of hydraulically active fractures in each borehole. This figure also shows bedding plane fractures and joint orientations in the outcrop along the northwest foundation of the EWM.

The key observations apparent from data presented in Figure 5 and 6 include:

- The dominant set of hydraulically active fractures is parallel to sedimentary bedding planes, which strike E-W and NE-SW, dipping to the south – southeast.
- A smaller subset of north to northwesterly trending fractures (joints) is also hydraulically active.
- These two sets of fractures dictate groundwater flow and transport patterns at the site.
- The orientation of the pumping test drawdown cone represented in Figure 5 as well as the orientation of the Sunshine Village pumping cone, are readily explained by these features.
Figure 6 presents a summary of the heat pulse flow meter data under ambient and stressed conditions for each borehole in conjunction with mapped fracture strike and dip tad-pole plots generated from the BIPS and ATV borehole geophysical data. The small circle in the tadpole plots identifies the fracture or fractures that is/are the dominant water transmitting feature of a given borehole. Key observations apparent from Figure 6 include:

- Bedding plane fractures dipping approximately 60 to 65 degrees to the southeast are the dominant hydraulically active fractures.
- The majority of the hydraulic activity (e.g., the depth of the most hydraulically active fractures under stressed conditions) in the aquifer is shallow; generally within the top 150 feet of the bedrock aquifer.
- The No. 1 production well at Sunshine Village is hydraulically transmissive or active throughout its entire depth to about 270 feet below ground surface.
- Under ambient conditions, flow within the boreholes is generally less than is measurable with the HPFM.

This data together with the pumping test data and groundwater contaminant distribution data confirm the major elements of the site conceptual model.

**Groundwater Pumping Test**

A constant-rate pumping test was completed by October 26, 1999 to estimate values for the hydraulic parameters (i.e., transmissivity, hydraulic conductivity and storativity) of the overburden and bedrock aquifers. Following a step test, the former shallow bedrock groundwater recovery well, R2, was pumped at a rate of approximately 4 gallons per minute (gpm) for a duration of 33.5 hours. Water levels were measured in twenty-four observation wells and one river stilling tube. Sixteen wells were equipped with pressure transducers connected to data loggers for automatic water level recording.
Overburden Response

Interpretation of the pumping test results indicates the overburden aquifer appears to contain distinct upper and lower water-bearing zones or units. Pumping the bedrock aquifer affects water levels in the lower zone of the overburden system, but not in the upper zone. The ESBR bisects the area of the test. One side of the bedrock-pumping cone of depression reached underneath the river, and was very symmetrical in dimension compared to the other side. The average transmissivity of the deeper overburden wells is 426.24 square feet per day (ft$^2$/day) with a storativity of 8.5 x 10^{-3} (dimensionless). The vertical hydraulic conductivity of the semi-confining layer within the overburden is estimated to be 5.8 x 10^{-4} ft/day (2 x 10^{-7} cm/sec) to 5.2 x 10^{-3} ft/day (1.8 x 10^{-6} cm/sec). As a potential recharge boundary, the river system had no apparent effect on the shape of the cone of depression that developed as the test progressed.

Bedrock Response

Three pairs of nested bedrock wells installed across the study area exhibited a downward vertical hydraulic gradient under “static” or ambient conditions, which includes pumping stresses from other local water supply wells. The downward gradient in BM-99-05 A/B increased with pumping stress even when water was pumped from a shallow fracture in R2. This suggests that contaminants at some depth within the bedrock aquifer will also migrate downward vertically, as well as downgradient (horizontally), as they migrate away from the source area under the influence of distant pumping stresses.

The drawdown cone surrounding the pumping well is not circular, as would be produced in a homogeneous isotropic aquifer. Instead, the drawdown cone is elliptical, due to anisotropy of the bedrock fracture pattern, which indicates a preferred groundwater flow direction resulting from pumping stresses (see Figures 5 and 6). The orientation of the major axis of the drawdown ellipse is North 43° East.

The angle of maximum transmissivity will be affected by of the frequency of intersection of bedding plane fractures and cross-cutting joints, and lateral variations in strike direction. The resulting average bearing of combined joints and bedding plane fractures is roughly North 50° East. The similarity between the orientation
of the drawdown ellipse and this “average direction” of fracture bearings indicates that groundwater, while under a hydraulic stress, moves preferentially along an interconnected network of these joints and bedding plane fractures.

The estimated transmissivity of the bedrock in the principal direction of anisotropy is 204.5 ft²/day, with a storativity of 0.001. Assuming an effective aquifer saturated thickness of 300 feet (e.g., thickness of aquifer with observed response to pumping), the transmissivity would equate to a bulk hydraulic conductivity of approximately 0.68 feet/day (2.4 x 10⁻⁴ cm/sec).

