Town of Hopkinton

LNG Spill Dispersion Report

Smith & Burgess Project #0639

February 9, 2016

Executive Summary

Smith & Burgess was contracted to perform a Computational Fluid Dynamic (CFD) modeling study for the town of Hopkinton, MA. The study models Liquefied Natural Gas (LNG) dispersion patterns from a processing and storage facility. The dispersion was based upon developing "worst" case, or possible, release scenarios from LNG piping and a storage tank. The worst case scenarios consider unmitigated releases of a portion of material contained in the storage tank (up to 34,580 m^3 in volume). Atmospheric conditions and terrain were considered in the model. This model considered only a worst case possibility and is not to be considered a risk assessment, which considers likelihood. The facility was not required to generate this type of report due to any rule, law or other requirement.

The Hopkinton LNG facility is bisected by a public road and consists of a gas liquefier/expander plant and LNG storage tanks. The plant and storage tanks are connected by piping which transitions underground below the road and returns aboveground on either roadside. The facility maintains large quantities of LNG. Thus, the worst case would be considered large.

A scenario was developed based upon a release from the storage tanks through the piping. The release scenario is initiated by a vehicle striking the piping at an above/underground transition point beside the road. The strike results in a "guillotine" piping break.

Another scenario was developed based upon a release from the storage tank. This release scenario is initiated by an unspecified heater malfunction which ultimately causes an external tank wall failure.

The study accomplished the LNG gas dispersion patterns which are represented by the distance and time at which 50% of the lower flammability limit (LFL) is reached within the boundary of the model. Depending on wind speed and direction, each dispersion pattern could extend into sections of the area surrounding the town of Hopkinton:

- A proposed development will fall within gas release 50% LFL,
- Existing residential and commercial areas will fall within dispersion patterns,
- The dispersion patterns resulting from either scenarios could cover an area greater than 3.8 miles (limit of modeling region),
- And all of these conclusions are based on only possible risk probabilities with the models of gas release from the facility.

Worst case scenarios are typically used for emergency planning and communication. The model is based on a possibility, or the capability, of a consequence occurring. This approach does not account for mitigation/controls and other factors, such as ignition sources, which could disrupt the magnitude of dispersion. Conversely, a typical risk assessment expresses the likelihood of a scenario and initiating events and would account for mitigation/control efforts and other scenario limiting factors.

See Appendices for the plots of results.

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Introduction

Smith & Burgess was contracted to perform dispersion modeling of Liquefied Natural Gas (LNG) spills for the town of Hopkinton, MA. This study uses a computational fluid dynamics (CFD) modeling system. CFD is an engineering analysis tool which relies on numerical methods to analyze fluid mechanical properties and interactions. CFD simulates the interaction of liquids, gases, and other substances with surfaces, taking into account variables such as heat transfer, mixing, and flow conditions. Cryogenic fluids, due to the extreme temperature and density changes from temperature changes will sometimes form small pools of liquids, but sometimes not. However if the rate of release is sufficient, the release will cause the generation of a sustained plume of extremely cold gas that moves as a structure. As long as the rate of release is large and long enough, it will sustain the plume structure. Wind and terrain will influence the direction and time for plume generation. But this plume will not be same as other models of compressed gasses, where other compressed gasses or volatile liquids that are released could form a pool, but immediately start to disperse in all directions.

"Standard" dispersion modeling software will model non-cryogenic gasses/liquids with a fairly reasonable amount of accuracy assuming there are no obstacles or significant changes in terrain; However, these models are not sophisticated enough to define the plume formation of a cryogenic fluid. Thus, the need to use a CFD software is necessary for this modeling.

Smith & Burgess used Star-CCM+ CFD modeling software to analyze the LNG fluid flow and dispersion patterns. Worst case, or possible, release scenarios were developed to determine dispersion patterns in the areas around the LNG Plant near Hopkinton. The scenarios involved releases from a piping breach and a tank failure.

Star-CCM+ can incorporate wind profile boundary conditions and surface roughness settings just like GexCon FLACS, which is another CFD modeling software, as well as all required thermodynamics for the LNG vaporization and dispersion process. It is reliable because it incorporates the topography of the region, which is a known limitation of both FLACS and DNV-GL PHAST (an empirical modeling tool), which are the only two officially approved tools by the US Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA). Unofficial tools are not less accurate than officially approved ones, and have simply not been taken through the formal approval process. Care has been taken to take the weather parameters that were present in FLACS and mimic them in Star-CCM+ to have comparable configurations.

The Hopkinton LNG facility consists of a gas liquefier/expander unit and LNG storage tanks, which are bisected by a public road. The plant and tanks are connected by piping which is above ground on either side of the road, and transitions underground to cross below the road. The facility stores LNG to be converted into Natural Gas (NG) for local distribution. The facility also receives NG to convert to LNG for storage. The facility maintains large quantities of LNG. Thus, the worst case would be considered large.

Scenario Generation

Two release scenarios were developed to establish dispersion patterns. The releases involved a piping breach initiated by a hypothetical vehicle strike and a tank failure initiated by an unspecified equipment malfunction.

A Google Earth image was used to observe the piping above/underground transition and the proximity to the road. At the transition point the piping is anchored with a concrete pier. The piping then makes a 90 degree turn then follows the slope of the ground. A vehicle leaving the road, missing the "jersey wall type" barricade, and breaching the chain link fence could come in contact with the above ground piping. Upon hitting the pipe, a vehicle would damage the piping. The damage could be as minimal as a surface blemish to as large as a shearing or guillotine effect on the pipe near the point at which the piping is anchored. Smith & Burgess considered the guillotining of the pipe as the worst case scenario to model. Any guillotining of pipe will cause a large release of material.

The LNG tank is an internal tank built within an external atmospheric tank. The tank release scenario is initiated by a loss of heating in the space between the internal tank and of the external tank. The heater is necessary to stop ice buildup. Ice buildup can cause a lifting or pushing force on the internal tank. This force could shift the internal tank off the fixed support system. And the shift could cause a breach in the internal tank wall, exposing the external tank walls to LNG. Typically, the materials of the external tank wall will not withstand the pressure and cryogenic temperatures of LNG. The failure could result in the release and dispersion of LNG.

For both scenarios, only eight (8) models were generated, so for the piping only the four (4) wind directions and two (2) different speed for each wind direction were modeled. For the tank, Smith & Burgess considered that the tank could be at different liquid levels at any single time. So, different release rates were generated to show the effect of differing liquid levels on the dispersion patterns for the four (4) wind directions and two (2) speeds.

Methodology and Modeling Assumptions

This analysis was performed using a computational fluid dynamics (CFD) model. The CFD software package used to perform this analysis was Star-CCM+ by CD-Adapco. Each CFD model was performed in the following steps:

1. Steady (averaged) simulation of the wind blowing through the region at a specified wind speed and direction
2. Transient (time dependent) simulation of the wind blowing through the region to properly develop turbulence eddies at small time steps
3. Transient (time dependent) simulation of each liquefied natural gas (LNG) release scenario to dynamically model the LNG blowing out of the ruptured pipe or tank, which included:
    - A fixed opening with a liquid release for all models
    - Boiling of the liquid into a gas
    - Dispersion of the gas into the environment

  - o Flow of the liquid and gas over the terrain

The following information was provided or retrieved from appropriate sources and used as inputs into the model:

- Topography information up to 2 miles from the site from the United States Geological Survey (USGS) website with a resolution of 1/3 arc second (accurate to roughly 10 meters east-west and 12 meters north-south)
- Locations of proposed housing development from Legacy Farms
- Documents containing information on the LNG tanks and respective containment area, including the applicable 3-dimensional (3D) geometric dimensions
- Documents containing information on the facility including locations of major buildings
- Drawings of the LNG tanks for gathering mechanical / internal construction information as well as applicable piping for a potential LNG release
- The LNG pipe is assumed to have a pressure of 800 psig (pounds per square inch gauge) as per the emergency response plan (ERP) and redacted testimony document D.P.U. 14-64
- Operating conditions of each LNG tank:
  - o Temperature of -260°F (Fahrenheit)
  - o Maximum expected inventory of the tank, 34,580 m^3 (cubic meters) of LNG, which may be smaller depending on upon tank utilization and seasonal variation
  - o Operational pressure of the tank ranging from 0.5 to 0.8 psig.
- Information taken from weather stations KMASOUTH33 and KMAHOPKI9 from Wunderground:
  - o Average annual temperature of the region, 50°F
  - o Lowest wind speeds occurring in the region, excluding the lowest 10%, which came out to 1.02 MPH (miles per hour) or 0.46 m/s (meters per second)
  - o Average barometric pressure of the region, 29.99 inches of mercury or 101,719.5 Pa (Pascals)
- Average daytime solar radiation taken over the last solar cycle (1991-2005) from station KORH 725095 from the National Solar Radiation Database (NSRDB), 298.7 W/m^2 (watts per square meter)
- Average tree height taken from a sample of 25 trees, 71.2 feet
- Average height of housing in proposed development area of 31 feet
- LNG properties taken from a material safety datasheet (MSDS) taken from the U.S. National Oceanic and Atmospheric Administration (NOAA) Cameo Chemicals online hazardous materials database
- Typical wind turbulence and speed variation with height
- GPS coordinates of the site
- Locations of buildings, trees, roads, and other types of terrain from Google Earth images retrieved between December 2015 and January 2016

Intermediate calculations were performed to provide additional inputs into the model. The software tools used to make these calculations included the spreadsheet tool Microsoft Excel and the process simulator Aspen HYSYS. Information taken from Aspen HYSYS included:

- Instantaneous flow rate from the pipe due to a guillotine break (complete severance)
- Thermodynamics and other physical properties of LNG at the specified process conditions
- Thermodynamics and other physical properties of natural gas vapor at the expected temperature ranges
- Thermodynamics and other physical properties of air at 50% humidity

One of the intermediate calculations made in Excel was the maximum flow rate through a 1.27 m x 2.6 m triangular hole. The total open area of the triangular hole is 1.65 m^2 (square meters). Using the Bernoulli equation, a full tank with a liquid level of 19.4 meters and a gauge vapor pressure of 0.8 psi is calculated to produce a flow rate of 13,531 kg/s (kilograms per second) using a liquid density of 410 kg/m^3 (kilograms per cubic meter) for LNG.

The following methodologies and assumptions were used in the model:

- Ignition of the natural gas cloud does not occur at any point during the model
- Heating from solar radiation is approximated as directly coming from the ground, with appropriate reductions due to shading
- The maximum ground temperature due to solar radiation was limited to 80.33°F
- Wind resistance and turbulence due to physical obstacles smaller than buildings such as vegetation were approximated using a specified surface roughness length, which is a typical industry practice. The roughness lengths used in the model came from either The Netherlands Organization (TNO) Yellow Book, an equation used to approximate roughness length formulated by Panofsky & Dutton ("Atmospheric Turbulence Models and Methods for Engineering Applications", Panofsky and Dutton, J. Wiley and Sons, New York), or the European Wind Atlas:

Table 1 Roughness Lengths Used in Model

Landscape Type	Roughness Length (m)	Information Source
Metal, Pipes, Buildings	0	Assumed perfectly smooth
Lake	0.0002	Yellow Book
Pavement	0.0024	European Wind Atlas
Dirt	0.005	Yellow Book
Short Grass	0.03	Yellow Book
Low Crops, Pipe Bundles	0.1	Yellow Book
High Crops	0.25	Yellow Book
Housing	0.31	Panofsky & Dutton (calculated)
Forest	0.72	Panofsky & Dutton (calculated)

- Atmospheric turbulence mixing parameters under stable atmospheric conditions were calculated in accordance with the TNO Yellow Book
- Atmospheric turbulence properties were calculated based on a National Aeronautics and Space Administration (NASA) research paper ("An Estimation of Turbulent Kinetic Energy and Energy Dissipation Rate Based on Atmospheric Boundary Layer Similarity Theory", Han, Arya, Shen, Lin, 2000)
- Variation of atmospheric pressure and temperature with elevation were taken from the Chemical Engineering Reference Manual for the PE Exam, 7th edition, by Michael R. Lindeburg, PE
- Flow from each release scenario was taken at the instantaneous flow rate, and any decrease in flow was expected to be minimal due to the very small percentage of total inventory released
- The pipeline broken was the largest horizontal section of pipe holding LNG on the east side of Wilson Street, to represent any number of pipe break locations or orientations
- The tank ruptured was the easternmost LNG tank and was a 1.3 m x 2.6 m triangular rip of the seam, to represent any number of types of tank ruptures that could occur
- The tank liquid level is varied to provide comparisons of consequences depending upon the utilization of the tank whether due to seasonal variations or different tank filling orders
- The scenario total elapsed time is varied to provide a better picture on progression of the unignited gas cloud at different time intervals
- Other information used to perform calculations was taken from CFD Online (http://www.cfd-online.com/), from the Star-CCM+ manuals, or directly from CD-Adapco personnel wherever appropriate

Each simulation was run using high performance computing (HPC) on a cloud based server hosted by Penguin Computing, Inc. The server cluster used ranged between 8 – 10 computers and a total of 120 – 128 CPU cores. The duration of each run ranged from roughly 8 hours to 16 hours. The total number of cells used in the CFD model to subdivide the region into smaller calculated volumes ranged from 2 million to 3 million.

A 3D image of the topography used in the model is shown in Appendix R.

Assumptions for each scenario

Each scenario was modeled in accordance with the criteria specified by the National Fire Prevention Association (NFPA) standard 59A, Production, Storage, and Handling of Liquefied Natural Gas, as well as the U.S. government standard 49 Code of Federal Regulations (CFR) 193. These references dictate that models of LNG spill dispersion are done under the following conditions:

- Two wind speeds, one at 2 m/s and another that results in the longest predictable downwind dispersion distance that is exceeded less than 10% of the time
- Measured contours of methane are taken from 0.5 meters (1.6 feet) above the ground and at a concentration of 50% of the lower flammability limit (LFL), or a 2.2% methane concentration in air

The following table has scenarios were used for the case of a guillotine break of the LNG pipe:

Table 2 Scenarios and Conditions for Pipe Guillotine

Scenario #	Wind Speed (m/s)	Wind Angle and Origin	LNG Flow Rate (kg/s)	Elapsed Time (min : sec)
1	2	30° (Southwest)	509	3:10
2	2	300° (North-northwest)	509	17:20
3	2	90° (South)	509	17:20
4	2	322° (West-northwest)	509	17:20
5	0.46	30° (Southwest)	509	35:25
6	0.46	300° (North-northwest)	509	35:25
7	0.46	90° (South)	509	33:45
8	0.46	322° (West-northwest)	509	20:24

The following table has the scenarios were used for the rupture of the LNG tank:

Table 3 Scenarios and Conditions for Tank Rupture

Scenario #	Wind Speed (m/s)	Wind Angle and Origin	Liquid Level (m)	Calculated Flow Rate (kg/s)	Elapsed Time (min : sec)
9	2	30° (Southwest)	2.6	5613	16:11
10	2	300° (North-northwest)	10.4	10103	17:01
11	2	70° (South-southwest)	3.2	6087	13:45
12	2	325° (West-northwest)	19.4	13531	17:51
13	0.46	30° (Southwest)	4.5	7016	20:22
14	0.46	300° (North-northwest)	15.4	12123	5:21
15	0.46	70° (South-southwest)	6.9	8419	6:16
16	0.46	325° (West-northwest)	7.6	8770	17:01

Risk Considerations

The scope of this project was to obtain a "worst" case, or possible, scenario of dispersion from the LNG plant. The worst case scenario represents a possible outcome based upon a quantity of material being released by a possible initiating event. These scenarios are typically used for emergency planning and communication.

