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# Quantitative Policy Analysis to Evaluate Air Quality Impacts of Unconventional Oil and Gas Development (UOGD) Regulations

Matthew Alongi
*University of Colorado at Boulder*, malongi87@gmail.com

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# Quantitative Policy Analysis to Evaluate Air Quality Impacts of Unconventional Oil and Gas Development (UOGD) Regulations

by

Matthew Alongi

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written by Matthew Alongi
has been approved for the Department of Civil, Environmental and Architectural Engineering

Joseph Kasprzyk

Jana Milford

Joseph Ryan

Sherri Cook

Date ________________

The final copy of this thesis has been examined by the signatories, and we and find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Matthew Alongi (M.S., Civil Engineering)

# Quantitative Policy Analysis to Evaluate Air Quality Impacts of Unconventional Oil and Gas Development (UOGD) Regulations

Thesis directed by Professor Joseph Kasprzyk

Unconventional oil and gas development (UOGD) using hydraulic fracturing and horizontal drilling has recently fostered an unprecedented acceleration in energy development. Regulations seek to protect the public health of communities in proximity to UOGD and the environmental quality of these regions, while maintaining economic benefits. One such regulation is setback distance, which dictates the minimum distance between an oil and gas well and an occupied structure, such as a residential or commercial building, or an area of special concern. This study discusses a new policy analysis framework for UOGD regulations. We use this framework to generate plausible configurations of well pads based on setback distance policy alternatives and model potential air quality outcomes based on these configurations and policy alternatives. In this analysis, air quality impacts are characterized by concentrations of BTEX compounds, a group of hazardous air pollutants that has been linked to cancer and other detrimental health effects through simulation of short-term and long-term concentration averages using meteorological data from Denver, CO. Our framework also compares these concentrations to regulatory guidelines. Results indicate potential issues with acute benzene and to a lesser extent toluene concentrations based on current regulations. Comparison between setback distances suggest that the effectiveness of alternatives depends on the location of the well pad with respect to the home as well as the volume of emissions from the pad.

# Dedication

To my family, Marty, Mary, Kristi, and Livi.

# Acknowledgements

Everyone that works near me in SEEC – especially Jenna, Kelsey, Billy and Danny, have been incredibly supportive throughout this process. I would like to take a moment to praise Jenna's ability to write poems, truly a modern Shakespeare. I want to thank my research group as well, Rebecca, Melissa, Mikaela, Elliot, and Billy (again). To my roommate Joey and other friends that I have not already mentioned, including Diane, Colleen, and Mickey, I could not have done this without you.

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# Chapter 1: Introduction

Unconventional oil and gas development (UOGD) refers to the processes of hydraulic fracturing and horizontal drilling. The goal of this process is to extract oil and natural gas from subterranean shale formations. The first documented hydraulic fracturing experiment took place in the 1940's, but the process did not become popular until it became significantly more efficient due to technological advances in the 1990's (Robbins 2013). Although it did not immediately become widely practiced, further advances throughout the late 90's and early 2000's accelerated the growth of UOGD. Between 2007 and 2013, natural gas production in the United States grew by 25 percent despite stagnation in oil and gas development in the previous decades (Hausman & Kellogg 2015).

On the surface, the primary goal of UOGD is extracting natural gas and generating profit for oil and gas companies. However, from a regulatory standpoint there are numerous objectives, which most notably include:

- Increase economic benefits
- Create jobs
- Prevent induced seismicity
- Reduce air pollution
- Reduce noise pollution
- Prevent decreases in property value

These objectives conflict with each other, from the standpoint that UOGD activity can increase economic benefit and create jobs, but also incurs an environmental risk. Furthermore, these conflicting aspects of UOGD impact different stakeholders as well. The benefits are only loosely tied to proximity to hydraulic fracturing wells while the costs are very closely related to distance from a well.

In the past, it was far more feasible economically to extract oil through conventional oil and gas development (COGD), which refers to drilling into a high permeability oil reservoir to directly extract resources. Doing this requires little additional stimulation beyond drilling the well (Holditch 2013). Conventional oil and gas development (COGD) raises many of the same concerns mentioned above, which raises the question as to why UOGD is so much more controversial an issue. The answer to that question lies in the location in which the two processes take place. The scale of onshore UOGD operations is much larger than that of its counterpart due to the presence of shale deposits beneath large urban areas (Jackson et al. 2014), which causes a closer interface between urban and suburban areas and UOGD activity. See Figure 1 for a map of shale major shale deposits in the United States.

The expansion of UOGD operations has caused public concern and prompted discussion of the regulations surrounding the practice. As was discussed above, UOGD is an inherently difficult practice to regulate because of the multitude of competing objectives and interested

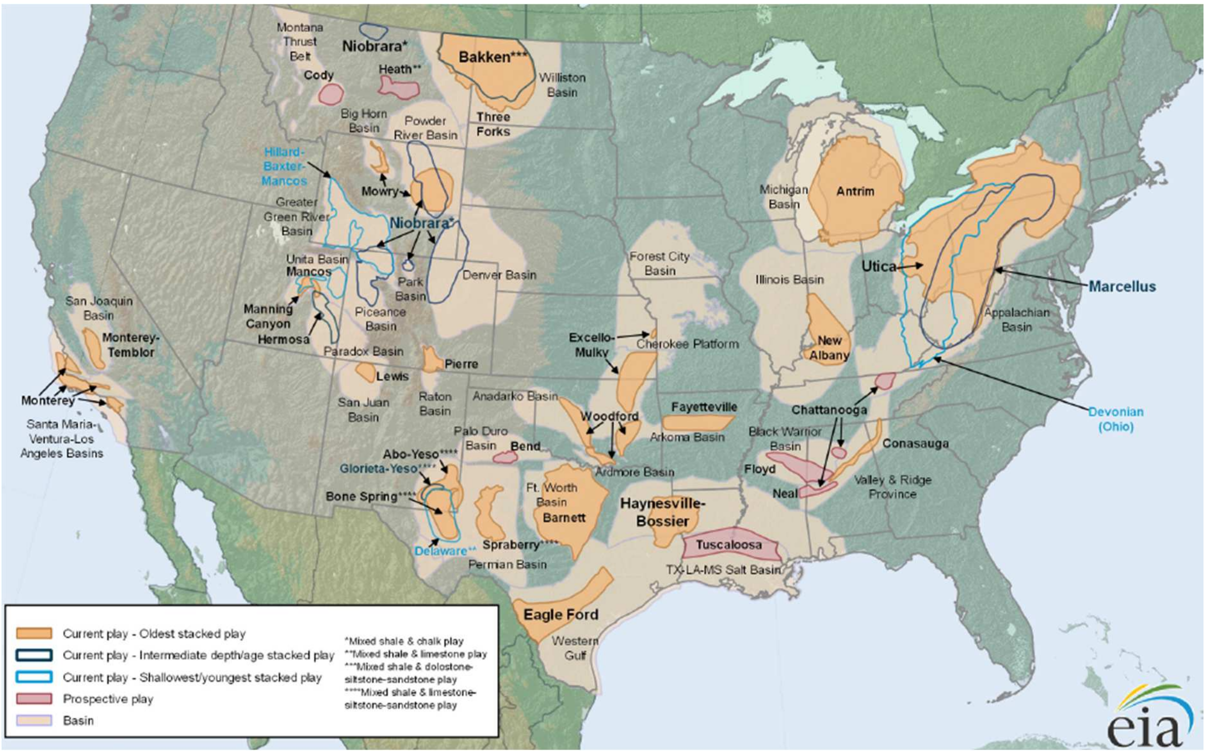


*Figure 1: Shale plays in the U.S. lower 48* (U.S. Energy Information Administration 2016)

parties involved. Further, the boom in UOGD was accelerated through regulatory loopholes that allowed for the process to expand across the U.S. before substantial environmental research could be conducted (Robbins 2013). These two factors led to the current body of under-researched and considerably varied regulations.

In the United States, environmental protection is regulated at the federal, state, and local levels. The federal regulatory body for oil and gas operations, the Bureau of Land Management (BLM), manages leasing of federal lands for UOGD (Milford 2014). However, aside from this responsibility the BLM has taken a hands-off approach to regulating the practice, claiming that policies are more appropriately determined at smaller scales due to unique circumstances among regions (Bureau of Land Management 2015). UOGD has even been excluded from some federal environmental regulations, most notably the Safe Drinking Water Act (Cupas 2009).

However, regulations such as the Clean Air Act (CAA), the National Environmental Policy Act (NEPA), and the Clean Water Act (CWA) do apply to UOGD. NEPA requires the BLM to review proposals for operations on federal lands and in some cases develop an environmental impact statement (Milford 2014). Further, operators are required by the CWA to apply for a permit to dispose of fluids used in hydraulic fracturing operations. The CWA also regulates the discharge of pollutants into surface water (Environmental Protection Agency 2016b). New Source Performance Standards (NSPS) and National Emissions Standards for Hazardous Air Pollutants (NESHAPs), regulations developed to protect the public from air pollutants as a result of the CAA, apply to UOGD operations as well. However, many aspects of UOGD regulation are not covered by these policies. Further, NEPA only applies to federal lands and the CAA requires states to develop additional air quality regulations (Milford 2014).

Consequently, the task of regulating UOGD has been primarily left to state governments. State governments regulate many issues such as noise pollution, disclosure of pertinent information, and drilling site locations. The balance of power between state and local governments varies depending on the state, which sometimes leads to conflict over regulations. One such contentious regulation is setback distance, which dictates the minimum distance between a well and a building property line, water source, or other activity. It is a controversial issue in highly populated regions because drilling in residential areas causes concerns over noise, traffic, neighborhood aesthetics, and environmental degradation. Further, the setback distance has important implications on the spread of air toxics related to UOGD in residential areas. In fact, Fry (2013) characterized the setback distance as an attempt for regulators to integrate all concerns about UOGD into a single policy. This study motivates the research presented in this thesis.

This thesis attempts to provide relevant scientific evidence that can be integrated into the policymaking process by studying UOGD in Colorado. To do so we attempt to model and characterize UOGD-related air quality impacts for different setback distances. In Section 1.1, we will explore the mechanics behind the decision-making process using Texas, and the Fry study, as an example case study. Then in Section 1.2 we will provide background on the landscape of UOGD regulations in Colorado. Next we present a brief overview of the UOGD process in Section 1.3 followed by a breakdown of the associated air quality impacts in Section 1.4. Finally, in Section 1.5, we end with an overview of quantitative policy analysis and how this research contributes to this field.

## 1.1 Development of Setback Distance Regulations in Texas

Texas is one of the states that has ceded jurisdiction over UOGD regulation to municipalities, which makes it an interesting case study on the policymaking process. The Barnett Shale, one of the most actively fracked shale plays today, lies underneath much of the Dallas-Fort Worth Metroplex (DFW). Aside from being a hotspot for oil and gas drilling it is home to nearly seven million residents, making it one of the most populous metropolitan regions in the United States. The statewide minimum setback distance is 200 feet, but many municipalities have passed ordinances requiring longer setback distances. As previously discussed, Fry (2013) examined setback distance regulations and attempted to determine the justification behind each regulation for 26 municipalities in Denton County, using the DFW as a case study to explore how negotiations and public sentiment interacted with the UOGD regulation process.

The statement of purpose behind these regulations defines setback distance as a tool to protect public health, safety, and welfare along with environmental protection and property owner rights. This statement is almost identical in 21 of the 26 counties studied within DFW. Most of these statements follow the first setback regulation written in Denton County, Fort Worth's Ordinance 14880. At least 12 ordinances were rewritten or amended over time, which often involved increasing the setback distance. Not a single municipality in Texas has ever decreased their setback distance.

The study found that there is no clear technical justification in the setback distance ordinances for choosing a specific distance. Empirical data, although sometimes collected, does not drive these regulations. Noise and air pollutant emissions are cited as drilling impacts that need to be regulated, however they do not actually factor into the setback distance determination. Several municipalities list specific decibel level thresholds that should not be exceeded, but the distance at which these thresholds are specified is not the same as the setback distance. Other municipalities specify distances at which noise levels should be monitored rather than providing a threshold. Similar trends were found in relation to the air quality aspect of the regulations. Many municipalities specified distances at which emissions should be monitored or suggested efforts be taken to minimize air pollution but did not provide any metrics.

Setback distances in Texas are ultimately formed as compromises between industry attempts to maximize production and public concerns over the practice. Studies on policymaking in Colorado have similarly shown that while involving stakeholders is considered an important part of the process, politics influence which stakeholders are introduced to the process and when (Rinfret et al. 2014). Rinfret solicited comments from both environmentalists and oil and gas representatives on their experience with policymaking in Colorado. Environmentalists had a suspicion that they were being excluded from parts of the process while the industry representatives expressed that environmentalists were difficult to negotiate with. Although many of the circumstances surrounding UOGD in Texas are different than those in Colorado, the stakeholders driving these regulations remain the same. In fact, Fry (2013) suggested that more scientific information, such as simulations of benzene, could be beneficial to informing future UOGD regulation, which motivates the work in this thesis.

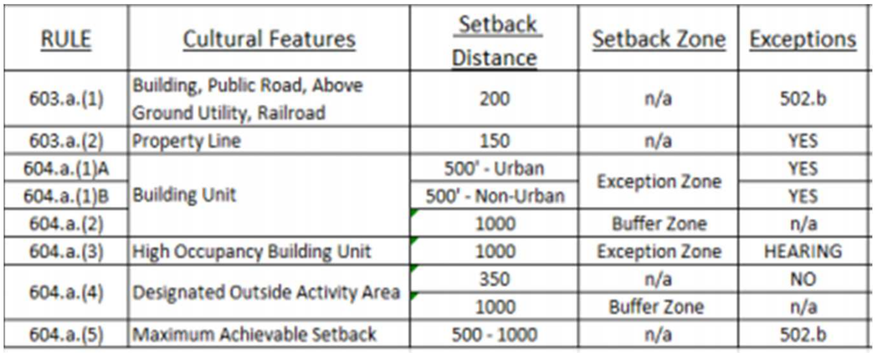
## 1.2 UOGD Regulations in Colorado

Oil and gas regulations in Colorado are maintained by the Colorado Oil and Gas Conservation Commission (COGCC), a division of the Colorado Department of Natural Resources. Unlike the regulatory structure in Texas, local governments in Colorado have less power to regulate oil and gas operations than the COGCC does. For example, both the City of Fort Collins and the City of Longmont attempted to implement a moratorium on oil and gas production within their respective city limits but were overruled by the Colorado Supreme Court when the COGCC challenged their jurisdiction (Colorado Supreme Court 2016b; Colorado Supreme Court 2016a).

These cases affirmed that local governments can only regulate aspects of oil and gas development in a manner that aligns with statewide regulations (Minor 2014). If local ordinances conflict with statewide laws, they will be preempted and overturned as in the case of Fort Collins and Longmont. The Colorado Department of Local Affairs (DOLA) created a guide to assist local governments in understanding the extent of their regulatory powers. However, the DOLA guide provides a conservative description of local government powers claiming the impacts of UOGD extend beyond the scope of issues local governments traditionally handle, which limits the usefulness of the document (Dahl et al. 2010).

The Fort Collins and Longmont cases were not the first time the COGCC has clashed with local governments over regulatory authority. Two similar cases, La Plata County vs. Bowen/Edwards Associates and Voss (City of Greeley) vs. Lundvall Brothers, set the precedent

*Table 1: Setback distance regulations in Colorado (Colorado Oil and Gas Conservation Commission 2013)*



| RULE | Cultural Features | Setback Distance | Setback Zone | Exceptions |
|---|---|---|---|---|
| 603.a.(1) | Building, Public Road, Above Ground Utility, Railroad | 200 | n/a | 502.b |
| 603.a.(2) | Property Line | 150 | n/a | YES |
| 604.a.(1)A | Building Unit | 500' - Urban | Exception Zone | YES |
| 604.a.(1)B | | 500' - Non-Urban | | YES |
| 604.a.(2) | | 1000 | Buffer Zone | n/a |
| 604.a.(3) | High Occupancy Building Unit | 1000 | Exception Zone | HEARING |
| 604.a.(4) | Designated Outside Activity Area | 350 | n/a | NO |
| | | 1000 | Buffer Zone | n/a |
| 604.a.(5) | Maximum Achievable Setback | 500 - 1000 | n/a | 502.b |

for these rulings in 1992 (Minor 2014). The COGCC has responded to such pressure by tightening oil and gas regulations throughout the years. The most recent set of regulations were overhauled in August 2013 (Colorado Oil and Gas Conservation Commission 2016b), only a year after Longmont passed a law prohibiting hydraulic fracturing through a citizen-initiated vote (City of Longmont 2016). The current statewide setback rules and exceptions are listed in Table 1. Refer to the COGCC 100 series regulations for definitions of each of these land use categories. There are no statewide regulations that require a minimum setback distance of greater than 1000 feet.

Exception 502.b from Table 1 refers to variances, which allow a well or production facility to be built within the typical minimum setback distance. Variances can only be approved by the COGCC director without a hearing or by the entire commission after a hearing. The variance applicant must prove that they have made efforts to comply with all applicable rules and is unable to due to special circumstances (often geographic restrictions). The request must also not “violate the basic intent of the Oil and Gas Conservation Act”, which is to foster responsible UOGD while protecting the public (Colorado Oil and Gas Conservation Commission 2015).

## 1.3 The UOGD Process

There are four stages involved in completing a well pad: drilling, hydraulic fracturing, flowback, and production. Vertical and then horizontal drilling are the first steps of the process and generally last four to 10 days (Collett et al. 2016). The drill is gradually shifted from the vertical to the horizontal direction once the depth of the shale deposit has been reached. This process is enabled by technological advancements in drilling technology in the 1980's and is far more efficient than drilling several vertical wells (Allouche et al. 2000).

The next phase is what separates this process from conventional oil and gas development, hydraulic fracturing. Numerous isolated fractures containing oil are normally present in shale deposits. These fractures are then connected through the fracking process and held open by small particle from the fracking fluid (Gregory et al. 2011). This stage is even shorter and generally only lasts two to four days (Collett et al. 2016).

During flowback fluids and loose particles from the well return to the surface and are collected. Aside from the desired products from the well, oil and natural gas, produced water and fracking fluid are collected as well. Produced water refers to any water that is returning from the well and may vary in composition (Mantell 2011). The length of this stage varies depending on the length of the fracturing phase and the number of wells on the pad, but can range from one to four weeks (He et al. 2015).

The final stage is production, which lasts for 20 to 40 years depending on the well until it is abandoned. The collection process becomes easier because there is no longer any fracking fluid returning to the surface that needs to be separated. Natural gas and oil produced by the well still needs to be processed which induces some additional traffic into and out of the well pad.

## 1.4 Air Quality Impacts of UOGD

Numerous hazardous air pollutants are released in significant quantities during hydraulic fracturing operations (Brandt & Pétron 2015). In this study, we will focus on benzene, toluene, ethylbenzene, xylenes, and hexane. The first four are a group of petroleum related air toxics known as BTEX pollutants. Hexane is included as well because it is another notable air toxic emitted from UOGD operations. Benzene is the most toxic from the BTEX group and can damage several organs in the body (Leusch & Bartkow 2010). It has also been consistently linked to leukemia through several studies (Agency for Toxic Substances and Disease Registry 2007).

Health impacts from BTEX chemicals vary depending on length of exposure and the concentration of the pollutant over the exposure period. Short periods of exposure to extremely high concentrations can be fatal, but concentrations this high are unrealistic in the context of UOGD. However, residents living near UOGD have reported respiratory, neurological, and dermatological symptoms (Adgate et al. 2014). The exact concentration above which health consequences can be expected is not known, however several government agencies including the Agency for Toxic Substances and Disease Registry (ATSDR), the EPA, and the Occupational Safety and Health Administration (OHSA) provide recommended acceptable exposure limits. OHSA maintains regulations but they only apply to work environments. At present, there are no regulations that provide an absolute threshold for the emission of most hazardous air pollutants from hydraulic fracturing wells.

Pollutant concentrations are reported for a specific averaging period. The averaging period refers to the duration of time over which a concentration is averaged. Wind direction and temperature frequently change, which in turn causes the concentration at a specific point to change over time. As discussed above, longer periods of high exposure carry greater health risks. For example, the ATSDR short-term exposure threshold for benzene is three times higher than the long-term exposure threshold (Agency for Toxic Substances and Disease Registry 2016).

## 1.5 Quantitative Policy Analysis

### 1.5.1 Background

Policy analysis is the “process of multidisciplinary inquiry aiming at the creation, critical assessment, and communication of policy-relevant information” (Dunn 2012). Incorporating scientific evidence into this process can be beneficial, but comes with challenges as well. The first and perhaps fundamental challenge of quantitative policy analysis is defining the problem itself

(Reed & Kasprzyk 2009). Regulatory problems are often very complex systems with multiple interested stakeholders and competing objectives as we have discussed with UOGD as our example. Recognizing these components along with the system boundaries and integrating them into the problem definition is necessary to perform effective policy analysis. Uncertainty is another concept that drives policy analysis because of its prevalence in nearly every aspect of the process. Will a policy, once implemented, have the expected impacts? This is an example of uncertainty, which characterizes how well something is known. Uncertainties cannot be removed, they must be accepted, managed, and integrated into the results (Walker & Marchau 2003).

