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TECHNICAL PAPER

Evaluating potential human health risks from modeled inhalation exposures to volatile organic compounds emitted from oil and gas operations

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ABSTRACT

Some states and localities restrict siting of new oil and gas (O&G) wells relative to public areas. Colorado includes a 500-foot exception zone for building units, but it is unclear if that sufficiently protects public health from air emissions from O&G operations. To support reviews of setback requirements, this research examines potential health risks from volatile organic compounds (VOCs) released during O&G operations.

We used stochastic dispersion modeling with published emissions for 47 VOCs (collected on-site during tracer experiments) to estimate outdoor air concentrations within 2,000 feet of hypothetical individual O&G facilities in Colorado. We estimated distributions of incremental acute, subchronic, and chronic inhalation non-cancer hazard quotients (HQs) and hazard indices (HIs), and inhalation lifetime cancer risks for benzene, by coupling modeled concentrations with microenvironmental penetration factors, human-activity diaries, and health-criteria levels.

Estimated exposures to most VOCs were below health criteria at 500–2,000 feet. HQs were < 1 for 43 VOCs at 500 feet from facilities, with lowest values for chronic exposures during O&G production. Hazard estimates were highest for acute exposures during O&G development, with maximum acute HQs and HIs > 1 at most distances from facilities, particularly for exposures to benzene, 2- and 3-ethyltoluene, and toluene, and for hematological, neurotoxicity, and respiratory effects. Maximum acute HQs and HIs were > 10 for highest-exposed individuals 500 feet from eight of nine modeled facilities during O&G development (and 2,000 feet from one facility during O&G flowback); hematologic toxicity associated with benzene exposure was the critical toxic effect. Estimated cancer risks from benzene exposure were $< 1.0 \times 10^{-5}$ at 500 feet and beyond.

Implications: Our stochastic use of emissions data from O&G facilities, along with activity-pattern exposure modeling, provides new information on potential public-health impacts due to emissions from O&G operations. The results will help in evaluating the adequacy of O&G setback distances. For an assessment of human-health risks from exposures to air emissions near individual O&G sites, we have utilized a unique dataset of tracer-derived emissions of VOCs detected at such sites in two regions of intense oil-and-gas development in Colorado. We have coupled these emission stochastically with local meteorological data and population and time-activity data to estimate the potential for acute, subchronic, and chronic exposures above health-criteria levels due to air emissions near individual sites. These results, along with other pertinent health and exposure data, can be used to inform setback distances to protect public health.

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Introduction

Colorado's rapidly growing population, in parallel with increased oil-and-gas (O&G) extraction in Colorado's Northern Front Range (NFR) and Garfield County (GC), has led to increasing numbers of people living and working in close proximity to O&G wells (McKenzie et al. 2016; McMullin et al. 2018).

The upper part of Colorado's NFR, in the Wattenberg Field area of the Denver-Julesburg (D-J) sediment basin (see Figure 1), saw population grow by 19% in 2008–2017 (CODOLA 2019). It is a particularly intense region of O&G development (COGCC 2007) where O&G production grew by over 300% in that period, almost entirely in Weld and Larimer counties (COGCC 2019).

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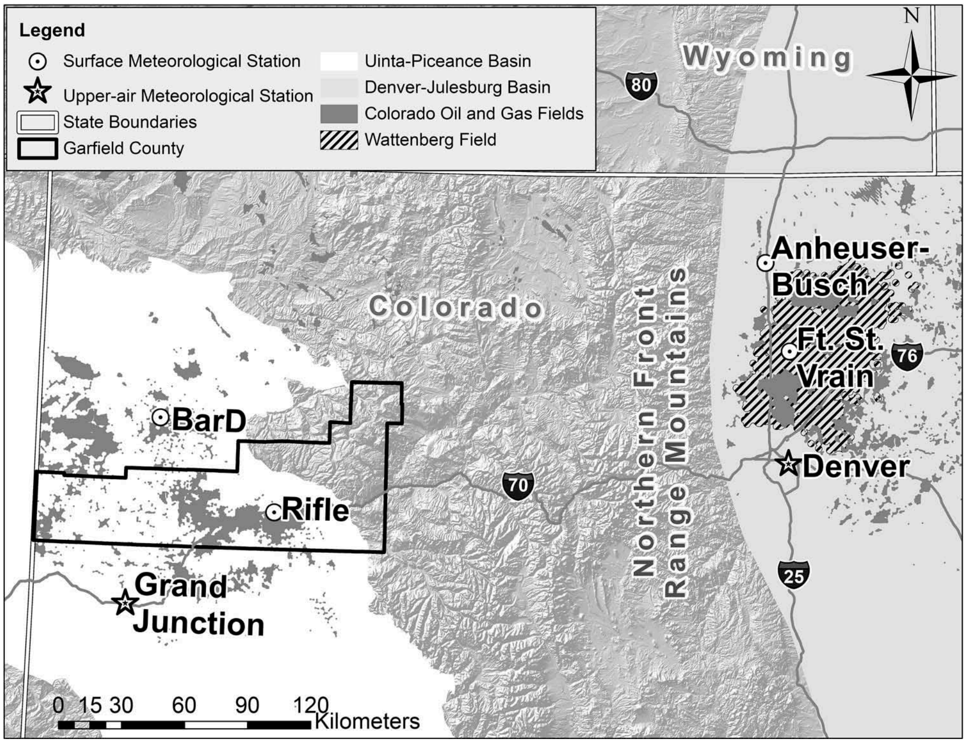


