

Massachusetts Department of
Environmental Protection

FINAL REPORT

Evaluation of Perchlorate
Contamination at a Fireworks Display
Dartmouth, Massachusetts

August 2007

Massachusetts Department of Environmental Protection
1 Winter Street
Boston, MA 02108
<http://www.mass.gov/dep/>

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Executive Summary

The Massachusetts Department of Environmental Protection (MassDEP) conducted a study at the University of Massachusetts Dartmouth (UMD) campus to evaluate the potential release of perchlorate to the environment as a result of a typical “community-type” fireworks display. This site was selected because of an 11-year history of fireworks displays at this location, the presumed lack of other sources of perchlorate-releasing materials and activities, and because of the excellent cooperation and assistance of campus officials.

Eight shallow groundwater-monitoring wells were installed proximate to and immediately downgradient of the fireworks display area. A series of groundwater samples were obtained before and after a launch event in September 2004, together with a limited number of surficial soil samples. Data from these efforts were used to further evaluate site conditions via the use of the coupled fate and transport computer models SESOIL/AT123D.

A maximum concentration of 560 micrograms per kilogram ($\mu\text{g}/\text{kg}$, which is approximately equal to parts per billion or ppb) perchlorate was found to exist in surficial soil in the fireworks launch area in the hours that followed the September 2004 display. Ten groundwater-monitoring sampling events have been conducted from June 2004 through July 2006 using eight shallow wells. The concentrations of perchlorate in the groundwater were found to range from not detected (ND) to a high of 62.2 micrograms per liter ($\mu\text{g}/\text{L}$, which is approximately equal to parts per billion or ppb), with the highest values measured before the September 2004 display.

Based on field investigations conducted since 2004, it appears that 11 years of fireworks displays have resulted in perchlorate contamination in soil and groundwater at the Perchlorate Study Area. These conclusions are consistent with fate and transport modeling results for this area.

A collection of MassDEP information on perchlorate, including a report summarizing the occurrence and sources of perchlorate found to date in Massachusetts, is available at <http://www.mass.gov/dep/water/drinking/percinfo.htm>.

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1.0. Introduction

The Massachusetts Department of Environmental Protection (MassDEP) conducted a study at the University of Massachusetts Dartmouth (UMD) campus to evaluate the impacts of perchlorate on soil and groundwater from the use of fireworks. The site locus map is shown in Figure 1. Fireworks displays have been performed at the UMD campus at least once a year since 1995 (with the exception of 2003). The fireworks have been launched from an area located at the southwestern corner of the UMD campus. The Fireworks Launch Area and Perchlorate Study Area are shown on Figure 2.

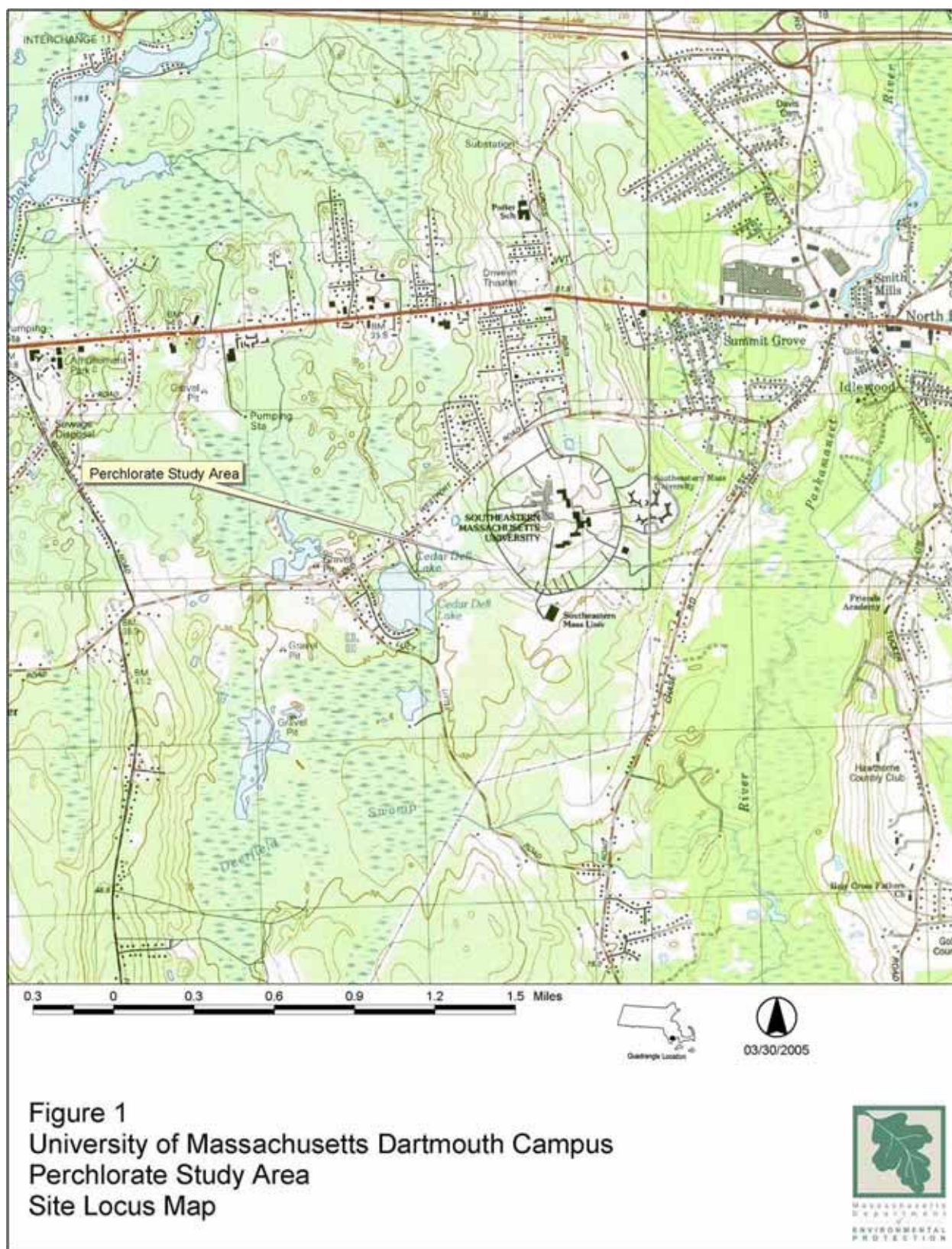
2.0. Background

While the formulations of fireworks vary, most fireworks are believed to contain potassium perchlorate, an inorganic salt that is a strong oxidizer. The manufacturers of fireworks use potassium perchlorate in the compositions that produce colored smokes and bursts. The use of fireworks at UMD may have resulted in the release of perchlorate into the environment from atmospheric deposition and from the washing off of paper debris left behind. Perchlorate is highly soluble, mobile in groundwater and surface water, and persistent in the environment.

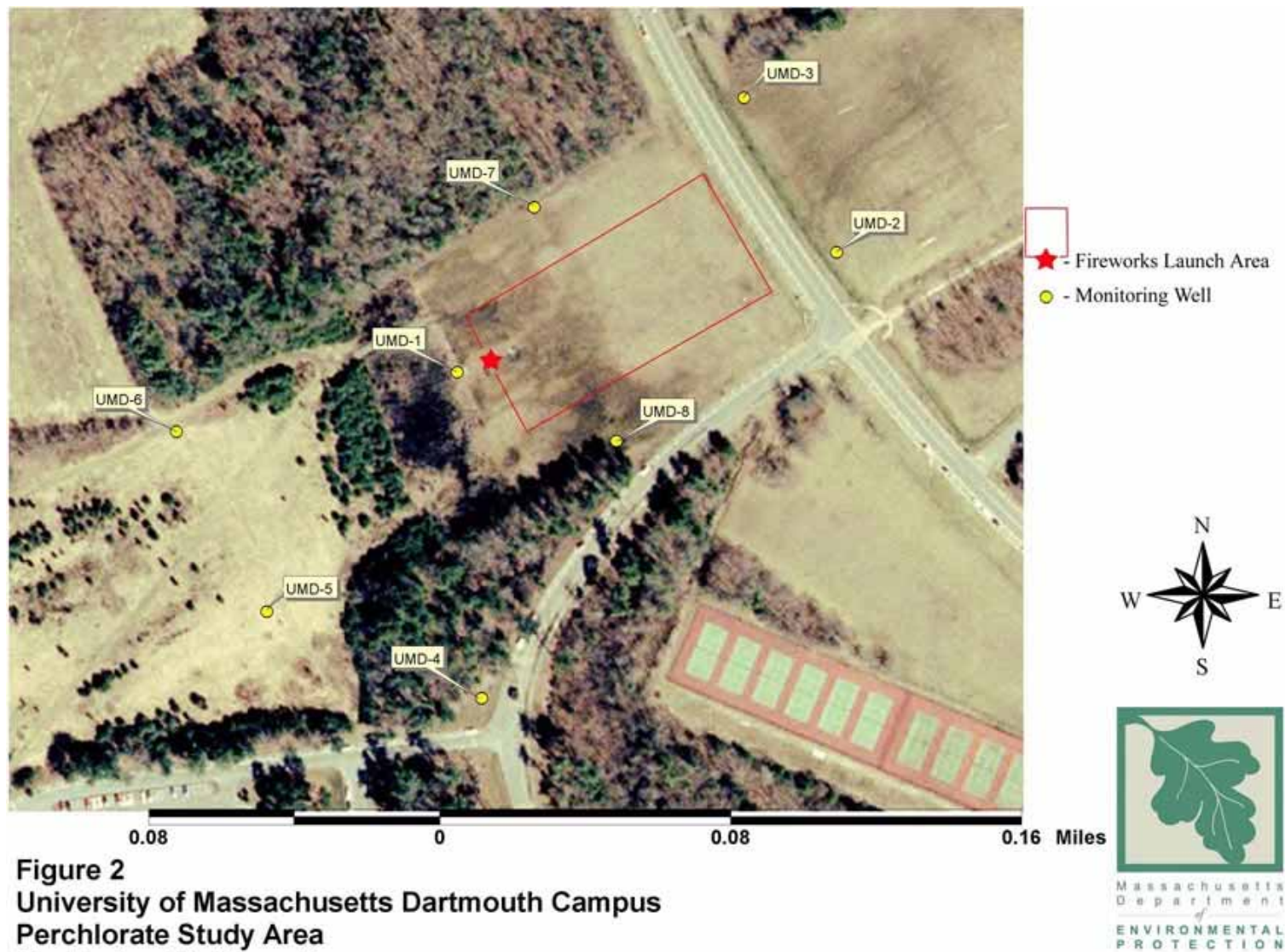
Perchlorate can affect the function of the thyroid gland, which regulates the body's metabolism. Pregnant women, infants, children up to the age of 12, and individuals with hypothyroidism are most susceptible. MassDEP has evaluated the possible toxicity of perchlorate (see <http://www.mass.gov/dep/water/drinking/percinfo.htm>) and established perchlorate cleanup standards to ensure that public health is protected and to facilitate the assessment and cleanup of perchlorate sources. In July 2006, MassDEP promulgated a Maximum Contaminant Level (MCL) of 2 µg/L for perchlorate. This standard considers the potential risk to humans through ingestion. At this level, perchlorate is not believed to be a risk to humans from dermal contact or a risk to the environment.

Since 2003, MassDEP has been investigating the occurrence of perchlorate in public water supplies (PWSs) in Massachusetts. Perchlorate has been confirmed at levels above 2.0 µg/L in nine PWS systems across the state (see <http://www.mass.gov/dep/water/drinking/perctest.pdf>). In response to exceedances of perchlorate in water supply wells in Massachusetts, MassDEP has investigated surrounding sites and activities that may have caused or contributed to the contamination. Fireworks displays have been identified as a likely source of drinking water contamination for at least three of the nine PWS locations. As a result, MassDEP conducted an independent investigation at the UMD campus to further evaluate the nature and extent of groundwater impacts by perchlorate associated with routine fireworks displays.

