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ASSESSMENT OF AN IRRITANT GAS PLUME MODEL FOR EPIDEMIOLOGIC STUDY

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Abstract

Previously, we reported the development of a Hazard Prediction and Assessment Capability (HPAC) plume dispersion model of the 2005 Graniteville, South Carolina, USA accidental release of chlorine (Jani et al, 2016). Here, we assess this model by spatial and statistical comparison with post-incident observed environmental indicators of exposure and other types of observations. Spatial agreement was found when the model was compared to phytotoxic bleaching and corrosion events observed in 2 km radius around the release site. When spatially compared to locations of injured or killed animals, model predictions of the plume footprint were in relatively good agreement. Model-predicted human casualties differed from observed casualty counts primarily due to the shielding effect of buildings. A statistical comparison of observed dog health outcome-derived exposure versus model predicted exposure showed relatively good agreement, particularly when a sub-cohort of indoor dogs was excluded. Evaluation and assessment of the building infiltration effect would further improve the model prior to application in epidemiologic study.

1. Introduction

The use of atmospheric transport and dispersion (AT&D) models in predicting the environmental and health impacts of toxic inhalational gas releases has been widely studied since the use of war gases during the 1920s (Hanna et al, 1982; Zou et al, 2009). Ensuring predictive accuracy has been a formidable challenge: these systems produce an ensemble of possible scenarios while the actual release is one iteration of an infinite number of scenarios. Although this limitation is unavoidable, emphasis on improving the algorithmic capabilities of this software includes the evaluation of AT&D models against post-release environmental indicators in both the experimental and natural setting. Numerous experiments have been performed in which inert and toxic gases are released, exposure observations collected and then compared to the model predicted dispersion and transport of the gas (Hanna et al, 2008; Warner et al, 2006a; Warner et al, 2006b; Warner et al, 2001; Warner et al, 2004; Pullen et al, 2005; among others).

As an example, several models, including the Hazard Prediction and Assessment Capability (HPAC), were compared to field experiment-derived mesoscale datasets of sulfur hexafluoride tracer gas by Chang and colleagues (Chang et al, 2003). This study found that only around 50% of HPAC predictions were within a factor of two of the observations. In URBAN 2000, the same tracer gas was again used in Salt Lake City, Utah trials and compared to HPAC predictions. Here, HPAC overpredicted the observed concentrations and dosages in 19 out of 20 model configurations (Warner et al, 2004). Similarly, Hanna and colleagues compared HPAC to the Joint Urban 2003 field trials in Oklahoma City and found that overprediction was common (Hanna et al, 2007). A 2010 study produced for the U.S. Department of Homeland Security (DHS) Chemical Security Analysis Center (CSAC) by the Institute for Defense Analyses compared HPAC and three proprietary models using data from the 1982-1984 Thorney Island field experiments (Urban et al, 2010). The CSAC study, which was designed to assess model ability to predict gravity-induced dense gas slumping, showed that while all of the models captured the slumping effect, they underpredicted and overpredicted dosage by up to a factor of five. Of the four models, HPAC tended to perform better and predicted dosages usually within a factor of two.

The Jack Rabbit trials by CSAC and DTRA (phase I in 2010 and phase II, which began in 2013) at the Dugway Proving Grounds in Utah are one example of the large-scale experiments being performed to study gas behavior and to validate existing modeling systems. The role of deposition as a removal mechanism, especially dry deposition and reactions with soil-based acids for highly reactive dense gases such as Cl_2 , is an emerging area of research and large focus of the Jack Rabbit I experiment (see Hearn et al, 2012; Hearn et al, 2013; Hanna et al, 2012; Bauer, 2013 among others). A multitude of sensors and prepared artificial deposition matrices surrounding the release site are utilized to analyze the dispersion, transport and interaction of Cl_2 and other gases post-release. This area of research has also expanded to account for deposition beyond greenbelts, such as on structures and other manmade objects (Dillon, 2009; Jonsson et al, 2005). In regards to greenbelts (areas of vegetation in and around urban development), there has been some research performed in the area of phytotoxic injury as a result of chlorine exposure, including the use of phytotoxic indicators during post-accident investigation (Griffiths and Smith, 1990; Khan and Abbasi, 2001). While the body of literature is limited, two seminal studies have shown that the sensitivity range of plants to chlorine exposure varies dramatically depending upon species (Brennan et al, 1965; Brennan et al, 1966).