Continuous Water Level Recorder Data

Fifteen continuous water level recorders were installed in wells surrounding the EWM source area to evaluate longer term groundwater responses after removal of the Sunshine Village Wells pumping stress. Recorders were in place following January 18 to May 2. The devices employed included five Troll 4000 and ten Global water transducers. To the extent access to vertical well pairs was not prohibited by frozen groundwater in the shallow wells (B zone), the vertical well pairs were monitored to observe vertical gradient conditions with time. Well pairs BM-99-05 A and B and BM-99-03 A and B were monitored. Deep bedrock wells BM-99-6A and BM-19-14A were also monitored; however, BM-99-06B and BM-99-14 B were frozen at the time of transducer installation, indicating that vertical gradients were downward in the bedrock well pairs in mid-January 2000.

Plots of well pairs BM-99-05 A and B and BM-99-13 A and B confirm the presence of downward vertical gradients across the site. These data are consistent with observed conditions in wells BM-99-06 and BM-99-14. BM-99-05 A and B were installed in a 150-foot deep borehole. The B zone was screened from 65 to 75 feet bgs, and the A zone from 121 to 131 feet bgs. BM-99-13 A and B monitor a deeper pair of zones in the aquifer, including the B zone at 99 to 109 feet and the A zone at 179 to 189 feet bgs. The deep zone in BM-99-14 (A) was screened from 278 to 288 feet bgs, and is located only a short lateral distance from BM-99-05 A/B. Water levels in this interval were consistently a foot or lower than the shallower BM-99-05A zone, possibly indicating a continuation of vertical gradients to deeper elevations in the fractured bedrock aquifer.

General trends for almost all of the bedrock wells and deep overburden wells south of the EWM are similar. Comparison of BM-99-04 and OM-99-04 indicate both these wells are responding in like manner to the same conditions in the deep overburden and bedrock aquifer. The open boreholes, BM-99-04 BM-99-10, and BM-99-12, reflect the averaged response within deep and shallow portions of the aquifer. The periodic local pumping activities provide “signature stresses” that can be observed across the site, particularly within the shallow bedrock. The deep bedrock well pairs BM-99-6A and BM-99-14A do not show significant daily variation due to pumping stresses in the bedrock aquifer. Pumping stresses in BM-99-13 are likely associated with water withdrawal from the adjacent apartment buildings, particular Sunshine Village. Pumping stresses observed in BM-99-05, BM-99-10 and Lot 62 appear to originate in the eastern portion of the site, and probably reflect the same pumping stresses apparent in Figure 3. The amplitudes of these signature stresses decrease with increasing distance to the west.

Groundwater Modeling

Numerical groundwater flow and transport modeling was conducted using MODFLOW. The model domain encompasses the East Branch Sebecook River Watershed in the vicinity of Corinna. The model contains three overburden layers and three bedrock layers to a depth of 300 feet. The model used the most compressive synoptic water levels as calibration targets as well as the simulation of bedrock groundwater pumping test. The model includes all known private water supply wells. One of the objectives of the model was to evaluate the long-term affects on the plume source posed by lateral pumping stresses. In modeling the bedrock a low porosity (1%) was assumed combined with the high degree of anisotropy, which was varied in simulations from 3:1 up to 10:1. The ranges in anisotropy are consistent with measured and expected values from field data.

Transient and steady state runs were completed and potential contaminant migration pathways were evaluated through forward and backward particle tracking as well as by transport simulations using MT3D. The most sensitive variables to cross gradient transport included: magnitude of pumping stresses, recharge (drought conditions persisted from 1999-2002) and aquifer anisotropy. Within reasonable ranges of these variables
modeling indicated that deep groundwater flow paths from the EWM source area, under the river, to the Sunshine Village supply wells would account for the lateral extent of contamination to the south west.

*Groundwater Contaminant Plume*

Figure 7 shows the magnitude and extent of the Bedrock VOC plume at the Site. The plume elongation agrees with the primary water bearing fracture orientation and anisotropy determined from geologic mapping, borehole geophysics and the groundwater pumping test. The effects of the historical pumping of several residential wells on contaminant migration are also apparent. The plume to the southwest was pulled by the Sunshine Village water supply well. A lobe of the plume has also been pulled to the east by small apartment building, but the contamination has not reached the pumping well which is located 100 feet east of the building. In the central portion of the site, the outline of a source area soil excavation is shown. The northwestern portion of that excavation cut into the weathered bedrock, which is contaminated. The eastern portion of the excavation could not be extended to the same depth and soils contaminated with DNAPL remain. Estimates of residual DNAPL saturation at the bottom of the excavation are shown in the source area.