Since 1995, thirteen fireworks events have occurred at the UMD campus. Table 1 provides a chronological list of fireworks events at the campus and the prevailing wind direction during those events. The prevailing wind directions are based on measurements recorded at the New Bedford Regional Airport, located approximately 4 miles northeast of the UMD campus. All events have used the same general launch area as shown on Figure 2.



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Table 1
University of Massachusetts Dartmouth Campus
Perchlorate Study Area
List of Fireworks Events and Prevailing Wind Directions

Event Date	Prevailing Wind Direction*
July 1, 1995	Data Not Available
July 5, 1996	North-Northeast
June 7, 1997	Southwest
July 3, 1997	North
July 3, 1998	North-Northwest
June 5, 1999	North
September 9, 1999	North-Northeast
July 2, 2000	Northeast
July 1, 2001	North-Northeast
July 3, 2002	Northeast
September 6, 2004	Calm
September 6, 2005**	Northwest
July 3, 2006**	North-Northeast

* Average hourly (8 p.m.) wind direction obtained from the Northeast Regional Climate Center, Ithaca, New York, from observations at the New Bedford, Massachusetts Regional Airport.

**Fireworks event occurred subsequent to MassDEP's initial perchlorate study at the UMD Campus.

3.0 Goals of the Study

Soil and groundwater sampling were conducted at the Perchlorate Study Area to better understand the magnitude of impacts to the environment from fireworks displays. Soil and groundwater samples were initially collected before the September 2004 fireworks display to

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assess pre-launch/event conditions in and near the Study Area. Additional soil and groundwater samples were collected shortly after the 2004 fireworks event to assess the immediate impact of perchlorate on soil and groundwater. A series of groundwater monitoring events have occurred since September 2004 to evaluate the effects of precipitation washing perchlorate further into the subsurface, and to assess long-term impacts of perchlorate on soil and groundwater.

4.0 Summary of Field Investigations

4.1. Summary of Groundwater Investigations

4.1.1 Monitoring Well Installation

Eight water table monitoring wells were installed at the Perchlorate Study Area in June and August 2004 (see Figure 2 for monitoring well locations). On June 24 and 25, 2004, four 1.05-inch diameter-monitoring wells (UMD-1 through UMD-4) were installed by a MassDEP contractor (Pine and Swallow Associates) using a “direct push” method. Well UMD-1 was installed at the westerly (downgradient) end of the launch area; wells UMD-2 and UMD-3 were installed just upgradient of the launch area and directly across Ring Road, and well UMD-4 was installed approximately 490 feet south of the launch area. The average depth to groundwater at these wells was approximately 5 feet below ground surface (bgs) and the total depth of the wells was less than 20 feet bgs. Due to the presence of large cobbles, small boulders, and gravelly till in the subsurface, it was not practical to install additional wells using the direct push method.

Accordingly, four 2-inch diameter monitoring wells (UMD-5 through UMD-8) were subsequently installed by another MassDEP contractor (Environmental Strategies and Management) on August 27, 2004, using a hollow stem auger method, which is more suitable for the subsurface conditions present at UMD. The purpose of these new wells was to better understand the direction of groundwater flow in the Perchlorate Study Area and the extent of perchlorate present in the groundwater. Wells UMD-5 and UMD-6 were installed downgradient of the launch area. These wells are located approximately 480 feet southwest and 440 feet west-southwest of the launch area, respectively. Wells UMD-7 and UMD-8 were installed approximately 240 feet to the west and 230 feet to the east of the launch area, respectively. The average depth to groundwater at these wells was approximately 4 feet bgs and the total depth of the wells was less than 14 feet bgs. It was not feasible to install deeper wells at the Perchlorate Study Area using either the direct push method or the hollow stem auger method due to the dense and gravelly till material encountered during drilling. The boring logs for wells UMD-5 through UMD-8 are provided in Appendix A.

The locations of monitoring wells UMD-1 through UMD-8 were approved by UMD personnel prior to installation. All wells were finished at or slightly below grade, minimizing disruption to the campus. These wells were installed before the annual 2004 fireworks display, which was conducted on the evening of September 6, 2004.

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4.1.2 Groundwater Monitoring

Groundwater sampling was conducted at the Perchlorate Study Area by Pine & Swallow (P&S) on June 24 and 25, 2004 and by Environmental Strategies and Management (ES&M) on August 30, 2004 to assess current groundwater conditions at the Study Area, before the 2004 fireworks display. Groundwater samples were collected by ES&M on September 13, 2004, shortly after the fireworks display, to assess the impact of the 2004 display. Groundwater samples were subsequently collected by ES&M on October 15, 2004, December 6, 2004, February 24, 2005, March 23, 2005, June 24, 2005, September 16, 2005, April 4, 2006, and July 25, 2006 to further evaluate groundwater conditions at the Perchlorate Study Area. Table 2 provides the depth to groundwater and total well depths for wells UMD-1 through UMD-8 measured at each of the sampling events conducted to date at the UMD campus.

Groundwater sampling was also conducted on March 23, 2005 at two monitoring wells (MW-1 and MW-23) located approximately ½ mile east-northeast of the Study Area, at the UMD campus power plant (See Figure 12). A release of petroleum was discovered in February 2003 at this location during removal of an underground storage tank. This site (MassDEP RTN 4-15272) is currently in Phase V of the Massachusetts Contingency Plan. A passive recovery system is currently operating to remove light non-aqueous phase liquid (LNAPL). Several monitoring wells have also been installed in this area. The groundwater from monitoring wells MW-1 and MW-23 was sampled and analyzed for perchlorate in March 2005 to assess the lateral extent of perchlorate contamination at the UMD campus. The sampling was conducted by ES&M.

All groundwater samples collected from the UMD campus were analyzed by a MassDEP contract laboratory (Alpha Analytical of Westborough, MA) for perchlorate analyses using Modified EPA Method 314.0 at a reporting limit of 1 µg/l.

4.1.3 Aquifer Slug Testing

The purpose of the aquifer slug tests was to estimate the hydraulic conductivity of the shallow overburden aquifer beneath the site. Hydraulic conductivity is a measure of the rate at which water can move through a permeable medium. Aquifer slug tests were performed by ES&M on November 23, 2004 at monitoring wells UMD-5, UMD-6, and UMD-7, which are located downgradient of the Perchlorate Study Area. Slug testing was not conducted at wells UMD-1, UMD-2, UMD-3 and UMD-4. Slug testing was attempted at well UMD-8; however, because the water table elevation at this well was at ground surface the test could not be conducted. Supplemental slug testing was performed by ES&M at wells UMD-5 and UMD-6 on December 14, 2004.

The testing was conducted by inserting a PVC cylinder (slug) into each well and allowing the water level in the well to return to static conditions. The slug was then rapidly removed and the resulting change in water level was measured by a submersible pressure transducer and recorded with an in-situ data logger at predetermined time intervals. After testing was complete, water level data stored in the data logger was downloaded to a personal computer for analysis. The slug test data were analyzed using methods derived for unconfined aquifers.

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4.2 Soil Sampling

Soil sampling was conducted on June 28, 2004 and September 7, 2004 at the Perchlorate Study Area to characterize perchlorate concentrations in surficial soil. Soil sampling was conducted before and shortly after UMD's 2004 fireworks display to assess the impacts of the fireworks display to soil in the Study Area. All discrete soil samples were collected by MassDEP personnel and shipped to Alpha Analytical of Westborough, MA. Under the direction of MassDEP personnel, Alpha Analytical personnel prepared composite samples. Alpha Analytical conducted the perchlorate soil analysis on selected composite and discrete soil samples using Method 314.0-modified Dionex method.

Table 2
University of Massachusetts Dartmouth Campus
Perchlorate Study Area
Depth to Groundwater and Bottom of Well

Well ID	Date	Depth to Water (ft)	Depth to Bottom (ft)
UMD-1	6/24/2004	4.3	15.6
UMD-1	8/30/2004	4.07	15.60
UMD-1	9/13/2004	4.22	15.60
UMD-1	10/15/2004	3.01	15.60
UMD-1	12/6/2004	1.42	15.60
UMD-1	2/24/2005	1.17	15.58
UMD-1	6/24/2005	2.94	15.6
UMD-1	9/16/2005	3.27	15.58
UMD-1	4/4/2006	1.84	15.58
UMD-1	7/25/2006	3.75	15.58
UMD-2	6/24/2004	10.95	19.40
UMD-2	8/30/2004	6.98	19.41
UMD-2	9/13/2004	7.15	19.45
UMD-2	10/15/2004	5.30	19.41
UMD-2	12/6/2004	3.24	19.42
UMD-2	2/24/2005	NM	NM
UMD-2	6/24/2005	5.6	19.4
UMD-2	9/16/2005	7.24	19.4
UMD-2	4/4/2006	4.92	19.4
UMD-2	7/25/2006	4.65	19.40
UMD-3	6/24/2004	8.75	18.90
UMD-3	8/30/2004	6.45	18.90
UMD-3	9/13/2004	6.80	18.98
UMD-3	10/15/2004	4.46	18.92
UMD-3	12/6/2004	1.60	18.90
UMD-3	2/24/2005	0.81	18.90
UMD-3	6/24/2005	4.14	18.9
UMD-3	9/16/2005	6.89	18.86
UMD-3	4/4/2006	3.1	18.86
UMD-3	7/25/2006	3.25	18.86
UMD-4	6/25/2004	4.80	14.54
UMD-4	8/30/2004	5.14	14.58
UMD-4	9/13/2004	5.04	14.60
UMD-4	10/15/2004	4.18	14.50
UMD-4	12/6/2004	2.81	14.45
UMD-4	2/24/2005	2.80	14.43

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Table 2, continued
University of Massachusetts Dartmouth Campus
Perchlorate Study Area
Depth to Groundwater and Bottom of Well

Well ID	Date	Depth to Water (ft)	Depth to Bottom (ft)
UMD-4	6/24/2005	4.39	14.43
UMD-4	9/16/2005	4.79	14.4
UMD-4	4/4/2006	3.87	14.4
UMD-4	7/25/2006	4.45	14.40
UMD-5	8/30/2004	6.32	13.73
UMD-5	9/13/2004	5.27	13.45
UMD-5	10/15/2004	5.61	13.45
UMD-5	11/23/2004	5.20	13.43
UMD-5	12/6/2004	4.39	13.45
UMD-5	12/14/2004	3.99	13.44
UMD-5	2/24/2005	4.57	13.44
UMD-5	6/24/2005	5.94	13.33
UMD-5	9/16/2005	5.84	13.4
UMD-5	4/4/2006	5.78	13.4
UMD-5	7/25/2006	6.00	13.40
UMD-6	8/30/2004	7.50	13.80
UMD-6	9/13/2004	7.31	13.80
UMD-6	10/15/2004	6.05	13.65
UMD-6	11/23/2004	5.62	13.68
UMD-6	12/6/2004	5.12	13.65
UMD-6	12/14/2004	4.86	13.67
UMD-6	2/24/2005	5.20	13.65
UMD-6	6/24/2005	6.15	13.62
UMD-6	9/16/2005	5.89	13.65
UMD-6	4/4/2006	6.2	13.65
UMD-6	7/25/2006	6.27	13.65
UMD-7	8/30/2004	6.80	11.09
UMD-7	9/13/2004	5.98	11.25
UMD-7	10/15/2004	4.12	11.10
UMD-7	11/23/2004	1.92	11.10
UMD-7	12/6/2004	1.24	11.10
UMD-7	2/24/2005	0.97	11.10
UMD-7	6/24/2005	4.24	11.1
UMD-7	9/16/2005	5.92	11.1
UMD-7	4/4/2006	2.92	11.1
UMD-7	7/25/2006	3.9	11.10
UMD-8	8/30/2004	2.41	11.40
UMD-8	9/13/2004	2.00	12.30
UMD-8	10/15/2004	0.30	12.21
UMD-8	12/6/2004	0.00	11.10
UMD-8	2/24/2005	0.00	12.25
UMD-8	6/24/2005	.9	12.22
UMD-8	9/19/2005	2.5	12.34
UMD-8	4/4/2006	0	12.34
UMD-8	7/25/2006	<1	12.34

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5.0 Results

5.1 Groundwater

5.1.1 Geology and Hydrogeology

Soil encountered during monitoring well installation ranged from fine, silty sand to medium sand. Large cobbles, small boulders, and gravel were encountered throughout the subsurface at various depths across the site. According to a previous subsurface investigation conducted at the UMD campus, the soil is mapped as “*compact unsorted silty bouldery gravel till (HA-560, 1978) and appears to include weathered gneiss (alternating layers of granular material and foliated material (schist)).*” (Vanasse Hangen Brustlin, Inc., Watertown, MA Phase II Comprehensive Site Assessment, July 2002).