This worst case or possible scenario represents the capability of a consequence to occur. Typical risk assessment based probable scenarios represent a quantified likelihood, or frequency, of a consequence to occur. Probability is considered a subset of possibility.

This model does not express probability:

- This model neither expresses the likelihood of the individual event which initiates the release, nor the likelihood that dispersion would be limited by mitigation/control measures or ignition sources.
- A facility risk assessment would consider control and mitigation measures such as, process controls, emergency shutdowns, operator intervention, and response efforts.
- Based upon the material properties, the presence of an ignition source could cause a fire which disrupts the dispersion. Ignition sources can be found at installations such as industrial sites and roadways.

While probability was not expressed, an industry reference exists for the release mechanism, which would result from an initiating event:

- A general reference frequency for a pipe guillotine break is 1/100,000 years per pipe and for a tank rupture is 1/100,000 years per tank, as given by the Center for Chemical Process Safety (CCPS) book from 2001 titled "Layers of Protection Analysis". CCPS is considered an industry resource providing data based upon industry experience and analysis.
- Frequency is an estimate of a given scenario over a period of time. The estimate is typically based upon statistical data associated with the event. Frequency can be as simple as the sun rises every day or 1 events per day (1/1day). It should be noted that these probabilities are generalized over a broad range of types of tanks and pipes, and the number provided is not a perfect representation of the actual chance of an accident. It is generally understood for practical application that this calculated frequency can be expected to vary by one order of magnitude.

Engineering Error Rate

Engineering error rate is a calculation of individual components of equations against each other to define propagation of error. This occurs due to the fact those equations whether based on facts or empirical data. The error rate derives from each of those factors in the equation due to significate figure limits, a data point or equation curve determined from observations. So, each component from the equation contributes an error and the error amount grows with the number of components. Thus, the error can be small as 5% to as large as 50%.

This calculation is complex and time consuming and the error rate is not the same for all uses of an equation. In this modeling case, you would have to calculate an error rate for each scenario. However, based on experience with these system, we would estimate the rate for this project to be in the range of 10 to 15%.

Results

The modeling results indicate that for any of the scenarios listed above, if the natural gas cloud were not to ignite, it may reach a large portion of the proposed housing development zones as well as a large number of homes that are already constructed and occupied. Of particular concern are those areas closest to the site and those lying at lower elevations where the cold gas tends to settle. Graphical images of the contours are shown in the Appendices.

The following table has the individual results for the pipe guillotine break scenarios:

Table 4 Pipe Guillotine Results

Scenario #	Wind Speed (m/s)	Elapsed Time (min : sec)	Furthest Contour Distance (miles)
1	2	3:10	0.97 (NE)
2	2	17:20	>3.8* (SE)
3	2	17:20	>2.3* (N)
4	2	17:20	>3.3* (SE)
5	0.46	35:25	2.7 (NE) >2.5* (N)
6	0.46	35:25	>3.5* (SE)
7	0.46	33:45	2.2 (NE)
8	0.46	20:24	1.4 (S)

*The ½ LFL contours extended to the edge of the computational domain and could not be estimated any further

The following table has the individual results for the LNG tank rupture scenarios:

Table 5 Tank Rupture Results

Scenario #	Wind Speed (m/s)	Elapsed Time (min : sec)	Furthest Contour Distance (miles)
9	2	16:11	>3.5* (NE)
10	2	17:01	>3.8* (SW)
11	2	13:45	>2.7* (NE)
12	2	17:51	>3.5* (SE)
13	0.46	20:22	3.4 (SE), >3.2* (NE)
14	0.46	5:21	0.96 (SE)
15	0.46	6:16	1.44 (NE)
16	0.46	17:01	1.8 (SW)

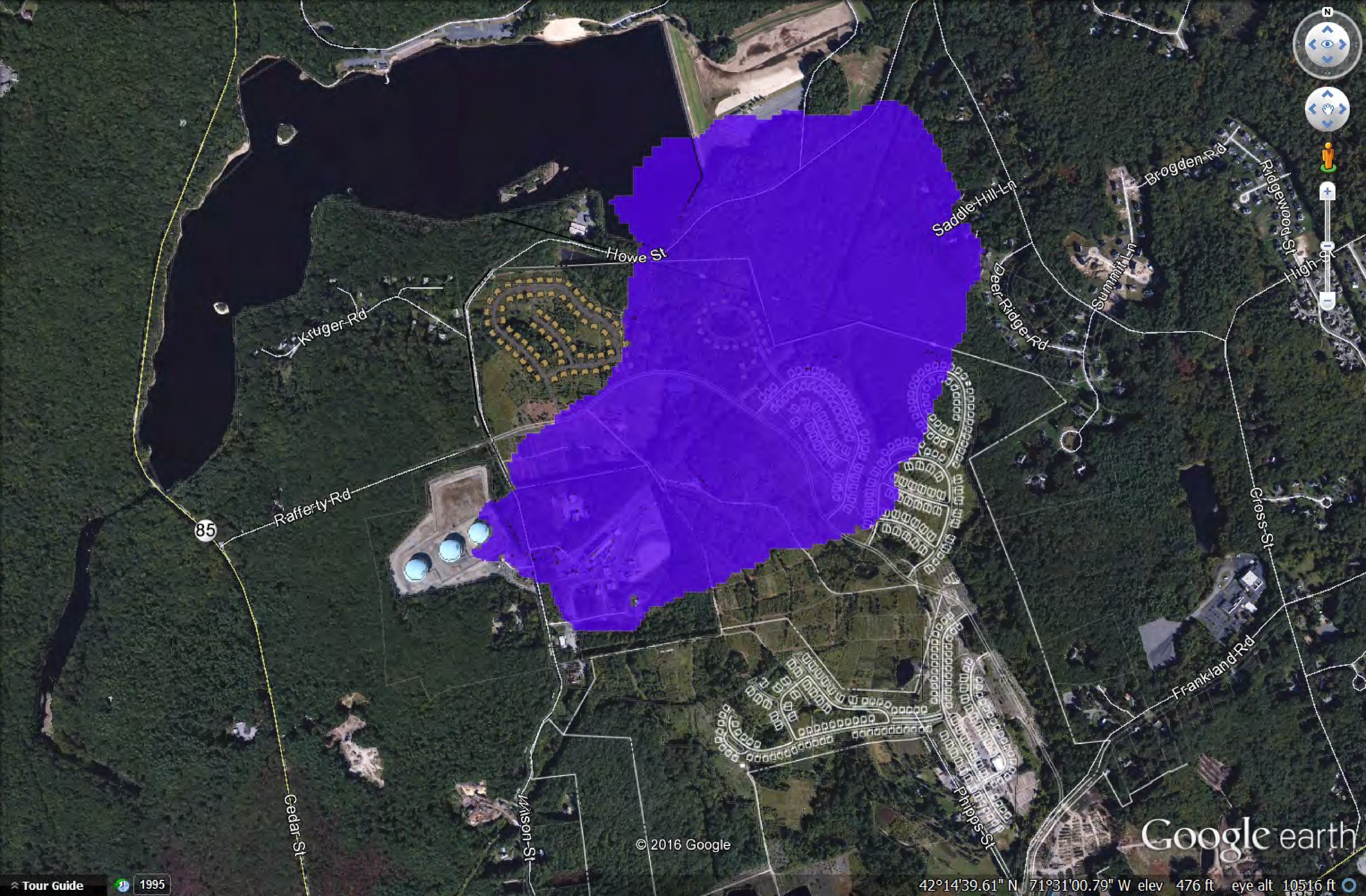
*The ½ LFL contours extended to the edge of the computational domain and could not be estimated any further

The contours for the natural gas cloud were narrower under a 2 m/s wind speed (scenarios 1-4 and 9-12) than the 0.46 m/s wind speed (scenarios 5-8 and 13-16). Also, by comparing simulations of shortened duration (simulation 1 and 8), it is apparent that the cloud travels much faster under higher wind speeds.

Appendix List

Appendix A: Pipe Guillotine Scenario #1; Wind from Southwest at 2 m/s

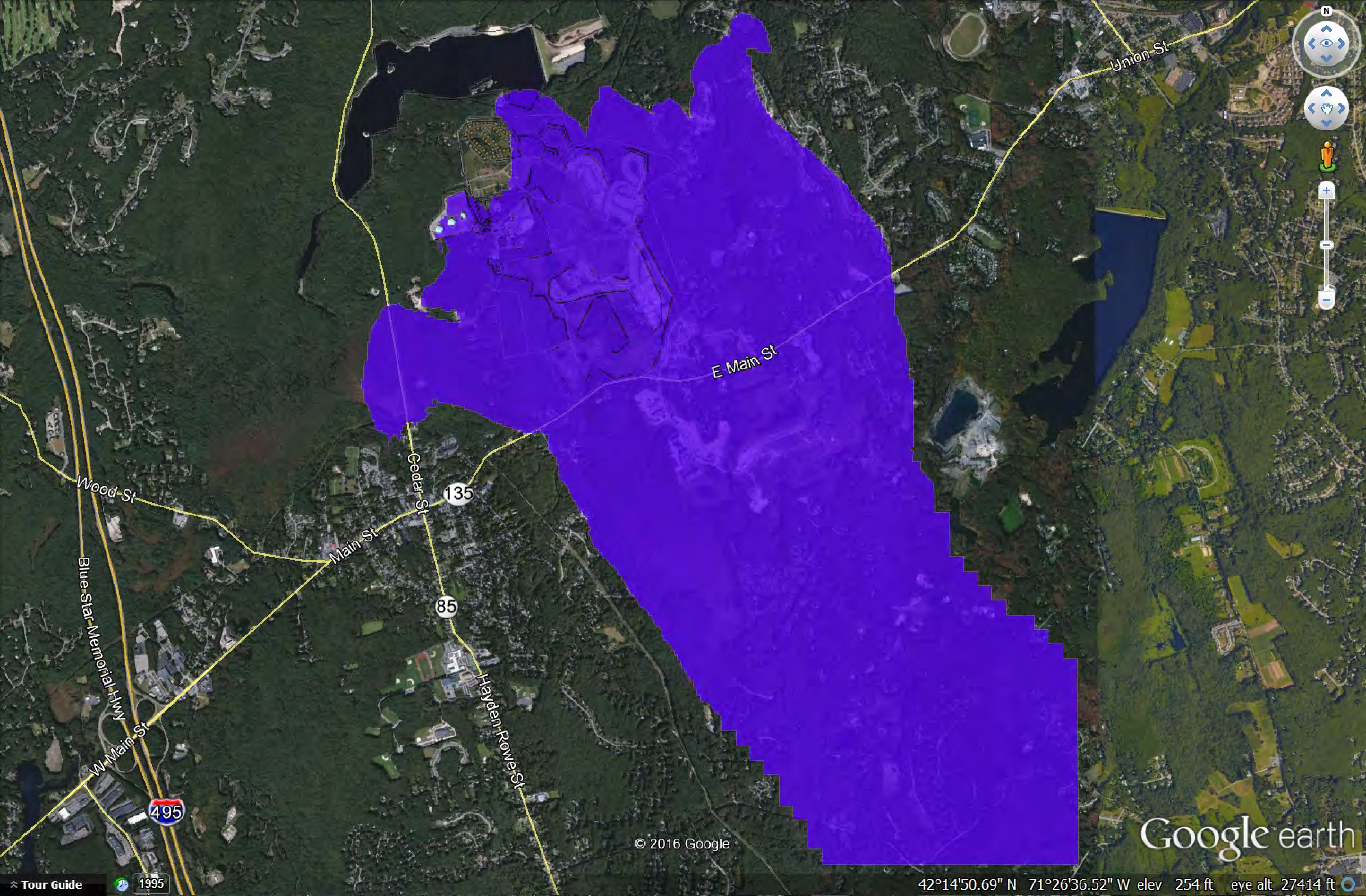
Scenario is with a 509 kg/s release rate over a period of 3 minutes and 10 seconds.