Figure 1. The major oil-and-gas-producing regions of Colorado and the locations of meteorological stations used for dispersion and exposure assessment. Interstate highways are also indicated.

In western Colorado, in GC and neighboring Rio Blanco and Mesa counties, population grew by 8% in 2008–2017 (CODOLA 2019). In those areas, O&G development of the Uinta-Piceance (U-P) basin (see Figure 1) has continued. O&G production declined 10% in 2008–2017 (peaking around 2012 at 26% over 2008 levels), though production in 2018 was higher relative to 2017, particularly in Mesa County with 48% growth (COGCC 2019).

In these Colorado regions, residential areas are often found within hundreds of feet (ft) of O&G wells. In 1992–2013, Colorado's Exception Zone Setback Distance was 350 ft (107 meters [m]) from the centre of new wells and production facilities to a building unit, and in 2013 the Colorado Oil and Gas Conservation Commission (COGCC) Rule #604 updated it to 500 ft (152 m). Analyses of residential locations in 2010 indicated 131,000 Coloradans lived within 400 m (1,312 ft) of a confirmed active well, with 255,000 people within 800 m (2,625 ft) (Czolowski et al. 2017). A more focused analysis of 2012 populations within 500 ft of active wells indicated 14,488 people in the D-J Basin live in such areas (up from 6,801 people in 2000) and 177 people in the more sparsely populated U-P basin live in that proximity (up from 72 people in 2000) (McKenzie et al. 2016). Because of continued population increases in these areas, a growing public-health concern has developed about the potential for inhalation health risks to people living near existing and future wells.

A number of studies have correlated proximity to O&G development with adverse health outcomes at different stages of life (Casey et al. 2016; Hill 2018; McKenzie et al. 2014, 2017; Rabinowitz et al. 2015; Stacy et al. 2015; Tustin et al. 2017; Whitworth, Marshall, and Symanski 2017, 2018). However, Haley et al. (2016) reviewed setback distances in Texas, Pennsylvania, West Virginia, Ohio, and Maryland, and they found the setbacks were not determined from peer-reviewed data analysis but were based on compromise between government agencies, the regulated community, environmental and citizen groups, and landowners. A limited number of studies which have provided more robust recommendations on safe setbacks (Maryland School of Public Health 2014) are based on limited data on epidemiology and air-quality monitoring.

Numerous studies in the literature analyzed ambient monitoring data near wells and locations of intense O&G development. Several studies analyzed airborne volatile organic compounds (VOCs) measured near O&G-production facilities in the Wattenberg Field (Gilman et al. 2013; McMullin et al. 2018; Thompson, Hueber, and Helmig 2014) as well as in the vicinity of tank batteries and O&G-processing and disposal sites in the NFR (Halliday et al. 2016; McKenzie et al. 2018). Swarthout et al. (2013) and Colborn et al. (2014) respectively measured VOC signals in the Wattenberg Field area and in areas of O&G development in western Colorado.

Studies have used such monitoring data to estimate exposures for people living near O&G operations. Long, Briggs, and Bamgbose (2019) did so for areas in Pennsylvania. For Coloradans within 0.5 miles of active wells in 2008, McKenzie et al. (2012) used measurements along well-pad perimeters to make conclusions about incremental exposures to O&G-related hydrocarbon emissions: higher-end subchronic exposures could be slightly above health-criteria levels, while all other subchronic and chronic exposures were below non-cancer criteria levels for individual critical-effect groups and chemicals, and cancer risks from individual chemicals were $< 1 \times 10^{-5}$. Similarly, McMullin et al. (2018) used existing Colorado monitoring data, generally at hundreds-to-thousands of feet from well sites, to extrapolate that incremental acute and chronic exposures to O&G-related VOC emissions were below non-cancer criteria levels, and cancer risks were $\leq 1x10^{-5}$, at $\geq$ 500 ft from wells (beyond the current setback distance).