Bedrock outcrops were not observed, nor was bedrock specifically investigated as part of this investigation. During the previous investigation activities referenced above, however, bedrock was encountered at approximately 20 to 30 feet bgs.

Groundwater elevation contours for elevation measurements collected from wells UMD-1 through UMD-8 for the June 2004 and August 2004 sampling events are provided on Figure 3. Based on these elevations, the groundwater flow direction is primarily from the north/northeast to the south/southwest.

5.1.2 Slug Tests

The results of the slug tests for wells UMD-5, UMD-6, and UMD-7 are presented in Table 3. The results of the slug tests indicated a hydraulic conductivity of 5.18, 10.8, and 33.3 gallons/day/feet² (0.69, 1.44, and 4.45 ft/day, respectively) for the aquifer material at wells UMD-7, UMD-6, and UMD-5, respectively. The recharge rates recorded at wells UMD-5 and UMD-6 were very fast during the November and December 2004 tests. The fast recharge rates resulted in relatively few data points, which made curve matching and hydraulic conductivity estimation difficult for the aquifer material in the vicinity of these wells. Therefore, the results for wells UMD-5 and UMD-6 should be viewed as rough estimates only. Overall, the results of the slug testing at wells UMD-5, UMD-6, and UMD-7 are comparable with values reported in literature for silty sands.

5.1.3 June 2004 Sampling Results

On June 24 and 25, 2004, groundwater samples were collected from wells UMD-1, UMD-2, UMD-3, and UMD-4. The results of the June 2004 sampling event are presented in Table 4 and Figure 4. The results indicate that perchlorate concentrations in the groundwater range from non-detect at cross-gradient well UMD-4, to 36.2 µg/L at upgradient well UMD-2. The groundwater from well UMD-1, which is located at the downgradient edge of the launch area, and upgradient well UMD-3, contained perchlorate concentrations of 5.14 µg/L and 7.10 µg/L, respectively.

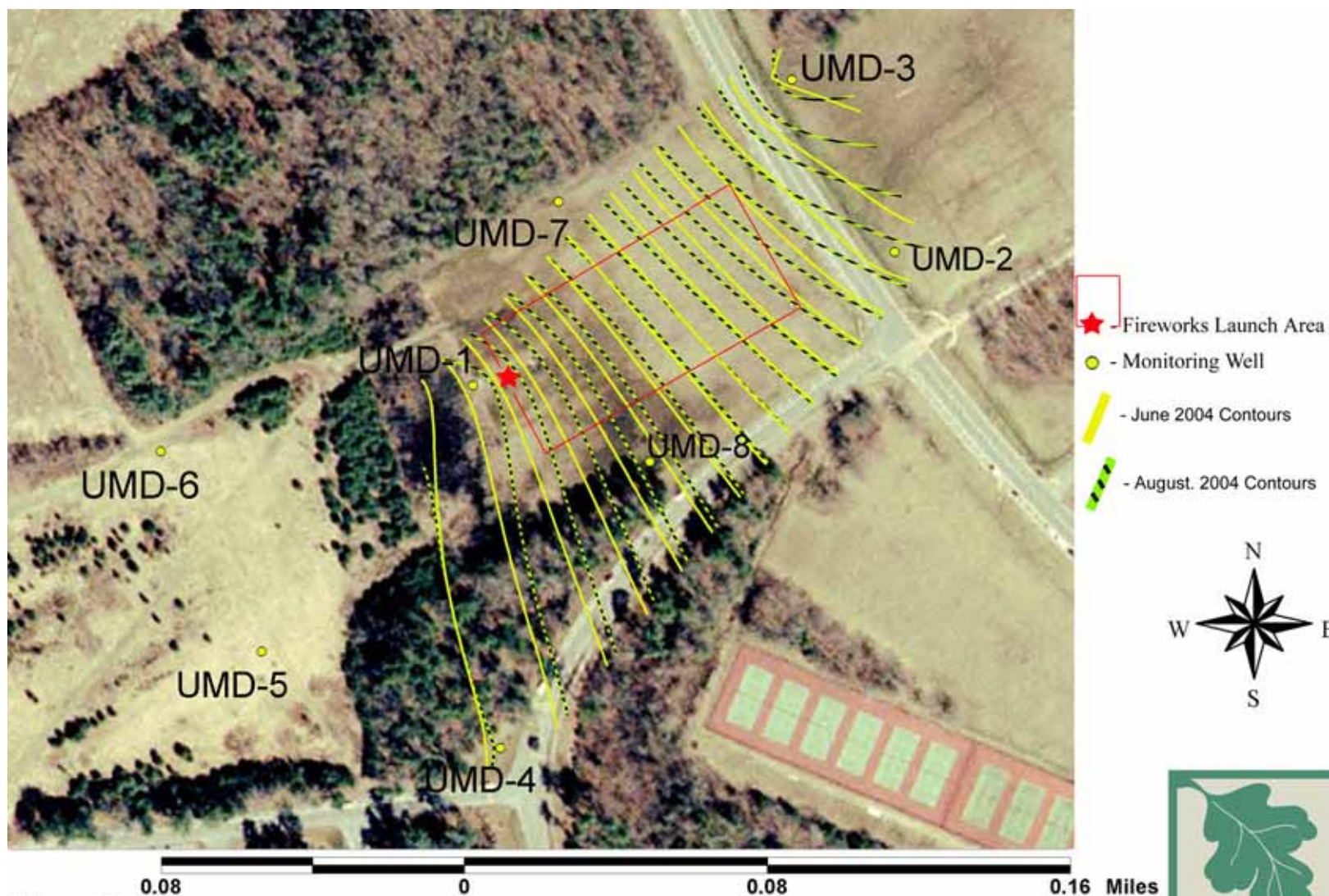


Figure 3
University of Massachusetts Dartmouth Campus
Perchlorate Study Area
June and August 2004 Groundwater Elevation Contours

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Table 3
University of Massachusetts Dartmouth Campus
Perchlorate Study Area
December 2004 Slug Test Results

Well	Hydraulic Conductivity (gallons/day/ft ²)
UMD-5	33.3
UMD-6	10.8
UMD-7	5.18

5.1.4 August 2004 Sampling Results

Groundwater samples were collected on August 30, 2004 from wells UMD-1 through UMD-8. The results of sampling ranged from non-detect at wells UMD-4, UMD-5, and UMD-6 to 62.2 µg/L at well UMD-7. The perchlorate concentrations detected in the groundwater samples collected from wells UMD-1 (2.39 µg/L), UMD-2 (28.5 µg/L), and UMD-3 (5.37 µg/L) were lower than the concentrations detected in the June 2004 sampling event. The perchlorate concentration detected in the groundwater at well UMD-8 was 37.4 µg/L. Wells UMD-2, UMD-3, UMD-7, and UMD-8 are located in the vicinity of the launch area in the prevailing wind direction recorded during several of the past fireworks displays. The results of the August 2004 sampling event are presented in Table 4 and Figure 4.

5.1.5 September 2004 Sampling Results

Monitoring wells UMD-1 through UMD-8 were sampled on September 13, 2004, one week after the fireworks display, which occurred on September 6, 2004. Sampling was conducted immediately following a rain event to allow for potential leaching of perchlorate from the vadose zone into groundwater. The results ranged from non-detect in the groundwater from wells UMD-4, UMD-5, and UMD-6 to 40.1 µg/L at well UMD-7. The perchlorate concentration decreased in the groundwater sampled from well UMD-8 (20.7 µg/L). The concentrations of perchlorate increased at wells UMD-1 (3.38 µg/L), UMD-2 (34.1 µg/L), and UMD-3 (7.96 µg/L). The results of the September 2004 sampling event are presented in Table 4 and Figure 4.

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Table 4
University of Massachusetts Dartmouth Campus
Perchlorate Study Area
Summary of Ground Monitoring Results

Well Location	Distance From Launch Area (feet)**	Sampling Event Perchlorate Concentration (µg/L)									
		Jun-04	Aug-04	Sep-04	Oct-04	Dec-04	Feb-05	Jun-05	Sep-05	Apr-06	Jul-06
UMD-1	40	5.14	2.39	3.38	1.67	<1	<1	<1	<1	<1	<1
UMD-2	550	36.2	28.5	34.1	32.8	13.4	9.42*	1.58	1.4	1.74	2.25
UMD-3	540	7.1	5.37	7.96	7.5	0.915J	1.98	.361J	1.58	<1	<1
UMD-4	490	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
UMD-5	480	NA	<1	<1	<1	0.644J	0.265J	<1	<1	.897J	5.16
UMD-6	440	NA	<1	<1	2.71	2.09	1.98	.962J	10.4	1.87	2.73
UMD-7	240	NA	62.2	40.1	31.2	20.5	24.8	24.7	20.2	14.6	12.4
UMD-8	230	NA	37.4	20.7	37.4	25.8	23	27.9	35	30	22.4

NA- Not Analyzed

J-Estimated Value

*Sampled on March 23, 2005

**Approximate distance measured from the center of the downgradient edge of the Fireworks Launch Area

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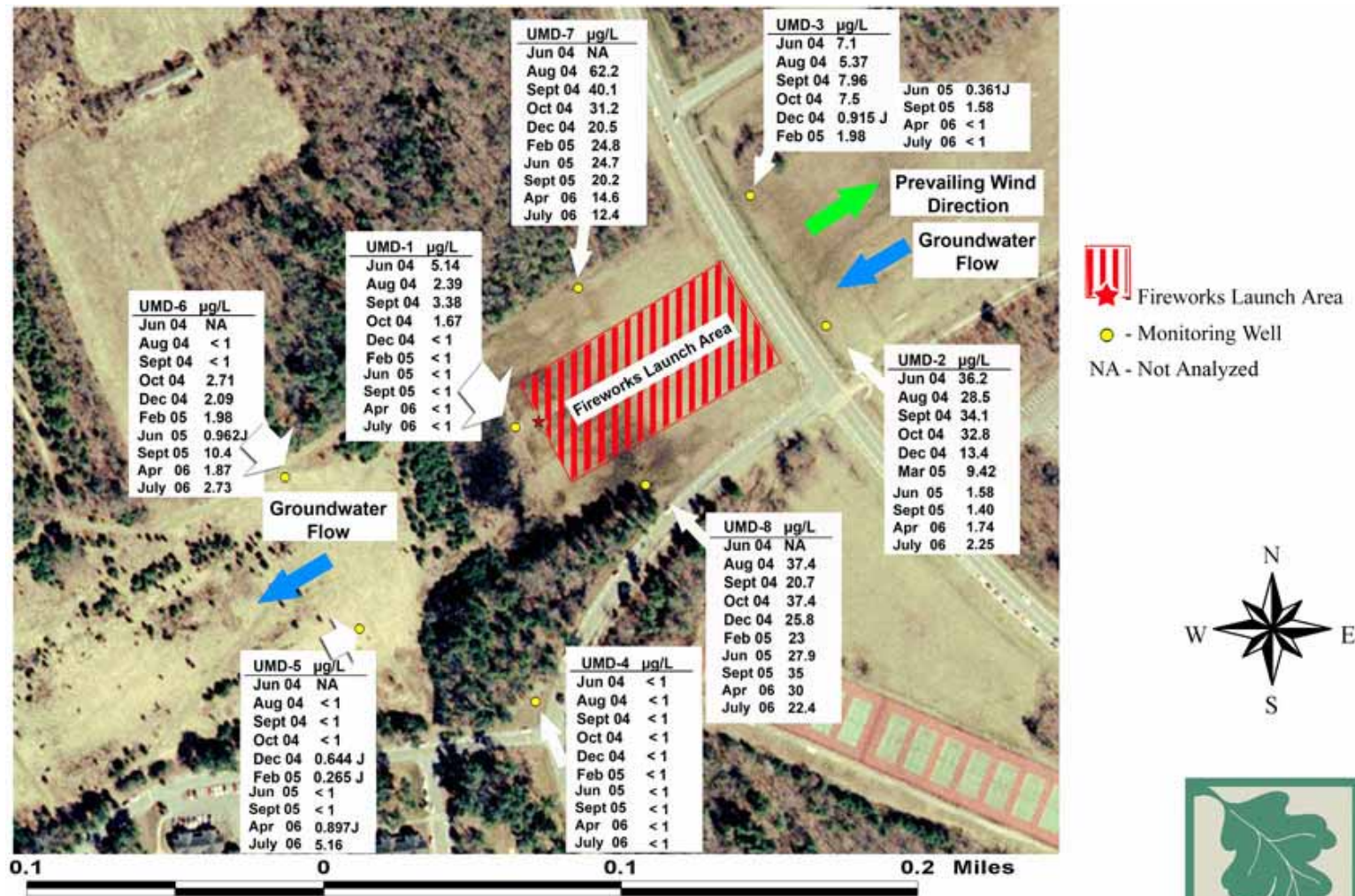