Howe St
Saddle Hill Ln
Brogden Rd
Ridgewood St
High St
Summit Ln
Deer Ridge Rd
Kruger Rd
Rafferty Rd
85
Cross St
Frankland Rd
Cedar St
Wilson St
Phipps St
© 2016 Google
Google earth
Tour Guide
1995
42°14'39.61" N 71°31'00.79" W elev 476 ft eye alt 10516 ft

Appendix B: Pipe Guillotine Scenario #2; Wind from North-northwest at 2 m/s

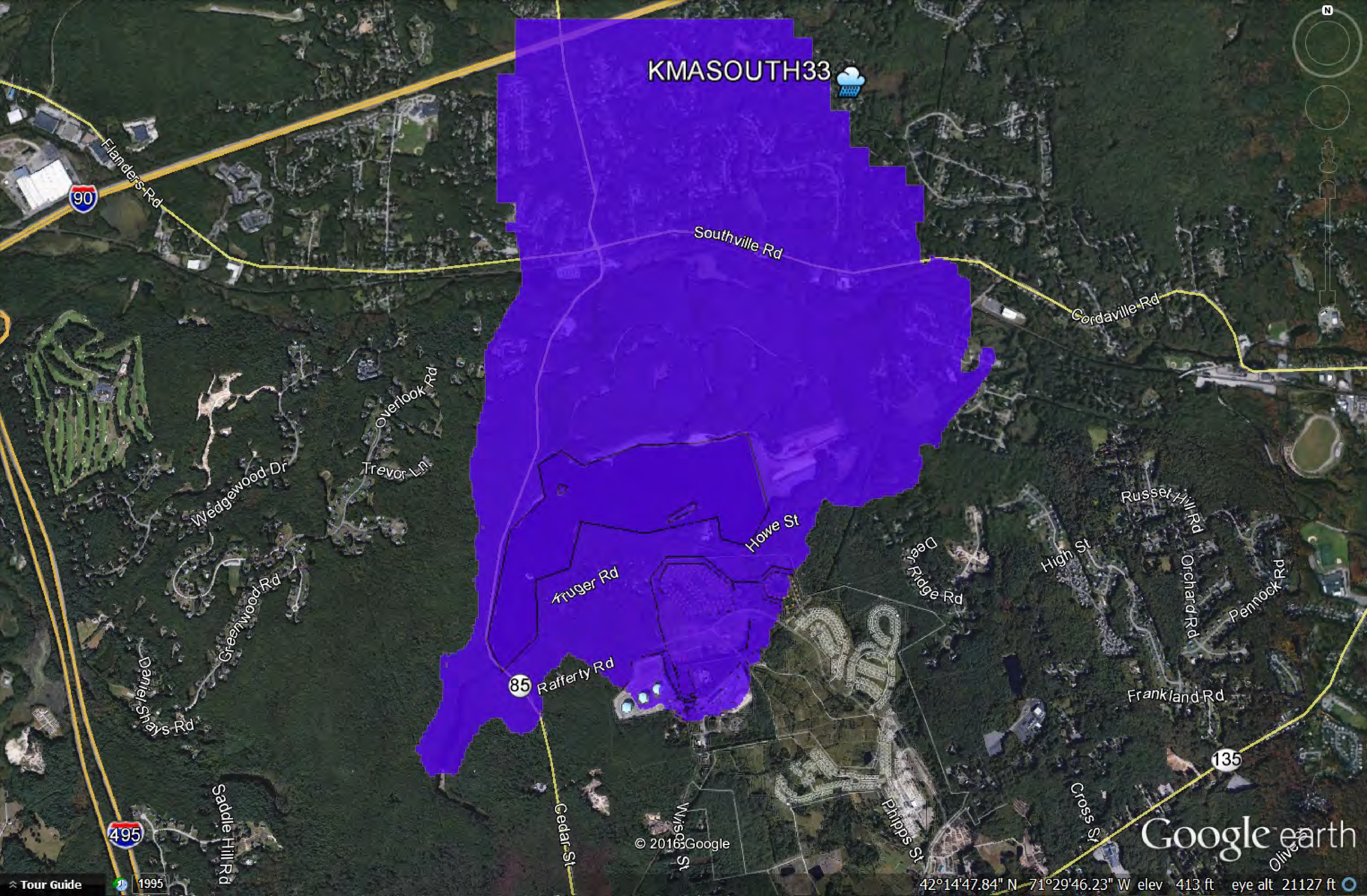
Scenario is with a 509 kg/s release rate over a period of 17 minutes and 20 seconds.



Union St
E Main St
Wood St
Main St
Cedar St
135
85
Blue Star Memorial Hwy
W Main St
495
Hayden Rowe St
© 2016 Google
Google earth
Tour Guide
1995
42°14'50.69" N 71°26'36.52" W elev 254 ft eye alt 27414 ft

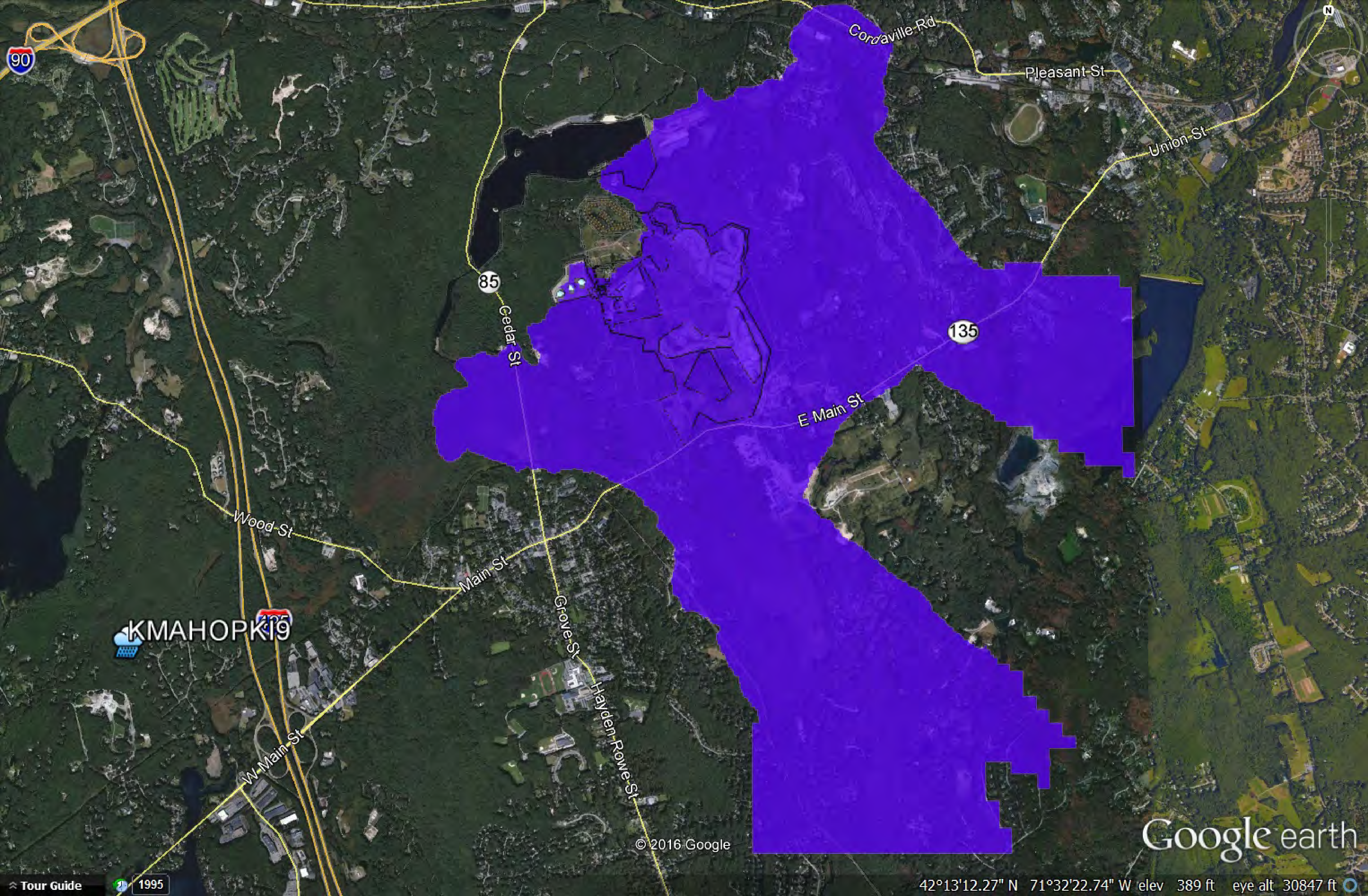
Appendix C: Pipe Guillotine Scenario #3; Wind from South at 2 m/s

Scenario is with a 509 kg/s release rate over a period of 17 minutes and 20 seconds.


KMASOUTH33
Flanders Rd
90
Southville Rd
Cordaville Rd
Overlook Rd
Trevor Ln
Wedgewood Dr
Greenwood Rd
Kruger Rd
Howe St
Deer Ridge Rd
High St
Russet Hill Rd
Orchard Rd
Pennock Rd
Frankland Rd
85
Rafferty Rd
Daniel Shays Rd
495
Saddle Hill Rd
Cedar St
Wisc St
Phipps St
Cross St
135
© 2016 Google
Google earth
Tour Guide
1995
42°14'47.84" N 71°29'46.23" W elev 413 ft eye alt 21127 ft

Appendix D: Pipe Guillotine Scenario #4; Wind from West-northwest at 2 m/s

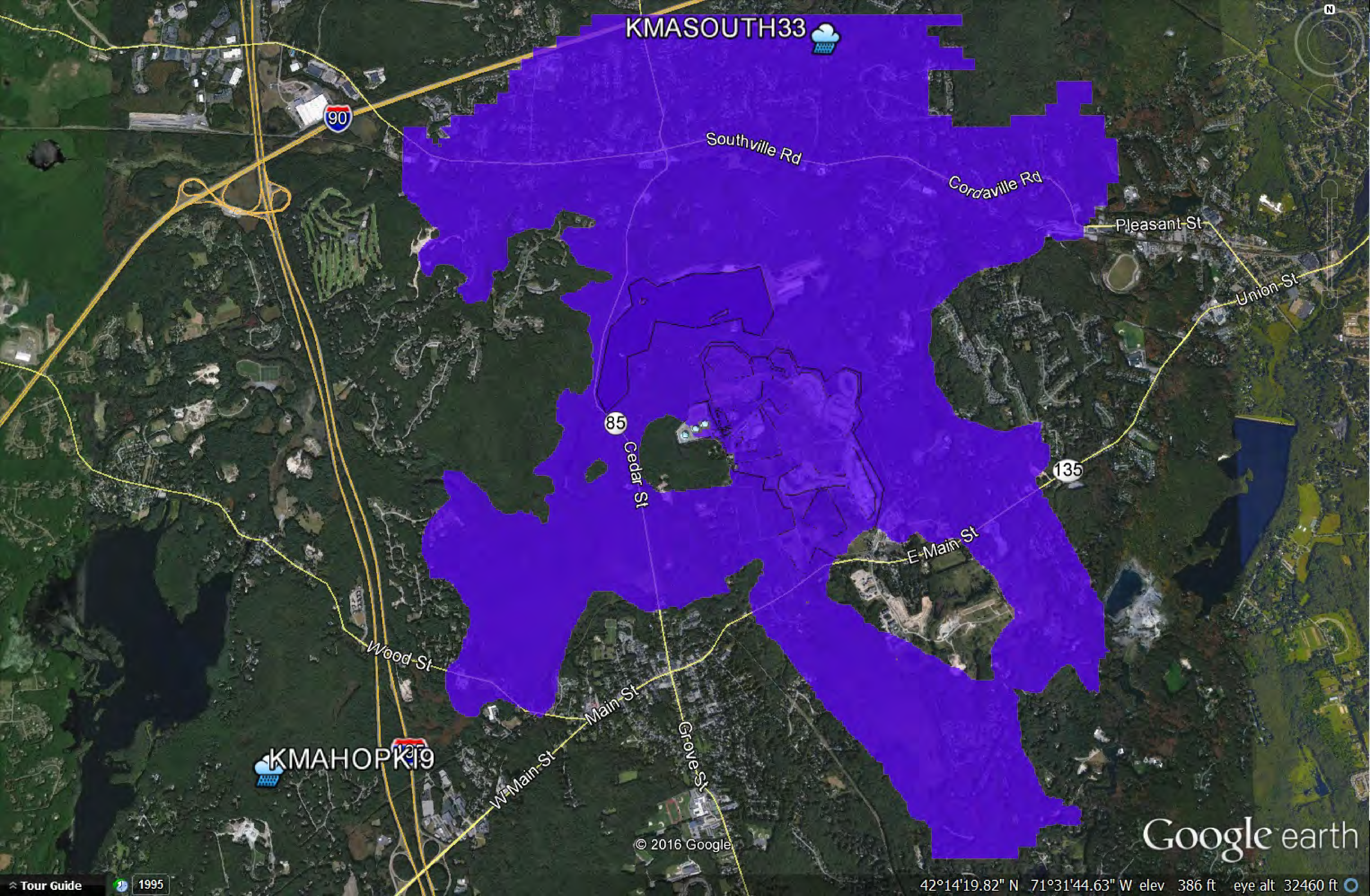
Scenario is with a 509 kg/s release rate over a period of 17 minutes and 20 seconds.



Cordaville Rd
Pleasant St
Union St
90
85
Cedar St
135
E Main St
Wood St
Main St
KMAHOPKI9
Grove St
Hayden Rowe St
W Main St
© 2016 Google
Google earth
Tour Guide
1995
42°13'12.27" N 71°32'22.74" W elev 389 ft eye alt 30847 ft

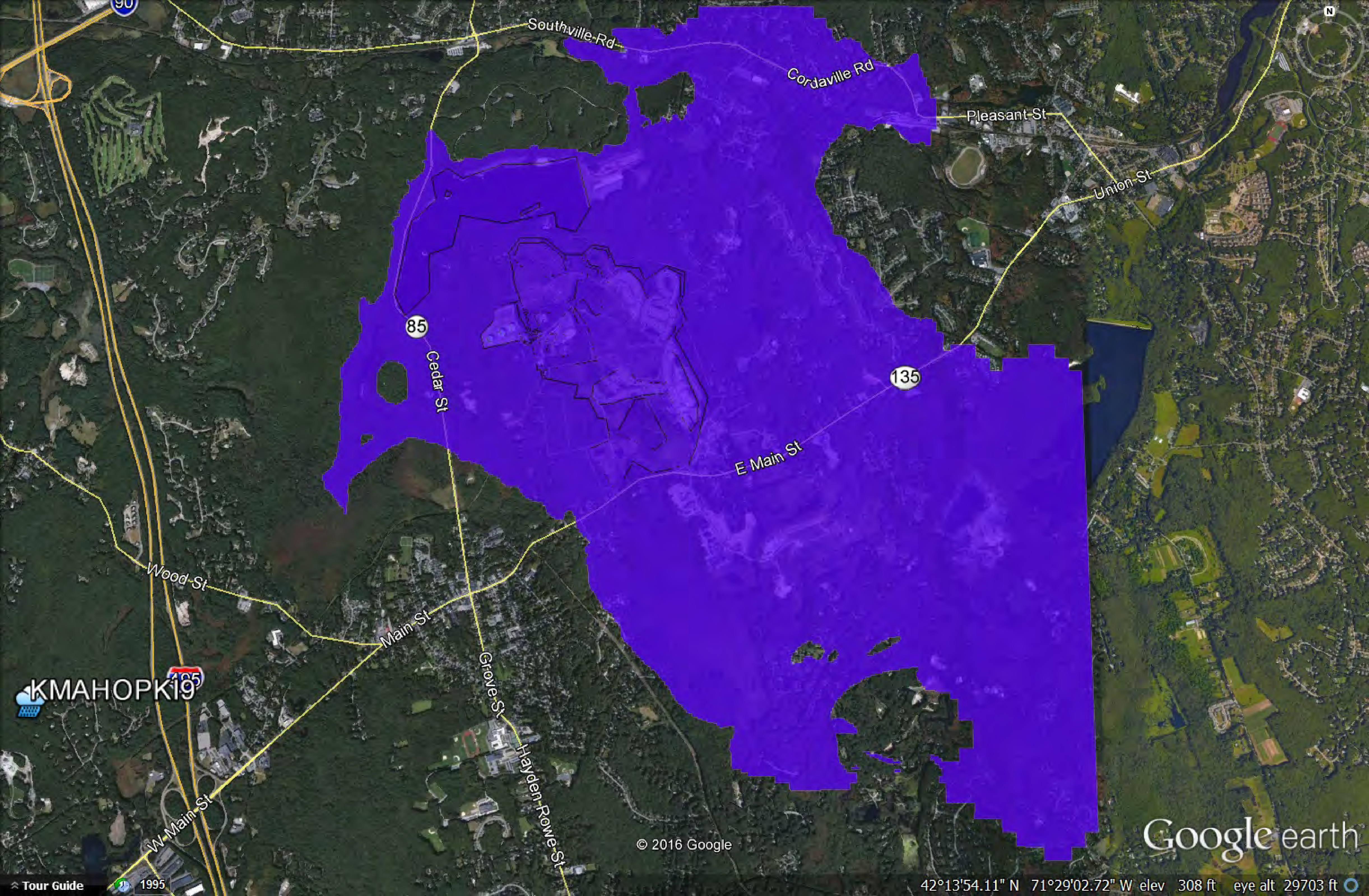
Appendix E: Pipe Guillotine Scenario #5; Wind from Southwest at 0.46 m/s

Scenario is with a 509 kg/s release rate over a period of 35 minutes and 25 seconds.