Attempts to solve these problems often involve choosing an appropriate methodology or framework through which to solve the problem and trying to find the optimal solution or the solution that best satisfies all criteria. Regulatory issues can be thought of as “wicked” problems, which are hard to define and are never truly solved, but instead put to rest when an analyst arrives at a solution that is “good enough” (Rittel & Webber 1973). There are several other properties that define a wicked problem, but the most relevant with respect to UOGD regulation are the ideas that there is only one chance to implement a correct solution and that the planner cannot afford to be wrong. Public health as well as the local economy depend on the setback distance to some extent.

In this case, “solving” the problem does not lead to a single solution, but rather a set of alternatives. Because of this, a key aspect of quantitative policy analysis is effective communication, transparency, and use of an analysis approach that is appropriate to the problem. In fact, some authors have commented that the process of using optimization and modeling to address wicked problems is a major “result” of the analysis and leads to better understanding of the dynamics of the problem, beyond simply providing a single policy recommendation (Liebman 1976).

### 1.5.2 Applying Quantitative Policy Analysis to UOGD

In this thesis, we present a policy analysis framework that generates plausible configurations of well pads based on setback distance policy alternatives, and uses atmospheric dispersion modeling to simulate potential air quality outcomes based on these configurations and policy alternatives. Our goal is to provide insight into the relationship between setback distance and outcomes such as the number of wells drilled under different policy alternatives, as well as concentrations of pollutants and public health measures. The framework is designed to be adaptable so that it can be run with different inputs as new data becomes available or to analyze different regions. This is critical for analyzing a wicked problem because the problem will need to be revisited to determine which solution is most appropriate in the future as the landscape changes.

A key aspect of the framework is generation of a set of plausible setback distance policy alternatives that are, in some cases, less restrictive than currently exists in Colorado, and in others more restrictive than the current regulation. Based on these setback distances, we generate plausible fields of randomly placed wells then quantify the air quality impacts from these wells on a representative receptor (i.e., a home). Each well is randomly assigned an emission rate based on a distribution developed from observed data. See Section 2.4.2 in Chapter 2 for more information. The air quality results will then be analyzed with respect to human health impacts. We will examine this problem from two viewpoints: policymaking in a region untouched by UOGD (phase I) and policymaking in a region with existing UOGD (phase II). In the former, we assume there has been no previous UOGD activity and that all future activity will be governed by the setback regulation being informed by this analysis. In the latter, previously completed wells may not comply with potential new setback distance regulations or even previous amendments to the setback distance and these must be considered in the decision-making process. Overall, the purpose of this research is to provide quantitative information to aid in policy discussions about setback regulations, not to provide a single setback distance recommendation.

## 1.6 Summary of Chapters

Chapter 2 provides an overview of the methodology used to analyze this problem, which includes a detailed explanation of the framework, a background on AERMOD, the air dispersion model used to predict pollutant concentrations in this analysis, and a discussion on managing uncertainty. Sensitivity testing for AERMOD and discussion of important parameters are presented in Chapter 3 followed by our results in Chapter 4. In Chapter 5, we discuss the implications of our results in the context of policymaking in UOGD. After revisiting the important outcomes from this analysis in Chapter 6 we end with a discussion of future work in this research including the potential to integrate other objectives into the framework in Chapter 7.

# Chapter 2: Methods

The methodology in this thesis combines random generation of UOGD wells, uncertainty sampling of emissions rates, and air quality modeling. In this chapter, each of these topics is discussed in detail. Section 2.1 serves as an overview of the modeling process including the framework and study site used to analyze this problem. Then in Section 2.2 the policy objectives and metrics are explained, which will be followed by a breakdown of modeling configurations in Section 2.3. Next, in Section 2.4, is an explanation of the air quality analysis including the model used to predict pollutant concentrations, the inputs to the model, and a sensitivity analysis of model parameters. Finally, Section 2.5 contains a detailed description of the workflow of the framework.

## 2.1 Modeling Overview

As we explained in the introduction to this thesis, analyzing UOGD regulations requires a framework to properly quantify air quality impacts for various policy alternatives and frame the potential utility of these results in the decision-making process. These policy alternatives are the drivers of the framework. The conceptual workflow of this framework is as follows: (i) we input a setback distance that determines the number of wells in the scenario, (ii) AERMOD then predicts the resulting concentrations at a home, (iii) the framework visualizes the concentration values, (iv) we calculate human health outcomes based on the concentrations.

We chose setback distances to analyze based on current regulations and distances that have been studied and discussed in other studies. The distances we chose range from 350 feet, the lowest distance to a location at which humans would spend a significant amount of time (Colorado Oil and Gas Conservation Commission 2013), to 2500 feet, the maximum distance that has been studied by the COGCC (Colorado Oil and Gas Conservation Commission 2016a). Setback distances to property lines are 150 feet, but we are not considering setback distances this low because many of our metrics are based on human health outcomes, and the assumption is that residents are not spending considerable time at a property line in comparison to the time they spend inside their home.

Our study site is a hypothetical location in Northeast Colorado. All inputs to the model are based on data from this region and will be explained in more detail in the following sections. A contribution of this study was in developing the analysis technique of randomly generating wells and emissions rates, connecting with real-world meteorological data and other air quality modeling inputs, and creating infrastructure to run air quality models thousands of times to develop the results. Thus, data from any region of interest could be input into our modeling framework to generate similar results for other regions.

## 2.2 Quantitative Metrics for Setback Distance Comparisons

As discussed in Chapter 1, there are many broad objectives associated with UOGD, and in this thesis we will focus on two: increasing the allowable number of wells and reducing air quality impacts at residential locations. Increasing the number of wells correlates with economic benefits, since having more wells will ostensibly increase the amount of revenue from UOGD activity. The air quality impacts analysis is the primary focus of the modeling in this thesis. Our goal is to show a comprehensive treatment of air quality as the first impact, such that future research can implement new types of broad UOGD objectives such as decreasing noise impact or quantifying the indirect economic benefits from the activity. Chapter 7 discusses this future work in more detail. A comprehensive treatment of air quality impacts requires several steps. Reporting air pollutant concentrations on their own is of limited use, since each pollutant has different magnitudes of concentration that can cause health problems. Therefore, there are also human health assessments that interpret the magnitudes of the concentrations. For more information on the model used to simulate air toxic dispersion see Section 2.4.

Recall that several government organizations provide non-regulatory concentration thresholds. The concentration guidelines that the ATSDR maintains are called Minimal Risk Levels (MRLs) and they outline air toxic exposure estimates beneath which humans are unlikely to experience adverse health effects. The first metric is the list of associated thresholds for each pollutant being analyzed in this study from the ATSDR MRLs.

The MRLs are determined through the no observed adverse effect level (NOAEL) approach. The NOAEL thresholds are then modified with one or more factors of safety to represent uncertainties in both the NOAEL approach and the increased impacts on the most sensitive portion of the population. It is important to note that the MRLs are screening levels, rather than action levels, and indicate the necessity for further examination of emitters that produce concentrations above the MRL thresholds (Agency for Toxic Substances and Disease Registry 2012).

Health impacts depend not only on the magnitude of the concentration, but the averaging period of the concentration as well. The MRLs provide concentration thresholds for both short-term (acute) and long-term (chronic) exposure. Table 2 contains values for these thresholds along with a list of the pollutants that we examine in this study. In this analysis, acute exposure will correspond to a 1-hour average concentration while chronic exposure will be associated with a 23-year average concentration. All concentrations in this analysis are measured at a height of two meters above ground-level, approximately typical human inhalation height.

*Table 2: ATSDR MRL Concentration Thresholds (Agency for Toxic Substances and Disease Registry 2016)*

| Pollutant | Acute Threshold (µg/m3) | Chronic Threshold (µg/m3) |
|---|---|---|
| benzene | 28.75 | 9.58 |
| toluene | 7540 | 3770 |
| ethylbenzene | 21710 | 260 |
| xylenes | 8680 | 220 |
| hexane | --- | 2110 |

*Table 3: Increase in cancer risk due to benzene exposure* (Environmental Protection Agency 2012)

| Exposure Range (μg/$m^3$) | Increase in Cancer Risk |
|---|---|
| 0.13 – 0.45 | One-in-a-million |
| 1.3 – 4.5 | One-in-a-hundred thousand |
| 13 – 45 | One-in-ten thousand |

The second metric is cancer risk, which is only applicable to benzene. The EPA provides estimates for increase in cancer risk associated with benzene inhalation based on mathematical models. Similar information is not available for the other four air toxics because there is insufficient data available to determine the associated risk according to the EPA (Environmental Protection Agency 2016a). The carcinogenic characteristics of benzene, however, have been studied and verified (Agency for Toxic Substances and Disease Registry 2007). As was previously mentioned, there is uncertainty in the relationship between pollutant concentration and health impacts. Depending on the range from Table 3 in which concentrations predicted during the simulations fall, policymakers will be able to decide if the risk outweighs the benefits for a specific policy alternative.

## 2.3 Modeling Configurations

In this analysis, we create one set of computational experiments termed ‘phases’, which reflect different possibilities for whether or not UOGD exists in an area; for each phase there are four experiments termed ‘scenarios’ that explore health impacts. Within each phase and scenario, a suite of setback distances, ‘policy alternatives’, are modeled. This set of model configurations helps our analysis be comprehensive and simulate air quality outcomes across the spectrum of different UOGD activities.

The two phases represent different regulatory standpoints. The first phase examines planning for operations in a currently undeveloped area and the tradeoffs involved with each setback distance. The second phase explores a region with existing operations and the impact

*Table 4: Scenarios*

| Scenario | Number of Wells | Exposure Time | Simulation Duration |
|---|---|---|---|
| Acute CT | 13 | 1-hour average | 1 year |
| Acute RME | 90 | 1-hour average | 1 year |
| Chronic CT | 13 | 23-year average | 23 years |
| Chronic RME | 90 | 23-year average | 23 years |

produced by drilling new wells. The purpose of the four scenarios is to provide an understanding of the air quality impacts from the standpoint of residents that are affected by UOGD to different degrees. The scenarios have two dimensions: exposure time and well density. There are two exposure times and two well densities, which results in four scenarios when combined. See Table 4 for details.

Exposure time is included within the scenario set because health impacts depend not only on the magnitude of the concentration, but the averaging period of the concentration as well. The two exposure time variations are acute (short-term) and chronic (long-term). The acute scenario is run for a single year of meteorological data, 2016, with the intention of observing 1-hour average concentrations. The chronic scenario is run for 23 years ranging from 1994 to 2016, which consists of every year of data available for the Denver International Airport MET station. The 23-year average concentration is the parameter of interest for the chronic scenario.

The second characteristic within the scenarios is well density variations, based on data for Greeley, CO from the Colorado Oil and Gas Information System (COGIS). The goal of the well

*Table 5: Setback distances studied in this analysis. Note that all setback regulations are from the COGCC* (Colorado Oil and Gas Conservation Commission 2013)

| Setback Distance (feet) | Reasoning |
|---|---|
| 350 | Designated outside activity area setback distance |
| 500 | Building unit setback distance |
| 750 | Relevant compromise between 500 and 1000 |
| 1000 | High occupancy building unit setback distance |
| 1500 | Relevant compromise between 1000 and 2500 |
| 2000 | Relevant compromise between 1000 and 2500 |
| 2500 | Maximum setback distance studied by the COGCC |

density portion of the scenario is to explore different numbers of wells that surround a typical home in our case study. The central tendency (CT) scenario is based on the median number of wells within one mile of a home, 13. The reasonable maximum exposure (RME) scenario is based on the 95th percentile number of wells within one mile of a home, which is 90. The final level within our analysis framework is 'policy alternatives', which explores different values of setback distance. Each policy alternative is run for each of the two phases and four scenarios, for a total of 8 analyses for each setback distance. The goal of this analysis is to capture the impacts of various setback distances within each of these phases and scenarios. Table 5 lists the different setback distance policy alternatives we considered in the analysis.

In summary, our policy analysis framework comprises hundreds of air quality simulation runs, which combine a phase (an assumption about whether UOGD is present or not), a scenario (a combination of exposure time and number of wells surrounding a home), and a policy alternative of setback distance. We refer to a combination of phase, scenario and setback distance as a 'configuration'. Subsequent sections in this chapter explain the phases (Sections 2.3.1 and 2.3.2), explain our methodology of air quality modeling (Section 2.4), and summarize the framework implementation (Section 2.5).

### 2.3.1 Phase I: Informing regulations in regions considering first time implementation of oil and gas development

The goal of this phase is to explore regulations in an environment that has not had UOGD activity in it before, assuming that new setback regulations would dictate the placement of new wells without any wells being 'grandfathered' before the regulations were in place. In other words, a region is considering UOGD for the first time and the governing body is discussing an appropriate level of setback distance for all future development. Rather than deciding on an uninformed policy and having to increase the setback distance later as has happened in many other regions, all well pads in the region would be completed in accordance with appropriately informed setback distance policies.

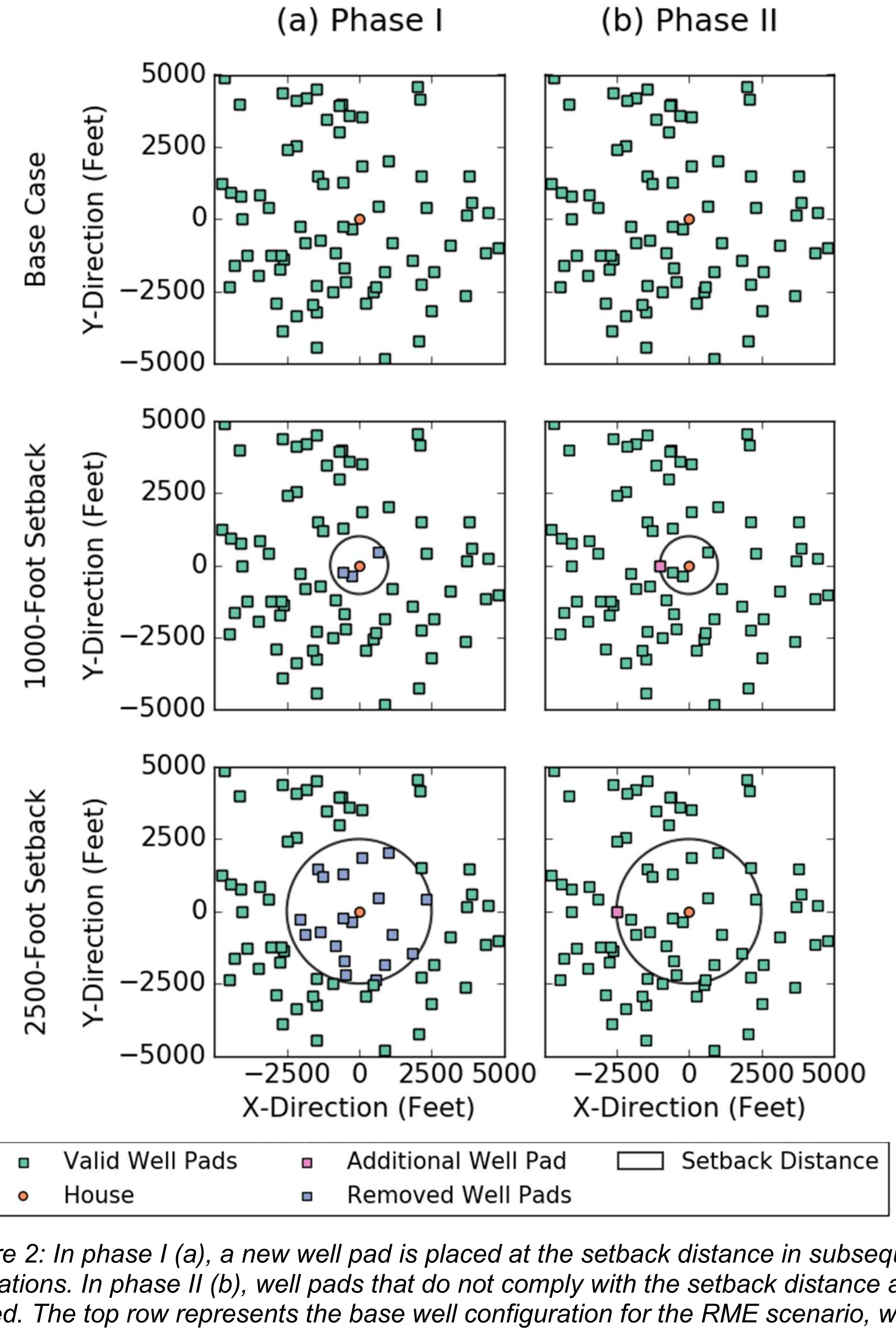


*Figure 2: In phase I (a), a new well pad is placed at the setback distance in subsequent iterations. In phase II (b), well pads that do not comply with the setback distance are removed. The top row represents the base well configuration for the RME scenario, which is the same in each phase. The middle and bottom row represent the 1000 and 2500-foot setback distance configurations respectively.*

In this phase we predict concentrations at a single home surrounded by a set number of wells that are removed from the simulation if they do not comply with the setback distance regulation for that particular configuration. The wells that are removed are not replaced to avoid an unrealistic saturation of wells outside of the setback distance. For higher setback distances, there will be fewer total wells contributing to pollution at the home, which would occur in a real-world situation as well.

### 2.3.2 Phase II: Adjusting regulations in regions with ongoing oil and gas development

In the current landscape of oil and gas development there are numerous well pads that were completed before hydraulic fracturing boomed and serious regulatory efforts were made toward fostering responsible development. However, new well pads are still going into construction and being planned for future implementation. Quantifying the impacts of new development is especially important considering that some old well pads do not comply with current regulations.

In Phase II, we are also considering concentrations at a single home surrounded by a specific number of wells, but in this case a new 10-well pad is added in each configuration. The setback distance in this case will only determine how close the new well pad is placed to home and will not impact any of the previously completed wells. See Figure 2 for an illustration of each phase.

## 2.4 Air Quality

As we mentioned in Chapter 1, AERMOD will be used to quantify the air quality outcomes in this analysis, across all phases, scenarios, and policy alternatives considered. Specifically, it will be used to predict hazardous air pollutant concentrations at homes based on the number and location of wells surrounding it. AERMOD is a steady state plume model developed by the American Meteorological Society (AMS) / U.S. Environmental Protection Agency (EPA)

Regulatory Model Improvement Committee (AERMIC) as a replacement for the Industrial Source Complex Model (ISC3). AERMIC's goal was to update antiquated ISC3 algorithms while maintaining the same model architecture. Upon release AERMOD featured several advancements in air dispersion modeling including updated treatment of boundary layers, improved understanding of turbulence and dispersion, and the ability to handle complex terrain interactions (Cimorelli et al. 2004).

AERMOD is currently the EPA preferred model for regulatory applications. It is designed to simulate short-range dispersion of air pollutants from stationary sources. Numerous supplemental programs were developed to improve AERMOD prediction accuracy and visualize results. AERMET and AERMAP are the two primary input data processors and are both required for regulatory applications. AERMET processes hourly meteorological data including upper air soundings, surface data, and data collected on-site. AERMAP processes complex terrain data from USGS and provides 3-dimensional receptor point coordinates. Other notable pre-processors include BPIPPRM, which calculates downwash values for nearby structures, and AERSURFACE, which processes land cover data.

AERMOD has been used previously to model oil and gas wells in the City of Fort Worth Air Quality Study, which was proposed in response to public concerns about the air quality impacts of unconventional oil and gas development (Eastern Research Group 2011). The research group that conducted the study used AERMOD to predict concentrations and compare them to on-site observations. Another study in British Columbia undertook the task of modeling emissions of sulfur and nitrogen oxides from resource development operations (Krzyzanowski 2011). AERMOD has been used in numerous other applications along with significant testing and comparisons to previous studies that have validated it as the premier air dispersion model (Paine et al. 1998).

### 2.4.1 AERMOD Input Data

Running AERMOD requires writing an input file that follows a specific structure and set of formatting rules. The key information that must be included in this file is the number and location of receptors of sources, the meteorological data file names, and the output options. Aside from the input file, AERMOD requires two supplementary files to run: a surface meteorological data file and a profile meteorological data file, both of which are generated by the associated meteorological data preprocessor AERMET.

AERMET requires meteorological data in the form of both surface observations and upper air soundings. At minimum the following parameters must be present in hourly surface observation data (Environmental Protection Agency 2004):

- Wind speed and direction
- Ambient temperature
- Opaque sky cover[1]
- Station pressure[2]

For upper air sounding data, only the morning sounding (1200 GMT) is required for applications in the United States. These are the minimum data requirements to create a basic simulation using AERMOD. However, for regulatory applications surface roughness, albedo, and Bowen ratio are required in addition to the previously listed parameters, which we generated using AERSURFACE. Further, five years of representative data is required in the absence of on-site data (Cimorelli et al. 1998). Representative data refers to similarities in weather patterns and land cover characteristics.