Figure 4
 University of Massachusetts Dartmouth Campus
 Perchlorate Study Area
 Groundwater Sampling Results

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5.1.6 October 2004 Sampling Results

Groundwater sampling occurred on October 15, 2004 at wells UMD-1 through UMD-8. The results of the October event ranged from non-detect for the groundwater samples collected from wells UMD-4 and UMD-5 to 37.4 µg/L at well UMD-8. The groundwater from wells UMD-2 and UMD-7 contained 32.8 µg/L and 31.2 µg/L of perchlorate, respectively. The groundwater sample from well UMD-1 contained 1.67 µg/L of perchlorate. The groundwater sample collected from the downgradient well UMD-6 contained 2.71 µg/L of perchlorate. The sample from this well did not contain detectable concentrations of perchlorate during the previous two sampling rounds. The results of the October 2004 sampling event are presented in Table 4 and Figure 4.

5.1.7 December 2004 Sampling Results

Groundwater sampling occurred at wells UMD-1 through UMD-8 on December 6, 2004. The results of the December 2004 event ranged from non-detect at wells UMD-1 and UMD-4 to 25.8 µg/L at well UMD-8. Well UMD-7 contained 20.5 µg/L of perchlorate. Downgradient wells UMD-6 and UMD-5 contained 2.09 µg/L and 0.644J µg/L of perchlorate, respectively (the J value indicates that this is an estimated value below the quantification limit). Perchlorate was not detected in well UMD-5 during the previous three rounds of monitoring. The groundwater from wells UMD-2 and UMD-3 contained 13.4 µg/L and 0.915J µg/L of perchlorate, respectively. The results of the December 2004 sampling event are presented in Table 4 and Figure 4.

5.1.8 February 2005 Sampling Results

Groundwater sampling occurred at wells UMD-1 through UMD-8 on February 24, 2005. The groundwater analytical results of the February 2005 event ranged from non-detect for the samples collected from wells UMD-1 and UMD-4 to 24.8 µg/L at well UMD-7. The groundwater from well UMD-8 contained 23 µg/L of perchlorate. The groundwater from the downgradient wells UMD-6 and UMD-5 contained 1.98 µg/L and 0.265J µg/L of perchlorate, respectively. The samples collected from the upgradient well UMD-3 contained 1.98 µg/L of perchlorate. UMD-2 was not sampled on February 24, 2005 because it was not possible to locate this well under the snow. The groundwater from this well was resampled on March 23, 2005. The results of the February sampling event are presented in Table 4 and on Figure 4.

5.1.9 March 2005 Sampling Results

Groundwater sampling occurred at wells UMD-2, MW-1 and MW-23 on March 23, 2005. The concentration of perchlorate detected in the groundwater collected from well UMD-2 was 9.42 µg/L. The other sampling results indicated that perchlorate was not detected in the sample from MW-23 and at a concentration of 0.257J µg/L in the sample from MW-1. The results of the March 2005 sampling at well UMD-2 are presented in Table 4 and on Figure 4.

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5.1.10 June 2005 Sampling Results

Groundwater sampling occurred at wells UMD-1 through UMD-8 on June 24, 2005. The results of the June 2005 event ranged from non-detect at wells UMD-1, UMD-4, and UMD-5 to 27.9 µg/L at well UMD-8. The groundwater from well UMD-7 contained 24.7 µg/L of perchlorate. The sample from downgradient well UMD-6 contained 0.962J µg/L of perchlorate. The groundwater from wells UMD-2 and UMD-3, located upgradient of the launch area, contained 1.58 µg/L and .361J µg/L of perchlorate, respectively. The results of the June 2005 sampling are presented in Table 4 and on Figure 4.

5.1.11 September 2005 Sampling Results

Groundwater sampling occurred at wells UMD-1 through UMD-8 on September 16, 2005. The results ranged from non-detect for the samples from wells UMD-1, UMD-4 and UMD-5 to 35 µg/L in the sample from well UMD-8. The groundwater from wells UMD-7 and UMD-6 contained 20.2 µg/L and 10.4 µg/L of perchlorate, respectively. The sample from the upgradient wells UMD-2 and UMD-3 contained 1.4 µg/L and 1.58 µg/L of perchlorate, respectively. The results of the September 2005 sampling event are presented in Table 4 and on Figure 4.

5.1.12 April 2006 Sampling Results

Groundwater sampling occurred at wells UMD-1 through UMD-8 on April 4, 2006. The results ranged from non-detect in the samples from wells UMD-1, UMD-3, and UMD-4 to 30 µg/L in the sample from well UMD-8. The groundwater from upgradient well, UMD-2, contained 1.74 µg/L of perchlorate. The perchlorate concentration in the sample from well UMD-7 decreased from 20.2 µg/L to 14.6 µg/L. The concentration of perchlorate detected in downgradient wells UMD-5 and UMD-6 contained 0.897J and 1.87 µg/L, respectively. The results of the April 2006 sampling event are presented in Table 4 and on Figure 4.

5.1.13 July 2006 Sampling Results

Groundwater sampling occurred at wells UMD-1 through UMD-8 on July 25, 2006. The results ranged from non-detect in the samples from wells UMD-1, UMD-3, and UMD-4 to 22.4 µg/L of perchlorate in the sample from well UMD-8. Perchlorate has not been detected in the groundwater from well UMD-4 throughout the sampling events. Concentrations of perchlorate increased in the groundwater from wells UMD-2 (from 1.74 in April 2006 µg/L to 2.25 µg/L), UMD-5 (from 0.897J µg/L in April 2006 to 5.16 µg/L), and UMD-6 (from 1.87 µg/L in April 2006 to 2.73 µg/L). The concentration of perchlorate decreased at well UMD-7 from 14.6 µg/L in April 2006 to 12.4 µg/L. The results of the July 2006 sampling event are presented in Table 4 and Figure 4.

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Figure 5 presents the analytical results for the ten monitoring rounds for wells UMD-1 through UMD-8.

5.2 Soil

The locations of soil sampling events are displayed in Figures 6 through 8.

5.2.1 June 2004 Sampling Results

On June 28, 2004, MassDEP personnel collected ten discrete surficial soil samples (UMD SS-1 through UMD SS-10) from 0 to 1-inch bgs at the Perchlorate Study Area. Two of the samples (UMD SS-1, UMD SS-2) were collected in close proximity to wells UMD-2 and UMD-3; the remaining eight soil samples were collected around the launch area. Figures 6 and 7 show the locations of the June 2004 sampling event. In order to create a more representative sample of surficial soil while trying to be cost effective, soil samples were collected discretely, but composited by laboratory personnel. Three composite samples were formed from seven of the ten discrete samples. Composite 1 was comprised of UMD SS-1 and UMD SS-2; Composite 2 was comprised of UMD SS-3, UMD SS-4 and UMD SS-5; and Composite 3 was comprised of UMD SS-6 and UMD SS-7. Only Composite Samples 2 and 3 were analyzed; the results indicated no detectable concentrations of perchlorate. The remaining composite sample and the ten discrete samples were not analyzed. The sample results of the June 2004 soil sampling are provided in Table 5.

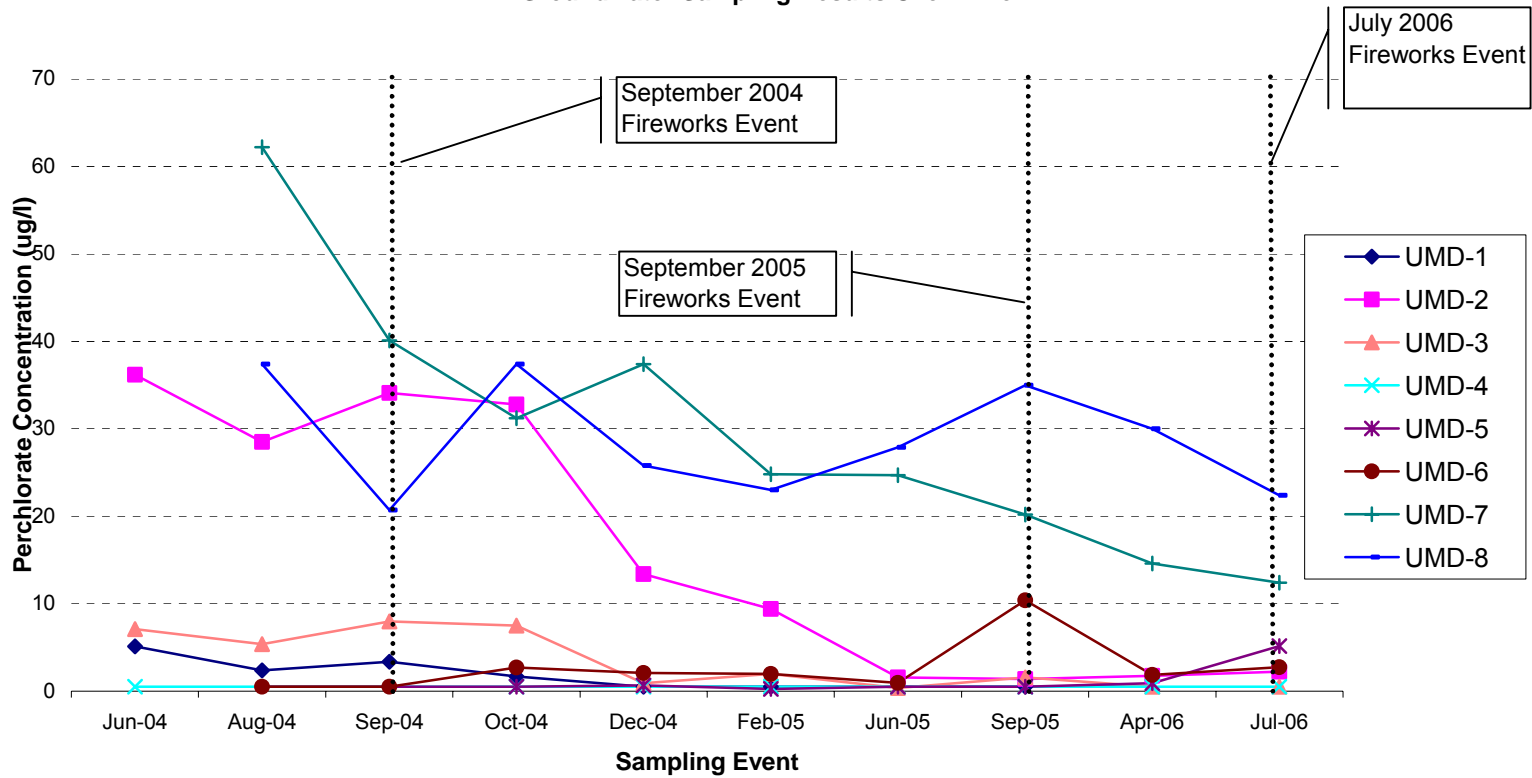
5.2.2 September 2004 Sampling Results

The fireworks display was performed on the evening of September 6, 2004. This 30-minute event was rescheduled from July 2, 2004 due to inclement weather. Soil samples were collected during the morning of September 7, 2004 to evaluate impacts of perchlorate in the shallow subsurface caused by fallout from the fireworks. Due to the high solubility and mobility of perchlorate, soil samples were collected within 12 to 15 hours after the fireworks event. No rainfall had occurred within this timeframe. Prior to sample collection, the area was visually inspected for paper fireworks debris to assess whether the debris was a continuing source of perchlorate contamination to soil and groundwater in the area. Based on this inspection, approximately 1 gallon of debris, predominately scrap paper, was observed in the area. The immediate area around the “finale” launch site appeared to be covered with a brownish-gray, coarse-grained, salt-like substance. The salt-like particles were located on the surface of the soil and grass around the launch area.