KMASOUTH33
Southville Rd
Cordaville Rd
Pleasant St
Union St
85
Cedar St
135
E Main St
Wood St
Main St
W Main St
Grove St
KMAHOPKI9
90
© 2016 Google
Google earth
Tour Guide
1995
42°14'19.82" N 71°31'44.63" W elev 386 ft eye alt 32460 ft

Appendix F: Pipe Guillotine Scenario #6; Wind from North-northwest at 0.46 m/s

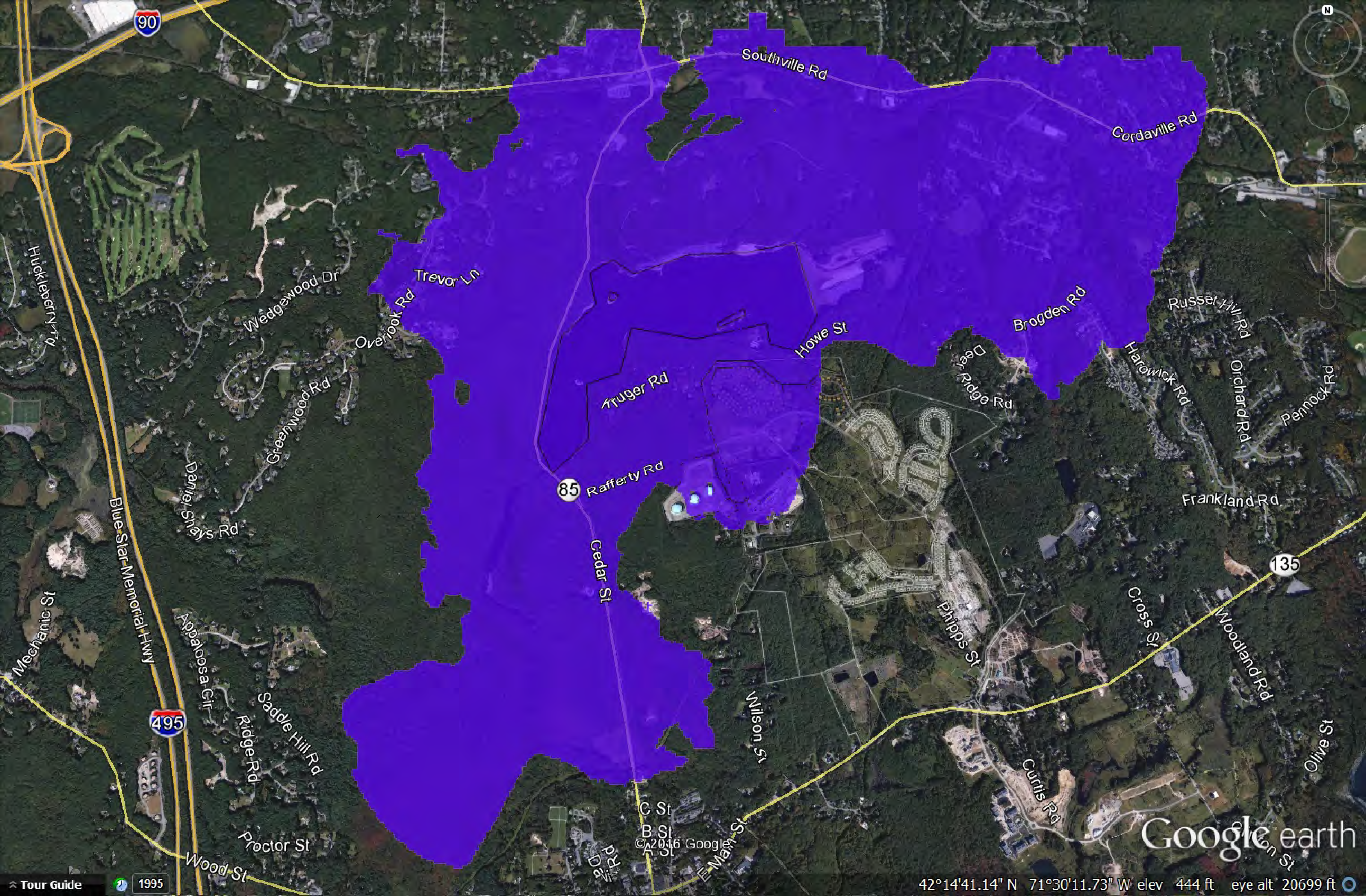
Scenario is with a 509 kg/s release rate over a period of 35 minutes and 25 seconds.



90
Southville Rd
Cordaville Rd
Pleasant St
Union St
85
Cedar St
135
E Main St
Wood St
Main St
495
KMAHOPKI9
Grove St
Hayden Rowe St
W Main St
© 2016 Google
Google earth
Tour Guide
1995
42°13'54.11" N 71°29'02.72" W elev 308 ft eye alt 29703 ft

Appendix G: Pipe Guillotine Scenario #7; Wind from South at 0.46 m/s

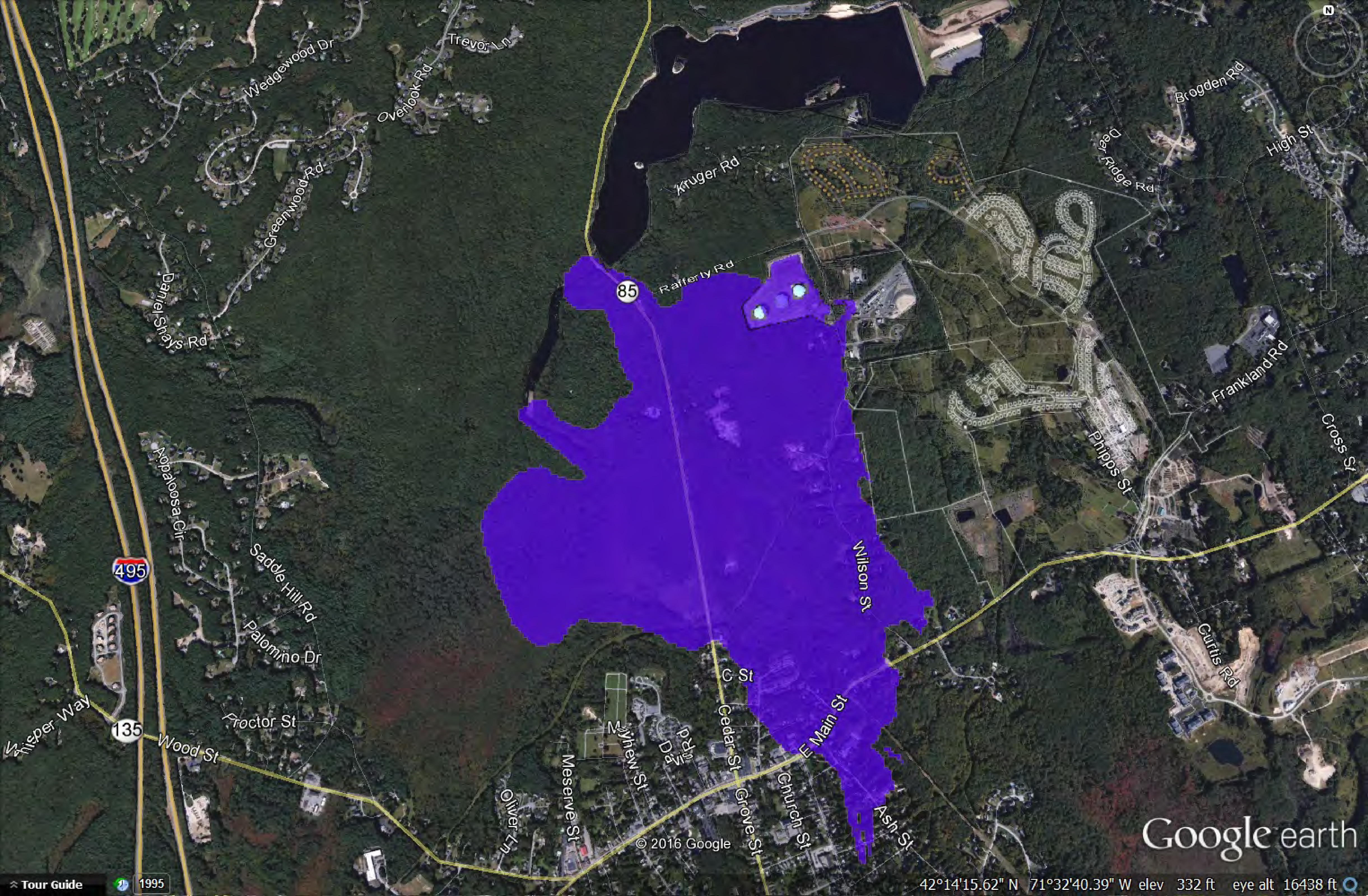
Scenario is with a 509 kg/s release rate over a period of 35 minutes and 45 seconds.



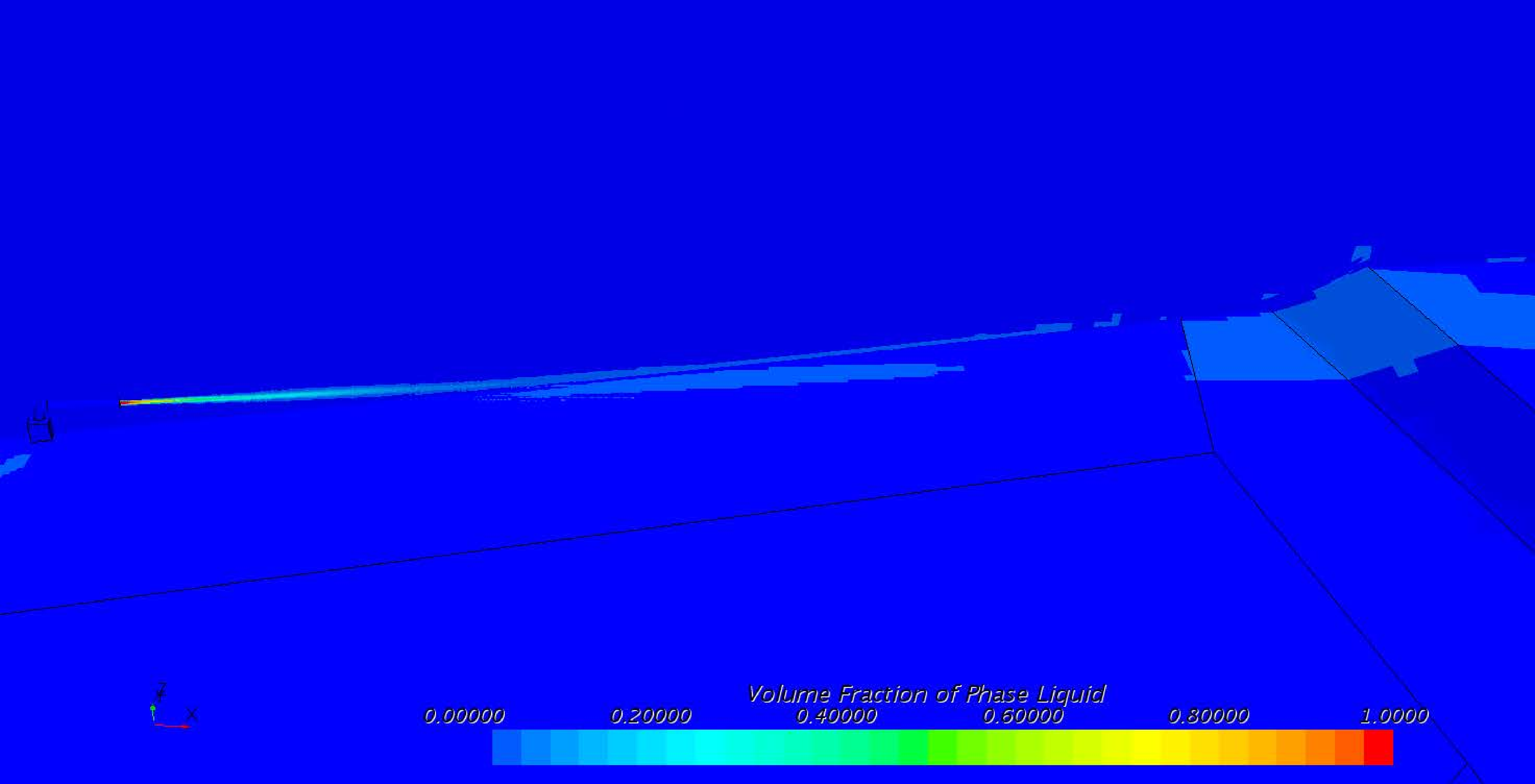
90
Southville Rd
Cordaville Rd
Trevor Ln
Overlook Rd
Wedgewood Dr
Huckleberry Rd
Howe St
Brogden Rd
Russet Hill Rd
Deer Ridge Rd
Harowick Rd
Orchard Rd
Pennock Rd
Kruger Rd
Greenwood Rd
Daniel Shays Rd
Blue Star Memorial Hwy
85
Rafferty Rd
Frankland Rd
Cedar St
135
Cross St
Woodland Rd
Phipps St
Mechanic St
Appaloosa Cir
Saddle Hill Rd
Ridge Rd
495
Wilson St
Curtis Rd
Olive St
C St
B St
A St
E Main St
Proctor St
Wood St
© 2016 Google
Google earth
Tour Guide
1995
42°14'41.14" N 71°30'11.73" W elev 444 ft eye alt 20699 ft