Most of the monitoring data used by McKenzie et al. (2012) and McMullin et al. (2018) were not at the hourly resolution ideal for acute-exposure analyses, and neither study used measured, source-attributable emission rates, nor human-activity patterns or other microenvironmental analyses, to more comprehensively examine spatiotemporal dispersion and exposure patterns. Studies or regulators conducting dispersion modeling of O&G operations often use limited, generic, and outdated emission factors (Small et al. 2014). This is particularly important because emissions from O&G activities can vary greatly in time and by phase of O&G activity (Adgate, Goldstein, and McKenzie 2014; Allen 2016; Brantley, Thoma, and Eisele 2015; CSU, 2016a, 2016b; McMullin et al. 2018; Thompson et al. 2017; Hecobian et al. 2019). This is especially pertinent to acute chemical exposures, which at high levels can be associated with headaches, nosebleeds, fatigue, dizziness, etc., depending on the chemical, intensity of exposure, and sensitivity of the individual.

In general, at sites using current well-development technologies, there remains a relative lack of studies utilizing measured emission rates to examine the direct impact from well-development and -production activities and corresponding patterns of acute human exposures. The relatively weak links between emissions and exposure must be strengthened to design and implement effective strategies to protect public health (Small et al. 2014). New studies are needed to help fill critical data gaps in O&G-related air-quality and exposure issues across geographies and communities, including using human-activity patterns to assess exposures that are epidemiologically meaningful (Shonkoff, Hays, and Finkel 2014).

In this article, we detail an assessment of human-health inhalation risks in Colorado regions of intense O&G activity (the NFR and GC), which helps to fill these data gaps. We utilized on-site VOC-emission rates derived by Colorado State University (CSU) during tracer studies, where during periods in 2013–2016 they measured 46 VOCs plus ethane (which we refer to as “47 VOCs” for convenience) at individual sites of O&G well development and production in the NFR and GC (CSU 2016a, 2016b; Hecobian et al. 2019). Their measurements indicated high intra-hour emission variability (by several orders of magnitude), occurring with no pattern. We used stochastic methods to model those variable emissions on an hourly basis, along with several sets of local hourly meteorological data and human-activity patterns in a variety of microenvironments (MEs). The modeled well sites are hypothetical because CSU measured the emissions at a variety of sites and times, and because the meteorological data we used in the modeling were not from the same sites and times. We stratified estimated risks by region, number of wells per well pad, O&G phase of activity (drilling, hydraulic fracturing (“fracking”), flowback, and production), VOC (and group of VOCs with similar critical effects), and duration of exposure (acute, subchronic, and chronic). The risk calculations, at distances $\leq$ 2,000 ft from the well pads, utilize health criteria issued by federal and state regulatory agencies, for non-cancer assessments of all VOCs and cancer-risk assessments for benzene. All exposures and risks are incremental (due only to each hypothetical well site being modeled) and do not consider aggregated exposure from background sources or other well sites. The risk estimates are only due to the 47 modeled VOCs and do not consider other compounds known to be emitted by O&G activities, and we do not account for synergistic health effects that may result from multi-chemical exposure.

While our chief concern is the highest simulated exposures (to determine if any exposure scenarios have the potential for adverse health impacts), we also characterize the distributions of potential non-cancer hazards across all modeled individuals at locations of higher average air concentrations.

The methodology developed and applied in this assessment can be applied to other O&G well operations which employ fracking and related processes. Ideally, local measurements of VOC emissions would be available, but the measurements used in this study could be used in a screening approach while still incorporating local meteorological, topographical, and human-activity data to inform determinations of safe setback distances.

Methods and approach

In this section, we describe the methods and approach of our assessment. We discuss the uncertainties of some of these methods, and the sensitivity of the assessment to those methods, in the Uncertainties and Limitations section as well as in Supplementary Sections F and G.

Air-dispersion modeling

Model selection

We used the American Meteorological Society/U.S. Environmental Protection Agency (EPA) Regulatory Model (AERMOD version 16216r) (EPA 2018a). AERMOD's formulation represents the state of the science, with similarity-theory-based boundary-layer calculations. The steady-state Gaussian assumption is appropriate over the distances under consideration in this study, which are 150–2,000 ft (46–610 m). Near-source air concentrations are largely determined from emission source strength and meteorological conditions.

Emission characterization

We used field measurements made by CSU (2016a, 2016b; Hecobian et al. 2019) in close proximity to individual O&G-well sites in GC and the NFR, for the 47 VOCs shown in Figure 2. They gathered measurements during O&G drilling (only at GC sites) as well as fracking and flowback (at GC and NFR sites), which are development activities, as well as during O&G production (only at NFR sites). There were ≥ 12 sampling events per O&G phase, and each event had at least one unique canister sample measurement. In their documentation, CSU does not provide the exact locations of the sampled sites. They derived emission rates using the tracer-ratio method (TRM; Lamb et al. 1995). Wells et al. (2015) analyzed of the accuracy of the TRM using several controlled-release experiments, finding a mean bias of +22.6% and a precision (relative standard deviation) of ±16.7%. The CSU studies did not examine any chemicals beyond these 47 VOCs and methane.