Ten discrete surficial soil samples (UMD SS-1A through UMD SS-10A) were collected by MassDEP personnel. Figures 7 and 8 provide the locations of this sampling event. Of the total, six discrete samples (UMD SS-1A, UMD SS-2A, UMD SS-5A, UMD SS-6A, UMD SS-7A, and UMD SS-8A) were collected from the immediate vicinity of wells UMD-2, UMD-3, UMD-5, UMD-6, UMD-7, and UMD-8, and the remaining four discrete samples (UMD SS-3A, UMD SS-4A, UMD SS-9A, and UMD SS-10A) were collected from the vicinity of the “finale” launch area (UMD-1). All samples were collected from 0 to 1-inch bgs. The sample locations were biased based on the appearance of the salt-like substance present following the fireworks display.

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Figure 5
University of Massachusetts Dartmouth Campus
Perchlorate Study Area
Groundwater Sampling Results Over Time



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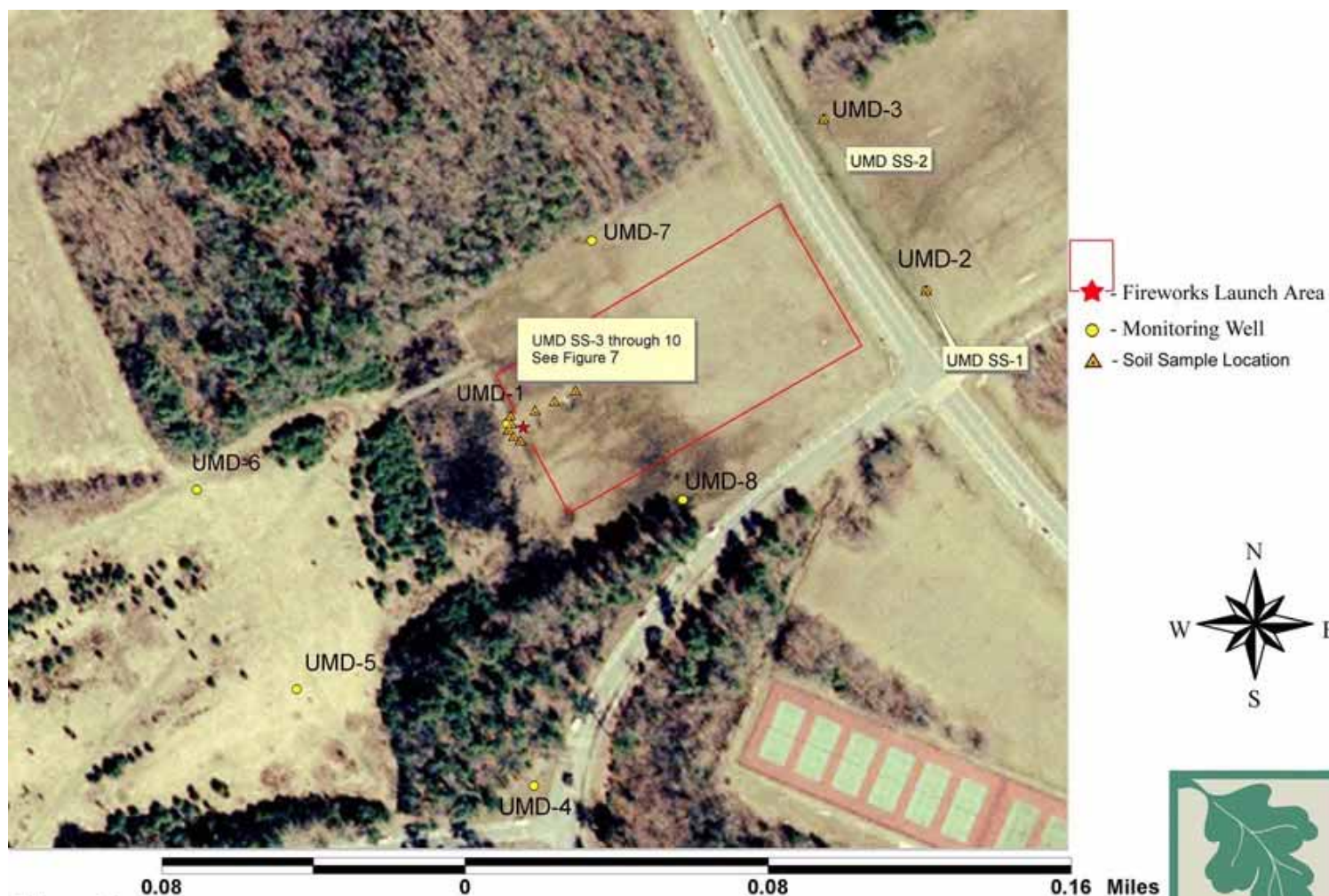


Figure 6
University of Massachusetts Dartmouth Campus
Perchlorate Study Area
June 2004 Soil Sample Locus Map

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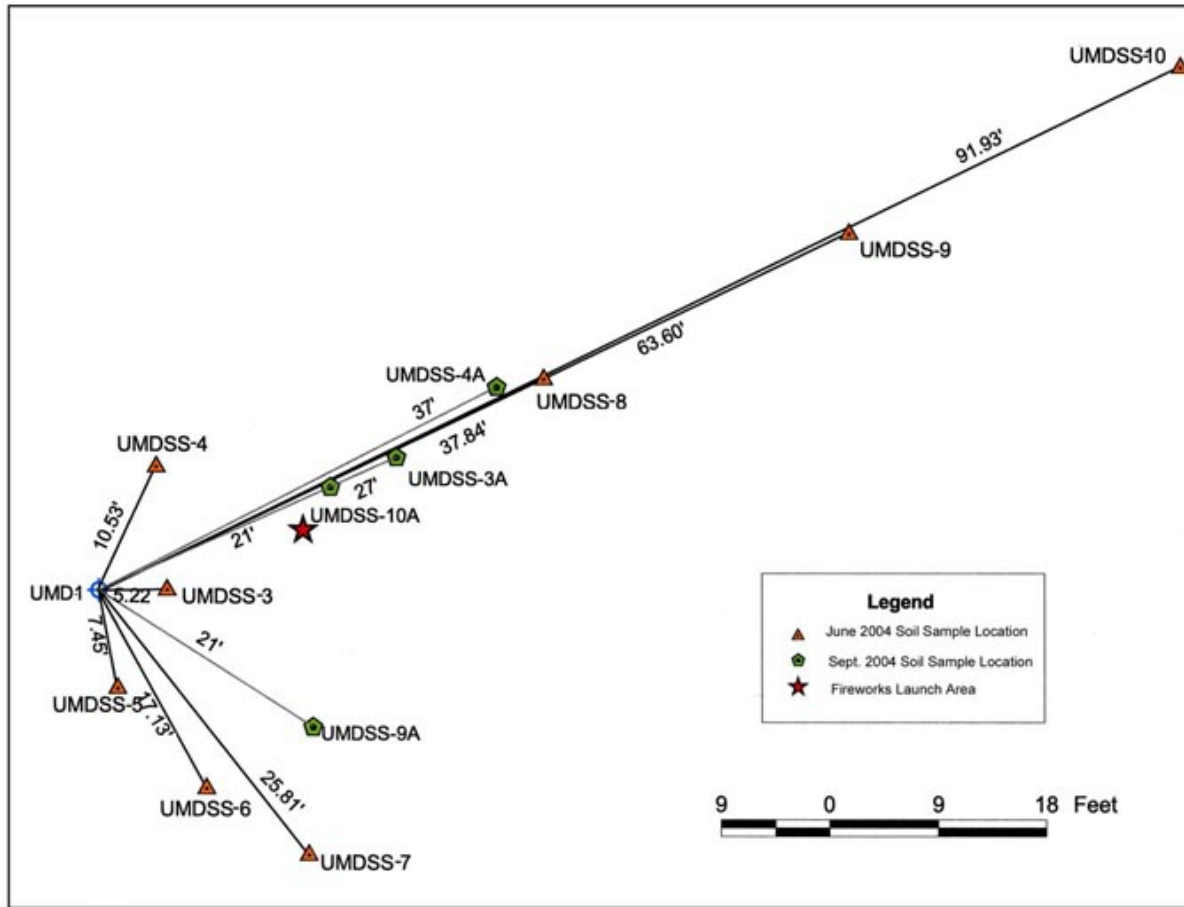
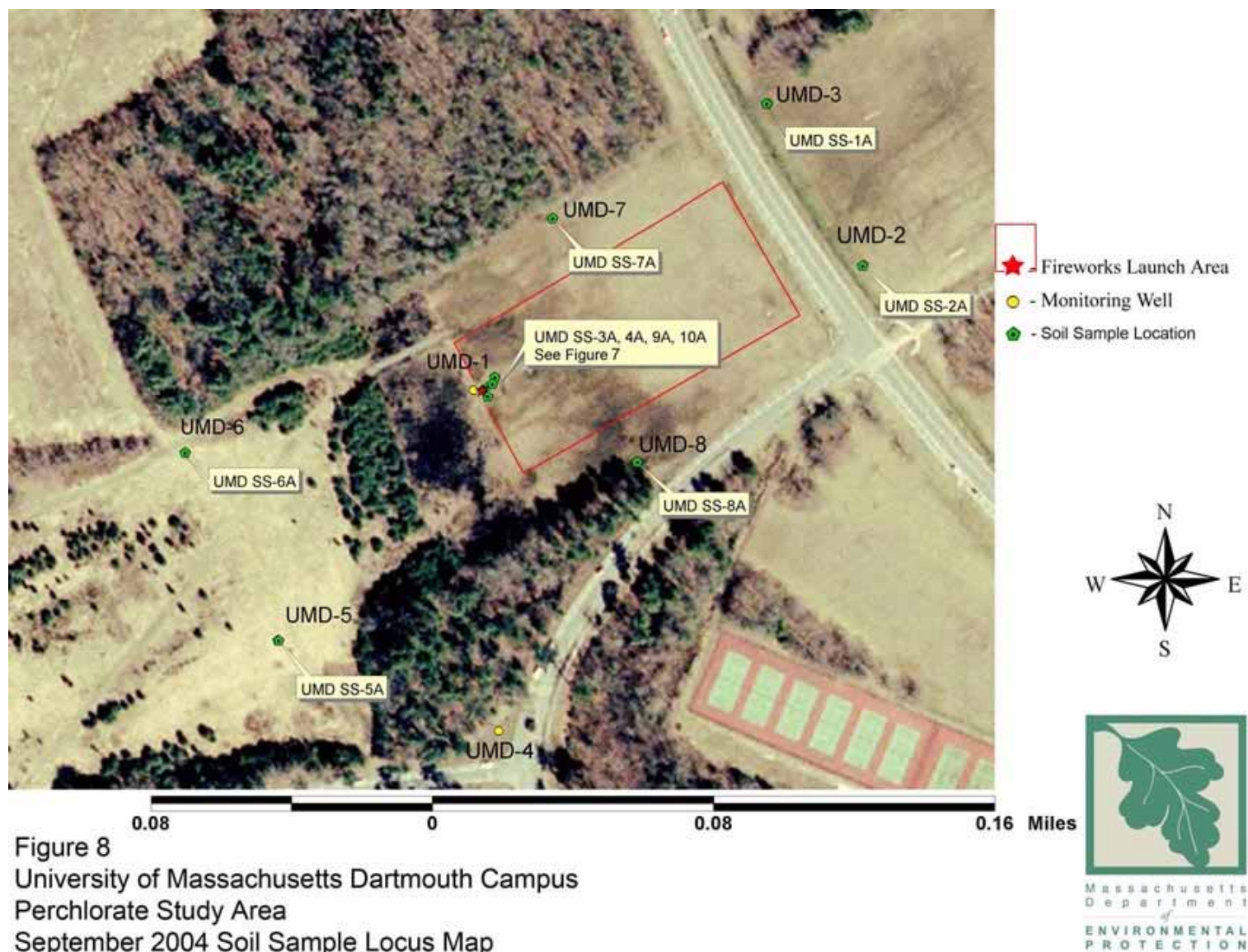