Surface observations are direct measurements of meteorological characteristics near the surface, which in practice corresponds to somewhere between ground level and 10 meters. Parameters measured include temperature, dew point, wind direction, wind speed, and cloud

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[1] Total sky cover in the absence of opaque sky cover

[2] Recommended but sea level pressure will be used if absent

cover among others (Environmental Protection Agency 2016c). Upper air soundings measure similar meteorological parameters for the upper layers of the atmosphere. While surface observations are frequently measured at weather stations located at various regions around the world, upper air soundings are often only collected twice daily by radiosondes that are carried into the atmosphere by a weather balloon.

Hourly surface observations were taken from the National Centers for Environmental Information (NCEI) Integrated Surface Database (ISD) (National Centers for Environmental Information 2017) and upper air soundings were taken from the National Oceanic and Atmospheric Administration (NOAA) Radiosonde Database (National Oceanic and Atmospheric Administration 2017). These databases contain data from meteorological stations around the world. In this study we used surface observations and upper air soundings from the Denver International Airport weather station for the years 1994 – 2016. Due to the absence of on-site data, more than five recent years of meteorological data was collected as required by the EPA (National Archives and Records Administration 2005). Although this study is not being directly submitted as evidence for a regulatory application, attempts have been made to produce as accurate concentration predictions as possible.

Another supplementary program is AERMAP, which processes terrain data and provides elevation data for AERMOD receptor and source points. It requires a digital elevation model (DEM) to extract these values along with hill height scaling factors that represent the height of nearby terrain that will have the greatest influence on dispersion (Environmental Protection Agency 2016d). However, it does not make any adjustments for buildings or other constructed objects. We used a DEM file for Denver International Airport based on the World Geodetic System of 1984 datum downloaded from the Multi-Resolution Land Characteristics Consortium (Multi-Resolution Land Characteristics Consortium 2017).

Although AERMAP is not built to handle man-made objects, the EPA developed another program entitled BPIPPRM, which simulates downwash effects from nearby buildings. Downwash refers to the presence of turbulent wakes caused by air flowing over buildings that drag pollutants with them and increase ground-level concentrations by influencing plume spread (Canepa 2004). However, downwash is only considered for point sources in AERMOD and residential buildings are rarely tall enough to make an impact according to Good Engineering Practice guidelines (Environmental Protection Agency 1995). We did not incorporate BPIPPRM into our analysis.

### 2.4.2 Emission Rates

Emission rate data for hazardous air pollutants released from hydraulic fracturing operations is limited because oil and gas operators do not consistently monitor or release them (Moore et al. 2014). However, several studies have made an effort to monitor and collect this data. In this study we use emission rate data from a study of hydraulic fracturing operations in the North Front Range of Colorado by the Colorado State University (CSU) Department of Atmospheric Science (Collett et al. 2016). We chose to use this data because it was collected in our region of study. Proximity is important because air pollutant dispersion is driven by meteorological processes, which can vary dramatically between regions. However, even within a single region emissions rates from well pads may be significantly different. The emission rate observations will be influenced by this trend as well as the meteorological conditions at the time of collection.

Recall from Section 1.3 that there are four stages in UOGD, during which emissions can vary considerably. The drilling, fracturing, and flowback stages normally last for about one to two months collectively while the production stage lasts for 20 to 40 years. Wells are occasionally refractured to boost production, but the bulk of the lifetime emissions from the well still stem from the production stage. The CSU researchers specified the stage of the hydraulic fracturing process during which each data point was recorded. They targeted well pads in the fracking, flowback, and production stages, but not the drilling stage so we will not consider it in our analysis. In the case of some multi-well pads, there were multiple operations occurring simultaneously, which we decided to include in the dataset for each stage.

To assign emission rates to well pads in AERMOD appropriately we must consider the length of each stage of the process. The differences in stage length do not present a problem for the acute scenarios because we are only simulating 1-hour average concentrations. However, in the chronic scenarios we are simulating over several years, during which time wells will move in and out of the phases prior to production. To deal with this issue in AERMOD we assume that at any given time, five percent of wells are in the fracking stage, five percent are in the flowback stage, and the rest are in the production stage. The framework randomly selects which wells will receive emission rates from each of the various stages. It is possible for a well pad to have mixed operations occurring simultaneously in the simulation. After separating the emission rate data in the spreadsheet by pollutant and operation, we fit a lognormal distribution to each of these datasets. With five pollutants and three operations there are a total of 15 emission rate distributions, which will be covered in Section 2.4.3.

The values generated by these distributions represent point source emission rates. However, a point source is more appropriate for modeling a single emitter or air stream rather than an open space such as a well pad. Well pads often consist of several emitters including compressor engines, separators, vehicles, wellheads and storage tanks among others and they are normally not located proximally enough to warrant modeling them with a point source. Instead we use an area source, which is normally applied for a group of emitters of similar magnitude. While still not ideal due to the difference in emission rates between emitters, area sources are a far better approximation of a well pad than point sources. We divide point emission rates by the area of the well pad to convert them to the area source emission rates AERMOD uses to calculate concentrations.

### 2.4.3 Uncertainty in AERMOD

Although comparing air pollutant concentration to reference guidelines is a helpful metric, the accuracy of this relationship is limited by the uncertainty present in the AERMOD simulation. The most notable sources of uncertainty are found in the emission rates and the meteorological characteristics.

Emission rates are influenced by several factors including regional and seasonal weather patterns, hydraulic fracturing production rate, equipment failure, and human error. The data collection process introduces uncertainty as well due to shifts in wind direction. Emission rates are ideally measured in the downwind direction; however, this direction does not remain constant and continuously moving the collection equipment to match these shifts is infeasible. To reduce uncertainty caused by seasonal weather patterns would require frequent observations throughout multiple years, which is not realistic because of how intensive the process is.

In Section 2.4.2, we mentioned that we fit the emission rate data to a lognormal distribution. The distribution fitting allowed us to create a representative sample of the data in the Monte Carlo simulations of AERMOD. We tried fitting the data to a gamma distribution as well and compared the two through Anderson-Darling goodness of fit tests to determine which was more appropriate. Although both distributions fit the data well, lognormal generally performs better for datasets with tails, which almost every dataset did. We chose to only use the lognormal distribution in this analysis. See Figure 3 for an example dataset fit with a lognormal curve.

As previously mentioned, publicly available emission rate data is limited, however the CSU team that collected our primary dataset from the Front Range conducted another study in Garfield County, CO (Colorado State University Department of Atmospheric Science 2016). Fortunately, both studies were conducted by the same team using a similar approach (Collett et al. 2016), which reduces the variability between the datasets. Upon comparing the results, we noticed that the Garfield County study yielded significantly higher emission rate observations, which cannot be attributed to a single factor. This comparison demonstrates the variation in emission rates between various well pads.

We deal with uncertainty in the emission rates in two ways. The first method of dealing with this uncertainty is through comparing the increase in pollutant concentrations caused by increasing the number of wells rather than examining absolute numbers. Locally collected emission rates can be applied to the percent increase in concentration to produce more appropriate absolute concentrations for the region. The second method for managing this uncertainty is through the random generation of emission rates. The framework can repeat the simulation with a different user specified random number sample each time and average the results. In this analysis results are averaged over 100 random samples.

Managing uncertainty in meteorological data is more complicated. The best approach available is to increase the period of time over which the simulation is run, which is inherently part of predicting chronic concentrations, or comparing the results while holding all parameters

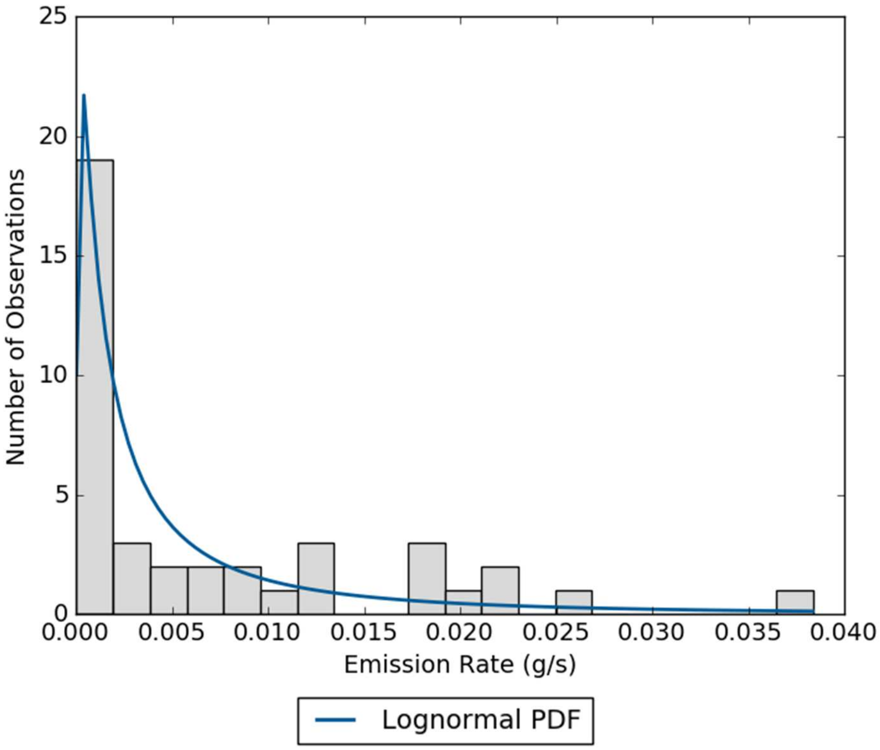

*Figure 3: Histogram with lognormal distribution fit line for benzene fracking stage emission rate data*

constant aside from the meteorological data. We chose not to run the simulation over several years of meteorological data to isolate the impact of varying the emission rates; though we acknowledge that running a larger number of years of meteorological data would give more robust results.

## 2.5 Framework Implementation

We developed a Python script to conduct this analysis and function as the backbone of our framework. This script handles all AERMOD processes, which include creating an input file, running the model, and parsing the outputs along with visualization of the results. The function that runs the simulation requires inputs for the pollutant of interest, meteorological files for the location of interest processed by AERMET, setback distances, exposure length, number of wells, and size of the model domain among others. Aside from running AERMOD, the primary operation of this function is to add wells at the setback distance during each iteration or remove wells that do not comply with the setback distance depending on the input specifications.

Once the inputs are chosen, the script generates several values per the random samples chosen in the function inputs. We incorporated several sampling techniques that are explained in Table 6 to ensure that each randomly generated parameter was done so appropriately. A specific random sample can be chosen for each parameter to maintain the reproducibility of the results. In both phases we are studying concentrations at a single receptor point or “home” around which well pad coordinates are generated within a radius specified in the function inputs. We held the random number generation samples constant for each of the parameters mentioned above between all scenarios and phases. Our goal in choosing a seed was ensuring a relatively

*Table 6: Random sampling techniques for applicable parameters*

| Parameter | Distribution | Notes |
|---|---|---|
| Number of wells per well pad | Weighted random sampling | Weights based on observed data |
| Emission Rates | Lognormal distribution | Based on observed data |
| Well Coordinates | Discrete uniform distribution | All values equally likely |

proportional number of wells existed in each setback distance bracket. Figure 4 shows the well pad configuration for the both the RME and CT scenarios. The data points on the plot represent well pads, not individual wells, which is why there are fewer than 90 points on the RME plot.

We generate well coordinates using a discrete uniform distribution through the NumPy[3] 'randint' function. The number of wells on each well pad is determined through the NumPy 'choice' function, which is a weighted sampling of a discrete number of wells per pad (range of 1 well per pad to 64 wells per pad). The distribution of weights is based on data from well pads in Greeley, CO taken from the COGIS. Single-well pads are by far the most common type, so '1' will have the highest weight and is most likely to be selected during the random sampling process.

After the number of wells is determined for each well pad, emission rates are generated by sampling from the lognormal distribution created for each stage of the fracking process as previously discussed. For multi-well pads the associated point source emission rates are summed

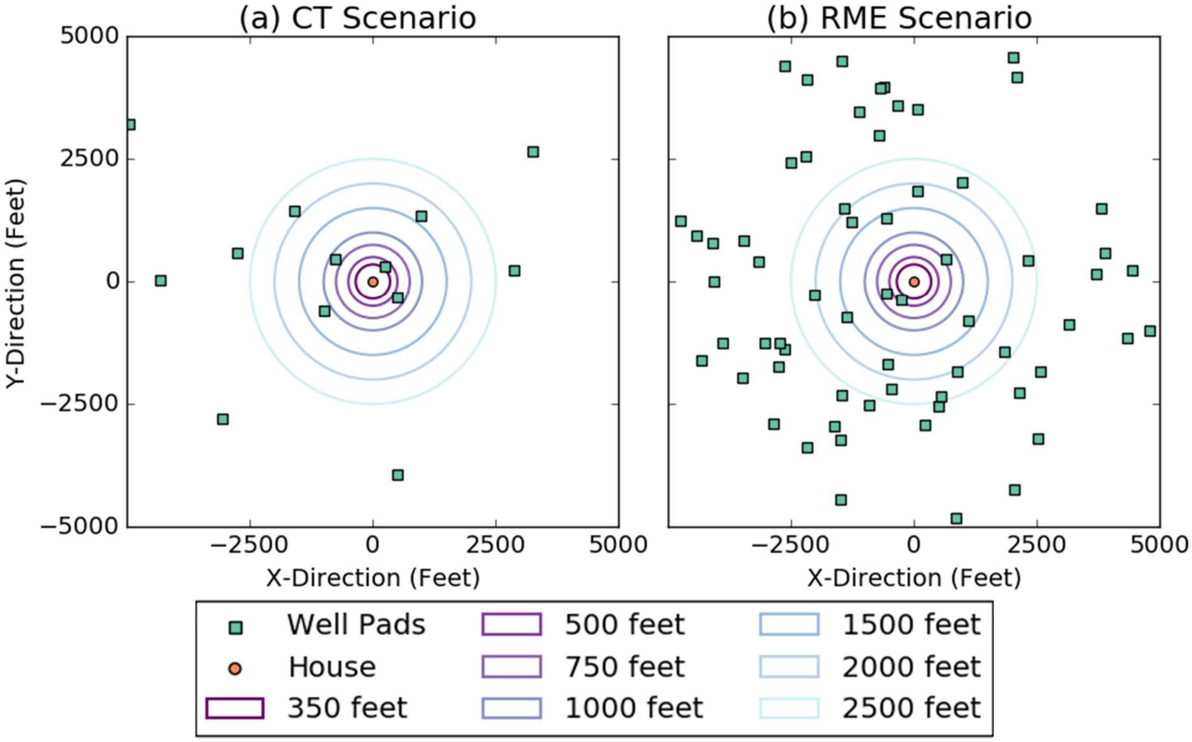

*Figure 4: Well pad configuration for the CT scenario (a) and the RME scenario (b)*

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[3] NumPy is a Python package that supports numerical analysis

and then divided by the area of the well pad before being transferred to AERMOD. The script automatically increases the size of multi-well pads based on the number of wells located on the pad.

In phase I, before the well pad locations are sent to AERMOD, the framework calculates the distance between all well pads and the home and removes well pads that do not meet the setback distance requirements for the current run. While studying regions with ongoing development in phase II we add a well pad at the setback distance in lieu of the previous distance checking function. An automated AERMAP function then provides elevation data for the well pads

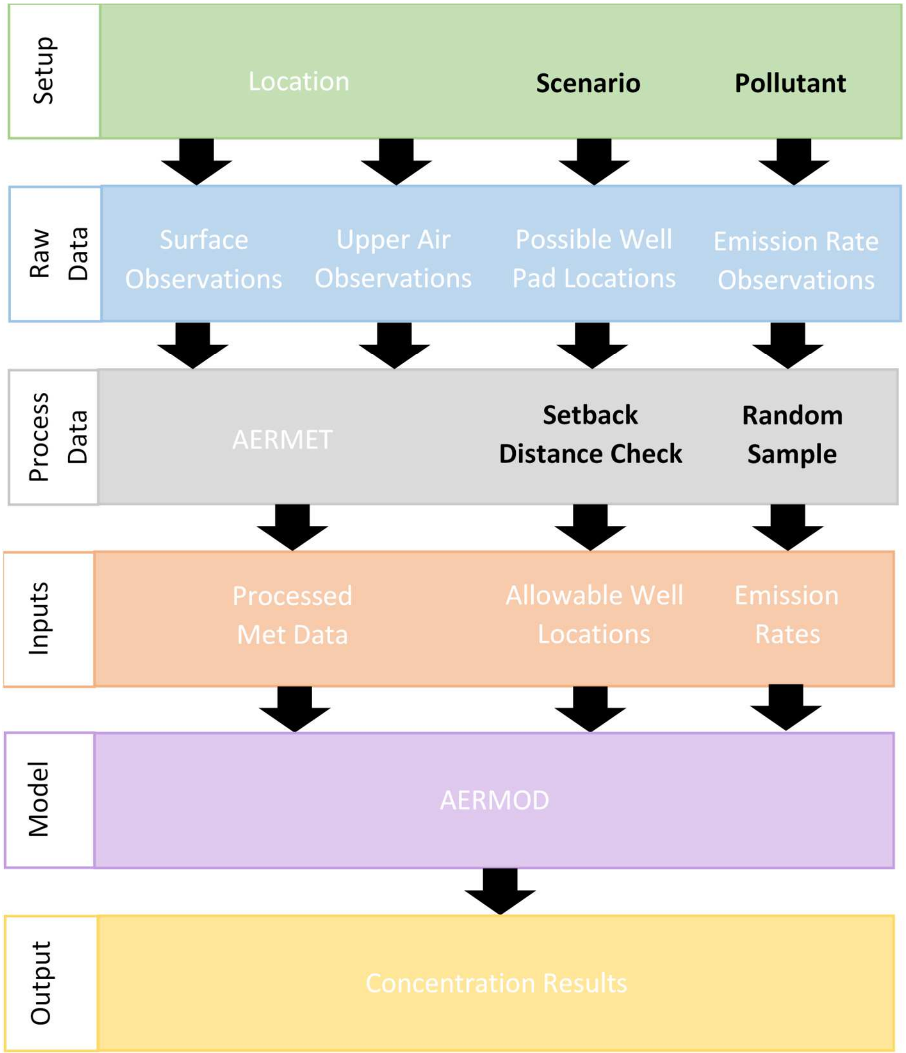

*Figure 5: Basic schematic of framework workflow. The black text refers to the independent parameters that change throughout the analysis. The white text refers to items that are either constant or dependent on the independent parameters.*

and home. At this point the well pad coordinates and parameters are ready to be sent to AERMOD, after which the results are returned through an output file parsing function.

The script runs through three ‘for loops’ to complete a full simulation. The inner loop runs through setback distances, which impacts the number of well pads or location of the additional well pads depending on the modeling phase. Additionally, the original well pad configuration and number of wells is determined by the scenario. The second level loop runs through pollutants, which impacts the emission rates. The final and outermost loop runs through random number samples, which again influence emission rates for each pollutant. The results for each setback distance and pollutant are averaged between runs of the outer loop. See Figure 5 for a visualization of the framework workflow.

# Chapter 3: Sensitivity Testing

This chapter presents a sensitivity testing analysis for AERMOD, which includes studying and confirming how AERMOD concentrations are predicted, testing for parameter sensitivity, validating the model setup on a smaller scale, and observing basic pollutant dispersion trends for a simple scenario of one well and one house. Before conducting a policy analysis, it was important to ensure our results made sense theoretically and that we understood which parameters had the greatest impact on the results.