Measured 3-minute-average emission rates for each VOC were highly variable. From the 3-minute-average rates, we derived 1-hour-average rates appropriate for dispersion modeling (1 hour is also the shortest time scale for acute health/toxicity information). We provide in Supplementary Section A further details on the

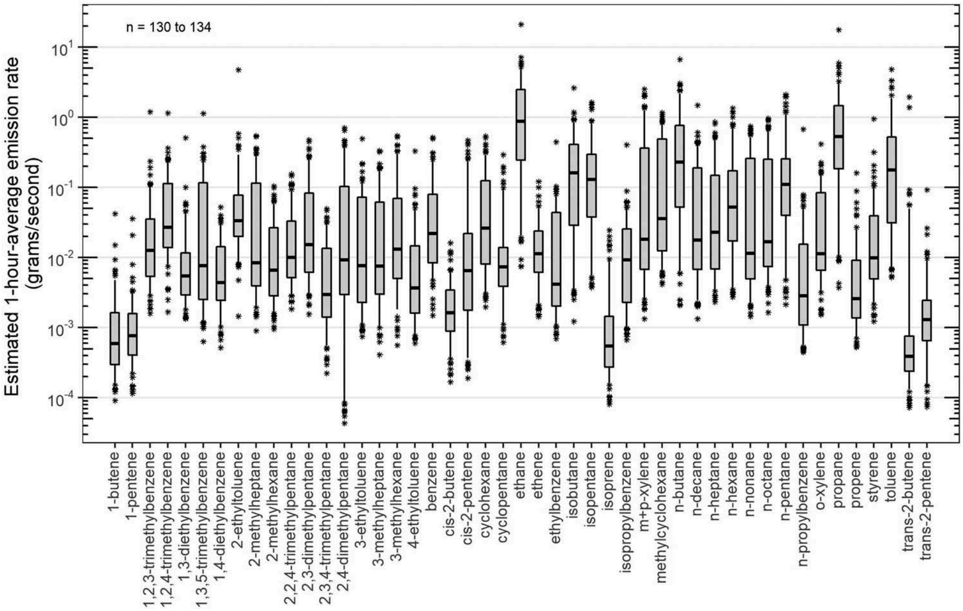


Figure 2. Emission rates utilized in this assessment. The values shown are the superset of rates from all sites and operations, and they are 1-hour-average rates derived from the 3-minute-average rates from CSU (2016a, 2016b; Hecobian et al. 2019). The bottom and top of the boxes are the 25th and 75th percentiles, respectively; the line inside the box represents the median; the bottom and top whiskers are the 5th and 95th percentiles, respectively; and the asterisks are outliers beyond the 5th and 95th percentiles.

characterization of emission variability and derivation of 1-hour-average emission rates. In Figure 2, for each VOC we show the superset of derived 1-hour-average emission rates (across all modeled sites and O&G activities).

To model emissions in AERMOD, we assumed multi-well development sites (which are increasingly common) would be larger than single-well sites. We modeled three source configurations for O&G development to reasonably represent current and near-future practices, based on professional judgement and recent O&G permits submitted to COGCC: a 1-acre site (for 1 well), a 3-acre site (for 8 wells in the NFR and 16 wells in GC), and a 5-acre site (for 32 wells). These acreages correspond to 0.4, 1.2, and 2 hectares. We modeled O&G well production using a 1-acre site (without consideration of the number of wells; production emissions were not well correlated with the number of producing wells). We characterized each site as a volume source, implying emissions come equally from all parts of the well pad, and with no chemical transformations during the short travel times/distances of interest (2,000 ft).

Meteorology

Meteorological data, provided by CDPHE, were representative of conditions in our two study areas (and generally representative of the regions where the CSU experiments occurred), and they included terrain-induced flows, mountain/valley wind systems, local-scale weather systems, and continental-scale weather effects. We show in Figure 1, and describe further in Supplementary Section B (including processing details and wind roses), the selected representative meteorological stations: a GC valley site (Rifle, Colorado), a ridge-top site 24 kilometres (km) north of GC ("BarD" site), an NFR site influenced by ridge flows (Anheuser-Busch site near Fort Collins, Colorado), and an NFR site influenced by mountain/valley flows (Ft. St. Vrain site near Platteville, Colorado). Terrain was generally flat within the immediate vicinity (500-m radius) of each station.

Receptors

We placed air-concentration receptors in a polar grid extending to 2,000 ft from the centre of a modeled well pad, at relatively regular distance intervals starting at 300 ft (91 m) from the development pad – at 100-ft (30-m) intervals to 1,000 ft (305 m), and then at 200-ft (61-m) intervals to 2,000 ft. We also included a 350-ft distance, and for modeling of well production we included receptors at 150 ft and 250 ft (76 m). Some distances (e.g., 350, 500, and 1,000 ft) correspond to setback distances from the centre of well or production facilities as listed under the COGCC Rule #600 Series Safety Regulations.