Figure 7
 University of Massachusetts Dartmouth Campus
 Perchlorate Study Area
 Soil Sample Locations in Fireworks Launch Area



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Table 5
University of Massachusetts Dartmouth Campus
Perchlorate Study Area
June 28, 2004 Soil Sampling Results

Sample Location	Perchlorate Concentration (µg/kg)
UMD SS-1	NA
UMD SS-2	NA
UMD SS-3	NA
UMD SS-4	NA
UMD SS-5	NA
UMD SS-6	NA
UMD SS-7	NA
UMD SS-8	NA
UMD SS-9	NA
UMD SS-10	NA
Composite 1 ^a	NA
Composite 2 ^b	ND
Composite 3 ^c	ND
Notes:	
^a Composite of UMD SS-1 and UMD SS-2	
^b Composite of UMD SS-3, UMD SS-4, and UMD SS-5	
^c Composite of UMD SS-6 and UMD SS-7	
ND-Not Detected	
NA-Not Analyzed	

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Four composite samples were prepared by Alpha Analytical. Composite 1 was comprised of UMD SS-1A and UMD SS-2A, Composite 2 was comprised of UMD SS-3A, UMD SS-4A, Composite 3 was comprised of UMD SS-5A and UMD SS-6A, and composite 4 was comprised of UMD SS-9A and UMD SS-10A.

The four composite samples were analyzed initially and the perchlorate results ranged from non-detect for Composites 1 and 3 to 130 µg/kg for Composite 2. The perchlorate concentration detected in Composite 4 was 120 µg/kg. Based on these results, discrete samples for locations SS-3A, SS-4A, SS-9A, and SS-10A were analyzed. The results ranged from non-detect at SS-4A and SS-9A to 560 µg/kg at SS-10A. The concentration of perchlorate at location SS-3A was 490 µg/kg. The results of the September 2004 soil sampling are provided in Table 6.

6.0 Conceptual Site Model

A conceptual site model (CSM) is a basic description of how contaminants enter a system, how they are transported within the system (or redistributed within the system) and where routes of exposure to humans and organisms occur. The CSM for the Perchlorate Study Area is shown on Figure 9.

Using a CSM approach, it is theorized that groundwater contamination results from two mechanisms:

- The area-wide “fallout” of fine particulates emanating from the atmospheric deflagration of aerial shells, based upon wind direction and speed; and
- The area-wide deposition and transport of shell fragments and paper debris emanating from ground-based launching operations as well as aerial bursts.

While the fallout of fine particulates is thought to occur in a somewhat uniform manner, deposition of shell fragments and debris will be irregular, depending upon wind conditions, terrestrial features, and “housekeeping” practices. Debris remaining on the ground for an extended period of time could provide a source of perchlorate to the soil, vadose zone and groundwater, especially following precipitation events. Other possible release mechanisms could include spillage, residue and debris from the launch area operations, or even the intentional burying of fireworks products (e.g., the burying of duds as a safety measure).

7.0 Groundwater Modeling

Groundwater fate and transport models were used to provide an “order-of-magnitude sense” of potential groundwater impacts from perchlorate-contaminated soils in the vicinity of the Perchlorate Study Area. The scope of the modeling exercise included predicting the highest concentration of perchlorate at a downgradient well (UMD-6) and predicting concentration changes at this well over time. SESOIL was used for modeling contaminant transport in the unsaturated zone and AT123D was used for modeling contaminant transport in the saturated zone.

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Table 6
University of Massachusetts Dartmouth Campus
Perchlorate Study Area
September 7, 2004 Soil Sampling Results

Sample Location	Perchlorate Concentration (µg/kg)
UMD SS-1A	NA
UMD SS-2A	NA
UMD SS-3A	490
UMD SS-4A	ND
UMD SS-5A	NA
UMD SS-6A	NA
UMD SS-7A	NA
UMD SS-8A	NA
UMD SS-9A	ND
UMD SS-10A	560
Composite 1 ^a	ND
Composite 2 ^b	130
Composite 3 ^c	ND
Composite 4 ^d	120
Notes: ^a Composite of UMD SS-1A and UMD SS-2A ^b Composite of UMD SS-3A and UMD SS-4A ^c Composite of UMD SS-5A and UMD SS-6A ^d Composite of UMD SS-9A and UMD SS-10A ND-Not Detected NA-Not Analyzed	

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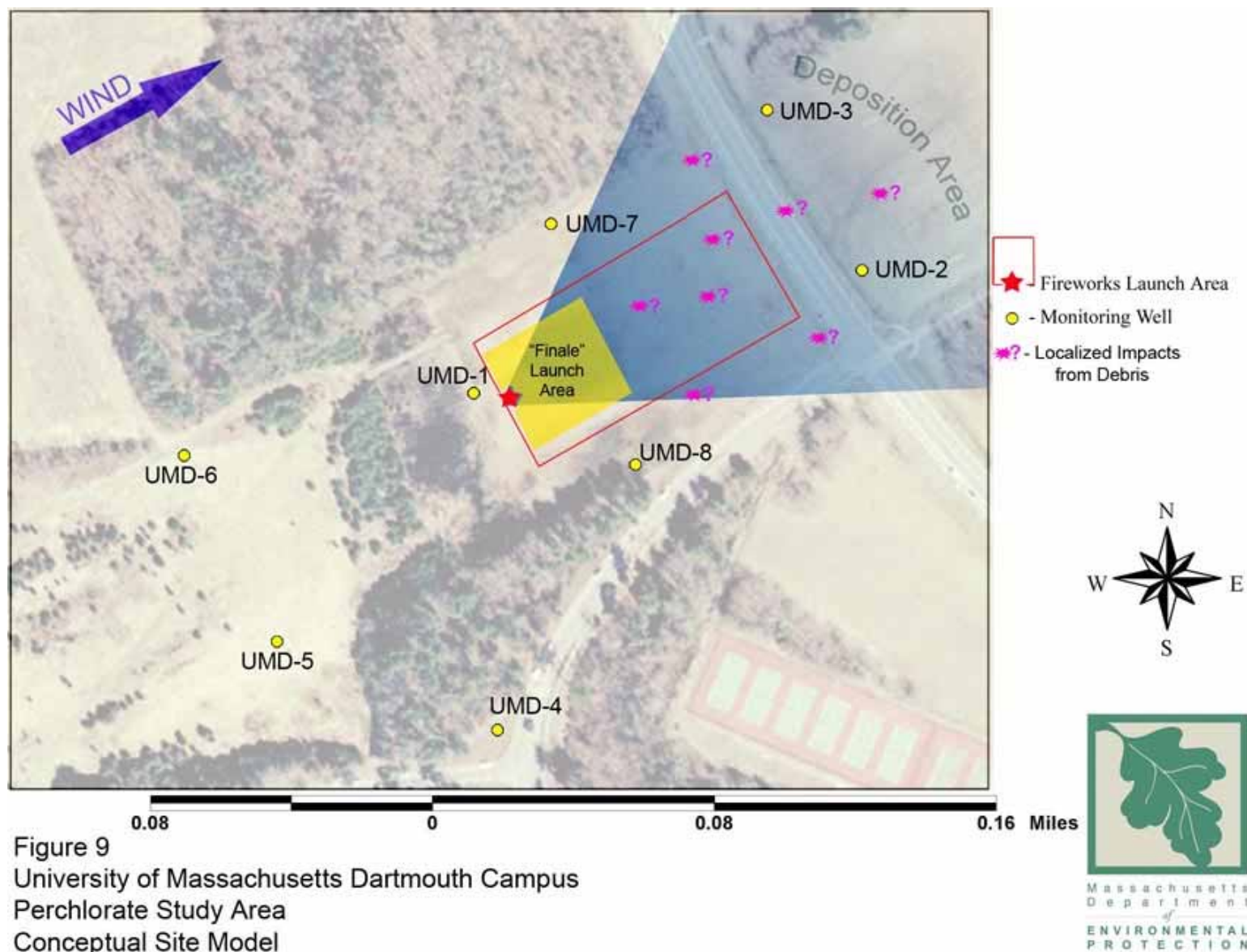


Figure 9
University of Massachusetts Dartmouth Campus
Perchlorate Study Area
Conceptual Site Model

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SESOIL is a one-dimensional vertical transport screening-level model that simulates long-term pollutant fate and migration in the unsaturated soil zone. SESOIL is an acronym for **Seasonal Soil** compartment model and was initially developed in 1981 for the EPA office of Water and the Office of Toxic Substances (OTS) by Arthur D. Little, Inc., Cambridge, MA (Bonazountas and Wagner, 1981). The model was updated in 1984 to add a fourth soil compartment and to incorporate soil erosion algorithms. Around 1985, SESOIL was enhanced by Hetrick et. al. at the Oak Ridge National Laboratory (Hetrick et. al. 1986, 1989)

AT123D is an analytical three-dimensional groundwater fate and transport model. AT123D was developed by G.T. Yeh in 1981 at Oak Ridge National Laboratory (Yeh, 1981). SESOIL and AT123D are interfaced so that the mass loading to the groundwater predicted by SESOIL is used as input to AT123D.

7.1 Assumptions

Although “loading” to the groundwater is believed to be attributable to a combination of area-wide particulate fallout and random/irregular deposition of firework debris, for simplicity, a small-area uniform-input condition was assumed. Specifically, a modeling source area was assumed to be approximately 150 feet by 150 feet, as indicated on Figure 10. This is consistent with soil sampling results obtained at UMD after the September 2004 fireworks event, and, as was the case during that event, representative of a launch on a calm day with minimal debris release and/or accumulation.

A model-loading rate of $2.52 \mu\text{g}/\text{cm}^2$ was assumed in this one-half acre source area. Again, this is based on data from the September 2004 event, and a “worse case” value of $560 \mu\text{g}/\text{kg}$ perchlorate that was detected in the top 1-inch of the ground surface, approximately 20 feet northeast of the “finale” launch area.

The hydraulic gradient varied across the Perchlorate Study Area, ranging from 0.007 ft/ft near wells UMD-1, UMD-5, and UMD-6, to 0.0267 ft/ in the vicinity of the launch area and wells UMD-1, UMD-7, and UMD-8. The arithmetic mean of the gradients was calculated to be 0.016 ft/ft and used to model perchlorate transport in the Study Area. Although groundwater gradients across sites have been described as exponential (EPACMTP, 1997) and logarithmic based on data collected from 200 hazardous waste sites in Massachusetts, the measured values of gradient at this site did not appear to follow an exponential or logarithmic distribution. Additionally, for this location, the geometric and arithmetic average of the two gradient values are similar (0.016 compared to 0.014). Therefore, the arithmetic mean was used as an estimator based on the nature of distribution of gradient at this site.