Appendix H: Pipe Guillotine Scenario #8; Wind from West-northwest at 0.46 m/s

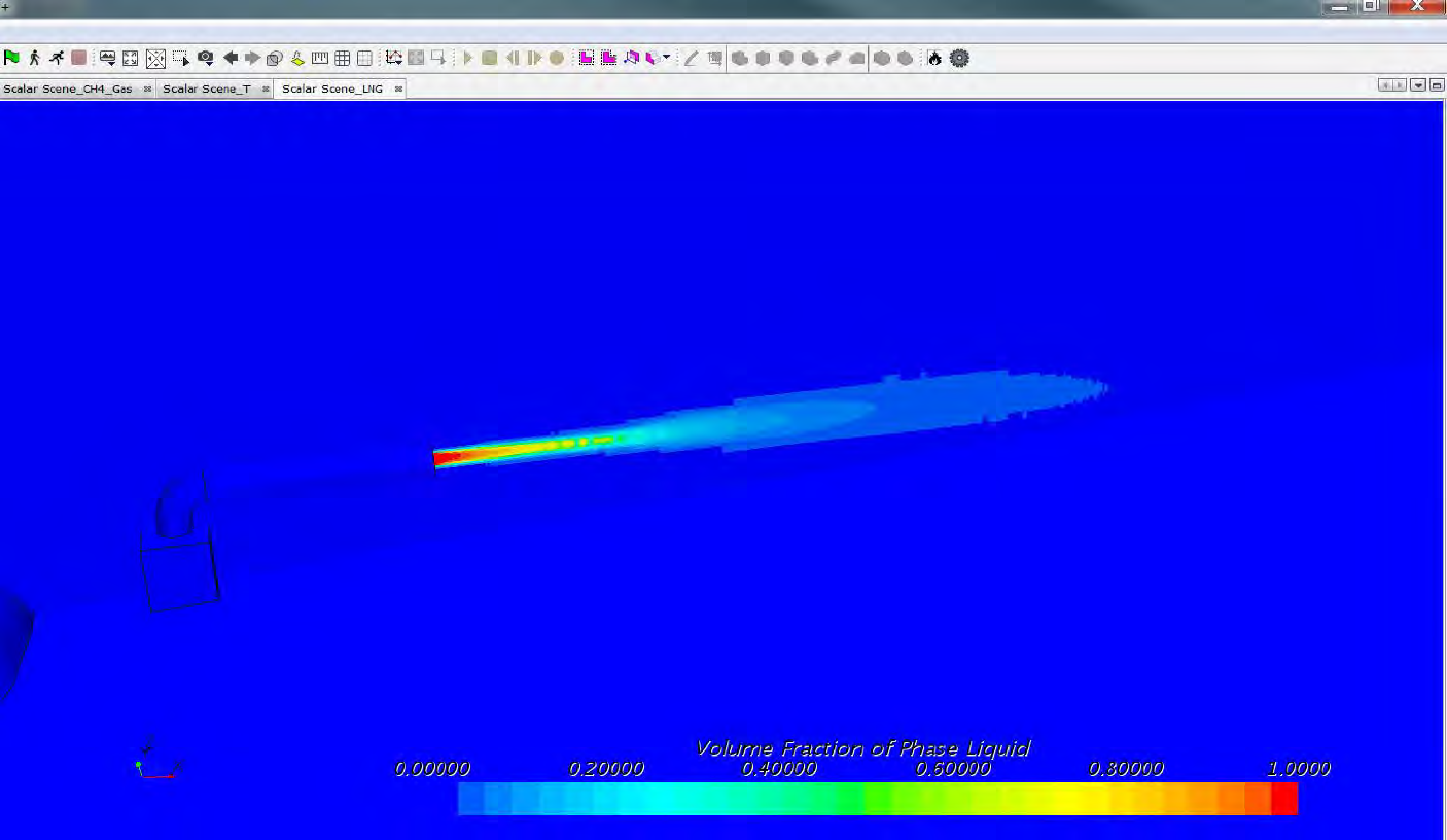
Scenario is with a 509 kg/s release rate over a period of 20 minutes and 24 seconds.

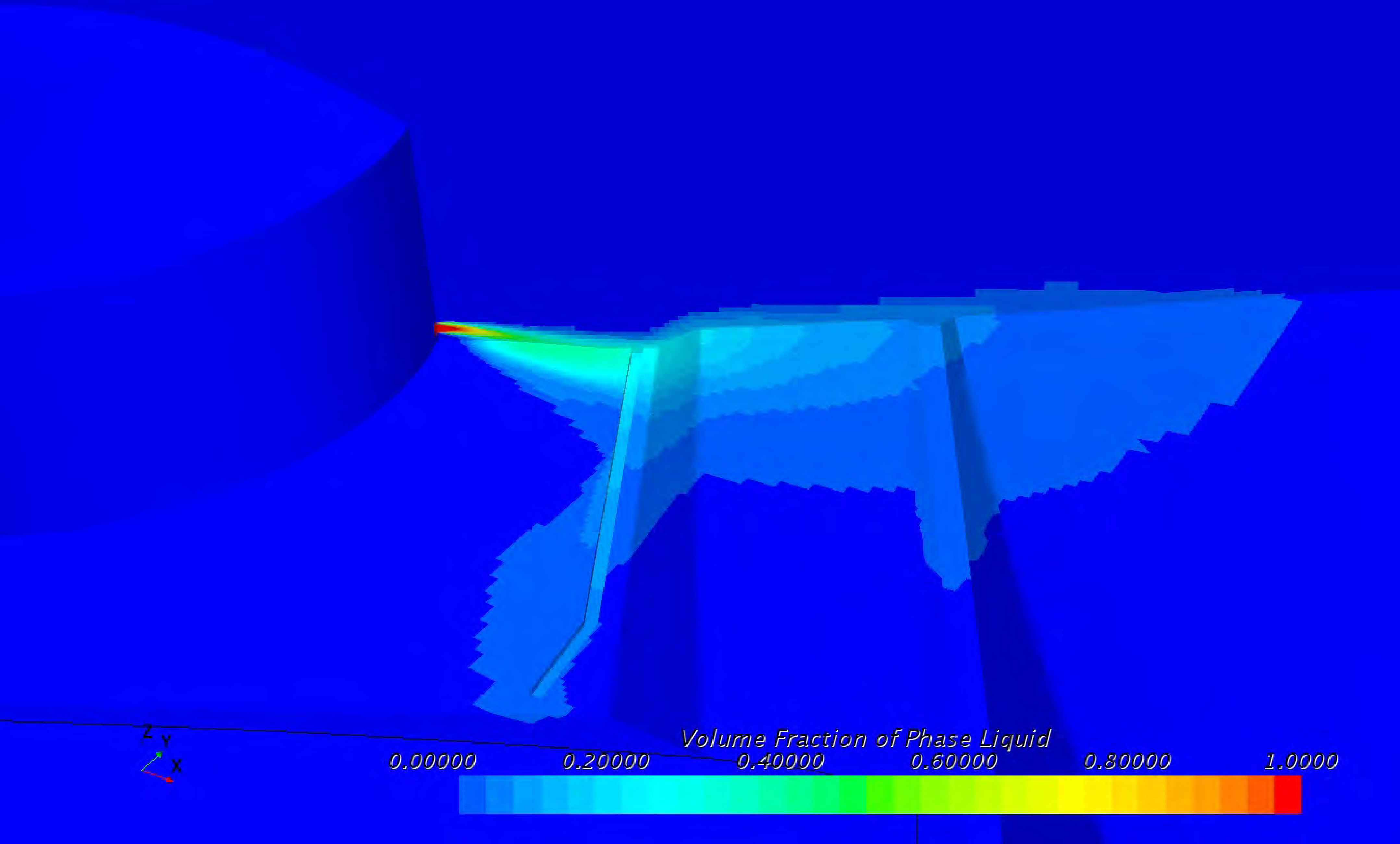

Wedgewood Dr
Trevor Ln
Overlook Rd
Greenwood Rd
Kruger Rd
Brogden Rd
Deer Ridge Rd
High St
Daniel Shays Rd
Rafferty Rd
85
Frankland Rd
Cross St
Phipps St
Appaloosa Cir
Saddle Hill Rd
Wilson St
495
Palomino Dr
Curtis Rd
C St
Proctor St
Whisper Way
135
Wood St
E Main St
Cedar St
Mayhew St
Meserve St
Oliver Ln
Grove St
Church St
Ash St
© 2016 Google
Google earth
Tour Guide
1995
42°14'15.62" N 71°32'40.39" W elev 332 ft eye alt 16438 ft

Appendix I: Side Views of Piping Releases at 0.46 m/s and 2 m/s Wind Speed and a Tank Release at 2 m/s Wind Speed



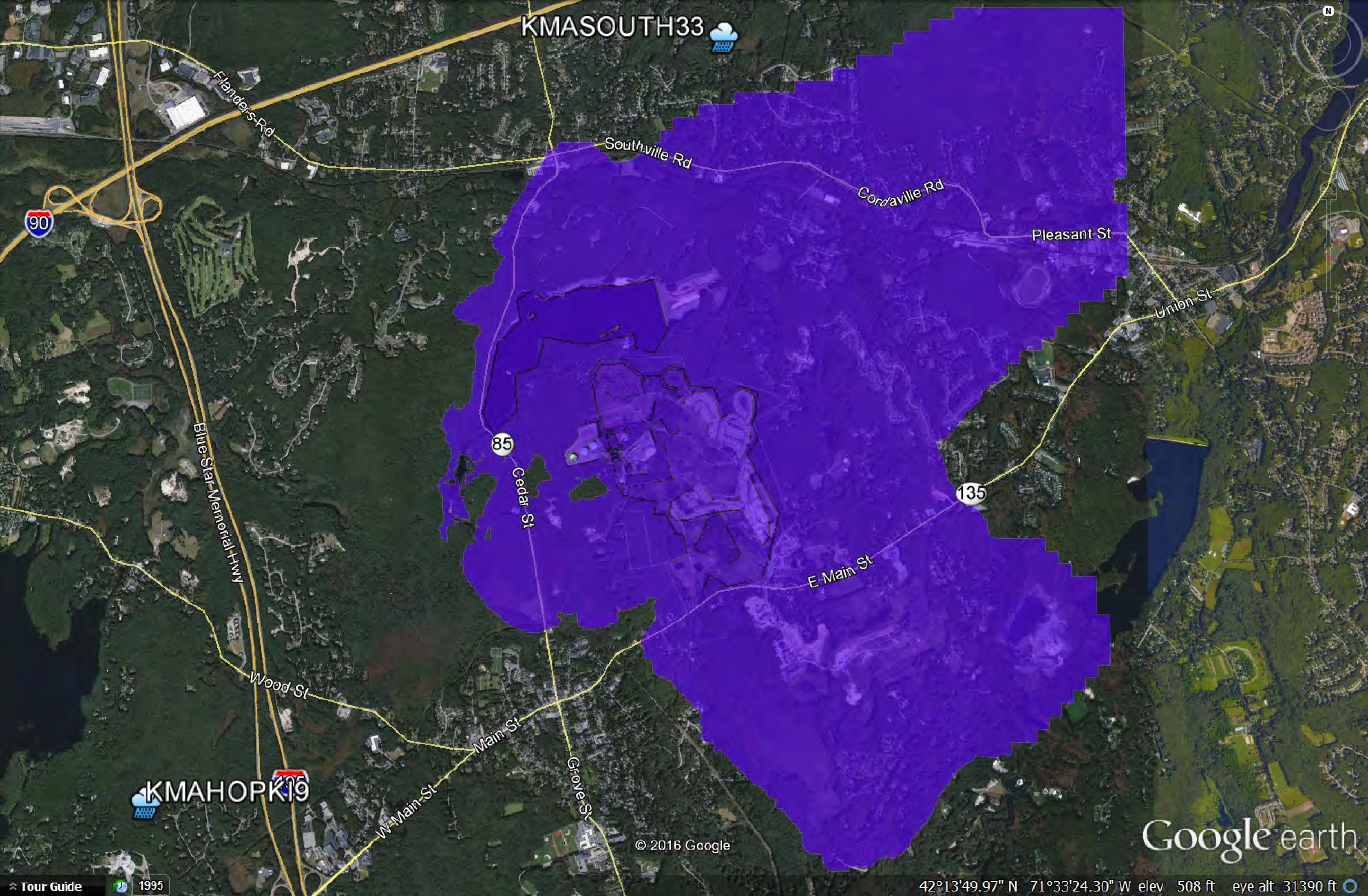
Volume Fraction of Phase Liquid
0.00000
0.20000
0.40000
0.60000
0.80000
1.0000
Z
X


Scalar Scene_CH4_Gas
Scalar Scene_T
Scalar Scene_LNG
Volume Fraction of Phase Liquid
0.00000
0.20000
0.40000
0.60000
0.80000
1.0000


Volume Fraction of Phase Liquid
0.00000
0.20000
0.40000
0.60000
0.80000
1.0000
Z
Y
X