Monte Carlo simulations for O&G development

Since O&G well development typically lasts days to months, the focus was on short-term concentrations, which can vary drastically depending on meteorology and activities at the well. Dispersion models are designed primarily for sources with known emission rates or well-defined temporal patterns. For sources like O&G facilities emiting with substantial irregularity, the acute health risk can be exaggerated when applying an air-dispersion model to the improbable coincidence of the highest emission rate with worst-case meteorological conditions. To provide information on the probability of these events, the results are best expressed as a probability distribution simulated by randomizing the emission rate, O&G-activity duration, and meteorological conditions through application of the Monte Carlo method. The Monte Carlo approach is widely used in addressing problems associated with emissions from irregularly emitting sources, as it provides more realistic estimates of health risk (Li, Huang, and Zou 2008; Lonati and Zanoni 2013). Monte Carlo has been used to determine protective zones for intermittent irregular sources (Balter and Faminskaya 2016). For irregularly varying power-plant emissions, the Electric Power Research Institute sponsored the development of a Monte Carlo tool, EMVAP (Paine et al. 2014), useful in assessing compliance with National Ambient Air Quality Standards (NAAQS; Guerra 2014). The approach has been endorsed by the State of Washington's Department of Ecology (Bowman and Dhammapala 2011) for use in compliance with the 1-hour NAAQS for nitrogen dioxide.

To determine the concentration distributions of VOCs emitted by development activities, we used the Monte Carlo approach illustrated in Figure 3, whereby we randomized key inputs: meteorology, emissions, and O&G-activity duration. Per-well activity durations ranged 3–7 days for drilling, 1–5 days for fracking, and 1–30 days for flowback (with typically longer flowback durations at GC sites) (see Supplementary Section A, Table A-1). These durations were developed from information provided by COGCC and O&G operators/supervisors in GC and the NFR. The output of the Monte Carlo approach provides a representative distribution of possible VOC concentrations (EPA 1994).

In Stage 1, for each of the four sites and three well-pad sizes, we ran AERMOD using unit-emission rates (1 gram/second/pad) for the full meteorological period, retaining all hourly results and producing

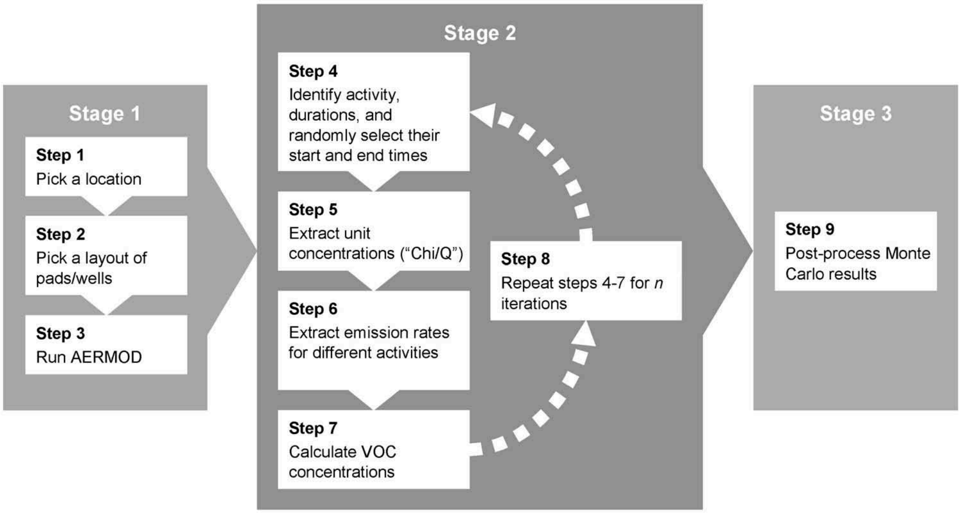


Figure 3. Monte Carlo simulation logic for estimating the concentration distribution of volatile organic compounds (VOCs) emitted by oil-and-gas well-development activities.

concentrations per unit emissions ("Chi/Q"). In Stage 2, for a given O&G development activity, we randomly selected a duration per well for the activity (from the ranges and probabilities shown in Supplementary Section A, Table A-1) and a time when the activity occurred. Then, for each VOC, we randomly selected an emission rate from available measurements and multiplied it by the Chi/Q values, resulting in a period of hourly modeled VOC concentrations (per well) based on the emission rate and meteorological variability. Each scenario developed in this way is termed an "iteration." This process was repeated 2,000 times for each well-pad size, meteorological dataset, O&G activity, and VOC. We identified 2,000 iterations was sufficient for result stability by running 10,000 simulations for VOCs with large emission-rate variations, examining maxima and standard deviations in the maximum concentrations. We assumed with all other O&G activities and VOCs that additional iterations would not noticeably alter the distributions of results, as they have less variability. Note: because the NFR is so large, neither meteorological station's data set fully characterizes the geographical region; as a result, for the NFR we randomly selected the iterations from the model outputs using the Anheuser-Busch or Ft. St. Vrain meteorological data, producing a blended single set of model results broadly representative of the NFR.