The seepage velocity of groundwater was calculated to be 0.09 feet per day based on an effective porosity of 0.3, an average hydraulic conductivity of $12.30 \text{ gallons}/\text{day}/\text{ft}^2$ and an average hydraulic gradient of 0.016 ft/ft. Hydraulic conductivity typically varies by several orders of magnitude and is generally described as a log-normal distribution. A distribution developed by MassDEP, based on samples collected from 200 individual sites, fit a Johnson SB distribution with a mean of -5.16 and a standard deviation of 2.32. The hydraulic conductivity was

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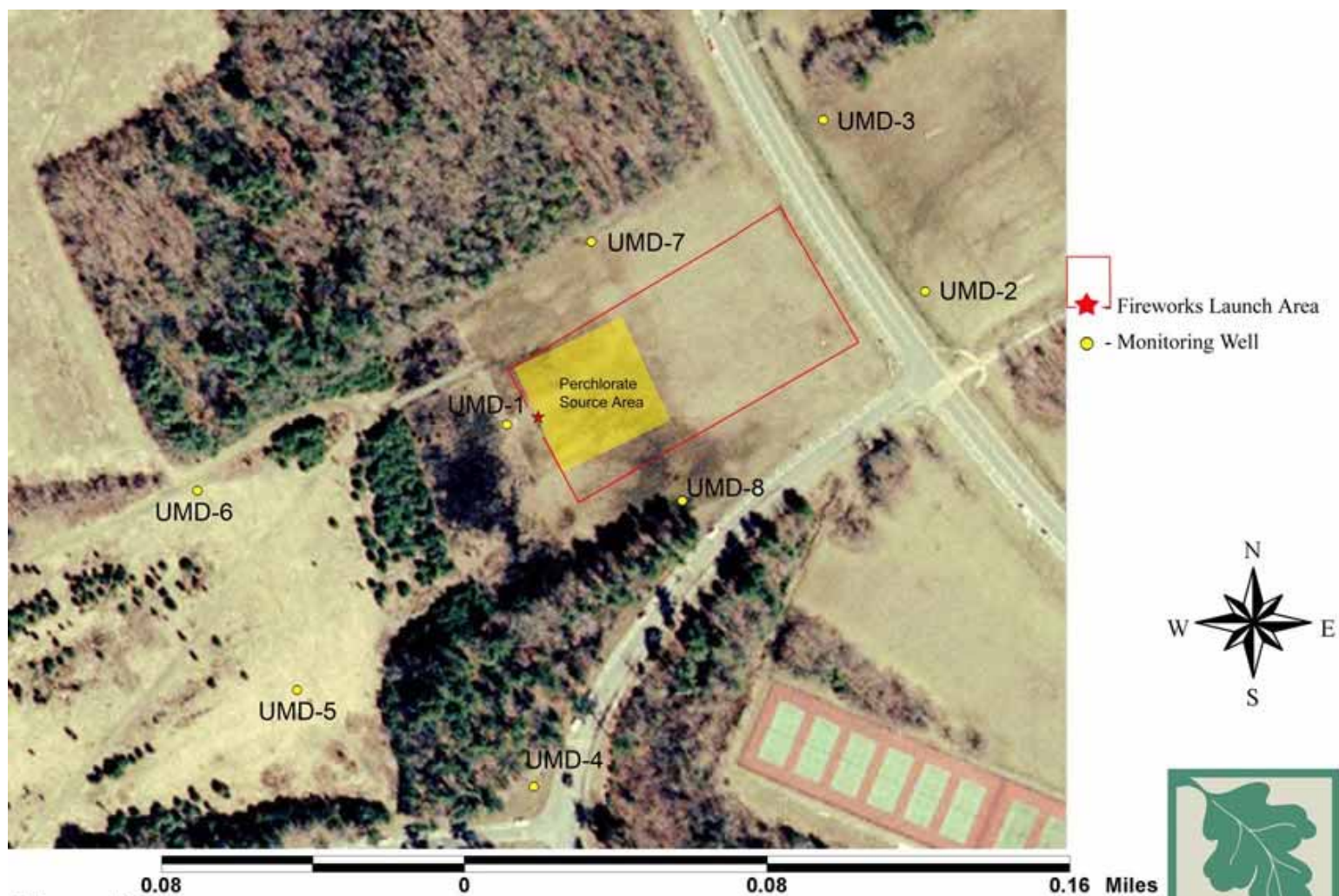


Figure 10
University of Massachusetts Dartmouth Campus
Perchlorate Study Area
Modeled Source Area

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estimated by geometrically averaging the borehole slug test results from wells UMD-5, UMD-6, and UMD-7.

The model evaluated the concentration of perchlorate approximately 440 feet downgradient of the launch area at well UMD-6 at the water table, approximately 5 feet bgs.

SESOIL was used to estimate the mass loading rates of perchlorate in groundwater based on the climate recorded at the New Bedford rain gauge station, the city adjacent to Dartmouth.

The following input parameters were used in the SESOIL model:

Soil Properties (based on the soil type at the location):

- Bulk density of soil = 1.8 g/cm^3 (typical value for sandy soil)
- Intrinsic Permeability = $6.65\text{E-}9 \text{ cm}^2$ (converted from hydraulic conductivity)
- Disconnectivity Index = 8.5 (a SESOIL-specific value used for calibrating the soil type to recharge)
- Organic Carbon Content = 0.02 percent
- Effective Porosity = 0.32

Chemical Properties (Syracuse Research Corporation):

- Solubility = 15,000 mg/l (based on the solubility of potassium perchlorate)
- Diffusion Coefficient = 0
- Henry's Law Coefficient = 0
- $K_{oc} = 0$

Application Parameters:

- Number of Soil Layers = 2
- Source Area = 150 feet by 150 feet
- Steady application (contamination in soil from the single modeled source acts as a steady source to groundwater)
- Soil properties uniform with depth
- Climate of the City of New Bedford, Massachusetts

AT123D was then used to predict the concentration of perchlorate in groundwater in downgradient well UMD-6. The following input parameters were used for this modeling exercise:

- Aquifer was assumed to be infinite in width
- Hydraulic Gradient = 0.0167 ft/ft
- Hydraulic Conductivity = 0.02 meters/hour (based on site-specific measurements)
- Longitudinal Dispersivity = 5.910 meters
- Transverse Dispersivity = 0.5910 meters
- Vertical Dispersivity = 0.1477 meters
- Organic Partitioning Coefficient = 0

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A copy of the input and output files for SESOIL and AT123D are provided in Appendix B. Appendix C provides justification for selection of dispersivity coefficients.

7.2 Modeling Results

The model predicted that detectable concentrations (1 µg/l) of perchlorate would be present in UMD-6 in approximately 11.5 years after the first fireworks display. The maximum concentration would be reached at this well in approximately 18 years at a concentration of 5.2 µg/l. Figure 11 provides the predicted perchlorate concentrations at well UMD-6 with time to show the trend of migration and the time it is expected to peak at this location.

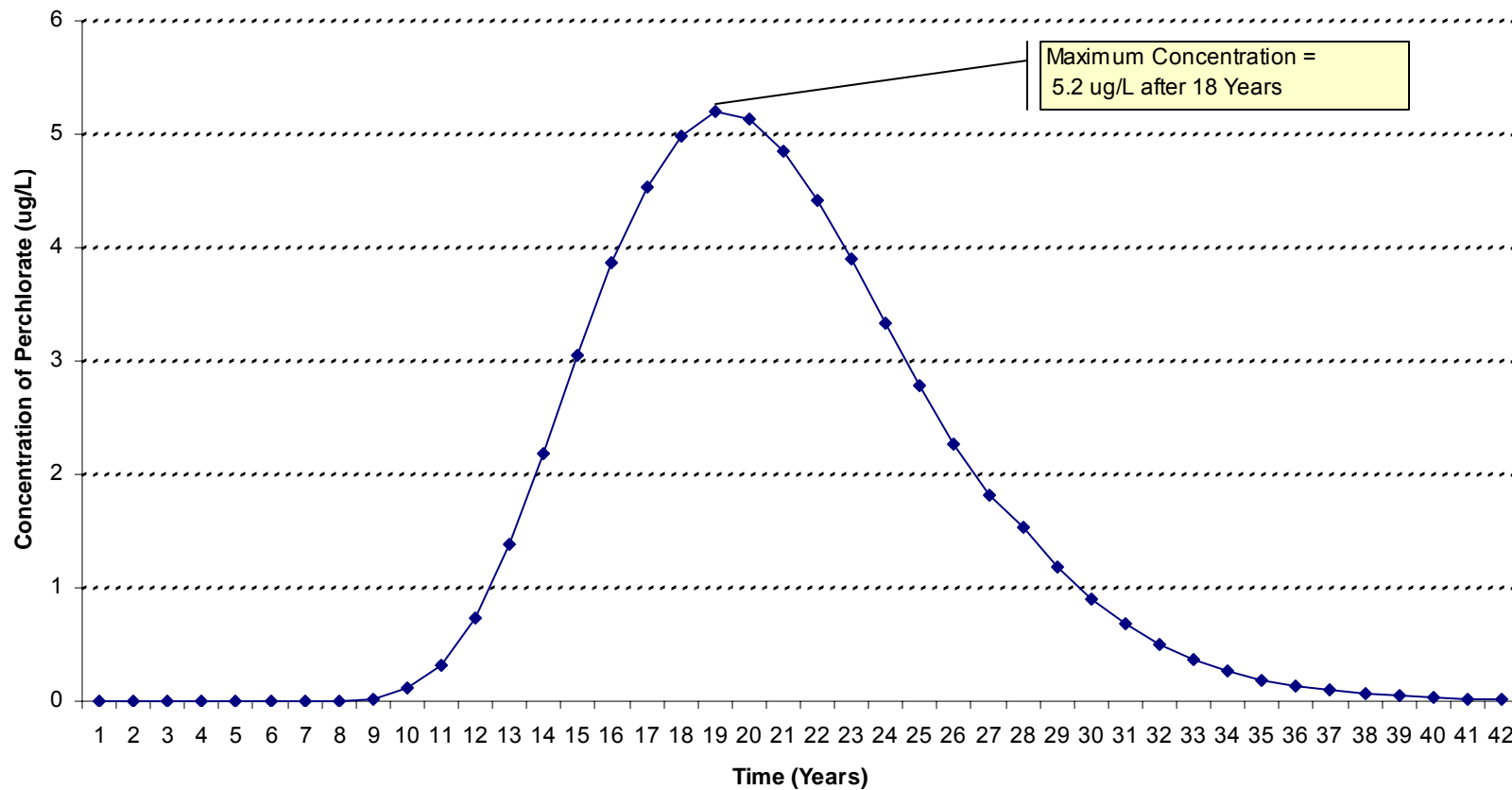
Before and immediately after the 2004 fireworks display, well UMD-6 was non-detect for perchlorate (August 2004 and September 2004 events). With the exception of the September 2005 monitoring round, a perchlorate concentration of approximately 2 µg/l has been detected in well UMD-6 since October 2004. Well UMD-6 is located approximately 440 feet downgradient of the launch area. The model predicted concentrations of 1.0 µg/l and 2.18 µg/l (at the water table) in UMD-6 in approximately 11.5 and 13 years, respectively. It is noted that with the exception of 2003, fireworks displays have occurred at the same general launch area at least once a year since 1995.