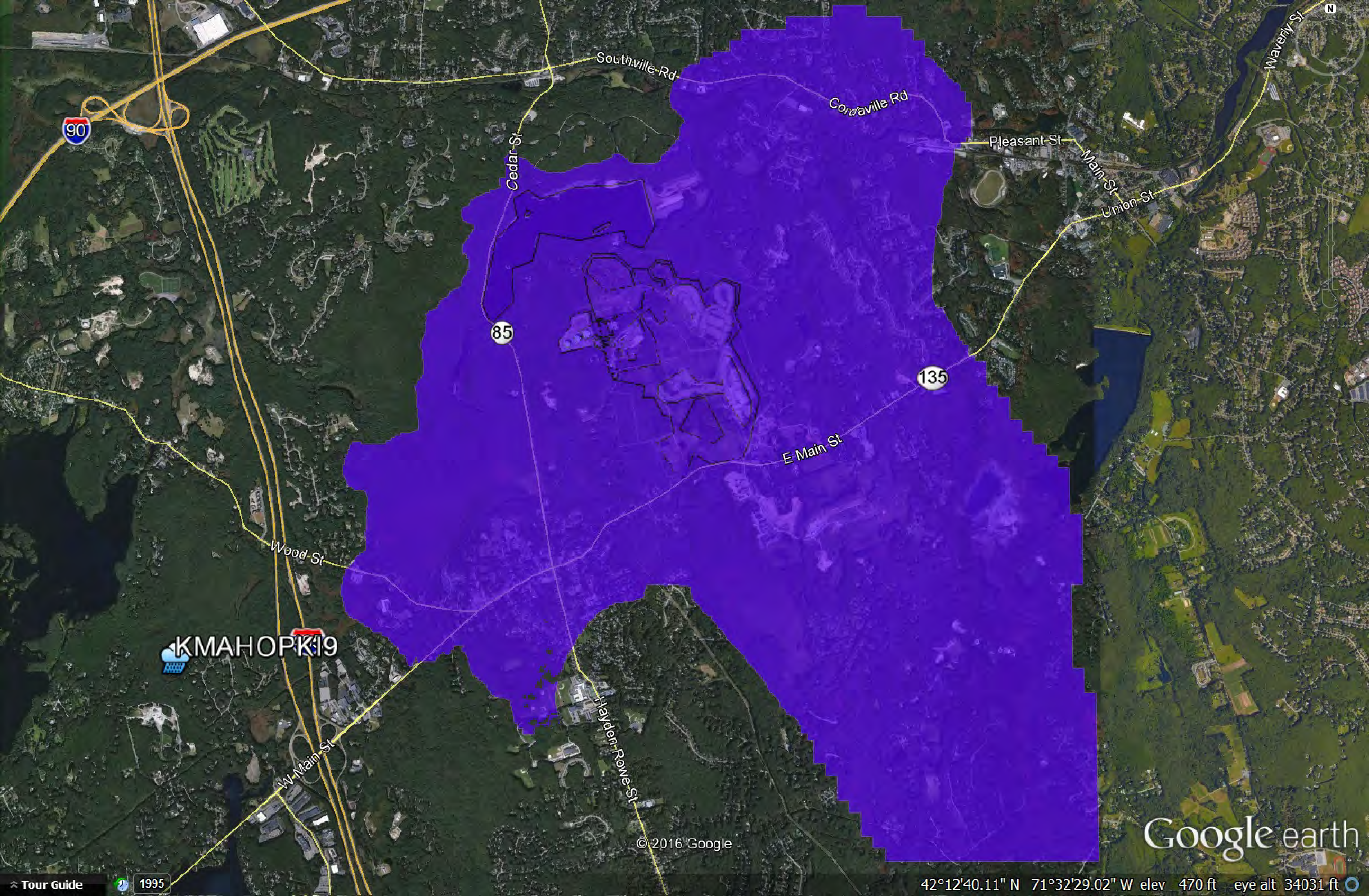
Appendix J: Tank Rupture Scenario #9; Wind from Southwest at 2 m/s

Scenario is with a 5,613 kg/s release rate over a period of 16 minutes and 11 seconds.


KMASOUTH33
Flanders Rd
Southville Rd
Cordaville Rd
Pleasant St
Union St
90
85
135
Cedar St
E Main St
Blue Star Memorial Hwy
Wood St
Main St
W Main St
Grove St
KMAHOPKI9
© 2016 Google
Google earth
Tour Guide
1995
42°13'49.97" N 71°33'24.30" W elev 508 ft eye alt 31390 ft

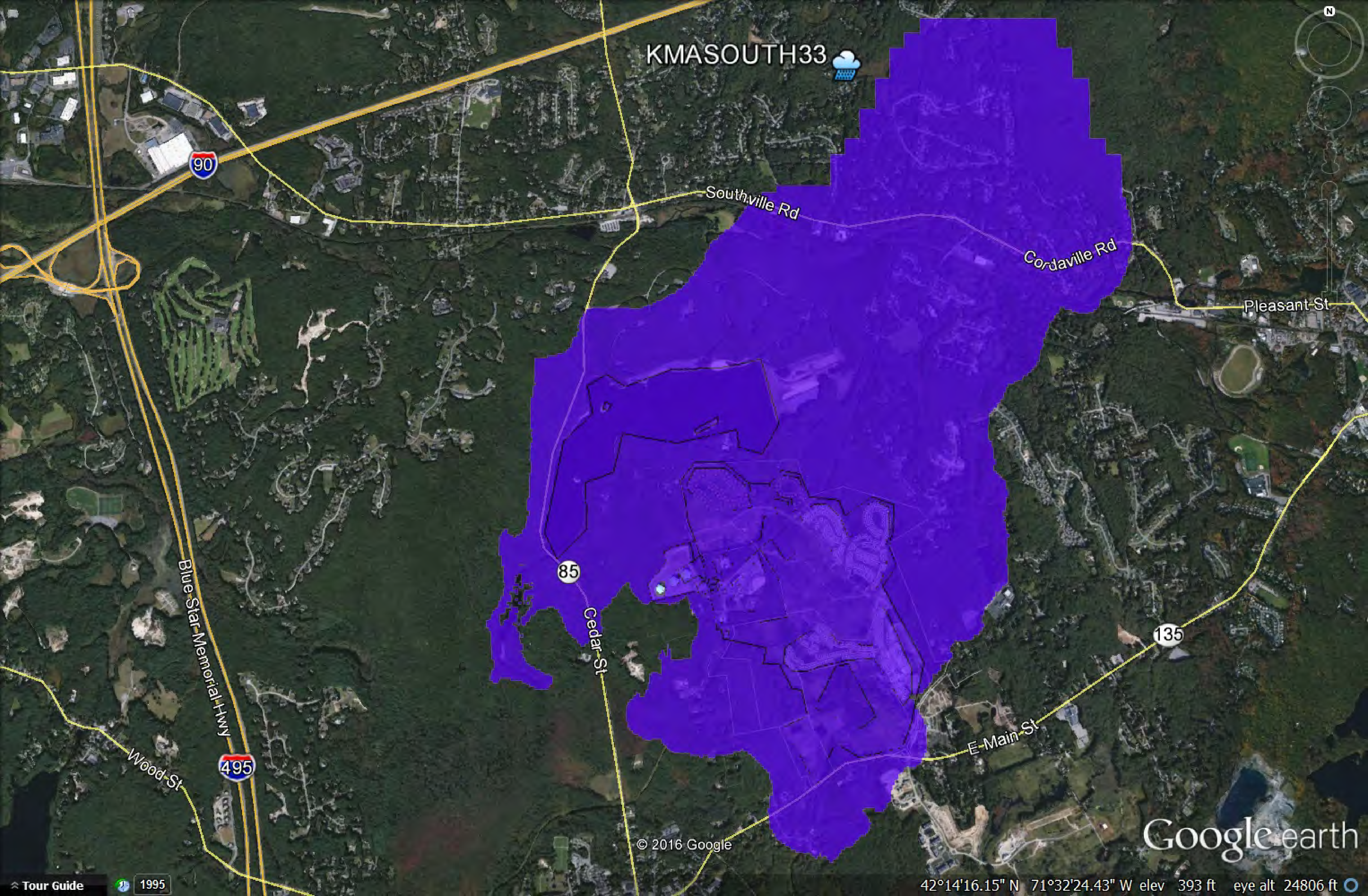
Appendix K: Tank Rupture Scenario #10; Wind from North-northwest at 2 m/s

Scenario is with a 10,103 kg/s release rate over a period of 17 minutes and 1 second.


Southville Rd
Cordaville Rd
Pleasant St
Main St
Union St
Waverly St
Cedar St
90
85
135
E Main St
Wood St
KMAHOPKI9
W Main St
Hayden Rowe St
© 2016 Google
Google earth
Tour Guide
1995
42°12'40.11" N 71°32'29.02" W elev 470 ft eye alt 34031 ft

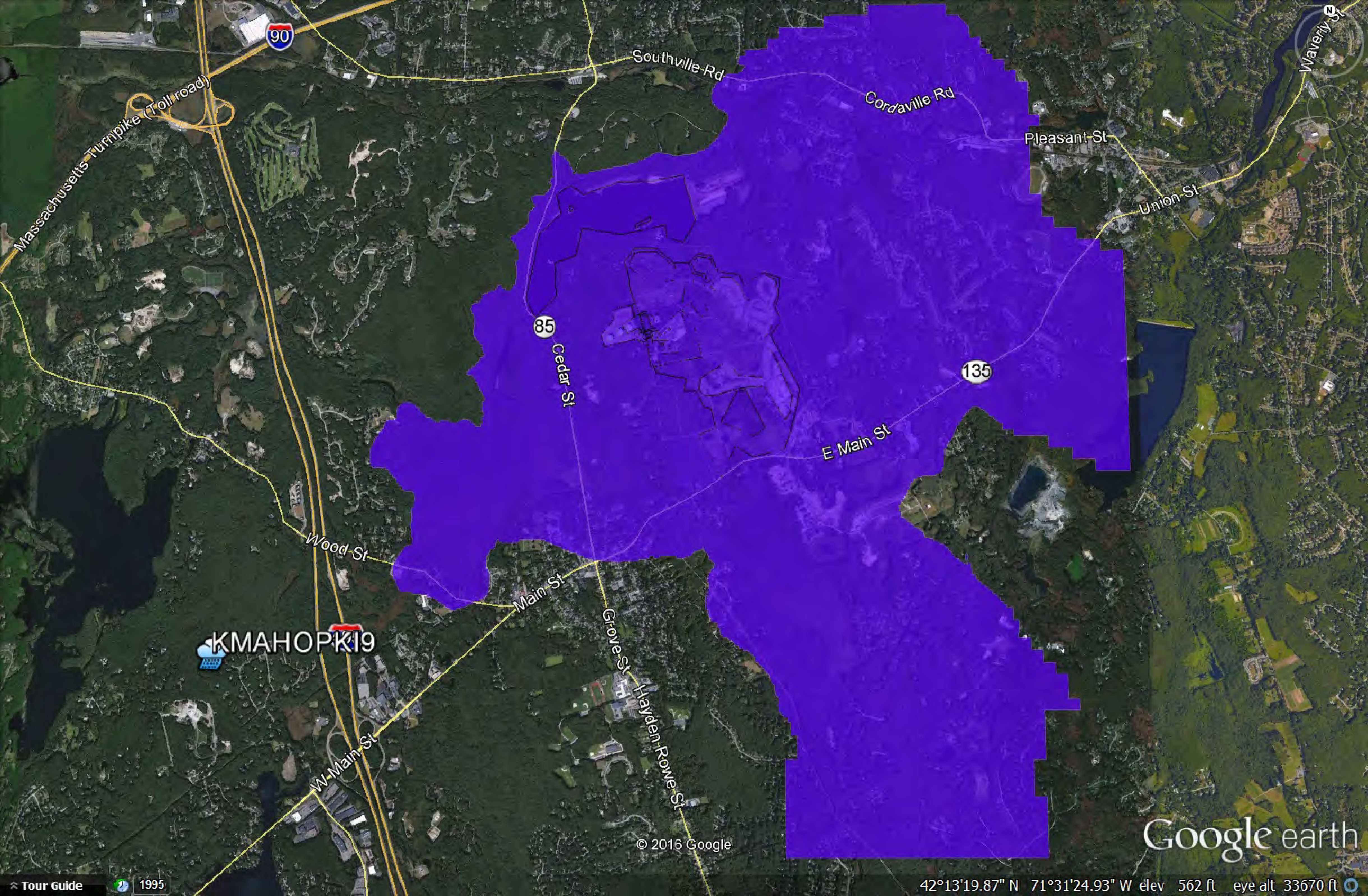
Appendix L: Tank Rupture Scenario #11; Wind from South-southwest at 2 m/s

Scenario is with a 6,087 kg/s release rate over a period of 13 minutes and 45 seconds.


KMASOUTH33
90
Southville Rd
Cordaville Rd
Pleasant St
85
Cedar St
135
E Main St
Blue Star Memorial Hwy
495
Wood St
© 2016 Google
Google earth
Tour Guide
1995
42°14'16.15" N 71°32'24.43" W elev 393 ft eye alt 24806 ft

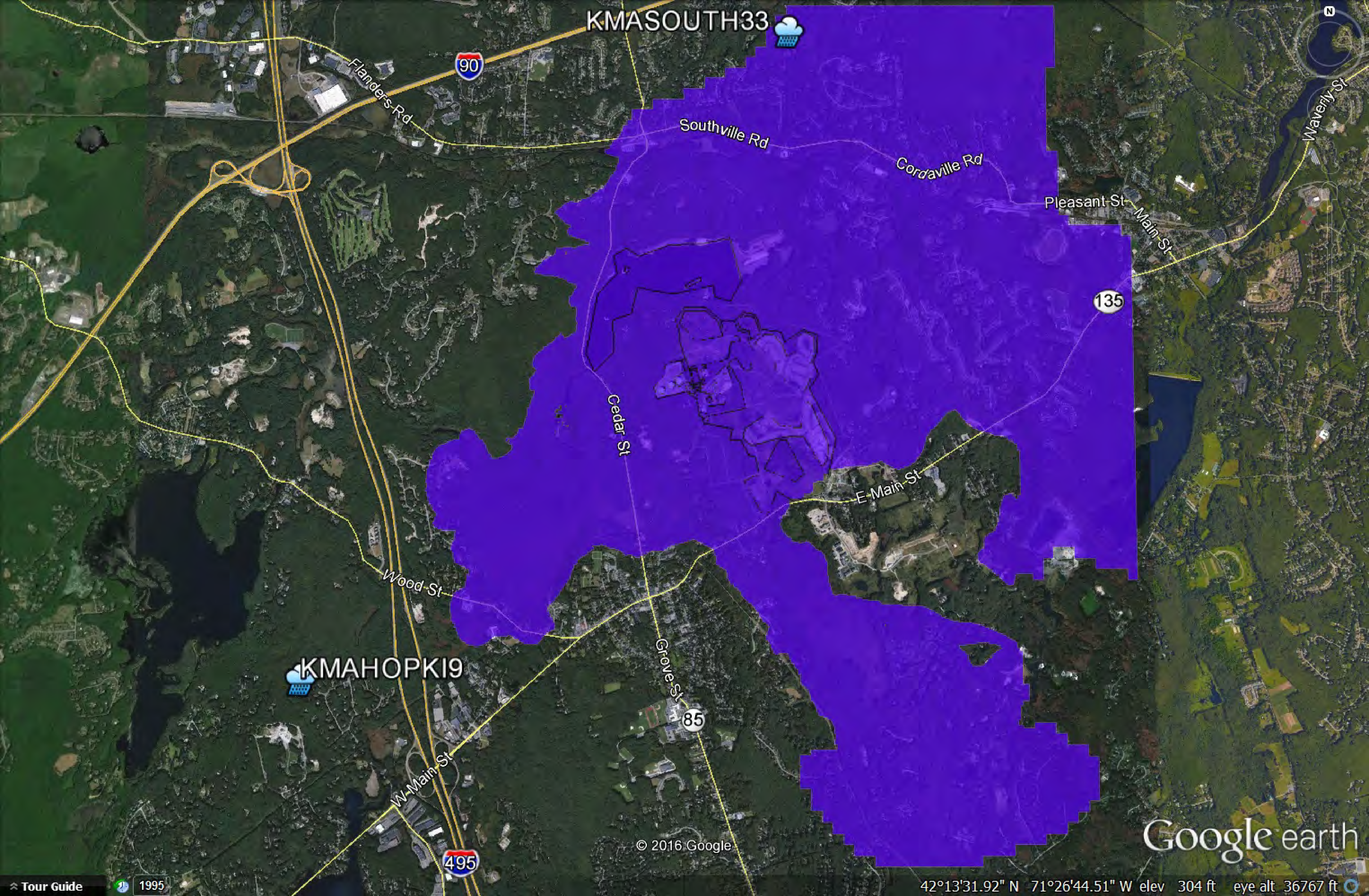
Appendix M: Tank Rupture Scenario #12; Wind from West-northwest at 2 m/s

Scenario is with a 13,531 kg/s release rate over a period of 17 minutes and 51 seconds.