In Stage 3, we post-processed the Monte Carlo results by summarizing their statistical distributions. The goal was to constrain the amount of data passed to the exposure assessment of O&G-development emissions, utilizing only the receptors with the highest concentrations and only summary statistics of the Monte Carlo results at those receptors. First, we identified the maximum 1-hour-average concentration from each iteration, at each receptor for a specific O&G site (GC valley and ridge-top sites; NFR blended site), activity, and VOC. Second, we calculated the means from each set of maxima (the mean-maximum values, representing the expected maximum concentrations). Third, from among all the receptors at a given distance from the well pad, we identified the receptor with the highest mean-maximum concentration, for a specific O&G site, activity, and VOC. Fourth and finally, for each highest-mean-maximum receptor identified (one per receptor distance), we characterized the distribution of the concentrations from across the iterations for use in exposure assessment.

O&G production

Since O&G production typically lasts decades, the focus was long-term air concentrations. We used AERMOD to generate full years of hourly Chi/Q values for receptors at each O&G site, from which we calculated the annual-average values. As with O&G development, we sought to constrain the data passed to the exposure and risk assessments by focusing on the higher-concentration locations. We identified the year with the highest annual average for each site, and then we identified the receptor at each distance with the highest annual average. These receptors (one per receptor distance) with the highest annual-average Chi/Q represent the locations with the highest long-term concentrations, based on prevailing meteorological conditions. For each receptor identified, we later used the Chi/Q values directly in exposure and risk assessment, where we randomly combined the hourly Chi/Q values with the VOC emissions rates, creating many random hourly combinations of emission rate and meteorological conditions.

Comparison with monitored data

We cannot compare directly to CSU's canister measurements (2016a, 2016b; Hecobian et al. 2019) because we were not attempting to simulate the conditions and other specifications under which they took the measurements. We considered comparison to samples collected in other O&G studies. Halliday et al. (2016) collected samples of ambient VOCs, but they mostly focused on a regional scale and captured other VOC sources such as on-road mobile sources, biogenic emissions, other O&G-processing facilities, and industrial sources. However, we considered one site in that study appropriate for comparison: the PAO site was located 9 km southeast of Platteville, Colorado (in the NFR), in a fairly isolated, primarily rural location surrounded by agricultural and grazing lands but with active wells in close proximity and collection tanks 500 m to the southwest. The maximum benzene concentration reported at this location, using observations at 1-second time resolution, was 29.3 parts per billion (ppb). Our Monte Carlo dispersion simulations during well-development activities using the Anheuser-Busch meteorological data found an expected-maximum 1-hour concentration of 87.3 ppb at the much closer distance of 152 m, decreasing to 13.8 ppb at 610 m. While these data cannot be directly compared given the different source mix and distances, they indicate peak benzene concentrations are likely to be in the range of 10–100 ppb in the nearby vicinity under reasonable worst-case conditions. Other studies such as Thompson, Hueber, and Helmig (2014) only measured concentrations from samples in close proximity to producing wells and lack information on meteorology or emission rate needed to make a model-to-monitor comparison. McMullin et al. (2018) argued the need for more extensive and detailed air and exposure monitoring to improve the body of real-world data.

Human-exposure modeling

Model selection

We conducted inhalation-exposure modeling using the U.S. EPA Air Pollutants Exposure (APEX) Model, a stochastic, ME model used by EPA for assessments of criteria air pollutants (e.g., assessments for NAAQS; see, for example, EPA 2018b) and other airborne-chemical scenarios (EPA 2017). It generates time series of estimated inhalation exposure across a population by combining data on demographics, human activity, pollutant-ME interactions, and ambient pollutant concentrations.

Characterization of ambient air concentrations

We developed APEX runs whose results could be combined with the modeled air concentrations to obtain exposure estimates for a wide variety of scenarios. As illustrated in Figure 4, each run utilized unit ambient-air concentrations, resulting in time series of exposure concentrations per unit outdoor VOC air concentration, specific to the O&G site as well as chemical-penetration group and age group (discussed later). We multiplied the exposure time series by time series of air concentrations constructed from the Monte Carlo dispersion iterations.