In the case of Graniteville (see section 2.1 for description of event), a large portion of the greenbelt vegetation consists of mature pine trees. Shreuder and Brewer (2001) studied the effects on transpiration, growth and mortality on pine trees following an acute daytime chlorine exposure event (Schreuder and Brewer, 2001). In these studies among others, a noticeable injury and bleaching effect occurred when the species was exposed to 5 ppm or greater concentration of chlorine gas for over 2 hours. It is important to note that these exposures are longer than that of the major cloud during the Graniteville incident. Further, both species of pine studied showed foliar injury, decreased photosynthetic efficiency and increased rates of cuticular transpiration until the affected needles defoliated. In laboratory studies with other vegetation species, damage thresholds of less than 5 ppm for two hours

were apparent (Sikora and Chappelka, 1996; Buckley et al, 2012). Clearly, both acute and chronic health effects in living organisms result from short-term exposure to chlorine gas.

A body of literature spanning back to the late 1800s does exist regarding animal toxicity to chlorine. Particularly, a seminal and foundational series of experiments on dogs has shown that 30-min acute exposures of below 250 ppm tend to have no health effects, while exposures between 251-649 ppm may cause immediate or delayed injuries and those above 650 ppm generally results in mortality (Underhill, 1919). Similar experiments have been also performed on primates, rabbits, cats and rodents, but dogs are employed far more often in occupational and recreational settings (Coppinger et al, 1995). As performed here, the observed health effects in 63 dogs is an innovative comparative method to assess in-situ models when data exists. Animal health effects data, when combined with other environmental indicators of exposure such as the aforementioned phytotoxicity, corrosion or deposition benchmark data, can be utilized as important evaluation criteria when assessing model predictive accuracy and informing potential toxicity in humans.

Of the aforementioned experimental releases, even the largest have not exceeded 20,000 kg, less than half of the total multiphase volume expelled in the 2005 Graniteville, South Carolina, USA railcar release of chlorine. Large-scale releases, particularly those in urban or settled areas, generally utilize inert tracer gases for public health and safety. Although experiments such as the Jack Rabbit trials are performed at military proving grounds, safety concerns, environmental regulations and financial constraints often prevent scientists from releasing large quantities such as the 80,000 kg that an average chlorine tanker railcar carries. The comparison of model predictions to exposure observations collected following an actual release is difficult due to the lack of data. Indeed, the immediate priority post-release is emergency response and life safety. Although the data set is somewhat limited, the Graniteville incident presents a unique opportunity to assess a model prediction against actual environmental and spatial distribution of observed concentrations and dosages collected post-incident.

2. Methods

2.1 Description of the exposure event

A detailed description of the Graniteville incident is presented in Jani et al, 2015 and summarized here. On January 6, 2005, a freight train traveling at approximately 76 km/h was unintentionally diverted onto an industrial spur at the Avondale Mills complex in Graniteville, South Carolina, United States of America. Due to an improperly configured switch, the traveling train collided with a stationary train at approximately 2:39 AM Eastern Standard Time (EST). Three railcars containing chlorine were among the 14 that derailed and one of these railcars was ruptured, releasing an estimated 54,915 kg of chlorine (both in gaseous and liquid form) into the surrounding community (Jani et al, 2016; NTSB, 2005). As a result of this accidental release of toxic dense gas, 5,400 people were evacuated, over 550 were treated at the hospital and nine were killed. It is important to note that the evacuation occurred at approximately 4:00 PM EST on the day of release due to the cleanup process and was not an immediate incident response. Rather, the local public safety answering point (PSAP) issued a shelter-in-place order for all residents in the Graniteville

area using reverse 911 within 30-minutes post-release (NTSB, 2005). Graniteville is a small industrial town located within a shallow creek valley. Due to the dense gas effect, this terrain likely contributed to limiting the crosswind dispersion and enhancing the downwind dispersion, as our HPAC 5.3 plume model illustrates (Figure 1). The ambient weather conditions prevented the plume from dispersing towards Aiken, with an estimated 28,000 residents in 2005 (U.S. Census Bureau).