First, the wind rose in Figure 6 was created from the NCEI meteorological data and compared to the results from AERMOD. A wind rose is a visual representation of the most common wind directions over a long time scale. Air pollutant concentrations should be highest in

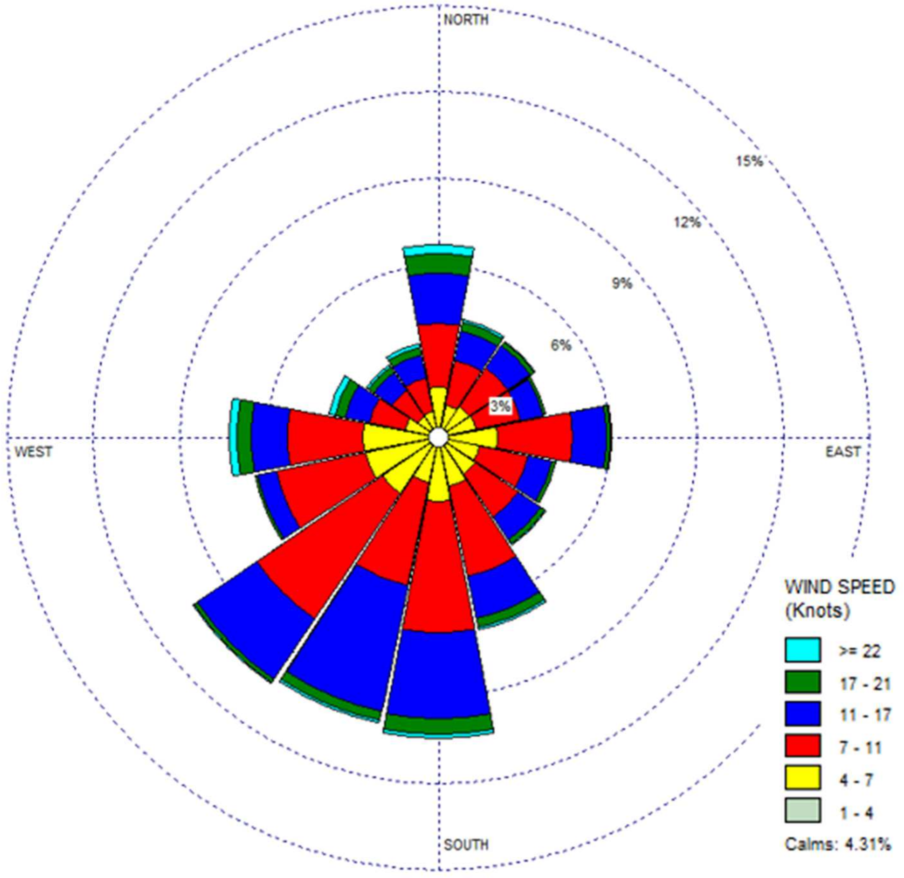

*Figure 6: Wind rose for the Denver International Airport MET station for the years 1994-2016. The resultant mean wind vector points toward the North-Northeast direction*

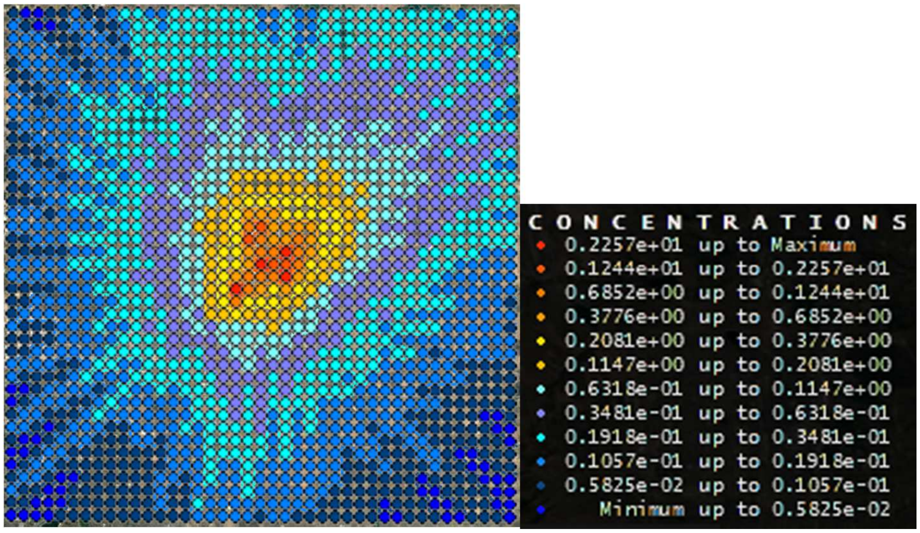

*Figure 7: Contour plot generated by AERPLOT. Notice that the higher concentrations are skewed to the Northeast, which aligns with the resultant wind vector from the wind rose in Figure 6*

the direction the wind blows toward. Comparing the contour plot of annual average concentrations in Figure 7 to the wind rose proves that the model is appropriately incorporating wind patterns into the concentration predictions. AERPLOT, a supplementary AERMOD program created by the EPA, generates contour plots from the results.

## 3.1 Concentration-Distance Relationship

Beyond the initial quality checking of our model setup, testing was required to determine which variables influenced our predicted concentrations the most and characterize these impacts. Our first diagnostic test involved visualizing the reduction in concentration at a given receptor point as a result of increasing the distance between the pollutant source and the point. The meteorological parameters for each data point were held constant to provide an accurate comparison between setback distances. For a simple setup such as this one that is restricted to a single receptor point and pollutant source, the hour of meteorological data that produces the highest concentrations will not change between runs.

The trend lines in Figure 8 exhibit a close fit to a power law approximation. However, simply using a power law relationship to predict concentrations for a hypothetical well at various

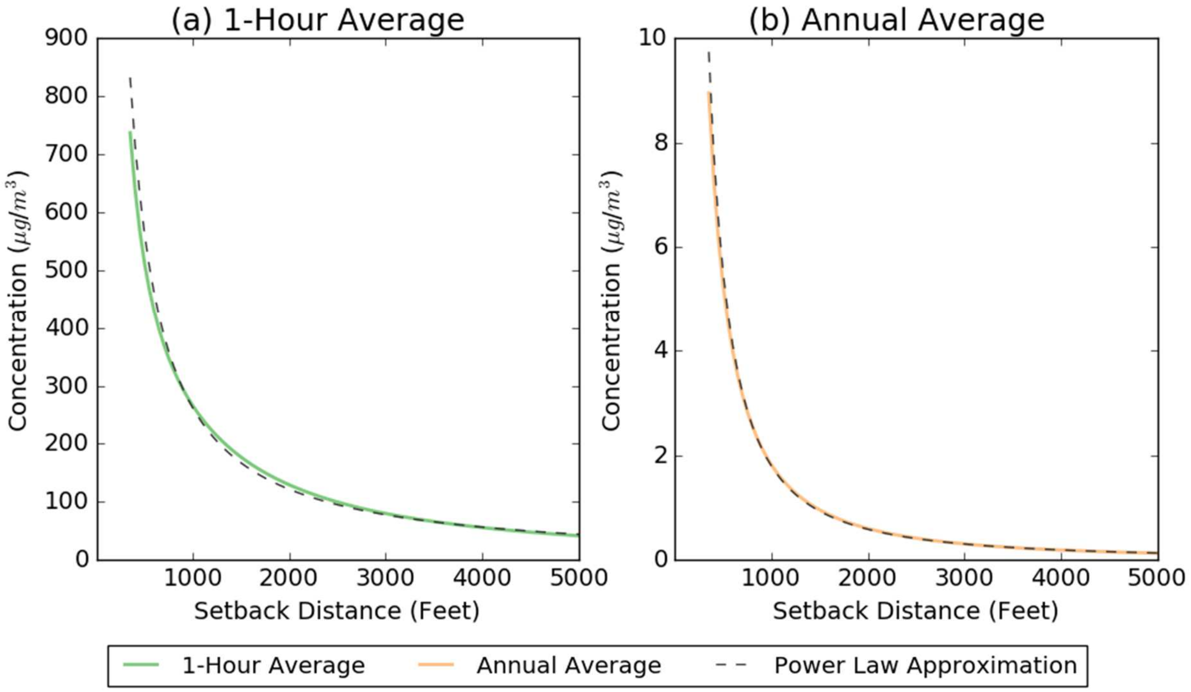

*Figure 8: General relationship between distance and concentration as predicted by AERMOD for 1-hour (a) and annual average (b) concentrations*

distances would not lead to reliable results. This test represents an idealized scenario with no obstructions to plume flow and constant meteorological parameters. Although it cannot be used for making specific concentration predictions, it does provide a visualization of the basic relationship between distance and concentration that can be expected from AERMOD predictions.

The plots in Figure 9 characterize how this relationship changes for predicted concentrations of different magnitudes. Comparison 1 in Figure 9a presents the power law curve for the 1st, 50th, and 100th highest 1-hour average concentration predicted during this sensitivity simulation. From examining the curves on the graph, we can draw the conclusion that lower magnitude concentrations yield a sharper drop off in concentration with distance. However, this relationship only applies to maximum concentrations. The orange curve in Figure 9b shows the trend line for the annual average concentration, which consists of far lower magnitude concentrations than any of the curves in Figure 9a. Despite the lower magnitude concentrations in the annual average predictions, the curve maintains a similar shape to the 100th highest 1-hour

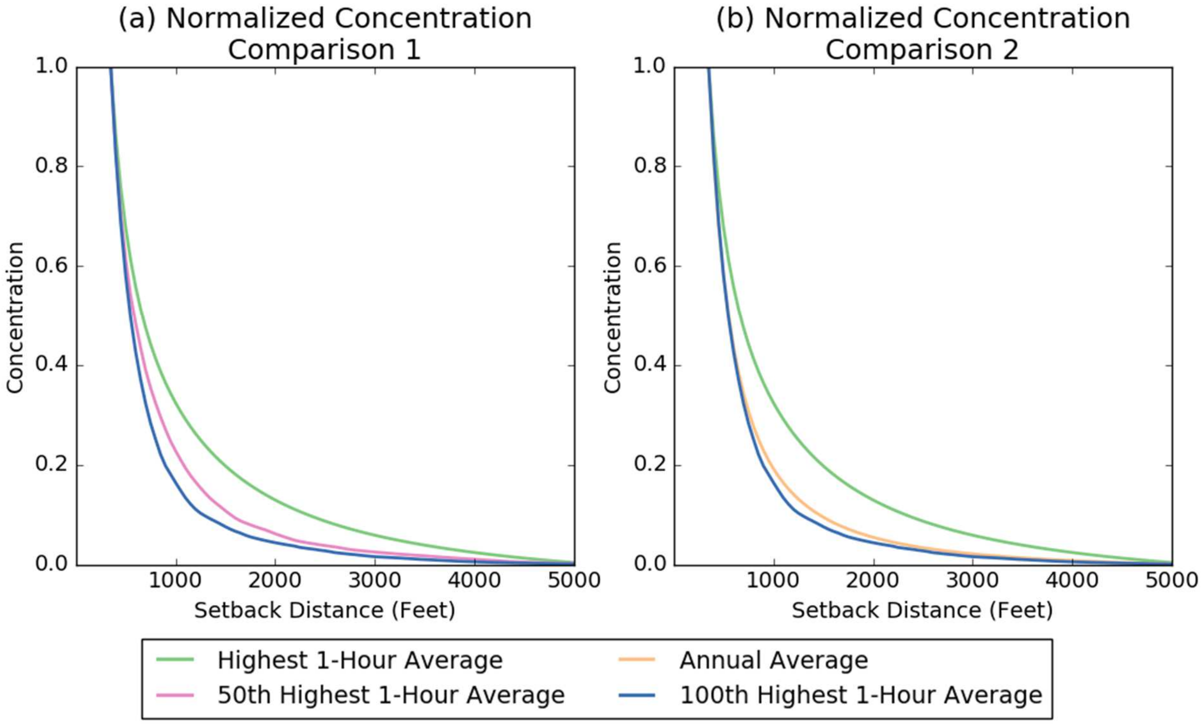

*Figure 9: Change in distance-concentration relationship by concentration magnitude. Only 1-hour averages are compared in (a), while in (b) the annual average concentration is substituted in for the 50$^{th}$ highest 1-hour average concentration of the simulation year*

average concentration curve. In fact, the 100$^{th}$ highest 1-hour average concentrations power curve is slightly steeper than that for the annual average concentrations, which is not the relationship that would be expected from examining Figure 9a. Although there is a correlation between concentration magnitude and shape of the distance-concentration curve, it is not strong enough to be used to make predictions.

## 3.2 Concentration-Release Height Relationship

Release height plays an important role in the dispersion process. Upon being emitted, a plume will spread in all directions, which reduces the concentration at any point in the plume. However, objects can impede dispersion and "reflect" the plume, which in turn causes the concentration to increase around these points. Emitters on a well pad are located near the surface, which will reflect emissions and increase pollution near ground-level (Masters 1998). The increase in concentration depends on atmospheric conditions and temperature, which makes developing a simple and accurate relationship impossible. Using AERMOD we can develop a general sense of the relationship between concentration and release height at various distances from the emitter.

Figure 10 shows the maximum annual 1-hour average concentrations for setbacks of 350, 1000, and 2500 feet at various release heights. As expected, increasing release height reduces concentrations around ground level. For each setback distance the concentration decreases by over 50 percent in comparison to the surface level scenario at a release height of 20 feet. Interestingly, the percent decrease in concentration for the 350-foot setback distance is the lowest up until a 10-foot release height, after which it rapidly becomes the setback distance with the greatest percent decrease.

We chose to use a release height of 3 meters because this value seemed to be most reasonable through both visual review of existing well pads and comparison with similar studies in which AERMOD was used to predict concentrations (Eastern Research Group 2011). Although

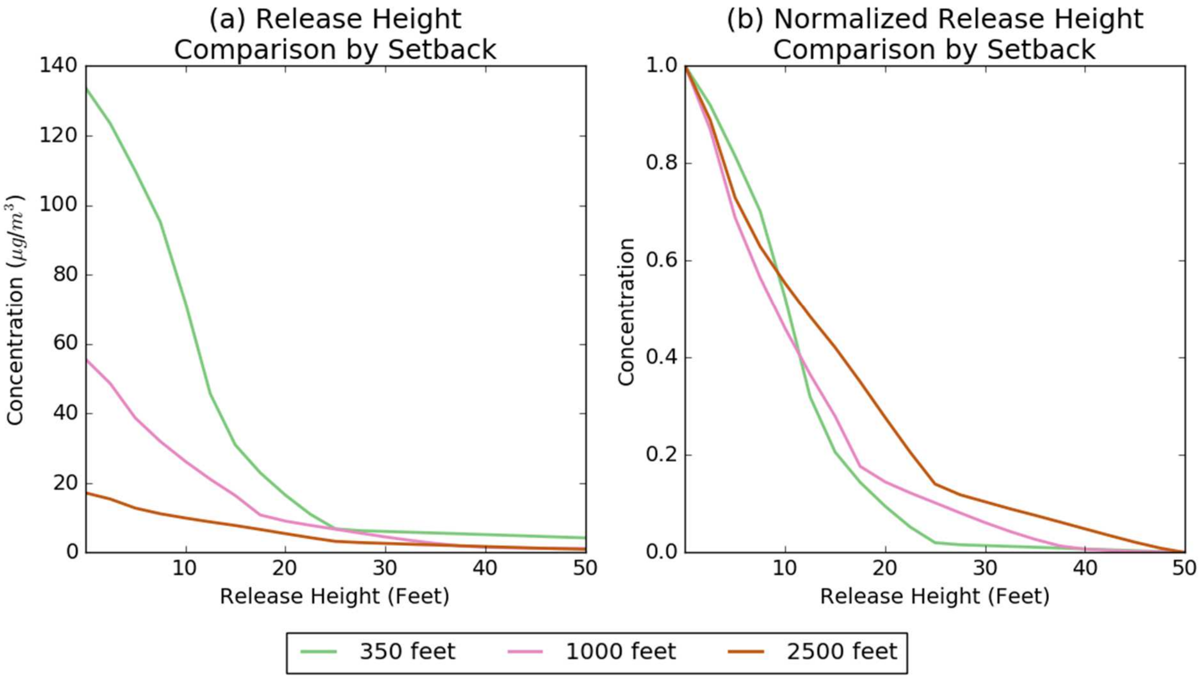

*Figure 10: Relationship between pollutant release height and concentration with absolute (a) and (b) normalized concentrations*

the release height remains constant in this study, the differences in absolute height between the sources and the receptor point calculated by AERMAP may vary along the spectrum in Figure 10.

## 3.3 Area Source Size

Area sources release the same total mass of pollutant as a point source, but the emissions are distributed along the entire area and released in a larger diluted plume. We expect point sources to produce higher maximum concentrations but also to reach the receptor with less frequency. Area source plumes are more wide spread, which means they have a greater chance at passing over a receptor point, but with a less concentrated plume.

Testing this hypothesis with AERMOD we see that area size has less impact at higher setback distances than release height or distance between receptor and concentration. Figure 11 shows that at shorter setback distances the impact is noticeable, but falls off relatively quickly in comparison to other parameters. The influence of area size scales in a more linear fashion that some of the previously tested parameters.

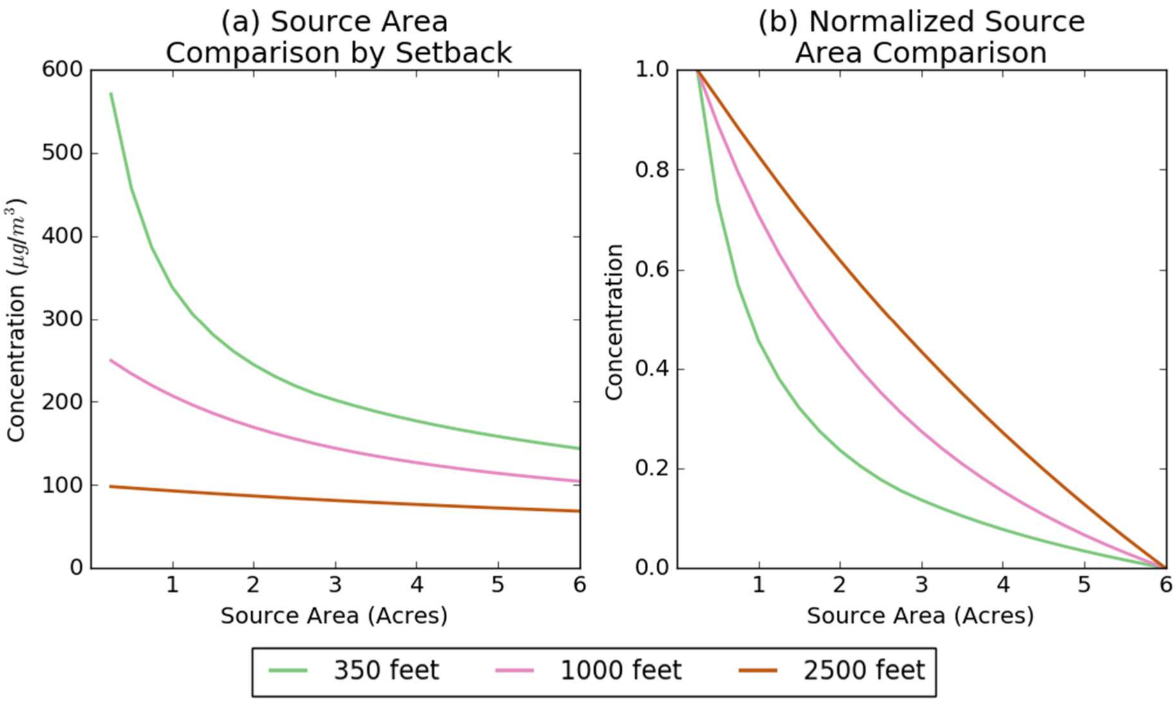

*Figure 11: Relationship between source area and concentration with absolute (a) and (b) normalized concentrations*

Well pad sizes range depending on the scale of the operation and the amount of wells on the pad but often range from two to six acres (Jiang et al. 2011). We chose to set the base well pad area on the smaller end of the spectrum at 2.5 acres because the study location is a residential area. For small well pad sizes the area source functions similarly to a point source because the emissions are still relatively concentrated, but beyond two acres this effect is nearly insignificant.

## 3.4 Conclusion

In this chapter we conducted some simple tests with AERMOD to understand how the model works and the impacts of changing various parameters. There are many contributing factors that determine how plumes spread. In the scope of this analysis the distance between the home and the well is the most influential on the concentration at the home. This parameter is influenced by the setback distance, which is desirable, because the main idea behind this study is that the setback distance is a major factor that influences air quality outcomes of UOGD.

The size of the area source was the next most influential parameter. At smaller sizes an area source functions similarly to a point source, which we are trying to avoid. We chose a base well pad size of 2.5 acres, which is convenient because it is large enough to be distinct from a point source while still being within the range of average well pad sizes. For the 350-foot setback the relationship between area and concentration becomes nearly linear beyond 2 acres as can be seen in Figure 11.

Release height was tested as well and found to have an important impact, but we have less freedom in changing this parameter in our study because most emitters on a well pad are relatively close to ground level. With higher release heights it is possible that the concentration may be highest at a significant distance beyond the emitter. For example, the emissions from a factory plume may be lowest at 350 feet and highest at 500 feet. However, in the case of well pads the emissions are not released high enough for this trend to occur at homes near UOGD operations.

# Chapter 4: Results

In this chapter, we present and explain the results from our analysis. Section 4.1 highlights the impact of random emission rate generation on the pollutant concentrations predicted by AERMOD. Then in Sections 4.2 and 4.3 we cover the results from phase I and II. Finally, in Section 4.4 we summarize the results from each of the eight configurations analyzed in this thesis.