Although the predicted and measured concentrations at well UMD-6 are on the same order of magnitude, the following issues and limitations of the modeling exercise should be considered:

- The model predicted the perchlorate concentration at downgradient well UMD-6 based on one fireworks event, including the expected peak concentration. However, since there have been 13 events at the Perchlorate Study Area over the last eleven years, the modeled peak concentration for one event will not coincide with the actual peak concentration from multiple events. The actual peak concentration from the cumulative impact of multiple fireworks events would be expected to be greater than that predicted by this model.
- A conservative concentration of the contaminant and estimate of the source area was considered for modeling due to the limited soil data in the Perchlorate Study Area.
- The maximum concentration of perchlorate in soil was assumed to be distributed over the entire source area. This is a conservative estimate and therefore if the actual averaged concentration was lower, a lower concentration may be expected at well UMD-6.
- The boundary of the contaminated area is currently unknown. There are different contaminated sub-areas around the launch area. Since the source area is a sensitive parameter for the model, some uncertainty is introduced into the model results.
- The modeled concentration profile of perchlorate in ambient groundwater is not uniform, i.e., the concentration is higher at the water table and becomes lower with depth. The measured concentration in the well is a concentration that is

Figure 11

University of Massachusetts Dartmouth Campus
Perchlorate Study Area
Predicted Perchlorate Concentrations at Well UMD-6 Over Time



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averaged over the entire screen height of the well. Therefore, the model predicted concentration at the water table is expected to be higher than the measured concentration.

8.0 Other Potential Sources of Perchlorate

MassDEP considered whether other potential sources of perchlorate could have caused contamination at the Perchlorate Study Area. These perchlorate source considerations are shown on Figure 12. The results of this effort indicate the following:

Blasting for various construction projects has occurred at the UMD campus over the last 40 years. Sixteen blasting permits were granted from the local fire department from 1964 through 2004. It is unknown at this time if perchlorate-containing agents were used for any blasting at the UMD campus. However, the blasting operations located in the vicinity of the Perchlorate Study Area occurred from 1966 through 1987 and it is unlikely that perchlorate was used as a blasting agent during that time period.

- Sodium hypochlorite, which can contain perchlorate, has reportedly been used for disinfection at the UMD pool since 1978. The pool is located at the Tripp Athletic Center, which is located about 2000 feet southeast of the Perchlorate Study Area (see Figure 12). There has reportedly been excessive loss of chlorinated water at the pool site leading campus officials to suspect leakage of pool water to the subsurface. However, the pool is located downgradient of the Perchlorate Study Area and is unlikely the cause of the observed perchlorate contamination.
- No fertilizers or herbicides have been used on the UMD campus for at least the last five years.

Other lines of evidence and consideration elements are also worth noting with respect to this issue:

- ☞ Perchlorate was not detected in the groundwater sampled from groundwater monitoring wells at the campus power plant (“Oil Remediation Site” on Figure 12) suggesting that area-wide sources like fertilizers, herbicides, and/or blasting activities do not appear likely.
- ☞ The study area is located on the side of a hill, relatively high in its sub-basin. As displayed in Figure 11, there is only a small watershed (20-25 acres) topographically upgradient of the fireworks launch area. If the groundwater recharge/flow zone mirrors this topographical condition, – which is likely, considering the shallow depth to bedrock – there is only a limited area of the campus that could contribute perchlorate from other release sources and activities.

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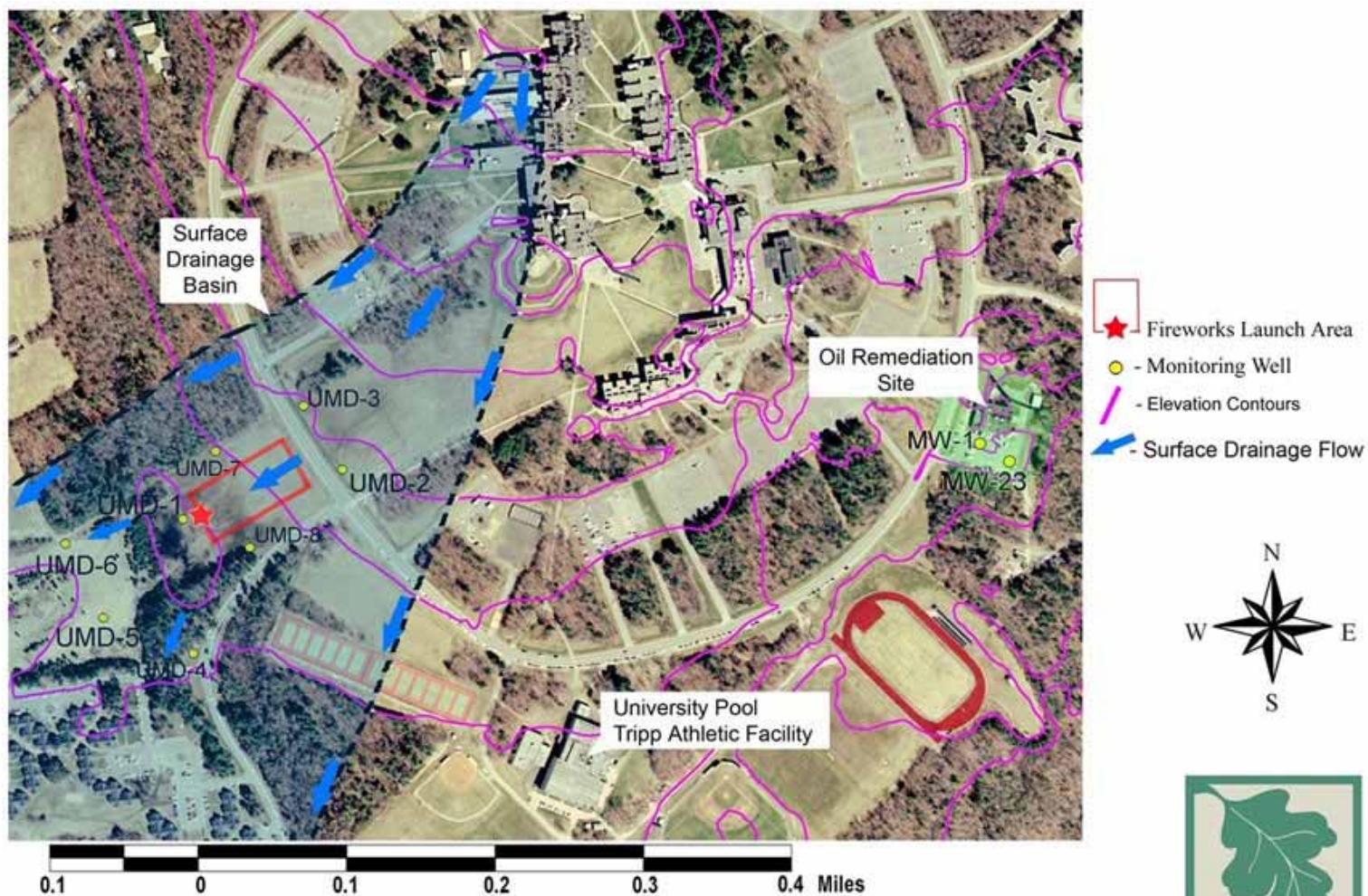


Figure 12
University of Massachusetts Dartmouth Campus
Perchlorate Source Considerations

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9.0 Conclusions

Based on field investigations conducted since 2004, it appears that 11 years of fireworks displays have resulted in perchlorate contamination in soil and groundwater at the Perchlorate Study Area. These conclusions are consistent with fate and transport modeling results for this location.

The results of soil sampling conducted the day after the 2004 fireworks display indicated that perchlorate was present in surficial soil. The maximum concentration detected in the top 1-inch bgs at the launch area was 560 ug/kg. This suggests that the source of perchlorate was the fireworks since the sampling event conducted prior to the display showed no detectable levels of perchlorate in surficial soil in the launch area. There are no other known sources of perchlorate at the UMD campus.

Levels of perchlorate above 2 µg/L were present in groundwater in the vicinity of the launch area (wells UMD-2, UMD-3, UMD-7 and UMD-8) before the September 2004 fireworks display. Supplemental monitoring since September 2004 has shown the concentration of perchlorate in these wells has decreased, indicating that the groundwater impacted with perchlorate from prior fireworks displays may be migrating downgradient. The prevailing wind directions measured during a number of the past fireworks displays have been in the northeast (hydraulically upgradient) direction, which would lead to particulate fallout and debris deposition and accumulation in the areas upgradient of the launch area near wells UMD-2 and UMD-3.

Perchlorate concentrations downgradient of the Launch Area have generally increased during the study period. Perchlorate was not detected in the groundwater at downgradient wells UMD-5 and UMD-6 during the two sampling events conducted prior to the 2004 fireworks display. However, perchlorate has been detected in groundwater at well UMD-6 at a concentration of approximately 2 µg/L since October 2004, with one noted exception. The concentration of perchlorate detected in groundwater at well UMD-6 during the September 2005 event was 10.4 µg/L. The two monitoring rounds conducted at well UMD-6 after the September 2005 round indicated concentrations of perchlorate of 1.87 µg/L (April 2006) and 2.73 µg/L (July 2006). Perchlorate has been detected in groundwater at well UMD-5 during four sampling events since October 2004. The highest concentration (5.16 µg/L) was detected in groundwater from well UMD-5 in July 2006. The remaining concentrations detected in groundwater from well UMD-5 were estimated values below the practical quantification limit of 1µg/L. The increase in concentration measured at downgradient wells UMD-5 and UMD-6 indicate that groundwater impacted with perchlorate from 13 prior fireworks displays from the same general launch area may be migrating downgradient. These results are consistent with the CSM.

The SESOIL/AT123D model predicted that a perchlorate concentration of 2 µg/L would be present at the water table in well UMD-6 approximately 13 years after the first fireworks event. The first fireworks event occurred at the Perchlorate Study over eleven years ago, on July 1, 1995, and fireworks have been launched from the same general location for all subsequent events. The results measured at well UMD-6, with one noted exception, are consistent with the model predictions, considering the uncertainties previously described. Although the modeling exercise only evaluated one fireworks event, it is reasonable to compare the results of the model to the

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results of field sampling in the area of the predicted leading edge of the plume. Given that the 13 fireworks events have occurred at the same general location at the UMD campus, it was also expected that there would be a cumulative effect on the concentration of perchlorate present in the subsurface in the vicinity of the source area.

Within the limited scope of the investigation at the UMD site, the perchlorate concentrations predicted by the model and those detected during the groundwater monitoring are in relative agreement.

10.0 Recommendations

While the results obtained during the research study at UMD indicated the need for caution when planning fireworks displays, the research also indicated how fireworks could be safely used while protecting drinking water resources.

Based on the results of the fireworks study at the UMD campus, MassDEP recommends the following:

- Be aware of the existence of surrounding drinking water supplies and plan the fireworks activities (including the location of the fallout zone) as far from them as possible (<http://mass.gov/dep/water/drinking/swapreps.htm>). The localized nature of the groundwater contamination underscores the importance of distance: distance between the launch/deposition area and nearby public and private drinking water supplies. Of particular concern are fireworks displays within the recharge areas of public drinking water supply wells (i.e., "Zone II" and "Interim Wellhead Protection" areas). Maps of these areas and surface water supplies should be available from local officials, and can be viewed on-line at <http://www.mass.gov/mgis/> (specifically <http://maps.massgis.state.ma.us/WSPA/viewer.htm>)
- In accordance with the requirements outlined in the permits for fireworks displays, clean up fireworks debris immediately following fireworks events to ensure debris is not leaching into soil and groundwater. Appropriate cleanup and disposal of shell fragments and duds, also a standard fireworks permit requirement, will eliminate the release of perchlorate from this debris.
- Request low (or no) perchlorate-containing fireworks. This may require making inquiries of suppliers and/or manufacturers.

These recommendations are the basis of guidance developed by MassDEP entitled "Potential Environmental Contamination From the Use of Perchlorate-Containing Fireworks" (<http://mass.gov/dep/water/drinking/fworkbmp.htm>).

A collection of MassDEP information on perchlorate, including a report summarizing the occurrence and sources of perchlorate found to date in Massachusetts, can be found at <http://www.mass.gov/dep/water/drinking/percinfo.htm>.