2.2 Description of the models and usage

Previously, we modeled the Graniteville incident with unclassified versions of both the Hazard Prediction and Assessment Capability versions 4.04 and 5.3 General Distribution (HPAC, Defense Threat Reduction Agency [DTRA]) and ALOHA (National Oceanic and Atmospheric Administration/US Environmental Protection Agency). As a software system, HPAC consists of several integrated modules which develop the source term based upon input parameters and then estimates transport and dispersion of the chemical away from the source location. The iTRANS source term model allows estimation of release quantity based upon the physical characteristics of the chemical and release mechanism such as mode of transport. HPAC utilizes Second-order Closure Integrated Puff (SCIPUFF) for estimating transport and dispersion. SCIPUFF is a Lagrangian model which simulates the released chemical as Gaussian puffs and is particularly well-suited for dense gas releases. For purposes of predicting the concentration variance due to meteorological conditions, HPAC utilizes the Stationary Wind Field and Turbulence (SWIFT) wind model which creates multi-dimensional wind fields based upon basic knowledge of localized topographical features and contours. In addition to direct input using observational weather data, HPAC can also import data from DTRA's Meteorological Data Service (MDS) (Urban et al, 2010). Here, we have utilized aggregated, previously validated meteorological data from 13 proximal weather stations (Jani et al, 2016). HPAC also contains several urban models; however, this function was not utilized in this study due to the lack of building databases for the Graniteville area. The plume model and isopleths can be exported to GIS software for visualization and further analysis. Here, we have plotted onto a ArcMap topographic base map (Figure 1).

2.3 Comparison to environmental exposure indicator and other types of observation

A range of available environmental data was evaluated for both comprehensiveness and feasibility of use within our comparative analysis. Eventually, we settled upon the use of phytotoxicity, corrosion location, literature-established deposition benchmark, casualty estimation and animal toxicity data. While no formal vegetation damage assessment was performed immediately following the incident, researchers from the Savannah River National Laboratory (SRNL) visually recorded the spatial extent of vegetation damage approximately one month post-release (Buckley et al, 2012). The researchers also noted that the bleaching effect was limited to a height of approximately 10 m in a 2 km radius around the release site. Based upon this observation, the HPAC 5.3 model was adjusted to estimate concentration at a height (z) of 10 meters. Based upon existing phytotoxicity research, an HPAC-predicted plume pattern was developed which suggested the predicted area at which an exposure of at least 5 ppm was sustained for two hours or more. This plume was plotted in ArcMap and compared to the imported vegetation damage survey shapefile. Similarly,

observed episodes of corrosion by on-site responders and environmental remediation personnel due to surface reactions with chlorine gas were plotted as a layer and compared.

There are limited datasets available on animals exposed during the Graniteville release due to the immediate priority of protecting human life. The animal secondary data set utilized for this study was sourced from three different sub-sets: a survey of eight veterinary practices within the Graniteville area who treated exposed pets, the South Carolina Department of Health and Environmental Control (DHEC) Acute Epidemiological Survey which was administered within 48 hours post-release, and the Norfolk Southern/DHEC Housing Inspection Survey (HIS) (GRACE Study, 2014). The majority of the usable animal data was from the first two sub-sets; the HIS focused heavily on the status of the physical residence itself and included minimal information on pet status. The initial larger database, which numbered 303 animals, was reviewed and any animals without reported location information were omitted. With the assistance of a public health veterinarian working as part of the Graniteville Recovery and Chlorine Epidemiology (GRACE) Study, each animal was then classified into one of seven outcome categories based upon reported outcome: died, euthanized due to unrelated reason, missing, injured/ill, no apparent effect, assume no apparent effect and unknown outcome. The data was trimmed further by removing those animals classified as euthanized (due to an unrelated reason), missing, assume no apparent effect, and unknown outcome. This reduced the overall dataset to 117 animals, comprised of birds (3), cats (32), chickens (6), dogs (63), ducks (2), a ferret (1), fish (5), a frog (1), goats (2), a lizard (1) and a possum (1). These animals were reclassified into three consolidated categories based upon reported health outcome: no health effect, injured, or killed. For spatial comparison, the locations of all animals were plotted in ArcMap along with the plume model (Figure 2).

2.4 Description of the dog comparative assessment criteria

A further analysis was performed utilizing the dog data ($n = 63$). Based upon existing toxicology profiles (Underhill 1919), a public health veterinarian assigned each dog to experimentally derived 30-min acute exposure ranges by observed health outcome: low exposure/no health effect (≤ 250 ppm), medium exposure/injured (251 - 649 ppm) and high exposure/killed (≥ 650 ppm). Each reported dog location was geocoded into the HPAC model and peak 30-min predicted exposure was generated for each dog. To identify the role of shielding (i.e. indoor vs outdoor location) and improve sensitivity and specificity, a sub-cohort which omitted all dogs that were reported to be indoors was created ($n = 56$). For both groups, a comparison of the observed health outcomes and model-predicted exposure was performed by first conducting exploratory data analysis such as descriptive statistics, scatterplots and box plots. Then, chi square analysis (goodness of fit) was performed using IBM SPSS Statistics. For the latter analysis, our null hypothesis states that the predicted exposures (by category) match the observed exposures.