## 4.1 Emission Rate Variability

In this section, we explain an interesting aspect of the phase I and II results that will be summarized in the subsequent sections. An important takeaway from the phase I and II simulations was the impact of variation in emission rates on the concentration results for each setback distance. To demonstrate this, Figure 12 provides a visualization of the time series of 1-hour average benzene concentrations for two representative random samples, the 8th and 17th samples. Throughout the course of examining our initial phase I results we found that there was often a dominating well or group of wells that contributed the clear majority of the total

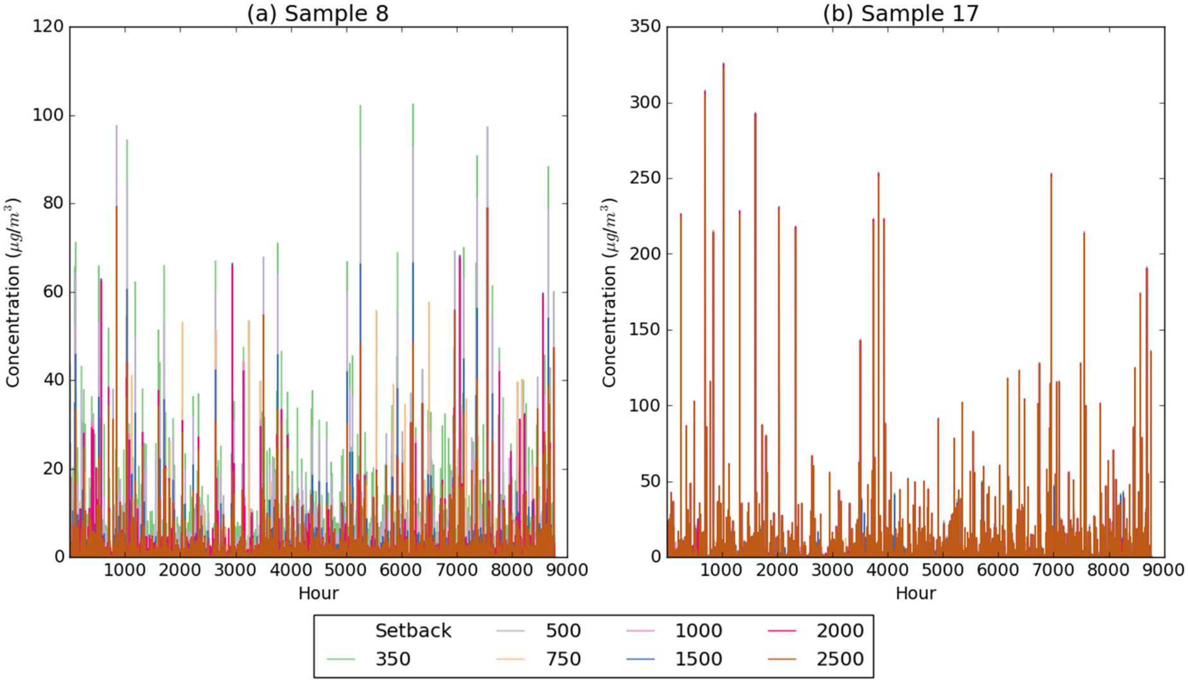

*Figure 12: 1-hour average concentration time series for sample 8 (a) and sample 17 (b) of the phase I acute RME benzene simulation*

concentration at the home despite being further away than several other wells. Figure 12a shows the time series for random sample 8 and it looks as expected: each setback distance is well represented with shorter setback distances producing the highest concentrations. However, in Figure 12b, which represents sample 17, the 2500-foot setback distance wells contribute by far the greatest portion of the emissions. The contribution from the shorter setback distances is barely visible in the plot.

Looking beyond the contribution from the wells in each setback distance bracket we see that the scale of the concentrations in Figure 12b is significantly higher than the scale of those in Figure 12a. Despite the wells in the 350-foot setback bracket dominating in Figure 12a, the emission rates generated by sample 8 were so low in comparison to those generated by sample 17 that the maximum concentration predicted in Figure 12b was nearly three times as high. This random variability is the reason 100 samples were averaged before trying to draw conclusions.

In the following sections, we will explore the 100 highest magnitude 1-hour average concentrations for each pollutant in the acute scenarios. We examine the highest concentrations because they are the best indicators of the likelihood of health impacts occurring. The magnitude is important because the consequences of being exposed to high concentrations are not binary; higher concentrations result in more serious health effects. We look at 100 concentrations to understand how frequently the public is being put at risk. If a resident is exposed to a high concentration one time, they may not experience any negative health impacts. However, repeated exposure increases the probability of incurring health effects.

## 4.2 Phase I: Informing regulations in regions considering first time implementation of oil and gas development

### 4.2.1 Acute RME Configuration

Recall that the RME scenario consists of 90 wells, which represents the 95th percentile number of wells within one mile of a home in Greeley. Figure 13 presents both absolute concentration values and magnitude trends for the 100 highest concentrations in the single year simulated during the acute RME configuration. Rather than visualizing the entire time series as was done in Figure 12, we rank and plot only the highest concentrations. Each line represents the results from a different setback distance. This visualization allows for more clarity between setbacks and highlights only the concentrations most relevant to public health concerns in comparison to the time series in Figure 12. Upon looking at each of the five air toxics we see that every 100 highest concentrations line follows a similar trend. This is a product of holding the meteorological data and well pad locations constant. Specific hours of meteorological data that

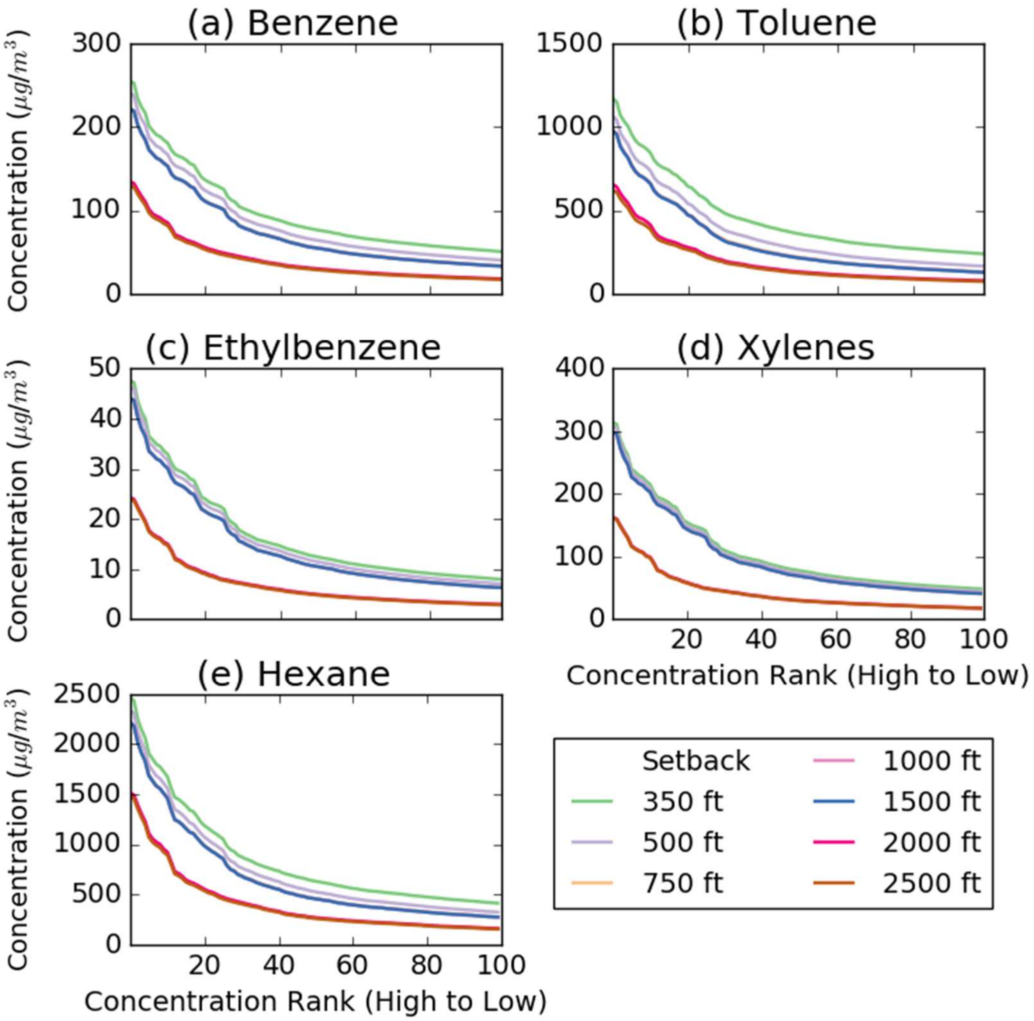

*Figure 13: Top 100 1-hour average concentrations for each pollutant for the phase I acute RME configuration*

occur throughout the year are responsible for these concentrations, and this trend may look different for a different year of meteorological data.

The scale of concentrations for each pollutant varies significantly, but there are clear trends between setback distances. As expected the concentration decreases in the shift from 350 to 500 feet and from 500 to 750 feet, although not by a significant margin. Surprisingly, increasing the setback from 750 to 1000 or 1500 feet results in an imperceptible decrease in concentration. As can be seen in Figure 14 there are only three total wells in the 1000 and 1500-foot setback distance brackets and they are located in the primary downwind direction with respect to the home based on the wind rose in Figure 6. Therefore, the plume from these wells will typically spread in the direction opposite the home.

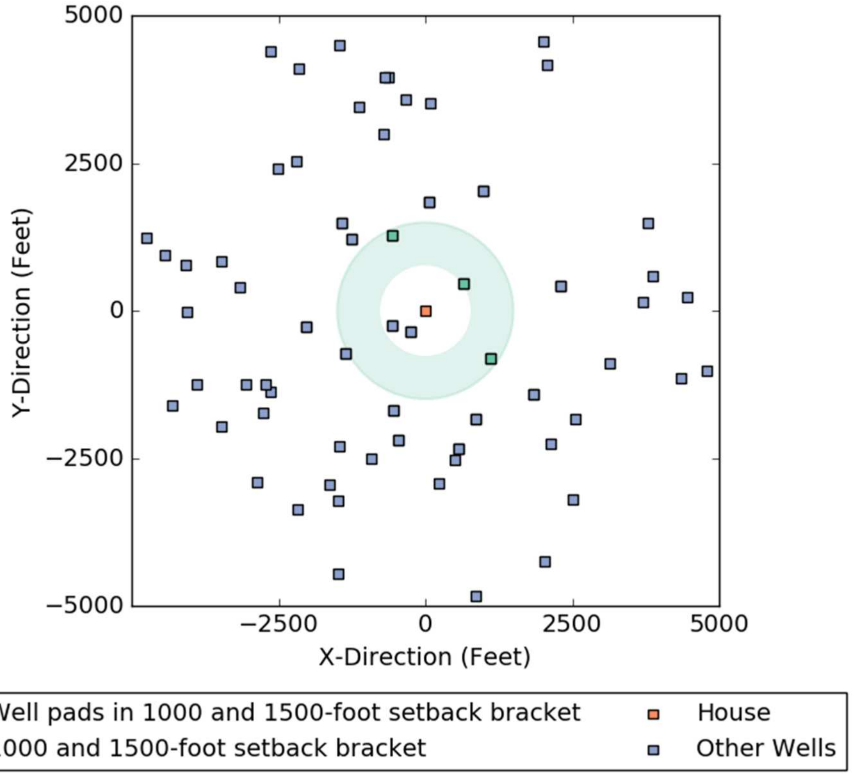

*Figure 14: Well pads in the 750 and 1000-foot setback distance bracket. They are located in the downwind direction with respect to the house, and therefore will contribute less to the concentration at the home in comparison to the other wells. As a result, increasing the setback distance from 750 to 1500 feet in this well configuration provides little benefit. Note that each of the three well pads in the 1000 and 1500-foot setback brackets are single-well pads.*

The 2000-foot and 2500-foot setback distances result in significantly lower concentrations than the other setback distances regardless of pollutant, although the air quality benefits from increasing the setback distance from 2000 to 2500 feet appear to be minimal. This can be explained in part by the distance-concentration relationship from Figure 8. Between 1500 and 2000 feet four wells[4] are removed while eight wells are removed between 2000 and 2500. Based on the exponential decrease in concentration with distance and the location of these wells relative to the house, the closer four wells have a much higher contribution to the total concentration at the house than the further eight wells do. Removing these closer four wells results in greater benefits with respect to air quality than removing the eight further wells does. Next we examine the relative quantity of emissions between pollutants.

Figure 15 presents a comparison of the highest concentration magnitude within the setback distance simulations, across different pollutants. Hexane produces by far the highest

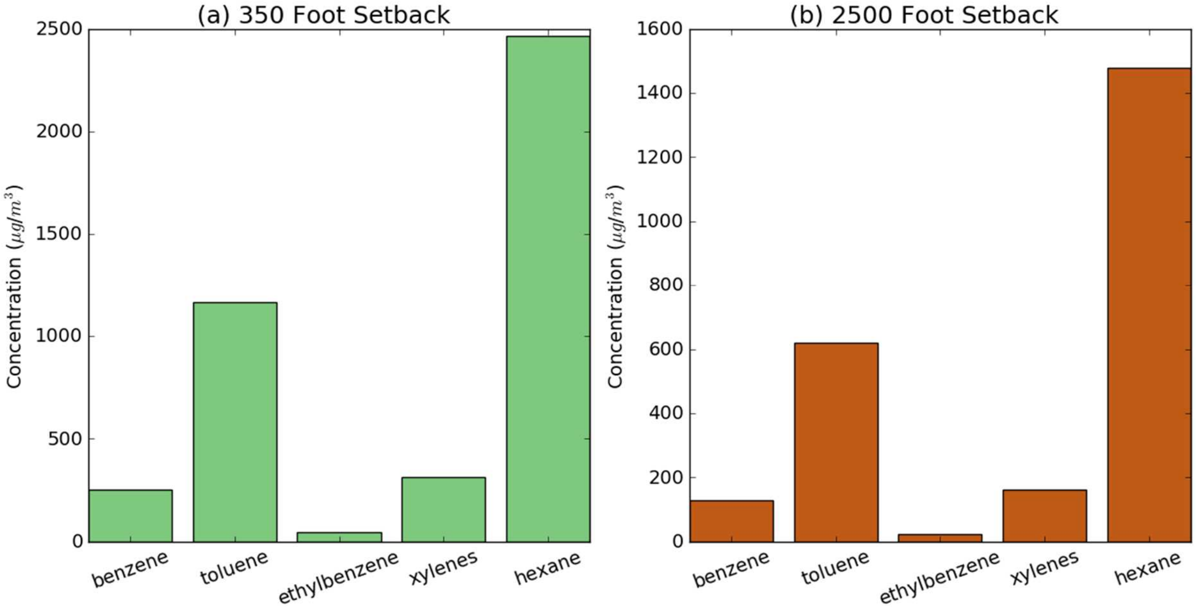

*Figure 15: Highest concentration comparison by pollutant at (a) 350-foot setback and (b) 2500-foot setback from the phase I acute RME configuration*

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[4] Recall that there are two well pad scenarios: RME (90 wells) and CT (13 wells). The locations of the wells in each scenario do not change regardless of phase. However, wells can be removed from the simulation in phase I if its Euclidean distance from the well is less than the setback distance. Because the location of each well pad is fixed, the same well pads (and number of well pads) will be removed for each iteration of a specific setback distance.

concentrations of any of the pollutants while ethylbenzene produces the lowest. This ratio does not change by setback or by concentration rank. Although Figure 15 displays only the highest concentration of the simulation, this plot looks almost identical for the 100th highest concentration. The ratio of emission decrease with distance for each pollutant is very similar.

Next we compare the average percent reduction in concentration by setback distance for the top 100 concentrations. Selecting the top 100 concentrations may not produce the most representative results for the entire set of concentration results, but the highest concentrations are the most important with respect to human health impacts. In Table 7 we see that for benzene the greatest decreases in concentration occur in the shifts from 350 to 500 feet, 500 to 750 feet, and 1500 to 2000 feet, which agrees with the anaylsis on Figure 13. Based on the random well locations in this scenario, the single well-pad removed when increasing the setback from 350 to 500 feet reduces the concentration at the home by nearly 20 percent. With 90 total wells in the simulation, removing one is a much smaller loss in production in comparison to the reduction in air pollution. The air quality benefits do not scale linearly with either distance or number of wells removed.

Now that relative trends between setback distances and pollutants have been established we can compare these results to human health standards to provide context for the concentration values. Recall that the ATSDR maintains a set of recommended concentration thresholds in relation to human health impacts called the MRLs. Table 8 provides a comparison between the MRLs and the highest 1-hour average concentration for each pollutant. Benzene is the only air

*Table 7: Comparison of average percent reduction between setback distances for the top 100 highest concentrations in the phase I acute RME configuration and percent reduction in number of wells*

| Setbacks | 350 -> 500 | 500 -> 750 | 750 -> 1000 | 1000 -> 1500 | 1500 -> 2000 | 2000 -> 2500 |
|---|---|---|---|---|---|---|
| Average % benzene conc. reduction | 18.5 | 15.7 | 0.65 | 0.21 | 85.6 | 4.5 |
| Well reduction | 1 | 2 | 1 | 2 | 4 | 8 |
| % well reduction | 1.1 | 2.3 | 1.2 | 2.4 | 5.0 | 11.1 |

*Table 8: Comparison between highest 1-hour average concentration from the phase I acute RME configuration and the corresponding ATSDR MRL threshold by pollutant for the 350-foot setback distance configuration*

| Pollutant | ATSDR Threshold (μg/m$^3$) | Highest 1-hour average concentration (μg/m$^3$) |
|---|---|---|
| benzene | 28.75 | 251.4 |
| toluene | 7540 | 1218 |
| ethylbenzene | 21710 | 46.4 |
| xylenes | 8680 | 306.5 |
| hexane | - | 2465 |

toxic that exceeds its corresponding threshold and it does so by a significant margin. The highest 1-hour average benzene concentration is 251.4 μg/m$^3$, which is nearly 10 times higher than the threshold of 28.75 μg/m$^3$. The 100th highest 1-hour average benzene concentration is slightly above 50 μg/m$^3$, which means that not only are the exceedances notable, but there are at least 100 of them. This configuration represents the nearly worst case scenario in the number of wells surrounding a home, so it will be important to make this comparison in the CT configuration as well in determining how much weight this result should hold for policymakers.

### 4.2.2 Acute CT Configuration

In Figure 16 we examine setback distance concentration trends in a similar exercise to that for the acute RME configuration. Some pollutants have a wider spread in concentrations between setback distances than others. For example, ethylbenzene concentrations have a very small range with a difference of only about 0.9 μg/m$^3$ in the highest 1-hour average concentration between the 350 and 2500-foot setback distance. Although one might argue there is less potential for reduction in concentration between setback distances for ethylbenzene because of how small the magnitude of these concentrations is, comparing benzene and the xylenes proves that concentration magnitude is not the only factor in this consideration. The difference in the highest concentration between the 350 and 2500-foot setback distance for benzene is approximately 16

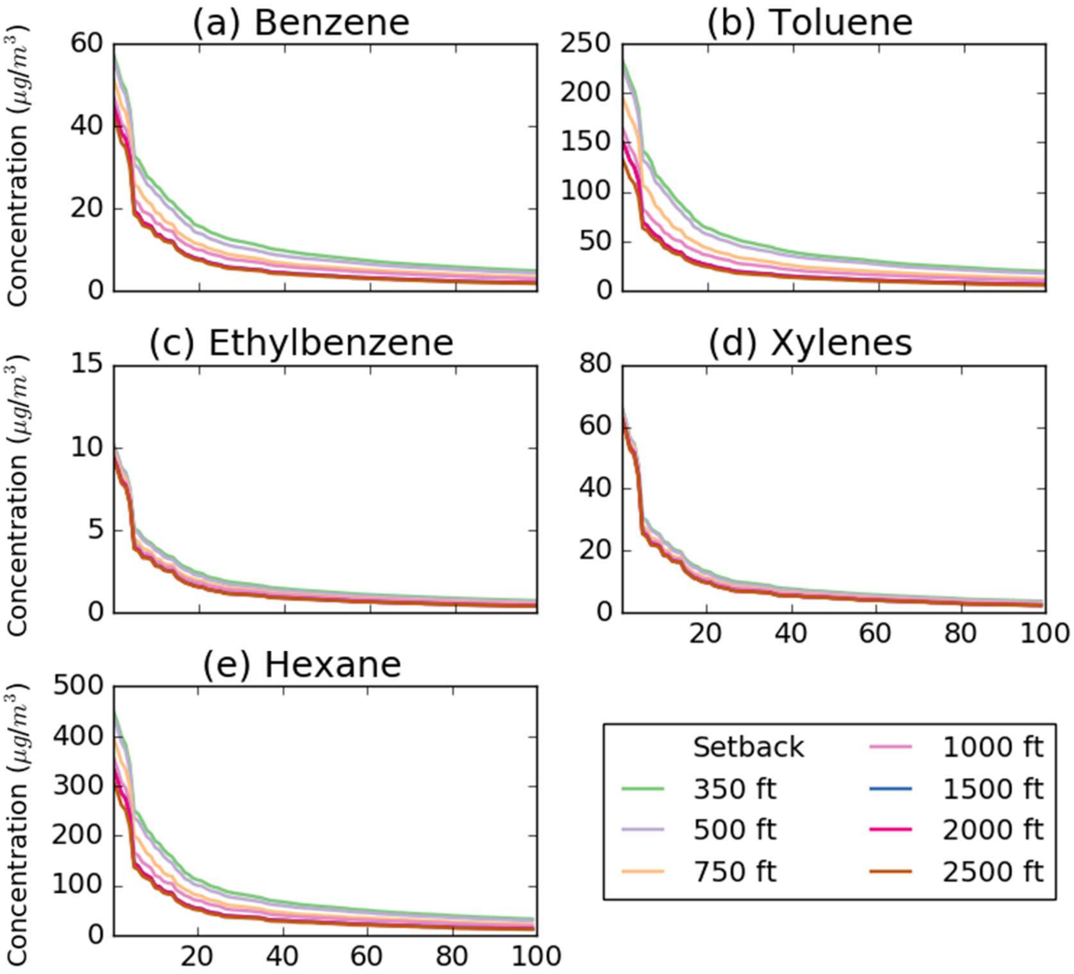

*Figure 16: Top 100 1-hour average concentrations for each pollutant for the phase I acute CT configuration*

μg/m$^3$ while it is less than 4 μg/m$^3$ the xylenes despite the benzene concentrations having a lower magnitude by comparison. Air quality benefits from increasing the setback distance vary depending on the pollutant.