High concentrations of chlorinated benzene compounds are present at depth beneath the EWM source area and indicate the potential presence of DNAPL in deeper regions of the bedrock. Groundwater gradients are upward from deep to shallow bedrock. DNAPL has been observed along the till–bedrock contact, and some bedrock fractures and adjoining rock matrix immediately below, in the upper weathered bedrock, are also strongly contaminated. The DNAPL mixture is enriched in 1,2,4 – trichlorobenzene (124 TCB), which is only moderately soluble compared to the other chlorinated benzene compounds present. Laterally, 124 TCB has not migrated far from the source area compared to chlorobenzene or 1,2 and 1,4-dichlorobenzene. The distribution of 124 TCB may be better indicator of the actual vertical penetration of DNAPL into the underlying bedrock. Chlorinated benzene compounds are present under the source area down to depths of at least 300 feet. The degree to which vertical aqueous transport of the more soluble chlorinated benzene compounds has been caused by past groundwater pumping stresses, is not clear, and therefore the vertical extent of these compounds may not necessarily be directly related to DNAPL penetration. These questions are currently being investigated.
Summary

The evolution of the EWM fractured bedrock site conceptual model has been important in decision-making from the early stages of the remedial investigation through the planning and implementation of groundwater remedial activities. Initial Site Investigation (SI) activities, including potentiometric surface mapping and groundwater sampling from existing residential wells, indicated localized bedrock groundwater contamination down gradient and cross gradient of the EWM. Several potential secondary source areas were also identified, in addition to the primary source areas beneath the EWM. The initial conceptual model developed after the SI suggested that a deep and discretely fractured system was controlling plume migration, which was expected to discharge along the river. A remedial investigation that included photo-lineament analysis, bedrock mapping, monitoring wells, borehole geophysical logging (optical, acoustic tele-viewer, and heat-pulse flow meter), low-flow straddle packer and multi-level groundwater sampling, pumping test analysis, and potentiometric surface mapping was undertaken to better define contaminant distribution, fate and transport.

Key observations made from the borehole geophysical data set show the dominant set of hydraulically active fractures were sedimentary bedding planes, which strike from E-W to NE-SW and dip 60-65 degrees to the south and southeast. The bedding plane fractures are only weakly cross connected by a smaller set of axial plane fractures and north to northwesterly trending joints, accounting for the high degree of anisotropy noted in a groundwater pumping test and plume alignment. The resulting average strike of combined joints and bedding plane fractures is roughly North 50° East. A pumping test conducted near the source area indicated a drawdown ellipse axis of North 43° East. The majority of the hydraulically active fractures (i.e., fractures with measurable flow under stressed conditions) in the aquifer are shallow relative to the depth of documented contamination. Hydraulically active fractures are generally within the top 130 feet of the bedrock aquifer, yet documented contamination extends nearly 300 feet deep under the former mill. A few hydraulically active fractures have been identified within the aquifer at depths down to 250 feet below the bedrock surface. Investigations were concluded to 600 feet at one location.

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Biographical Sketches

Mr. Scott Acone, P.E. is a Project Manager. He has been with the U.S. Army Corps of Engineers for 16 years and is responsible for executing investigations and cleanups at several Superfund Sites throughout New England. He earned as BS in Civil Engineering from the University of Lowell (1988) and is pursing a MS at Northeastern University in Environmental Engineering.

Mr. Scott Acone
U.S. Army Corps of Engineers – New England District
696 Virginia Road
Concord, MA 01774-2751
978-318-8162
Scott.E.Acone@usace.army.mil
Mr. Peter Baker, C.G. is a Principal Geologist/Project Manager with MACTEC Engineering and Consulting Inc. in Portland, Maine and holds a BA degree in Geology from the University of Maine (1982). He is a Maine Certified Geologist and has 22 years of experience conducting hydrogeologic and environmental investigations and designs.

Mr. Peter Baker, Principal Project Manager
MACTEC Engineering and Consulting
511 Congress Street, Portland, ME 04112-7050
Direct 207-828-3692
psbaker@mactec.com

Mr. Calkin is a Senior Geophysicist with MACTEC Engineering and Consulting in Portland, Maine and holds a BA (Interdisciplinary) from the University of Maine – Farmington (1987) and a MS in Geology from Northern Illinois University (1989). He has 14 years experience conducting environmental engineering investigations for government and private clients.

Mr. Scott F. Calkin, Senior Geophysicist
MACTEC Engineering and Consulting
511 Congress Street, Portland, ME 04112-7050
Direct 207-828-3545
sfcalkin@mactec.com

Mr. Edward Hathaway is a Remedial Project Manager with U.S. Environmental Protection Agency and has been with EPA for the past 15 years. He has degrees in Environmental Science and Business Management.

Mr. Ed Hathaway
EPA Region 1 – Office of Site Remediation and Restoration
1 Congress St., Suite 1100 (HBS)
Boston, MA. 02114-2023
Hathaway.Ed@epa.gov

Mr. Peter Thompson is a Senior Hydrogeologist with MACTEC, and earned a BA in Geology from Wesleyan University (1980) and a MS in Water Resource Engineering from University of New Hampshire (1989). He spent 6 years as a mineral exploration geologist and 14 years investigating hazardous waste sites in New England.

Mr. Peter Thompson,
MACTEC Engineering and Consulting, Inc.
511 Congress Street, Portland, ME 04112-7050
Direct 207-828-3490
phthompson@mactec.com