90
Southville Rd
Cordaville Rd
Pleasant St
Waverly St
Union St
Massachusetts Turnpike (Toll road)
85
Cedar St
135
E Main St
Wood St
Main St
Grove St
Hayden Rowe St
W Main St
KMAHOPKI9
© 2016 Google
Google earth
Tour Guide
1995
42°13'19.87" N 71°31'24.93" W elev 562 ft eye alt 33670 ft

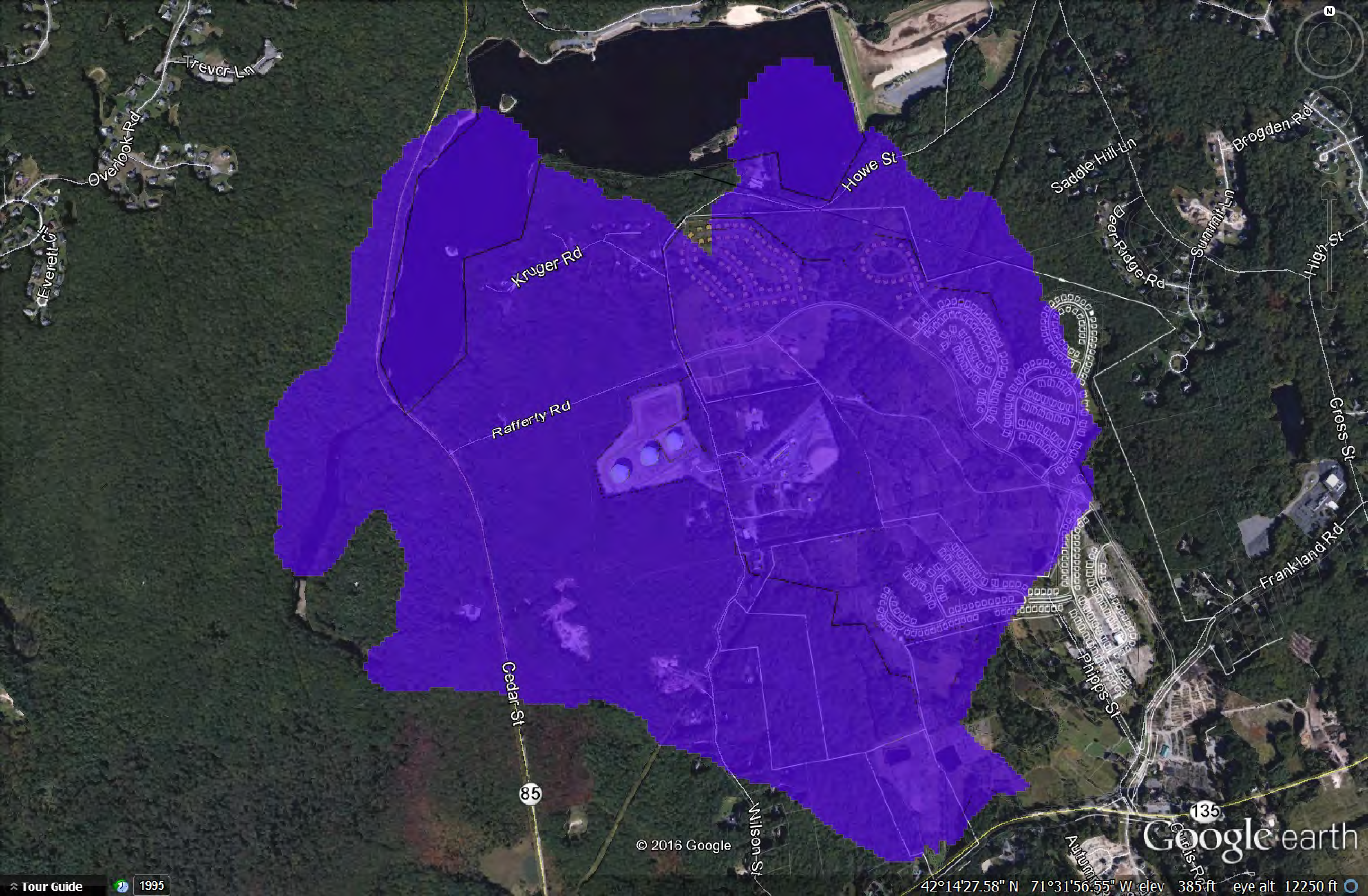
Appendix N: Tank Rupture Scenario #13; Wind from Southwest at 0.46 m/s

Scenario is with a 7,016 kg/s release rate over a period of 20 minutes and 22 seconds.


KMASOUTH33
90
Flanders Rd
Southville Rd
Cordaville Rd
Pleasant St
Main St
Waverly St
135
Cedar St
E Main St
Wood St
KMAHOPKI9
Grove St
85
W Main St
495
© 2016 Google
Google earth
Tour Guide
1995
42°13'31.92" N 71°26'44.51" W elev 304 ft eye alt 36767 ft

Appendix O: Tank Rupture Scenario #14; Wind from North-northwest at 0.46 m/s

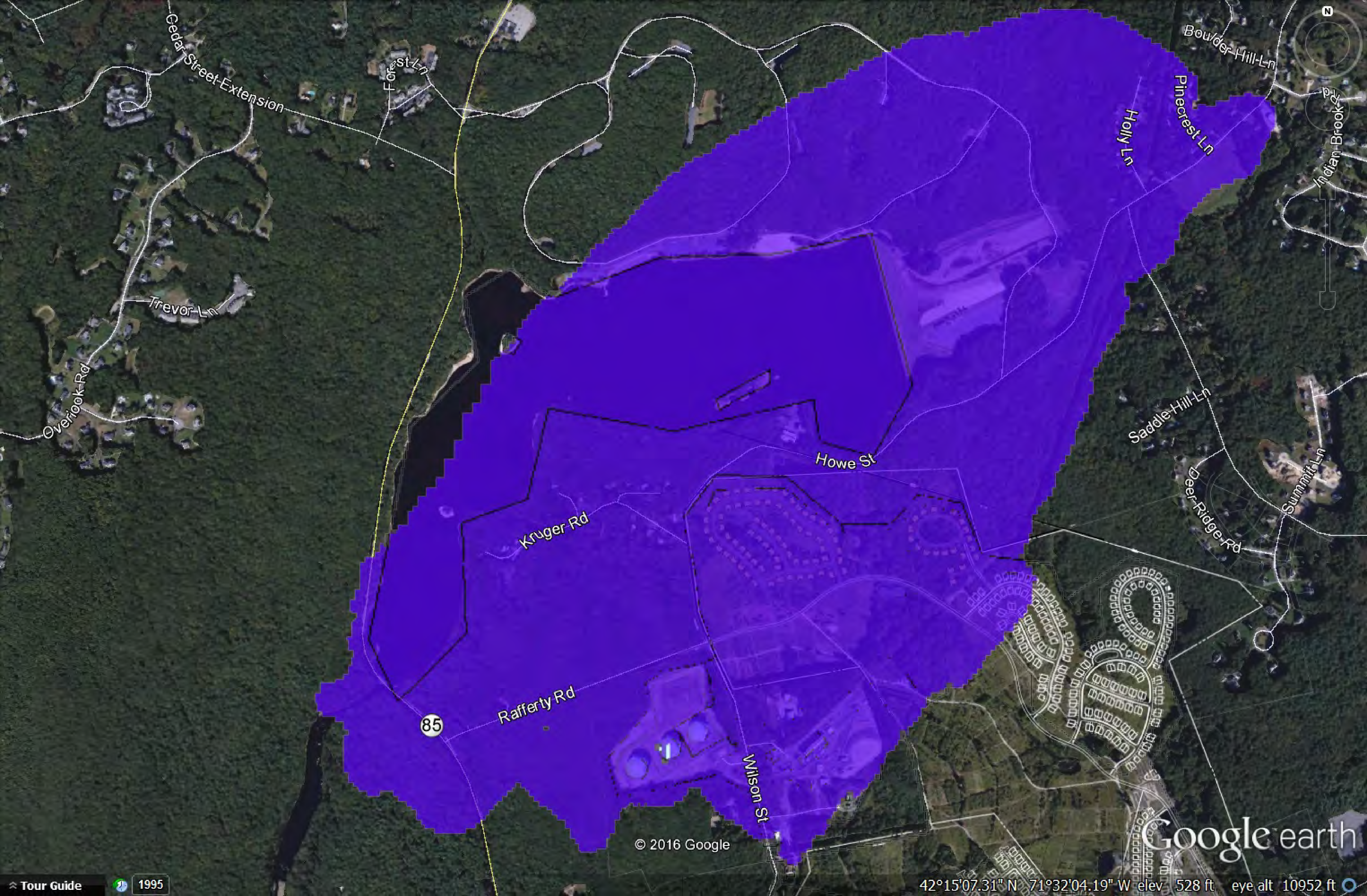
Scenario is with a 12,123 kg/s release rate over a period of 5 minutes and 21 seconds.



Trevor Ln
Overlook Rd
Everett Cir
Kruger Rd
Rafferty Rd
Howe St
Saddle Hill Ln
Brogden Rd
Deer Ridge Rd
Summit Ln
High St
Cross St
Frankland Rd
Phipps St
Cedar St
85
Wilson St
135
Autumn
© 2016 Google
Google earth
Tour Guide
1995
42°14'27.58" N 71°31'56.55" W elev 385 ft eye alt 12250 ft

Appendix P: Tank Rupture Scenario #15; Wind from South-southwest at 0.46 m/s

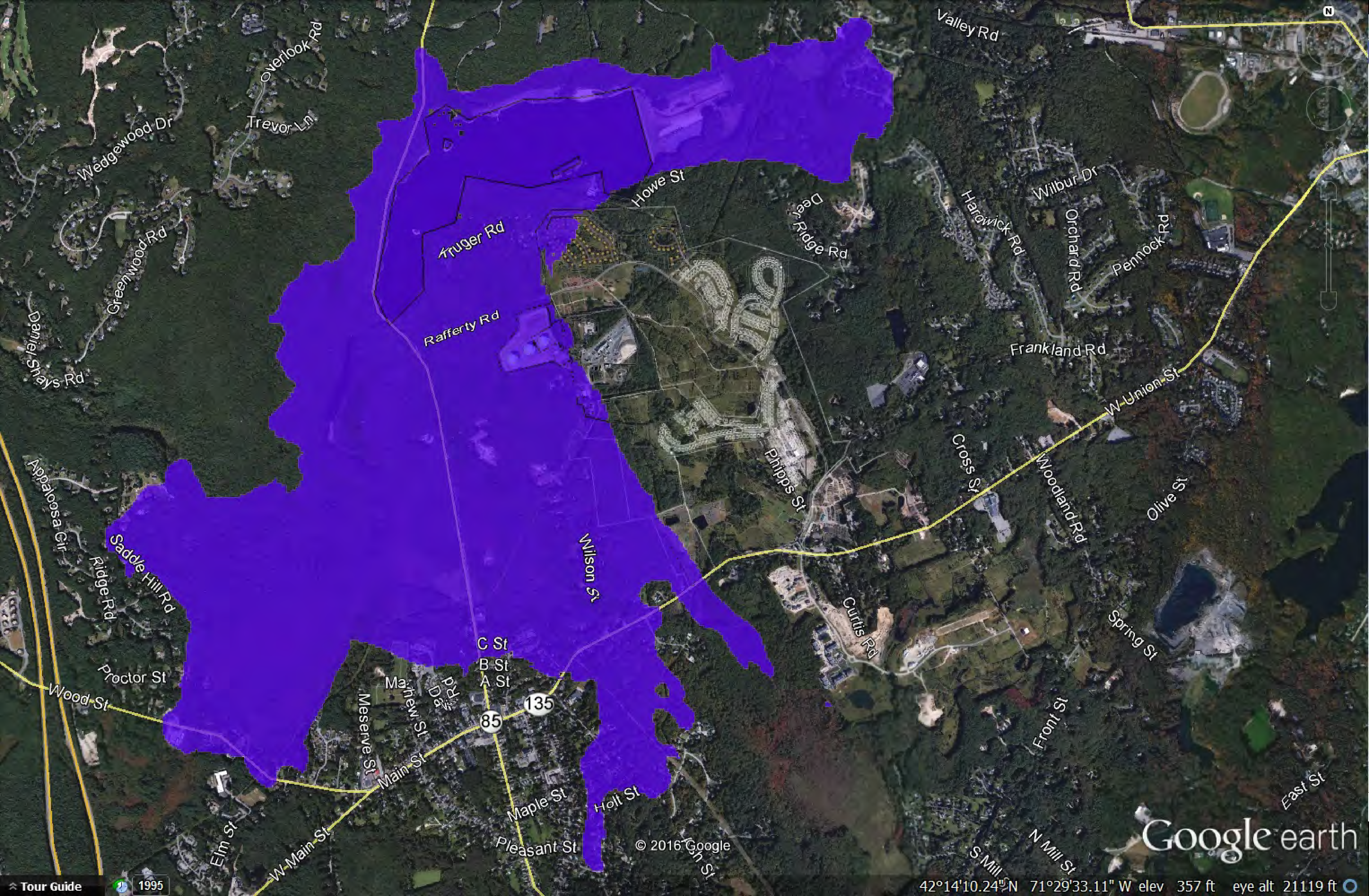
Scenario is with a 8,419 kg/s release rate over a period of 6 minutes and 16 seconds.