For the acute RME configuration in Section 4.2.1 we established that only benzene presented any problems relative to the ATSDR MRLs. As expected there were no exceedances for the other pollutants in this configuration with less wells either. However, benzene did produce some interesting results. Figure 17 provides a comparison between concentration for each setback distance and the short-term ATSDR MRLs threshold for benzene. The number of

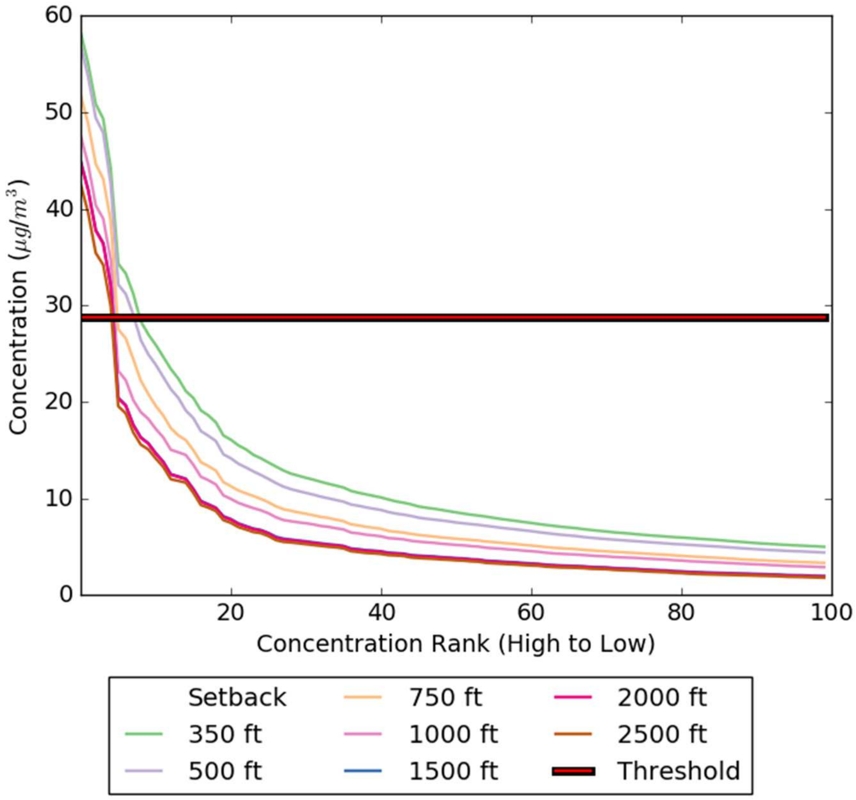

*Figure 17: Top 100 1-hour average concentrations for benzene in the phase I acute CT configuration compared to the ATSDR acute concentration threshold*

exceedances varies between five and eight depending on the setback distance but all setbacks results in multiple exceedances. Even at the 2500-foot setback the highest concentration is about 1.5 times higher than the threshold. Based on this phase of the simulation we can assume there are likely benzene related acute health issues for a significant portion of residents in counties with ongoing UOGD.

*Table 9: Comparison of average percent reduction between setback distances for the top 100 highest concentrations in the phase I acute CT configuration and percent reduction in number of wells*

| Setbacks | 350 -> 500 | 500 -> 750 | 750 -> 1000 | 1000 -> 1500 | 1500 -> 2000 | 2000 -> 2500 |
|---|---|---|---|---|---|---|
| Average % benzene conc. reduction | 12.6 | 26.5 | 13.4 | 34.6 | 1.6 | 4.9 |
| Well reduction | 1 | 1 | 1 | 1 | 1 | 1 |
| % well reduction | 8.3 | 9.1 | 10.0 | 11.1 | 12.5 | 14.3 |

In Table 9 we compare the percent reduction in number of wells and concentration for this scenario. Recall in the previous scenario in Section 4.2.1 the reduction in concentration between 1000 and 1500 feet was almost non-existent while the reduction between 1500 and 2000 feet was the highest overall. In this configuration, these trends have reversed, but this is not necessarily surprising. As was previously discussed, the contribution a well has towards the concentration at the home is highly dependent on its location. Figure 14 showed that in the previous scenario the wells within 1500-foot setback distance bracket were located downwind from the home. However, as can be seen in Figure 18, the well in this bracket is located nearly directly upwind of the house and consequently has a significant impact on the concentration at the home. The percent reduction in concentration is higher than the percent reduction in wells until the 2000-foot setback

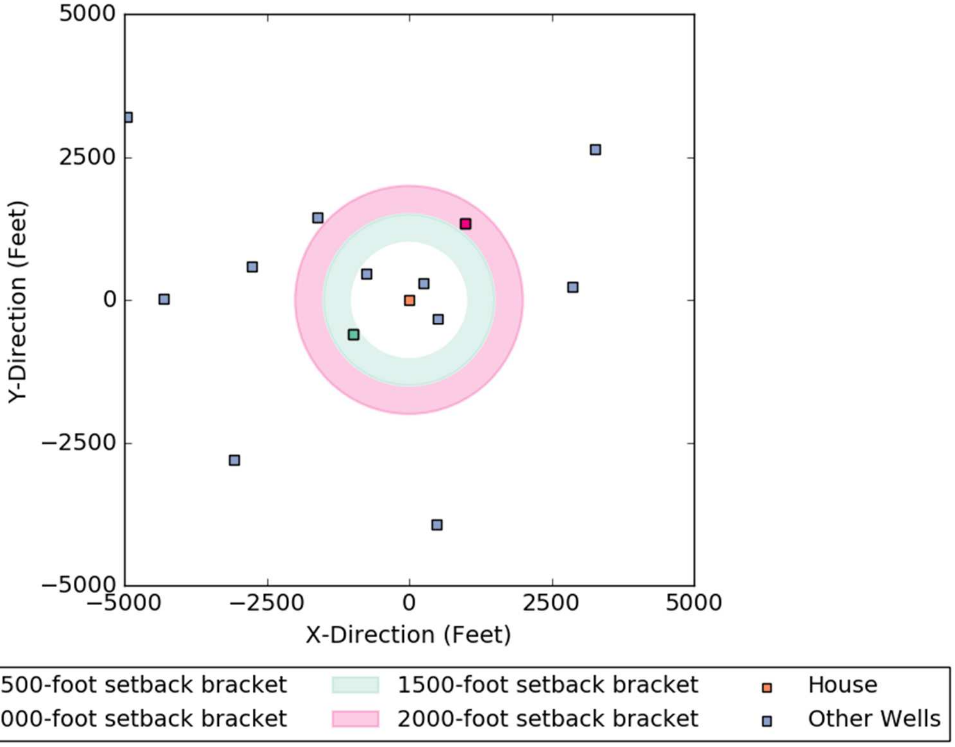

*Figure 18: Wells in the 1500 and 2000-foot setback distance bracket. The well in the 2000-foot bracket is located in the downwind direction with respect to the house, and therefore will contribute less to the concentration at the home in comparison to the other wells. The house is located downwind of the well in the 1500-foot setback well, which contributes significantly to the concentration at the home.*

distance bracket, which suggests that a setback distance of 1500 feet would be the most efficient with respect to both objectives for this configuration.

### 4.2.3 Chronic RME Configuration

Unlike in the acute scenarios, the chronic scenarios focus on the 23-year average concentration, which means we will only examine a single concentration for each setback distance. The well locations are the same as in the acute RME configuration so we expect the relative difference in concentration between each setback distance to be the same, which is what we see in Figure 19. Recall that the concentrations for the 1000 and 1500-foot setback distances was very similar to that of the 750-foot setback distance in Figure 13. This trend is also

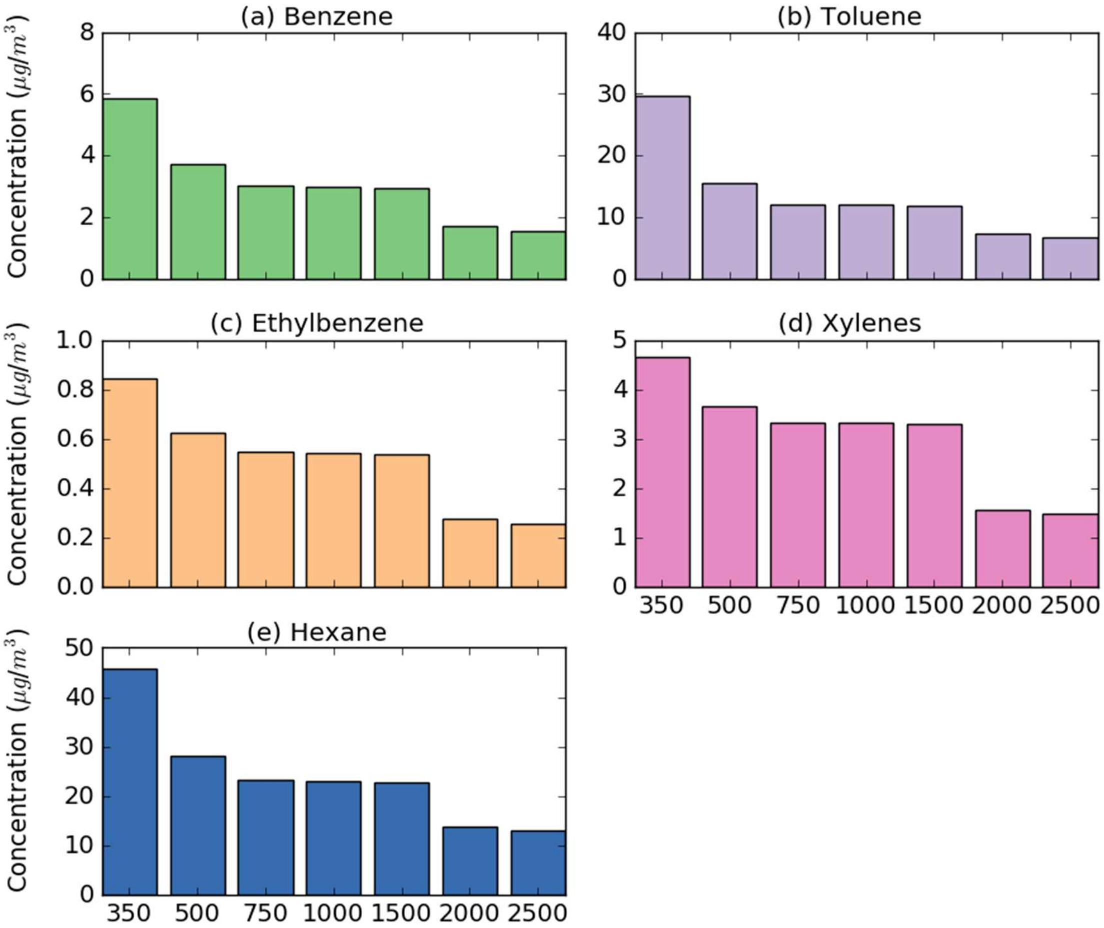

*Figure 19: 23-year average concentration by setback for each pollutant in the phase I chronic RME configuration*

*Table 10: Comparison of average percent reduction between setback distances for the 23-year average benzene concentration in the phase I chronic RME configuration and percent reduction in number of wells*

| Setbacks | 350 -> 500 | 500 -> 750 | 750 -> 1000 | 1000 -> 1500 | 1500 -> 2000 | 2000 -> 2500 |
|---|---|---|---|---|---|---|
| Average % benzene conc. reduction | 57.3 | 23.4 | 1.32 | 1.68 | 73.0 | 8.53 |
| Well reduction | 1 | 2 | 1 | 2 | 4 | 8 |
| % well reduction | 1.1 | 2.3 | 1.2 | 2.4 | 5.0 | 11.1 |

represented in the bar plots. The primary difference in the chronic scenario is the magnitude of the concentrations predicted by AERMOD. The pollutants with the highest concentrations, toluene and hexane, also have the largest relative drop in concentration between the 350 and 500-foot setbacks. This agrees with the trends from Figure 9a: concentration decreases at a faster rate with distance at higher magnitudes.

Next we examine the relative decreases in concentration between setback distance in Table 10. Although there are some similarities with the same analysis from the acute RME configuration in Table 7, the disparity in concentration reduction between setbacks has fallen off. The increase from 350 to 500 feet and from 1500 to 2000 feet produce the greatest decrease in concentration at 57 and 73 percent respectively. As we mentioned in the beginning of this section and before the decrease from 500 to 750 feet and 1000 to 1500 feet is insignificant for the RME configuration. Decreases in concentration are much greater or at least nearly equivalent to decreases in wells among every setback distance. However, in a real-world situation there would

*Table 11: Comparison between 23-year average concentration from the phase I chronic RME configuration and the corresponding ATSDR MRL threshold by pollutant for the 350-foot setback distance configuration*

| Pollutant | ATSDR Threshold (μg/m$^3$) | 23-year average concentration (μg/m$^3$) |
|---|---|---|
| benzene | 9.58 | 5.87 |
| toluene | 3770 | 29.6 |
| ethylbenzene | 260 | 0.841 |
| xylenes | 220 | 4.65 |
| hexane | 2110 | 45.8 |

be more than one house in a residential area and the reduction in allowable wells would be much greater than in this single home configuration.

In Table 11 we compare the absolute magnitudes of the 23-year average concentrations with the ATSDR MRLs. For the chronic scenario, all the pollutant concentrations are below their corresponding standard for the 350-foot setback configuration. The benzene concentration is close to its threshold in comparison to the other pollutants, but it is still less than two thirds of the threshold. Based on the results from this phase of the simulation we can assume there are no chronic health problems associated with the air quality impacts of UOGD.

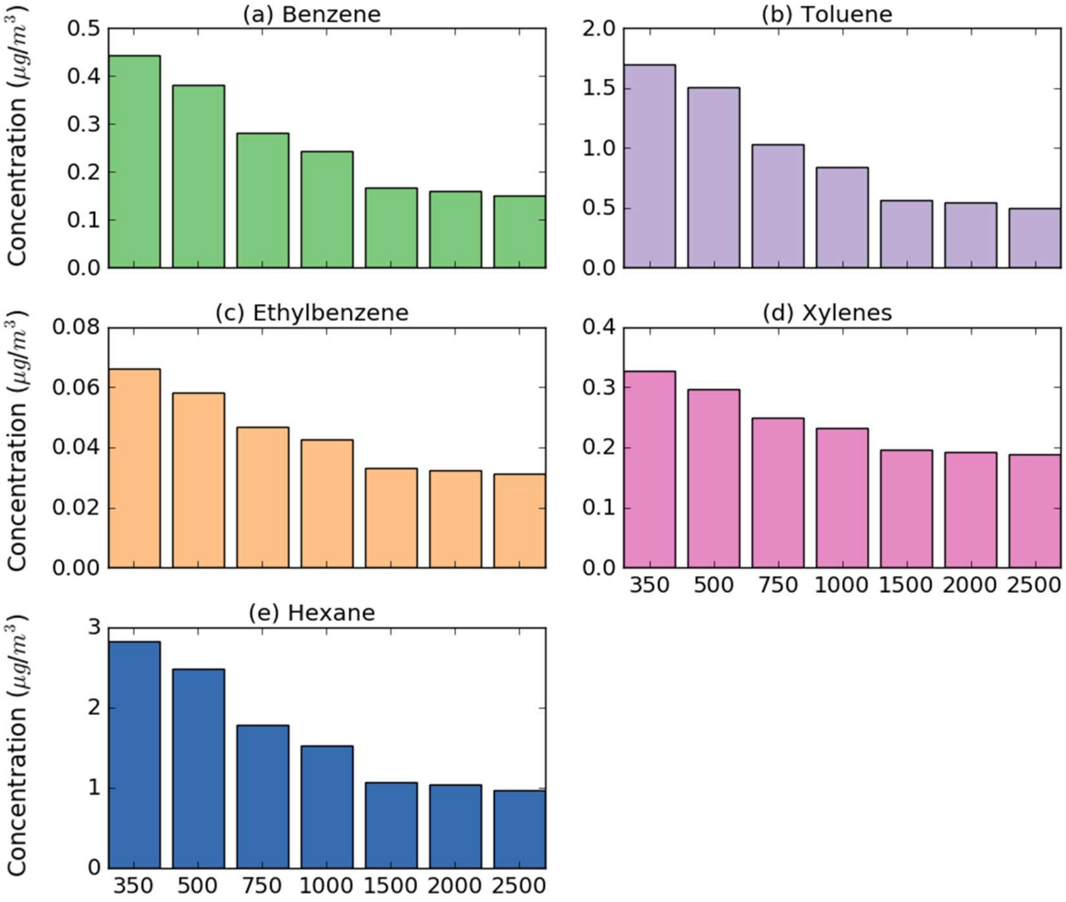

*Figure 20: 23-year average concentration by setback for each pollutant in the phase I chronic CT configuration*

### 4.2.4 Chronic CT Configuration

From the plots in Figure 20 the difference in concentration between setback distance appears to be more consistent than that from the chronic RME configuration. The air quality benefits of increasing the setback distance beyond 1500 feet are much smaller in comparison to those of the previous setback distances. This is expected because there is only one well in each setback bracket for the CT scenario as can be seen in Figure 21. The value of removing a single well at 2000 feet is much less than that of removing a well at 350 or 500 feet, which is why the returns diminish for the longer setbacks. In the RME scenario there are multiple wells in each of the last three setback distance brackets, which helps offset the distance.

Looking at exact percentages in Table 12 our visual assumptions hold true. For the setbacks between 350 and 1500 feet the reduction in concentration is above 15 percent, while it is 6 percent or below for 2000 and 2500 feet. This trend is similar to that for the acute CT configuration, but it is more exaggerated in this case.

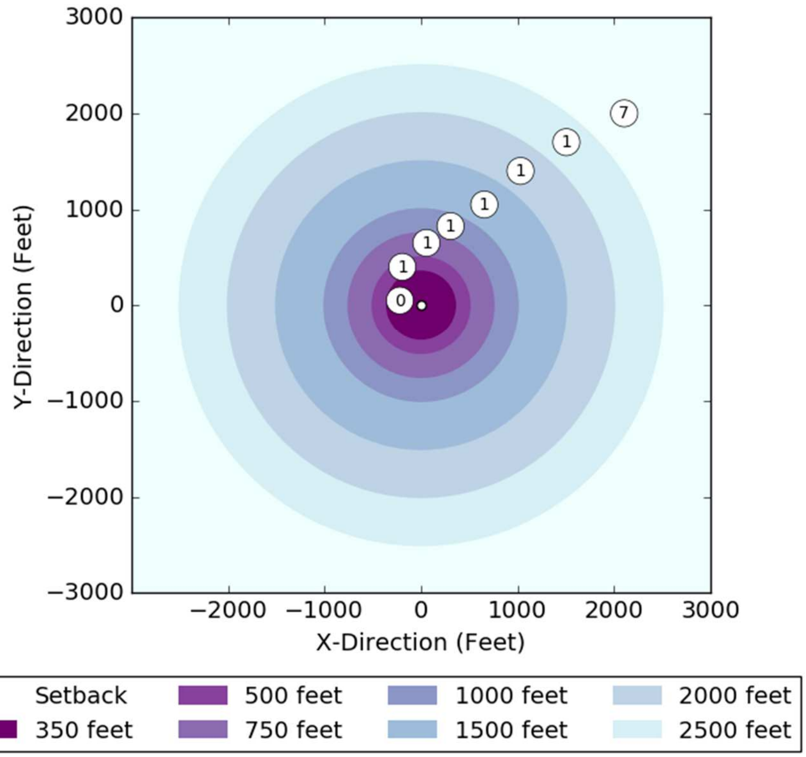

*Figure 21: Number of wells in each setback distance bracket for the CT scenario*

*Table 12: Comparison of average percent reduction between setback distances for the 23-year average benzene concentration in the phase I chronic CT configuration and percent reduction in number of wells*

| Setbacks | 350 -> 500 | 500 -> 750 | 750 -> 1000 | 1000 -> 1500 | 1500 -> 2000 | 2000 -> 2500 |
|---|---|---|---|---|---|---|
| Average % benzene conc. reduction | 16.3 | 35.9 | 15.6 | 44.7 | 4.35 | 6.06 |
| Well reduction | 1 | 1 | 1 | 1 | 1 | 1 |
| % well reduction | 8.3 | 9.1 | 10.0 | 11.1 | 12.5 | 14.3 |

### 4.2.5 Cancer Risk

In Table 13 we compare the 23-year average concentrations to the cancer risk thresholds from Table 3. In the RME scenario all setback distances increase the risk of cancer for those exposed by one-in-a-hundred thousand aside from the 350-foot setback distance, which is in between this threshold and the one-in-ten thousand threshold. In the CT scenario all setbacks results in a one-in-a-million increased risk of cancer. Although there is not much variation in risk between setback distances, the risk estimates have relatively wide ranges due to the uncertainty involved in defining such a threshold. Setbacks that carry risks in the lower end of the estimate are not necessarily equivalent to those in the higher end of the estimate.