3. Results

3.1 Phytotoxicity and Corrosion Analysis

When the visible vegetation bleaching effect was spatially compared to the model predicted area at which > 5 ppm exposure was sustained for two hours or more, the model-predicted plume pattern was larger (Figure 3). The bleaching of pine largely was confined to an elongated downwind shape that widened as distance from the source point increased. The model predicted area was largely circular, indicative of the gravity slumping effect of dense gas but not particularly fully representative of Graniteville's topographic contours. However, an important observation here is that the vast majority of the extent of vegetation bleaching was within the predicted isopleth. All of the observed corrosion on mill and other buildings were within the plume footprint in proximity to the source point (Figure 3).

3.2 Animal Health Outcome Analysis

The locations of animals with health outcomes of “injured” (Figure 4) and “killed” (Figure 5) was plotted against the HPAC plume. Of the total animal cohort ($n = 117$), 24 were reported injured and 31 killed. The remainder had no observed health effect. For injured animals, all but two (dogs) were located within the plume footprint, although both exhibited adverse health effects. The locations of all 31 animal fatalities were within the plume itself, largely centered around the source point and highest exposure threat zones. For dogs specifically, 14 of 63 were located outside of the plume footprint, but only two of those exhibited injuries (Figure 6). The remaining 49 were within the plume, largely centered around a 1.5 km radius from the release point. The remaining had no observed health outcome, in agreement with the model predicted lack of exposure.

For all dogs ($n = 63$), classification by health outcome (observed) and model exposure estimation (predicted) was reported (Table 1). The results were then stratified by whether or not the model prediction and field observation matched by exposure category (Table 2). Following the established standards in dispersion model evaluation exploratory data analysis, a scatter plot visualization (Figure 7) and box plot (Figure 8) comparing the model predicted exposure to the classification by health outcome (observed) suggested overall good agreement but a number of outliers in all three categories. To account for these outliers, dogs reported to be indoors were removed from the cohort. All dogs removed were mismatched between field observed health outcome versus model predicted exposure, with each predicted exposure far higher than what the observed health outcome supported. The results for this sub-cohort were also stratified by whether or not the predictions and observations matched (Table 1). A scatter plot (Figure 9) and box plot (Figure 10) was generated which suggested better agreement for all three categories, with fewer outliers. Chi square analysis for both dog cohorts was significant (Table 3).

3.3 Casualty Estimation Analysis

HPAC 5.3 model casualty predictions (a model output feature used for planning purposes) based upon night-time population differed significantly from the observed casualty statistics when differentiated between fatality and injury. Interestingly, total numbers were similar (Table 4). The model estimated 575 total casualties compared to the observed number of

563. Fatality numbers differed greatly, with the model estimating 500 fatalities compared to 9 observed. Similarly, the model predicted 75 injuries, compared to the 554 who were treated at local hospitals with respiratory distress and other symptoms (NTSB, 2005).

4. Discussion

Building upon our previous work, we have assessed a Hazard Prediction and Assessment Capability (HPAC) version 5.3 irritant gas plume model against applicable data (phytotoxicity, corrosion, deposition benchmark, casualty and animal toxicity) selected from a larger survey of available environmental exposure indicator data. An analysis of the severe phytotoxic bleaching effect clearly shows the limited horizontal dispersion due to terrain-induced dense gas effects such as gravitational slumping. As also shown in similar studies by Buckley and others, the observed vegetation damage pattern is clearly shorter and narrower than the exposure area predicted by our model. The differences in spatial distribution are likely due to an inability to fully account for the terrain effects, particularly in Graniteville where the valley extended and turned the plume direction within the creek valley. However, one consideration that may have limited the bleaching effect is that vegetation respiration rates are typically much lower at night compared to the day. The aforementioned studies which describe the response of pine trees to chlorine exposure were conducted in the laboratory and/or daytime setting, which is not fully representative of the Graniteville environmental conditions (including temperature and humidity) and time of release. Further, the rate of deposition will typically decrease when the surrounding environment is warmer than the releasing gas due to heat transfer-induced loss of gas stability. Although all of the corrosion episodes were located within the plume, further work analyzing the actual exposure at each of these locations should be performed to better quantify model bias.