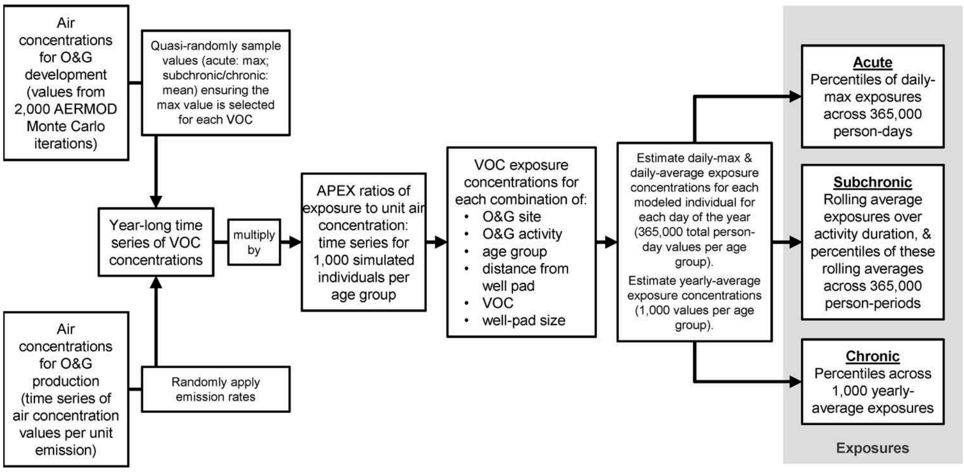


Figure 4. Flow diagram illustrating the steps in exposure assessment. Notes: O&G = oil and gas; VOC = volatile organic compound; AERMOD = American Meteorological Society/U.S. Environmental Protection Agency Regulatory Model; APEX = U.S. Environmental Protection Agency Air Pollutants Exposure Model; max = maximum.

For estimating exposure concentrations during O&G-development activities, we used outputs from the Monte Carlo dispersion iterations of O&G development to construct year-long time series of outdoor VOC concentrations. Each time series was specific to a VOC, O&G site, and development activity. For estimating acute exposure above criteria levels, each hour utilized the absolute-maximum 1-hour outdoor concentration from a randomly selected dispersion iteration (acute effects are likely to begin shortly after exposure but may persist for 24 hours or longer; we based our 1-hour time frame on the durations used to calculate acute health-criteria values). For estimating the potential for subchronic and chronic exposures above criteria levels, each hour utilized the mean outdoor concentration from a random iteration. Concentrations for all VOCs for a given hour originated from the same CSU sampling experiment, enabling evaluation of simultaneous chemical exposures.

For estimating exposure concentrations during O&G production, we generated year-long time series of outdoor VOC concentrations by multiplying hourly production emission rates (55 values per VOC available from the CSU experiments) by the Chi/Q outputs of the dispersion modeling of production activities. Each time series was specific to a VOC and O&G site. Each hour corresponded to a randomly selected emission rate, with rates for all VOCs picked from the same experiment on a given hour. As was done in the Monte Carlo simulations, for NFR modeling we randomly selected dispersion outputs from one of the NFR sites by hour.

Population characteristics

Age can affect personal activities and exertion levels. While exposures during individual activities can vary greatly with age, preliminary modeling indicated our exposure estimates of primary interest (the highest exposures within the population) would not vary substantially between basic stages of life (child vs. adult vs. elderly) and even less from year to year. Further, the very young and very old are not well represented in the time-activity data (discussed below), and the health-criteria values (discussed later) are assumed protective of these and all other identifiable sensitive groups. We modeled a single group of children (ages 0–17 years) and two groups of adults (ages 18–59 and 60–99 years; the 60-year cut-point was informed by time-activity availability). This is a hypothetical population split equally among males and females. APEX samples national distributions of U.S. demographic data to assign characteristics like age, height, weight, and employment (EPA 2017). Through convergence testing similar to that used in the dispersion modeling, we determined 1,000 modeled individuals per age group and receptor location was sufficient to capture the expected variability in exposures across a larger population.

Human-activity patterns

APEX constructs a timeline of activities and their ME locations for each individual by sampling from EPA's Consolidated Human Activity Database (CHAD) (EPA 2016) based on age and outdoor temperature. CHAD contains hundreds of activities and their ME locations for thousands of diary-days; APEX pairs them with exertion levels to estimate breathing rate and exposure. We constrained activity diaries for adults 18–59 years to those surveyed from U.S. Mountain West states (including Colorado). A sufficient number of diaries from that region was not available for younger and older individuals, for whom we sampled activity diaries from across the US. As discussed in Supplementary Section G, the geographic origin of activity data made minimal difference in estimated exposures.

We made the conservative assumption that an individual's exposures take place at his/her modeled receptor location (assumed to be their residential property). That is, we assume all individuals spend all their time at their property, in MEs defined as either indoors, outdoors, or in-vehicle depending on the activity. We discuss in Supplementary Section G the effect of this assumption, particularly that people do not commute away to work, finding modeled exposures may be overestimated by ≤ 25% for typical working adults.