*Table 13: 23-year benzene concentrations (µg/m$^3$) for the phase I CT and RME scenarios*

| Setback (feet) | Phase I RME | Increased Risk | Phase I CT | Increased Risk |
|---|---|---|---|---|
| 350 | 5.869 | $> 10^{-5}$ | 0.4431 | $10^{-6}$ |
| 500 | 3.730 | $10^{-5}$ | 0.3811 | $10^{-6}$ |
| 750 | 3.023 | $10^{-5}$ | 0.2805 | $10^{-6}$ |
| 1000 | 2.983 | $10^{-5}$ | 0.2426 | $10^{-6}$ |
| 1500 | 2.937 | $10^{-5}$ | 0.1676 | $10^{-6}$ |
| 2000 | 1.698 | $10^{-5}$ | 0.1607 | $10^{-6}$ |
| 2500 | 1.564 | $10^{-5}$ | 0.1515 | $10^{-6}$ |

## 4.3 Phase II: Quantifying air quality impacts in regions with ongoing oil and gas development

### 4.3.1 Acute RME Configuration

Similar to the prior scenarios, in Figure 22 we examine the trends in the top 100 highest 1-hour average concentrations by setback distance and pollutant. Recall in this phase no wells are removed; the only difference between each setback is the 10-well pad. The contribution from this well pad is much larger than that from any of the others because it contains 10 wells while most of the others are single-well pads. Therefore, it is expected to have a higher contribution. Compared to the previous phase results, the spread between the shorter setback distances is

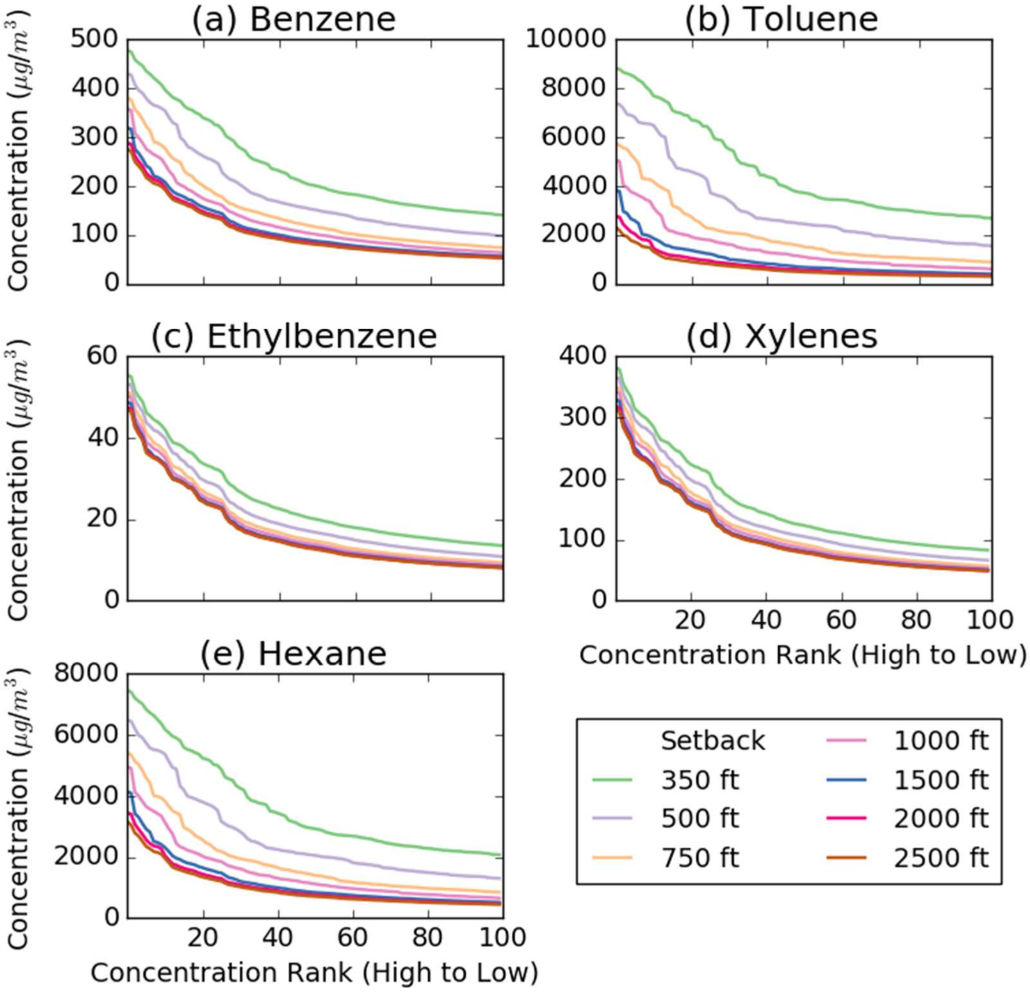

*Figure 22: Top 100 1-hour average concentrations for each pollutant for the phase II acute RME configuration*

much greater. Adding a significant source of emissions at such short ranges has immense implications for the total concentration at the home. Note the increase in the scale of the concentrations predicted in this configuration. The 350-foot setback toluene concentrations are nearly nine times higher than the equivalent configuration in the previous phase of modeling. Despite this notable increase, benzene is still the only pollutant with concentration exceedances.

In Figure 23 we see significant differences in the concentration comparison between each pollutant in comparison to the previous phase. In Figure 15, hexane concentrations were by far the highest, but in this case toluene concentrations have surpassed those from hexane for the 350-foot setback distance. Although this shift is smaller in scale, benzene concentrations are also higher than the xylenes concentrations at this distance, which was not the case previously. However, the 2500-foot setback distance plot is similar to the corresponding plot from phase I in Figure 15. The ratio of toluene emissions to emissions from the other pollutants is higher from the additional 10-well pad than from the other 90 wells. As the 10-well pad moves further away its influence decreases and the 90 existing wells start to determine the shape of the plot in Figure 23b.

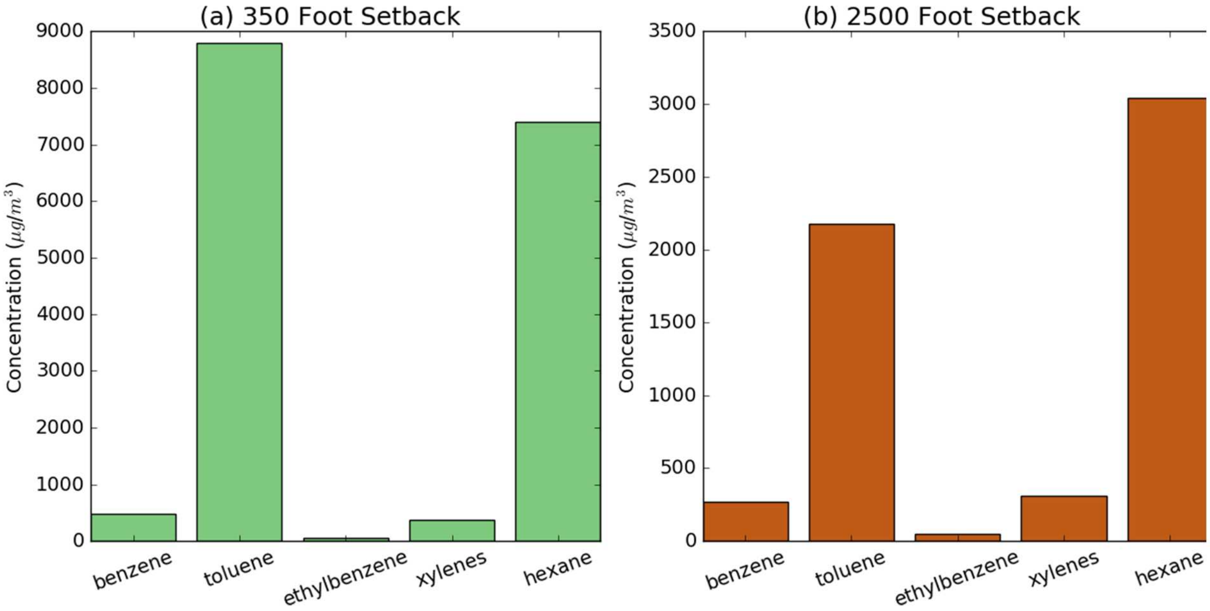

*Figure 23: Highest concentration comparison by pollutant at (a) 350-foot setback and (b) 2500-foot setback from the phase II acute RME configuration*

*Table 14: Comparison between highest 1-hour average concentration from the phase II acute RME configuration and the corresponding ATSDR MRL threshold by pollutant for the 350-foot setback distance configuration*

| Pollutant | ATSDR Threshold (μg/m$^3$) | Highest 1-hour average concentration (μg/m$^3$) |
|---|---|---|
| benzene | 28.75 | 477.9 |
| toluene | 7540 | 8830 |
| ethylbenzene | 21710 | 55.4 |
| xylenes | 8680 | 381.3 |
| hexane | - | 7447 |

This configuration has the potential to produce the highest concentrations of all the configurations in this analysis because there are no wells removed in this phase and the RME scenario contains more wells than the CT scenario. If there are no concentration threshold exceedances for a pollutant in this configuration, we can assume that current setback distances are adequate for the pollutant in question based on this analysis. From Table 14 we can see that toluene and hexane concentrations increased substantially. There is no short-term threshold for hexane, but toluene does exceed the threshold by approximately 1300 μg/m$^3$, which is significant. Although this is the worst-case scenario and the majority of the concentrations can be attributed to the 10-well pad added in this configuration, this result is important due to the increasing prevalence of multi-well pads in UOGD.

### 4.3.2 Acute CT Configuration

The only difference between the acute RME configuration in the previous section and this one is the background concentration resulting from the original 90 wells, or 13 in this case, that are held constant. The additional 10-well pad generated the vast majority of the concentration at the home in the previous configuration and in this scenario it contributes an even larger percentage. We expect the trends in Figure 24 to look similar aside from the trend lines being shifted down several hundred micrograms per meter cubed.

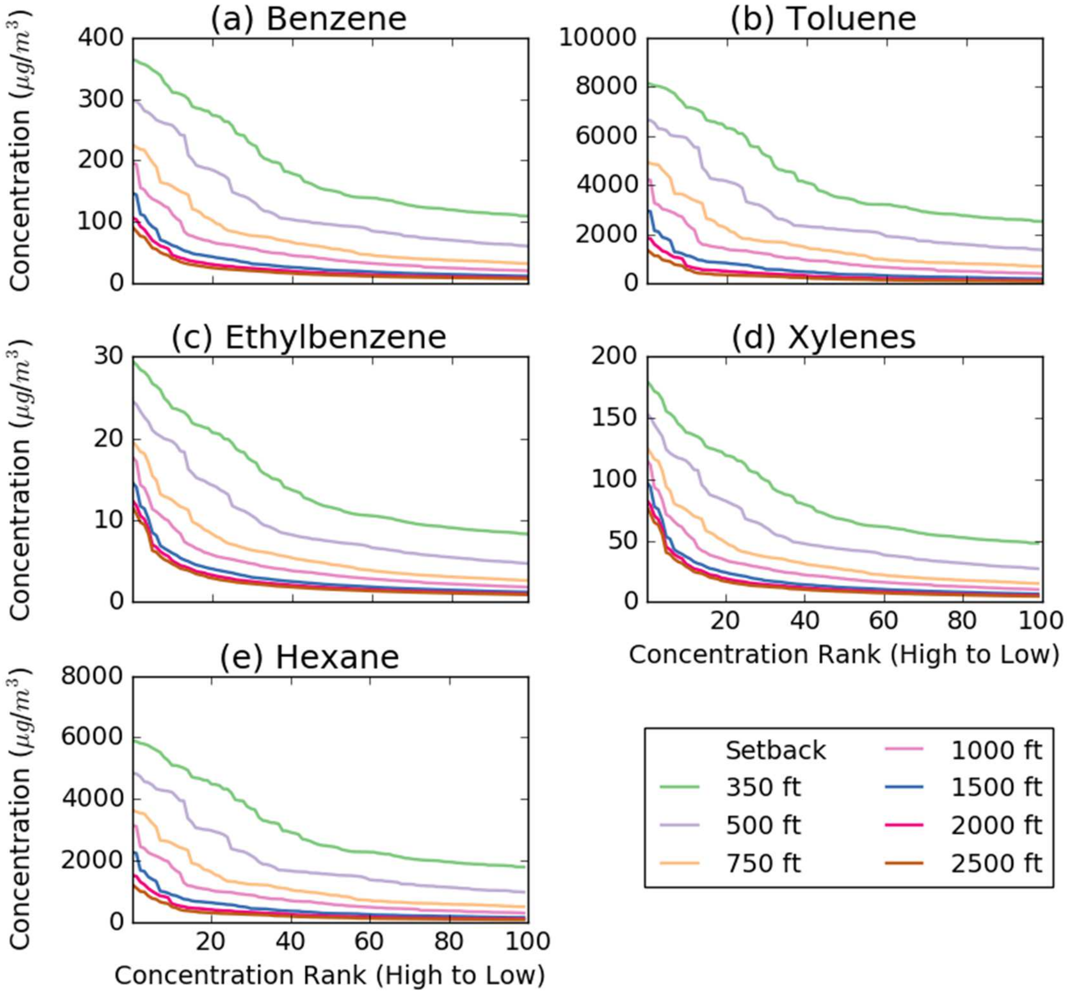

*Figure 24: Top 100 1-hour average concentrations for each pollutant for the phase II acute CT configuration*

Taking a closer look at the benzene results in Figure 25, we see that once again there are exceedances for every setback distance. However, there are more exceedances for every setback and in the case of the lowest three setbacks, 350 feet, 500 feet, and 750 feet, there are nearly or more than 100 exceedances. Although it may still be hard to believe that the new 10-well pad generates such a high concentration at the home, it makes more sense when looking at the context of how many wells are in each setback distance bracket in Figure 26. There are only 10 total wells (9 well pads) within the first 2000 feet from the home. Recall the exponential decrease in concentration with distance in Figure 8 in Chapter 3. Considering that 80 percent of the wells in the RME scenario are located beyond 2500 feet from the home, the tremendous

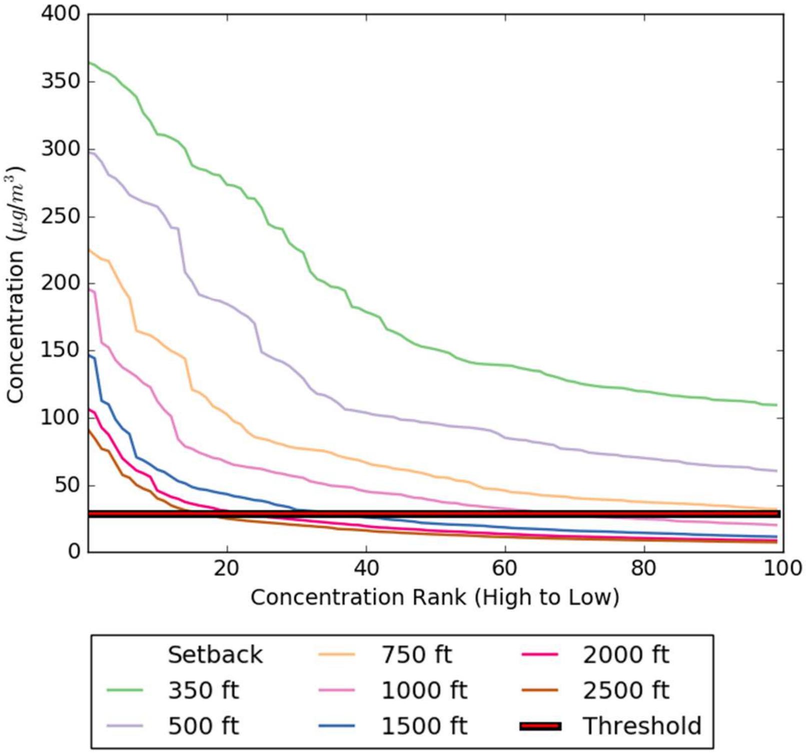

*Figure 25: Top 100 1-hour average concentrations for benzene in the phase II acute CT configuration compared to the ATSDR acute concentration threshold*

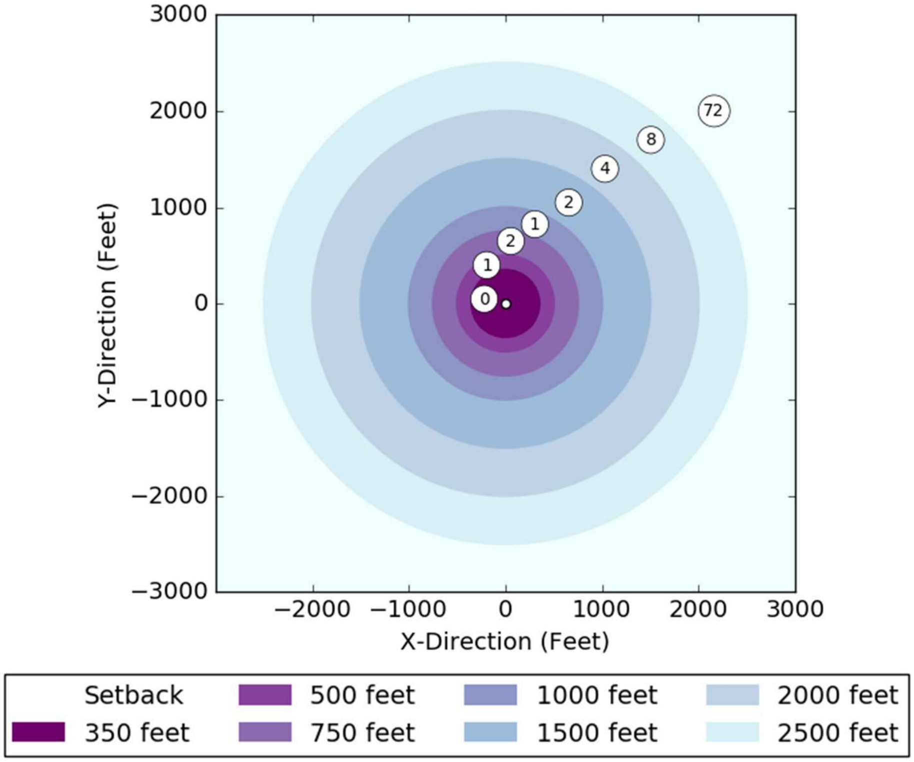

*Figure 26: Number of wells in each setback distance bracket for the RME scenario*

impact of adding these 10 wells at 350 feet seems more logical. Further, there are only six wells within the first 2500 feet of the home in the CT scenario, so this effect will only be exacerbated in this configuration. This result demonstrates the potential for human health impacts from multi-well pads drilled near residential areas.

### 4.3.3 Chronic RME Configuration

From Figure 27 we see that the concentrations in this phase are much higher than those from the phase I equivalent in Section 4.2.3. However, the scale of the concentrations in both cases is much smaller. As was the case with the other RME configurations, the reduction in concentration between the 350 and 500 feet setbacks is the most significant due to the immense influence of the additional 10-well pad. Although toluene and hexane are emitted in significant absolute amounts, only benzene exceeds its corresponding ATSDR threshold. At 19.8 $\mu g/m^3$ for the 350-foot setback the 23-year average benzene concentration more than doubles the threshold. It also exceeds the threshold for the 500-foot setback distance.

In Table 15 the results are closer to what would be expected from increasing the setback distance based on the sensitivity testing results. This is due to the additional 10-well pad contributing the majority of the concentration at the home. This configuration behaves similarly to the single home and single well set up from the sensitivity at shorter setback distances.