As noted previously, the impact of dense gas deposition into dry soils, greenbelts and environmental objects is an emerging area of research. The rate of deposition is highly incident-specific. The immediate area around the Graniteville release contained semi-rural surfaces for deposition and consists mainly of low buildings and industrial parks before opening to predominantly pine forest and residential neighborhoods. Additionally, a large-volume release will typically rapidly surpass the deposition capacity (i.e. dry deposition into soils) of the immediate surrounding environment, limiting the attenuation of a dispersing plume. Our model predicted that 30% of the airborne concentration was deposited within the first 150 meters. While this is within the up to 40% deviation expected between predictions and benchmark/observation data, it is below the 50% deposition rate suggested in the literature. The majority of models utilize a linear deposition velocity (V_d) and while HPAC utilizes a more dynamic approach, the model may be underestimating deposition rate. The slight increase in concentration observed beyond 120 m downwind on the centerline may be due to a dispersion and terrain effect (i.e. gravity slumping) over the 60-min output period. The fairly rapid and linear decrease in concentration after this is indicative of decreasing gas stability and increasing behavior similar to a neutrally buoyant gas as mixing occurs.

The majority of injured and killed animals were within the plume model footprint, which shows agreement with our model. Those that were reported ill or killed but were outside of

the plume footprint may have been exposed and then attempted to escape the plume before succumbing to the effects of exposure. When dogs were further investigated, it was apparent that a shielding effect protected dogs that were reported to be indoors. Particularly, each of the 7 dogs reported to be indoors had very high model predicted exposures, but no or low-level observed health outcomes. The differentiation between indoor and outdoor exposure is a critically important component of accurately estimating human exposures. In Graniteville, the majority of human exposures were indoors due to the time of day. The differences between model estimated casualties and actual observed casualties further supports this because the number of predicted fatalities far exceeded that which was observed. The HPAC estimations are for unprotected night-time population, which does not accurately reflect the reality due to the majority of human exposures being indoors. Similar to the dogs, this shielding effect likely prevented the greater number of casualties the HPAC model predicted. The infiltration of dense toxic gas into buildings is difficult to study due to the numerous regional differences in construction and individual behavior such as leaving windows open for ventilation. Given that the month of release was January, it is assumed that the majority of homes had most direct ventilation pathways closed due to colder weather. This likely prevented major infiltration of buildings, particularly for those residing within the high threat areas of the plume.

There are several limitations, including the intrinsic uncertainty of the HPAC predicted plume footprint, which may influence the results presented here. Particularly, although nearly all injured and killed animals were within the plume footprint, those locations may not necessarily represent exposures that result in illness or death for species other than dogs. The chlorine exposure toxicology is not known for many of the reported species, so this location bias is unverifiable. However, the general notion that the dose-response outcome for smaller animals is generally more severe compared to larger animals may support the belief that once exposed to high concentrations, the majority of smaller species within our sample likely did not travel great distances prior to being killed. For the dog analysis, it is important to note that several factors could have led to the existing mismatches between the model predicted exposure and observed health outcome derived exposure. For example, the existing physiology and/or existing illness in the identified dogs may have exacerbated the health effects of chlorine exposure. Some of the dogs were not located and treated until days after the release and the lack of nourishment may have contributed to health outcomes more severe than the original exposure (or model predicted exposure) may have caused. Further, a reporting bias may be present in some dogs because while all dogs were examined and treated by certified veterinarians, owners were asked to recall the location of the dogs at time of release and probable exposure. Many were located within a fenced in yard or compound and therefore could not escape or travel far distances. Individual dogs also tend to exhibit different behavior to exposure (i.e. some experiments have found more intelligent breeds utilize their paws to filter breath).

Beyond the limitations described above, the analysis here did not take into consideration several factors which may accelerate the removal process. For example, reactions that occur between chlorine, other ambient chemicals and surfaces (such as metallurgic corrosion) may significantly contribute to limit the hazard extent of the plume. Nearly all tracer gas studies, including those described here, evaluate the agreement between observed and predicted

dispersion, but usually do not study further the influence of ambient reactions on bias. This is a very dynamic factor which is difficult to properly account for and requires further study. Chlorine also rapidly reacts with water to form hydrochloric acid and the ambient atmosphere during the time of release was highly humid and foggy, which likely increased the removal rate and attenuated the dispersion and transport of the gas. The model itself does not fully account for this. Additionally, while the surrounding area was not densely packed with buildings, the effects of the urban canyon (or similar air-flow effects) are not accounted for by the HPAC model outside of areas which have specific urban model datasets built within the software package.