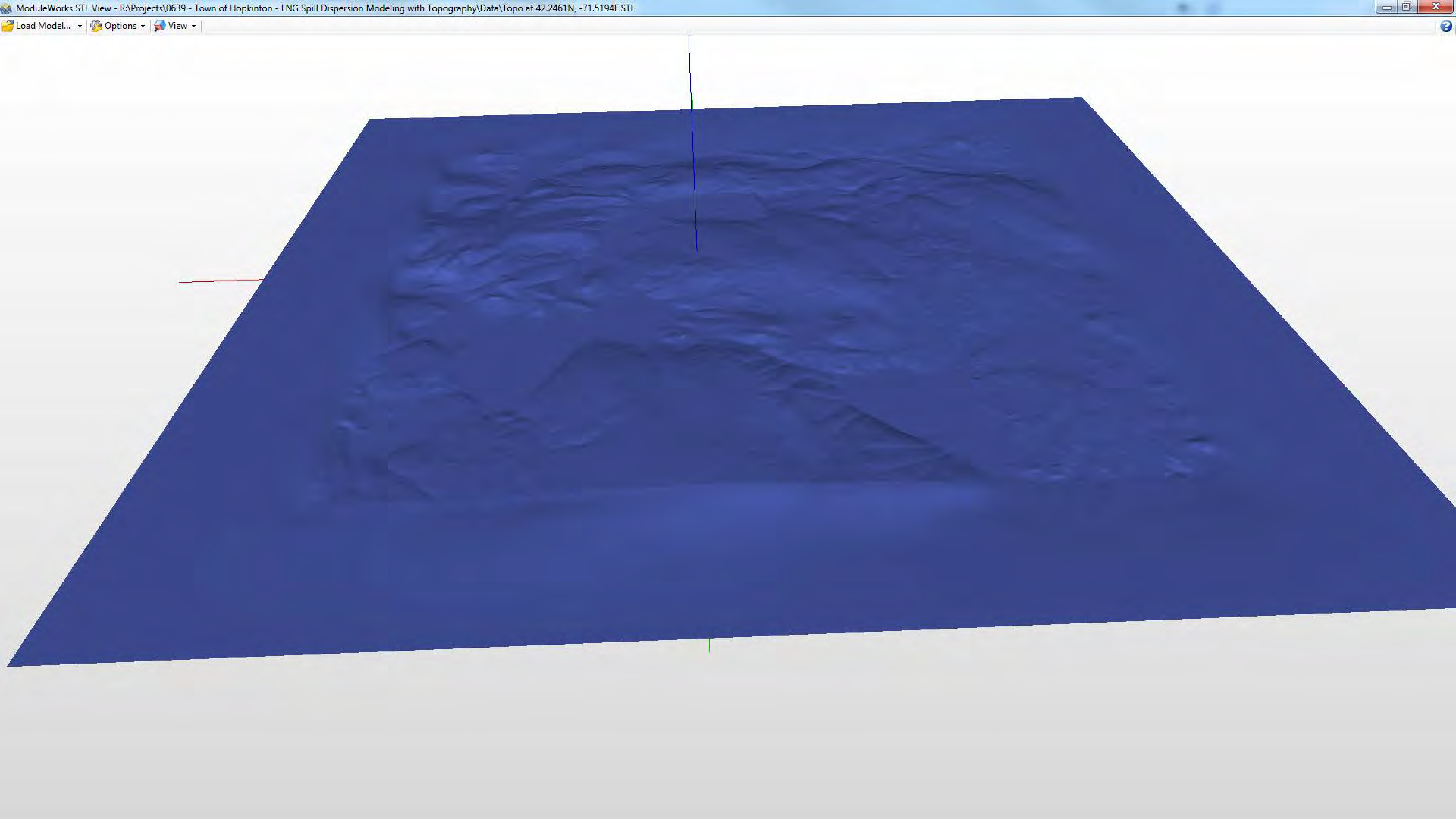
Cedar Street Extension
Forest Ln
Boulder Hill Ln
Pinecrest Ln
Holly Ln
Indian Brook Rd
Trevor Ln
Overlook Rd
Howe St
Kruger Rd
Saddle Hill Ln
Deer Ridge Rd
Summit Ln
Rafferty Rd
85
Wilson St
© 2016 Google
Google earth
Tour Guide
1995
42°15'07.31" N 71°32'04.19" W elev 528 ft eye alt 10952 ft

Appendix Q: Tank Rupture Scenario #16; Wind from West-northwest at 0.46 m/s

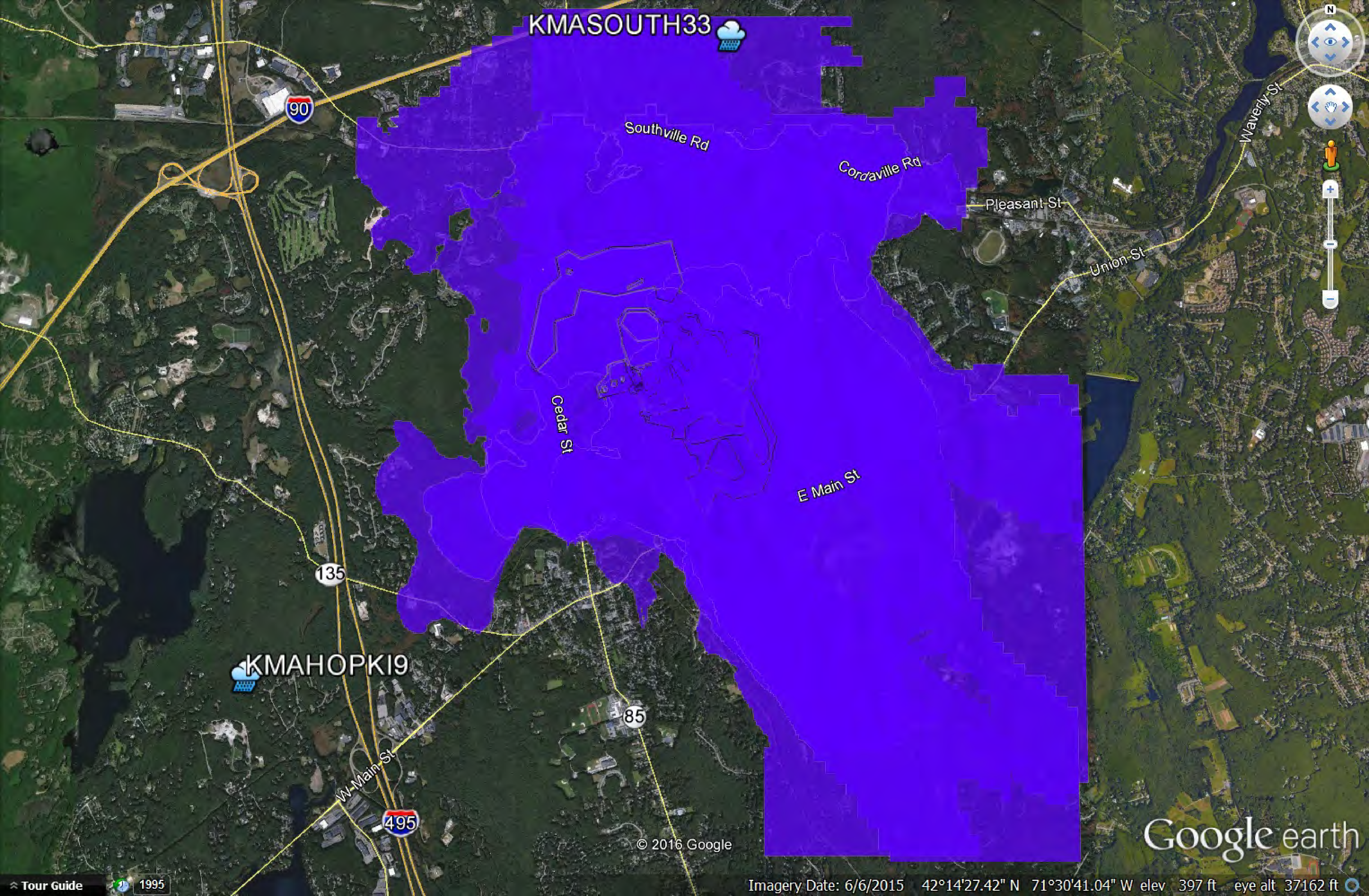
Scenario is with a 8,770 kg/s release rate over a period of 17 minutes and 1 second.


Valley Rd
Overlook Rd
Trevor Ln
Wedgewood Dr
Greenwood Rd
Daniel Shays Rd
Howe St
Kruger Rd
Rafferty Rd
Deer Ridge Rd
Hardwick Rd
Wilbur Dr
Orchard Rd
Pennock Rd
Frankland Rd
W Union St
Cross St
Woodland Rd
Olive St
Phipps St
Appaloosa Cir
Saddle Hill Rd
Ridge Rd
Wilson St
Curtis Rd
Spring St
C St
B St
A St
Proctor St
Wood St
Meserve St
135
85
Main St
Maple St
Holt St
Front St
East St
Elm St
W Main St
Pleasant St
S Mill St
N Mill St
© 2016 Google
Google earth
Tour Guide
1995
42°14'10.24" N 71°29'33.11" W elev 357 ft eye alt 21119 ft

Appendix R: Hopkinton Topography

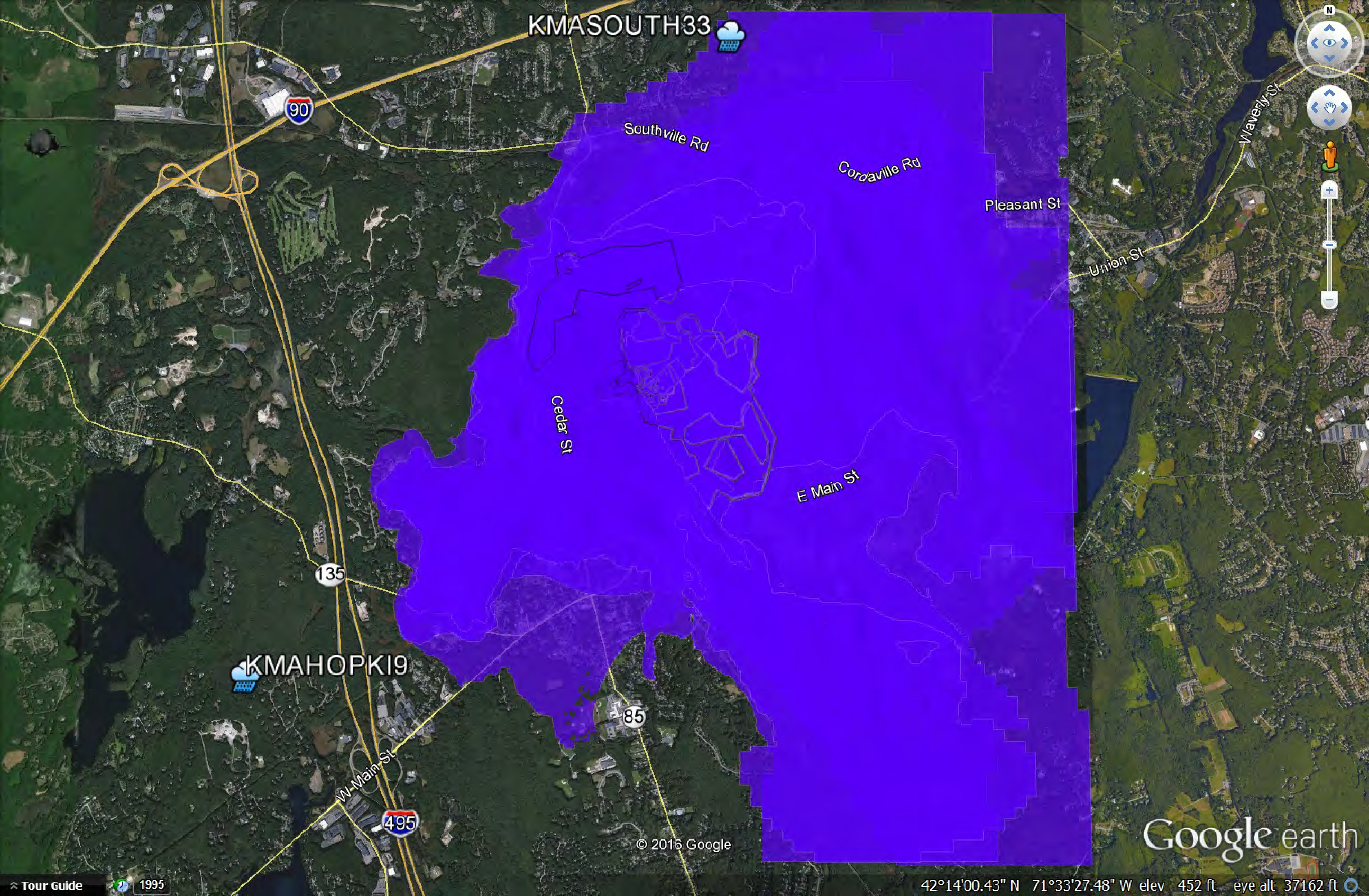

ModuleWorks STL View - R:\Projects\0639 - Town of Hopkinton - LNG Spill Dispersion Modeling with Topography\Data\Topo at 42.2461N, -71.5194E.STL
Load Model...
Options
View

Appendix S: Overlaid Pipe Guillotine Scenarios



KMASOUTH33
90
Southville Rd
Cordaville Rd
Pleasant St
Waverly St
Union St
Cedar St
E Main St
135
KMAHOPKI9
85
W Main St
495
© 2016 Google
Google earth
Tour Guide
1995
Imagery Date: 6/6/2015
42°14'27.42" N
71°30'41.04" W
elev 397 ft
eye alt 37162 ft

Appendix T: Overlaid Tank Rupture Scenarios


KMASOUTH33
90
Southville Rd
Cordaville Rd
Pleasant St
Waverly St
Union St
Cedar St
E Main St
135
KMAHOPKI9
85
W Main St
495
© 2016 Google
Google earth
Tour Guide
1995
42°14'00.43" N 71°33'27.48" W elev 452 ft eye alt 37162 ft