The air quality benefits rapidly wane with each increase in distance. The percent reduction in wells and concentration becomes nearly equivalent at 2000 feet and the reduction in wells

*Table 15: Comparison of average percent reduction between setback distances for the 23-year average benzene concentration in the phase II chronic RME configuration and percent reduction in number of wells*

| Setbacks | 350 -> 500 | 500 -> 750 | 750 -> 1000 | 1000 -> 1500 | 1500 -> 2000 | 2000 -> 2500 |
|---|---|---|---|---|---|---|
| Average % benzene conc. reduction | 70.1 | 34.9 | 13.6 | 11.1 | 4.15 | 2.05 |
| Well reduction | 1 | 2 | 1 | 2 | 4 | 8 |
| % well reduction | 1.1 | 2.3 | 1.2 | 2.4 | 5.0 | 11.1 |

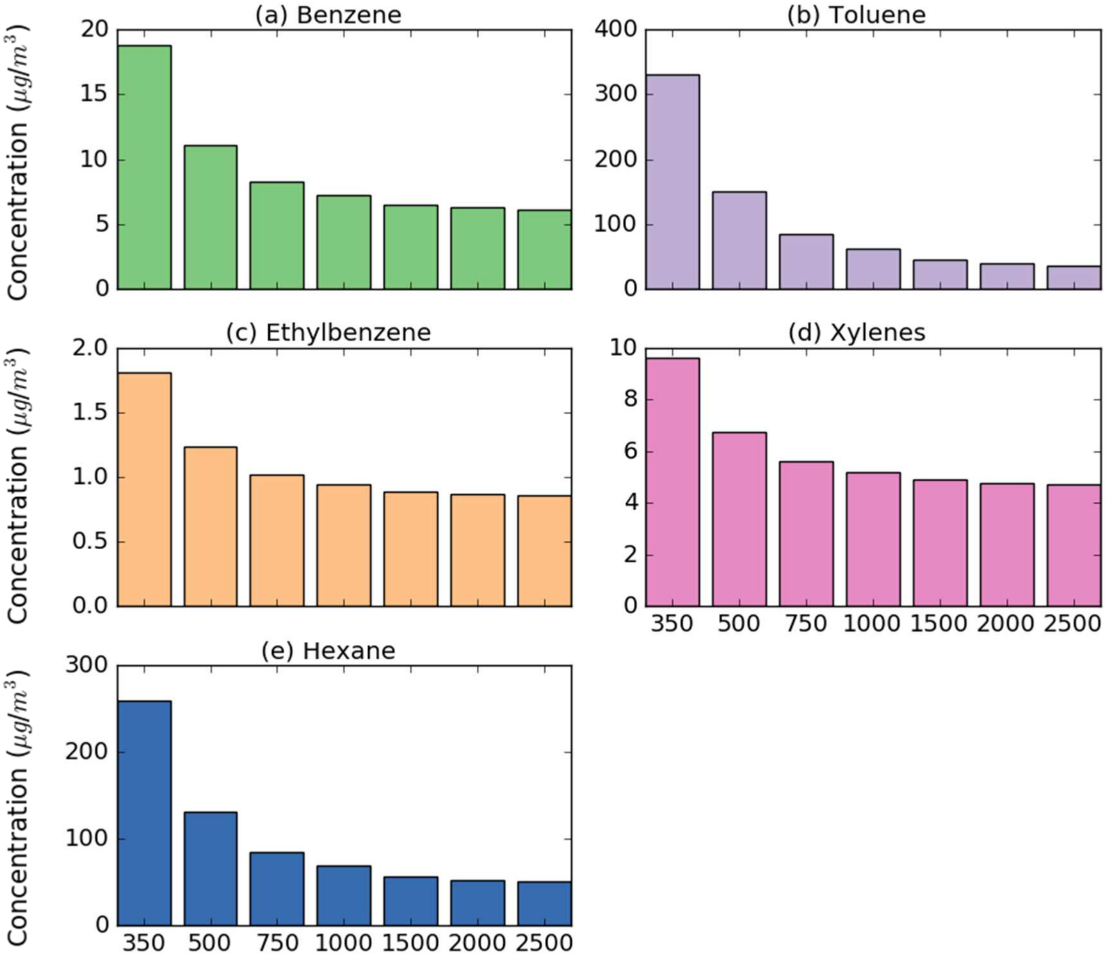

*Figure 27: 23-year average concentration by setback for each pollutant in the phase II chronic RME configuration*

becomes greater than the reduction in concentration thereafter. However, as was stated previously these are relative decreases and only the 350 and 500-foot setbacks raise any concerns based on the magnitude of the concentration.

### 4.3.4 Chronic CT Configuration

The results from this configuration in Figure 28 are similar to those from the RME configuration in Section 4.3.3. The only difference is the background concentration from the existing wells and the influence it has on the concentration at the home. The percent difference in concentration between each setback should be greater in this case because the 10-well pad has more influence than in the RME configuration, which is what we see in Table 16. The percent

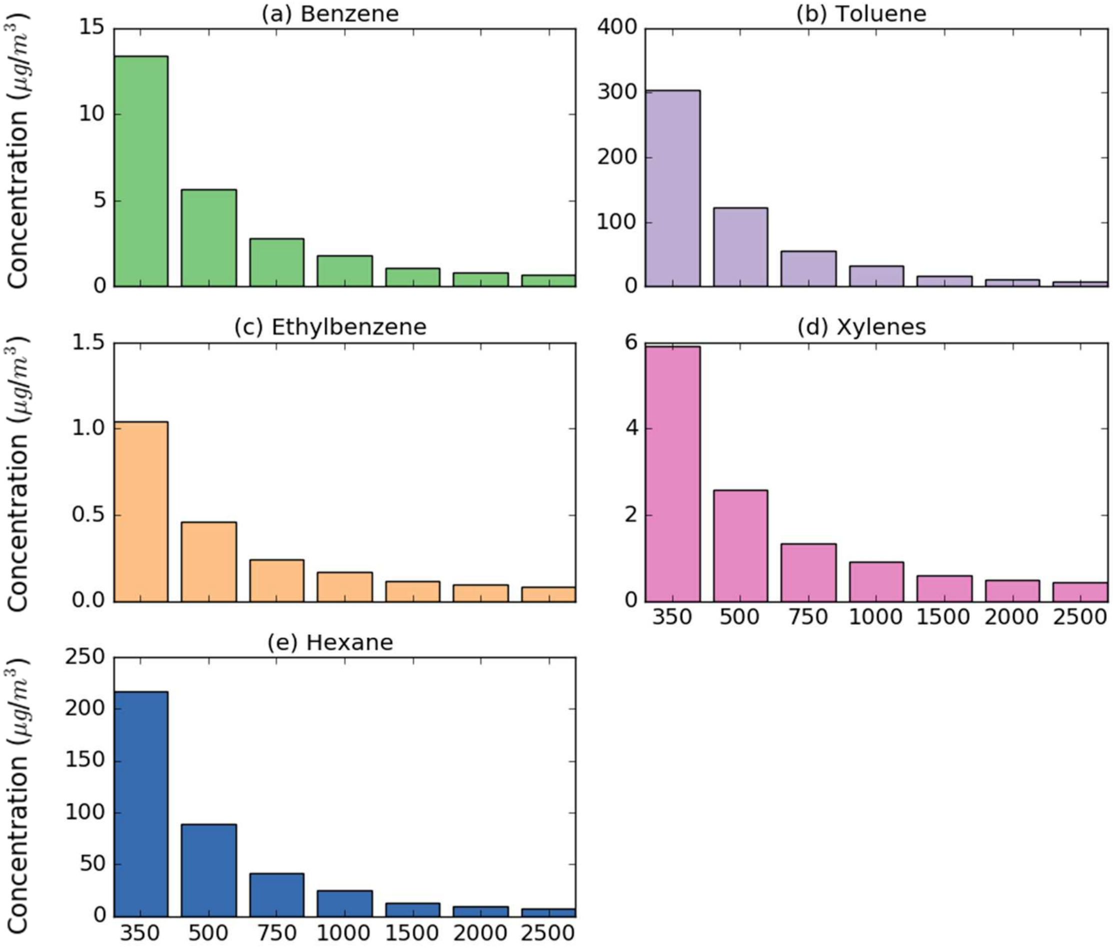

*Figure 28: 23-year average concentration by setback for each pollutant in the phase II chronic CT configuration*

decrease in benzene concentration when increasing the setback distance from 350 to 500 feet is nearly double that from the RME configuration at 137 percent and almost triple when increasing from 500 to 750 feet.

*Table 16: Comparison of average percent reduction between setback distances for the 23-year average benzene concentration in the phase II chronic CT configuration and percent reduction in number of wells*

| Setbacks | 350 -> 500 | 500 -> 750 | 750 -> 1000 | 1000 -> 1500 | 1500 -> 2000 | 2000 -> 2500 |
|---|---|---|---|---|---|---|
| Average % benzene conc. reduction | 137 | 103 | 54.5 | 66.3 | 31.5 | 17.9 |
| Well reduction | 1 | 1 | 1 | 1 | 1 | 1 |
| % well reduction | 8.3 | 9.1 | 10.0 | 11.1 | 12.5 | 14.3 |

*Table 17: 23-year benzene concentrations (µg/m$^3$) for the phase II CT and RME scenarios*

| Setback (feet) | Phase II RME | Increased Risk | Phase II CT | Increased Risk |
|---|---|---|---|---|
| 350 | 18.85 | $10^{-4}$ | 13.42 | $10^{-4}$ |
| 500 | 11.08 | $> 10^{-5}$ | 5.657 | $> 10^{-5}$ |
| 750 | 8.215 | $> 10^{-5}$ | 2.789 | $10^{-5}$ |
| 1000 | 7.231 | $> 10^{-5}$ | 1.805 | $10^{-5}$ |
| 1500 | 6.511 | $> 10^{-5}$ | 1.085 | $> 10^{-6}$ |
| 2000 | 6.251 | $> 10^{-5}$ | 0.8254 | $> 10^{-6}$ |
| 2500 | 6.126 | $> 10^{-5}$ | 0.7000 | $> 10^{-6}$ |

### 4.3.5 Cancer Risk

In Table 17 we again compare 23-year average concentrations to the EPA cancer risk thresholds. The risk levels for each setback distance are universally higher than their counterparts from phase I, which is to be expected. The 350-foot setback for both scenarios results in an increased cancer risk of one-in-ten thousand, which is relatively high considering the number of people that are exposed to UOGD operations. However, this is only for the shortest setback distance. For the CT scenario, the increased risk for the range of current setback distances, 500 to 1000 feet, the increased risk is one-in-a-hundred thousand.

## 4.4 Summary

The only pollutants that resulted in any exceedances in this analysis were benzene and toluene. Table 18 presents the number of benzene exceedances in each acute exposure configuration. The RME scenarios show significant problems with benzene concentrations that may require further regulatory efforts beyond increasing the setback distance to correct. The CT scenario also causes some problems, but in the case of phase I there are few enough exceedances that in real-world scenarios this will depend on the location of wells with respect to the house. Phase II concentration exceedances seem very problematic, but as was mentioned earlier this phase is highly dependent on multi-well pads. Based on these results it may be prudent

*Table 18: Number of benzene concentration exceedances in phase I (P1) and phase II (P2) by setback for the acute scenarios*

| Setback (feet) | P1 RME | P1 CT | P2 RME | P2 CT |
|---|---|---|---|---|
| 350 | > 100 | 8 | > 100 | > 100 |
| 500 | > 100 | 8 | > 100 | > 100 |
| 750 | > 100 | 5 | > 100 | > 100 |
| 1000 | > 100 | 5 | > 100 | 66 |
| 1500 | > 100 | 5 | > 100 | 34 |
| 2000 | 52 | 5 | > 100 | 23 |
| 2500 | 50 | 5 | > 100 | 16 |

to closely monitor emissions from multi-well pads. For chronic concentrations there no exceedances in phase I and only exceedances for the 350 and 500-foot setbacks in the phase II RME scenario and the 350-foot setback distance in the phase II CT scenario. Finally, the toluene exceedances only occurred in the phase II acute RME scenario for the 350-foot setback distance.

In Table 19 we review the percent benzene concentration reduction between setbacks for each configuration. In each phase the well density scenarios are grouped to highlight the similarities in the results between these scenarios. The concentration reduction is minimal when increasing the setback from 1000 to 1500 feet in both phase I RME scenarios but the highest in the CT scenarios. As was mentioned previously in this chapter the benefits of increasing the setback distance depend on the location of the well with respect to the house. When a house is

*Table 19: Percent benzene concentration reduction between setback distances for each configuration*

| Configuration | 350-> 500 | 500-> 750 | 750-> 1000 | 1000-> 1500 | 1500-> 2000 | 2000-> 2500 |
|---|---|---|---|---|---|---|
| P1 Acute RME | 18.56 | 15.75 | 0.65 | 0.21 | 85.60 | 4.49 |
| P1 Chronic RME | 57.34 | 23.39 | 1.33 | 1.58 | 72.99 | 8.53 |
| P1 Acute CT | 12.58 | 26.53 | 13.41 | 34.57 | 1.59 | 4.87 |
| P1 Chronic CT | 16.26 | 35.88 | 15.61 | 44.72 | 4.35 | 6.06 |
| P2 Acute RME | 33.29 | 29.44 | 14.56 | 14.57 | 5.72 | 2.64 |
| P2 Chronic RME | 70.05 | 34.91 | 13.60 | 11.06 | 4.15 | 2.05 |
| P2 Acute CT | 60.27 | 73.90 | 47.15 | 70.95 | 35.09 | 19.20 |
| P2 Chronic CT | 137.25 | 102.84 | 54.49 | 66.35 | 31.47 | 17.91 |

located downwind of a well, the air quality value of increasing the setback rises dramatically. The emission rate from a well pad is critical too, although this is not reflected in the results because they have been averaged over 100 random emission rate samples.

# Chapter 5: Discussion

## 5.1 Emission Rate Variability

Using random number generation rather than direct numerical data was useful for this analysis because similar variability exists in the real world. The difference in emission rates between the two data sets collected by CSU researchers provides some evidence for this claim. Other studies have proven that a small portion of wells are responsible for a disproportionate amount of the total emissions in a region (Rawlins 2013). This phenomenon occurs due to error, whether it arises in the form of an equipment failure, an operator leaving a valve open, or a myriad of other circumstances. Error is difficult to model, but fortunately it is partially already accounted for in the emission rate data that drives this study. It is further accounted for by the random number generation to create a more appropriate representation of reality.

As we saw in the results, including an element of randomness produces significantly varied results. The question is, where should policymakers draw the line? Perhaps if wells were monitored more closely we could get by with shorter setback distances so long as the most serious offenders are sanctioned. For example, in the phase I acute RME configuration we saw that increasing the setback distance from 750 to 1500 feet resulted in a less than one percent reduction in concentration. However, increasing the setback from 1500 to 2000 feet provided an 85 percent reduction. If the well or wells that caused this substantial increase in concentration were dealt with individually, there would likely be no need to increase the setback to 2000 feet and it could be left at 750 feet instead.

Ideally well pads would be monitored and either regulated on a case by case basis or regulations would be made based on collected emission rate data. However, this is infeasible due to the overwhelming number of wells in operation and the potential for drastic shifts in emission based on error. Regulators do create emission inventories to quantify the expected emissions from air pollution sources, but they are often based on a small set of observations, which prevents them from being a suitable solution to this problem. Increasing the number of gauges and evaluating the collected data is necessary to identify the greatest offenders (Pétron 2014).

## 5.2 Phase I Results

Based on the results from this phase we can assume that new wells drilled under the current setback distance regulations are not likely to cause long-term health problems. Even at the 350-foot setback distance, which only applies to outdoor areas and not homes, both scenarios result in 23-year average concentrations lower than the corresponding thresholds. However, the results do show short-term issues with benzene even for homes surrounded by the median number of wells within one mile.

It is important to note that the locations of wells relative to these homes in the real world will likely not be the same as the setup that was modeled in this analysis. Perhaps all the 13 wells are in the 2500-foot setback bracket or beyond, in which case benzene may not be an issue. Conversely, it is also possible that most of the wells are within 1000 feet if there is a multi-well pad nearby, in which case benzene concentrations would be higher than those predicted in this analysis. Further, the emission rate data used in this study was low compared to other observed data. Had the higher measurements been used, there may have been more cause for concern over acute benzene concentrations.

Through the phase I acute RME configuration in Section 4.1.1 we saw that the air quality benefits from increasing the setback distance do not scale linearly. As we discussed in Section 5.1, increasing the setback distance from 750 to 1500 feet provided very little benefit while increasing it from 1500 to 2000 feet provided the most significant benefits. However, in the phase I acute CT configuration, the greatest reductions in concentration occurred when increasing the setback from 750 to 1000 feet and 1000 to 1500 feet. This results shows that setback distances cannot be evaluated based on the number of wells they exclude alone. Rather, they depend on the location and emission rate of the wells in questions.

The impact of wells located downwind of a house will generally not produce significant air quality implications for that house. However, in a densely populated residential area wells will be surrounded by houses and therefore some residents are bound to be located downwind of a well. While increasing the setback distance from 750 feet to 1000 feet may not benefit some families, it will benefit others. Policymakers are tasked with deciding how to prioritize the economic benefits of drilling more wells with the health of the smaller percentage of homes that are most affected by pollutant emissions.

## 5.3 Phase II Results

The results from phase II call into question the regulation of multi-well pads. Setback distance regulations do not distinguish between single and multi-well pads (Colorado Oil and Gas Conservation Commission 2016b). Although the emissions from a 22-well pad may not be 22 times higher than those from a single-well pad, they will be significantly higher. The impact of the 10-well pad in the phase II scenarios demonstrates this point.

Most well pads are single-well pads, but multi-well pads do exist and are increasing in popularity. The COGCC database even showed a 64-well pad in Greeley, CO. This is not common, but the emissions from such a well pad will be much higher than from a single-well pad and it begs the question, do setback distances need to increase with the number of wells on a pad? We can also return to the previous question of do policymakers account for the small number of homes in the immediate vicinity of the 64-well pad when setting setback distance regulations?

In these results we saw significant relative decreases in concentration between setback distances. However, for most of the pollutants concentrations were far below their corresponding ATSDR threshold even in the worst-case scenario. Why should policymakers care if the toluene concentration is reduced by 150 percent when increasing the setback from 350 to 500 feet if the concentration is already tolerable? Recall that earlier we mentioned that the emission rate estimated used for this study were low in comparison to a similar study conducted by the same research group. With higher emission rates or a multi-well pad that reduction between 350 and 500 feet may be the difference between causing health issues for nearby residents. Sacrificing one or two wells may be worth achieving this factor of safety for policymakers.

# Chapter 6: Conclusion

In this study, we set out to provide some insight on how the benefits and costs related to UOGD change depending on setback distance alternatives. To do so we focused on the relative decrease in concentration and number of wells between setback distances as well as the absolute concentrations for each pollutant. This involved randomly generating fields of wells and modifying them based on the setback distance to predict air pollutant concentrations. We found that the decreases in concentration are dependent on meteorological patterns and well locations rather than setback alone. The results of this study cannot provide immutable values to characterize concentration decreases because of the variability in these factors. However, we can draw some general conclusions about setback distances.

Concentration decreases outweighed the reduction in wells for all setback distances up to 1500 feet, beyond which this trend reversed. For the RME scenario, the highest percent decreases in concentration typically occurred when increasing the setback distance from 350 to 500 feet and from 1500 to 2000 feet, while in the CT scenario the highest percent concentration decreases typically occurred when increasing the setback distance from 500 to 750 feet and 1000 to 1500 feet. The reason these results conflicted between the two scenarios was due to the location of the wells in within these setback distances in relation to the home. The contribution of a well to the air pollutant concentration at a home is dependent on whether the well is located downwind of the home.

We predicted concentrations for five pollutants in this study: benzene, toluene, ethylbenzene, the xylenes, and hexane. Aside from benzene, these pollutants produced concentrations well below their corresponding acute and chronic ATSDR thresholds. While chronic benzene concentrations were predicted below their corresponding threshold, the acute concentrations were problematic for not only the worst-case well density scenario, but the median well density scenario as well.

# Chapter 7: Future work

Throughout this thesis we have described UOGD as a complex regulatory problem with numerous impacts. We limited the scope of the modeling done for this analysis to the air quality and human health impacts and related them to setback distance, which were explored in depth. The next step of this research involves integrating the ability to quantify additional impacts and similarly relate them to UOGD policies. However, before adding on to the current framework, further analysis is required to validate these results.

## 7.1 Additional Modeling and Analysis

Environmental modeling can benefit greatly from model validation. Earlier in this thesis we conducted a sensitivity analysis to understand how AERMOD works and which parameters held the greatest influence on the results. However, these results were not compared against observed values. Although randomly generating parameters is beneficial in quantitative policy analyses, modeling a real-world scenario and assessing the model performance would provide credibility to the results.

The next step after evaluating the model is performing additional analyses. In this thesis, we explored several configurations in our attempt to achieve a comprehensive analysis, but limited the analysis to a single home. Future simulations could include a much large modeling domain, perhaps an entire neighborhood. This type of simulation would carry a significantly higher computational expense, but this expense could be partially offset through improvements to the modeling script. Simulating for a larger modeling domain would provide more insight into how many wells are invalidated in an urban area when setback distances are increased.

On a smaller scale, this same analysis can be conducted with different parameter values. Recall that the Monte Carlo simulation sampled numerous emission rates while the well pad locations and meteorological parameters were held constant. Similar Monte Carlo analyses can be performed with well pad locations or meteorological data instead. If not a full Monte

Carlo simulation, future analyses could be performed with different meteorological data or well pad locations to validate the conclusions presented in this thesis.

## 7.2: Additional Policy Alternatives and Objectives

As discussed in the introduction to this thesis, there are more regulations involved with UOGD than the setback distance. Other regulations that could potentially contribute to this type of analysis include well density and sound restrictions. Although there are no official regulations on well density, there are some guidelines. The COGCC 800 series rules cover sound regulations in detail.

Well density regulations could be incorporated with the expanded modeling domain discussed in Section 7.1. Random generation of well locations sometimes results in clusters of well pads that are located very close together, which could be avoided if well density were incorporated. In addition, this policy alternative linked with the presence of additional houses would also contribute towards a more realistic relationship between the total number of wells invalidated by increasing the setback distance in a residential scenario.

Incorporating the sound restriction policy alternative would require more detailed knowledge of how production and air pollutant emissions relate to the amount of sound emanating from a well pad. There would be two or more sound states during which production and air quality would be different and the amount of time in each would need to be totaled to calculate the objectives. Aside from the difficulty in finding relevant data, it would complicate the current process of running AERMOD automatically with a different input file in each iteration of the simulation.

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