5. Conclusion and Future Direction

While we have concluded that assessment shows merit in that the model could be used in epidemiologic study, further work is needed before it can be assumed to be fully validated. Plume models often significantly overpredict the exposure isopleths, fatalities and environmental effects of a dense gas release. The primary cause of this overprediction is the inability for even the most sophisticated models to account for all removal mechanisms and variability between individual toxic gases. The implications for health effects is profound and this work illustrates the need for further research in evaluation methodologies, particularly using observed indicator data from actual, not necessarily experimental, large-scale releases. Further, additional research should be performed to examine building infiltration and dynamic removal mechanisms such as dry deposition and ambient chemical reactions with the atmosphere and surfaces.

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Figure 1.
HPAC 5.3 surface dosage plume model at 6:39 EST (+4 hours post-release).

Figure 2.

Locations of all animals (n=117) plotted on the HPAC 5.3 surface dosage plume map. Some points may be on top or in close proximity to others.

HPAC 5.3 - Phytotoxicity and Corrosion Events

Figure 3.

HPAC 5.3 estimated exposure area of 5 ppm or greater for 2 or more hours with extent of visible vegetation bleaching and corrosion episodes plotted. Vegetation bleaching contour is from research conducted by Buckley et al, 2012.

Figure 4.

Locations of all injured animals plotted on the HPAC 5.3 surface dosage plume map. Some points may be on top or in close proximity to others.

Figure 5. Locations of all killed animals plotted on the HPAC 5.3 surface dosage plume map. Some points may be on top or in close proximity to others.

Figure 6.

Locations of all dogs (n=63) plotted on the HPAC 5.3 surface dosage plume map. Some points may be on top or in close proximity to others.

Figure 7.
Scatter plot of all dogs (n=63) binned by observed health outcome classification.

Figure 8.
Box plot of all dogs (n=63) binned by observed health outcome classification.

Figure 9.
Scatter plot of outdoor dogs (n=56) binned by observed health outcome classification.

Figure 10.

Box plot of outdoor dogs (n=56) binned by observed health outcome classification.

Table 1

Health outcome frequencies for n = 63 (all) dogs

Health Outcome	Observed	Predicted	p-value ^a
No Health Effects (≤ 250 ppm)	37 (58.7%)	44 (69.8%)	.003 *
Injured (251-649 ppm)	19 (30.2%)	5 (7.9%)	
Killed (≥ 650 ppm)	7 (11.1%)	14 (22.2%)	

Note: All results based expressed as frequency (%). Subgroup data unavailable for some subjects.

^a Corresponds to Fisher's Exact test for general association between health outcome and response type.

* Significant at the 5% significance level.

Table 2

Matched and unmatched frequencies between model predicted and field observed for n = 63 (all) dogs.

Health Outcome	Match	Mismatch	p-value ^a
No Health Effects (≤ 250 ppm)	31 (77.5%)	6 (26%)	.003 *
Injured (251-649 ppm)	3 (7.5%)	16 (69.6%)	
Killed (≥ 650 ppm)	6 (2.5%)	1 (4.3%)	

Note: All results based expressed as frequency (%). Subgroup data unavailable for some subjects.

^a Corresponds to Fisher's Exact test for general association between health outcome and response type.

* Significant at the 5% significance level.

Table 3

Chi square (goodness of fit) analysis for both dog cohorts

Cohort	Chi-Square (p-value)
All Dogs (n = 63)	21.454 (.000)
All Dogs (matched pred vs obs)	80.000 (.000)
All Dogs (mismatched pred vs obs)	12.901 (.012)
Outdoor Dogs (n = 56)	36.343 (.000)
Outdoor Dogs (matched pred vs obs)	80.000 (.000)
Outdoor Dogs (mismatched pred vs obs)	9.941 (.007)

Table 4

Model estimated vs actual observed casualties from the Graniteville incident.

Casualty	Model Estimation	Actual Observation
Fatalities	500	9
Injuries	75	554
Total Casualties	575	563