Chemical penetration

We organized the VOCs into several groups of penetration factors (PENs, or the fraction of ambient chemical infiltrating an ME) based on volatility-based clustering analysis (including vapor pressure [Vp]), literature search for ME penetration factors (see Supplementary Section C), and an assumption that PENs cannot exceed 1 because we are assuming O&G-related pollutant concentrations in MEs cannot be higher than in outdoor air (ignoring any time lags due to air-exchange delays). We set in-vehicle PENs to 0.9–1 for all VOCs (typical literature values were above 1, due to in-vehicle sources not utilized in our study). For the "benzene group" (benzene and toluene with functional groups, and very large alkanes; $\log Vp = 0–9$), we set indoor PENs to 0.1–1 based on numerous studies. For other (smaller) alkanes and alkenes ($\log Vp>5$), we set indoor PENs to 0.9–1; this was based on one study (for pentane), but high PENs are health-protective (indoor exposure levels will be higher and closer to outdoor levels) and expected for high-Vp chemicals. For the entirety of the simulation, a modeled individual is randomly assigned one PEN per ME from these uniform distributions. Depending on the VOC, we discuss in Supplementary Section G an assumption of "tighter" homes and vehicles would substantially reduce chronic exposures, while an assumption of constant outdoor exposure would increase chronic exposures.

Post-processing

For calculating exposure statistics, we assumed an O&G activity could occur any hour and time of year. While the Monte Carlo dispersion simulations utilized distributions of O&G-activity durations (based on the prevalence of vertical vs. horizontal drilling and the distance of horizontal drilling), for exposure analysis we simplified the durations through prevalence-weighting so there was one duration per site, well-pad size, and O&G activity. Multi-well scenarios are longer than single-well scenarios, proportional to the number of wells, and in some cases a single development phase can last more than one year, requiring a chronic-exposure assessment. We assumed the production phase was 30 years. These exposure durations, along with which activities underwent an acute, subchronic, and/or chronic assessment, are shown in Table A-2 of Supplementary Section A. Note we assume durations of development activities scale directly with the number of wells being developed (drilling occurs on each well sequentially, then sequential fracking, then sequential flowback, with no concurrence).

The goal was not to analyze all of the potentially millions of individual exposure events in the modeling; rather, we identified the exposure results of most interest for characterizing the potential (if any) of exposures above criteria levels. We isolated particular exposure statistics for each simulated individual at the locations of highest air concentrations, as shown on the right side of Figure 4 and described below.

For acute assessments (for 1-hour-average exposures), we identified the maximum 1-hour exposure concentrations per day for each modeled individual, resulting in a collection of hundreds of thousands of daily-maximum acute exposures per receptor distance and VOC.

For subchronic assessments (for average exposures lasting 1–365 days; note we did not evaluate exposures more than 1 hour but less than 1 day), we calculated multi-day-average exposure concentrations, based on assumed O&G activity durations, for all possible multi-day periods in the year (i.e., "person-periods"). For sequences of development activities (i.e., drilling followed by fracking then flowback), we calculated average exposure concentrations from randomly selected person-periods for each of the activities in sequence, with averaging weighted by activity durations. This resulted in a collection of hundreds of thousands of person-period values per receptor distance and VOC.

For chronic assessments (for average exposures lasting more than 1 year), we identified each modeled individual's annual-average exposure concentration, assuming continuous exposure to emissions from O&G activities on the hypothetical well pad, and, for the production activity, assuming these exposures accurately reflect those expected over a 30-year period. This resulted in thousands of chronic-exposure concentrations per receptor distance and VOC. Following these calculations, for sequences of O&G activities together lasting more than 1 year, we calculated average exposure concentrations from randomly selected person-periods for each of the development activities in sequence, followed by the corresponding production-period exposures, with averaging weighted by activity durations, leading to hundreds of thousands of exposure values per receptor distance and VOC.

We then calculated mean and percentile acute, subchronic, and chronic exposure concentrations for use in risk estimations, based on the many exposure estimates discussed above per receptor distance and VOC.

Evaluation of potential health risks

Non-cancer hazards

We evaluated the severity of potential non-cancer health hazards associated with chemicals in accordance with guidance from ATSDR (Agency for Toxic Substances and Disease Registry) (2018) and EPA (2009). We calculated hazard quotients (HQs; ratios of time-weighted exposure concentrations to health criteria) for each VOC emitted by each individual well site, for acute, subchronic, and chronic exposure periods. To evaluate hazards from exposures to multiple VOCs, we calculated hazard indices (HIs) by summing HQs (effect additivity) for specified critical-health-effect groups (ATSDR 2018); we did not evaluate any possible synergistic effects or other toxicological interactions.

We calculated HQs for each VOC, exposed individual, pad size, O&G activity, and exposure duration, along with HIs for each critical-effect group. We stratified HQs and HIs into order-of-magnitude ranges from > 10, 1–10 (inclusive), 0.1–1, and < 0.1; values greater than 1 indicate increased potential for adverse effects, but numerical values do not indicate the probability or severity of effects.

Sources of non-cancer health-criteria values

For each VOC and exposure duration when available, we identified acute, subchronic, and chronic health-criterion values (exposure levels defined as being without appreciable risk of adverse effects) issued by federal agencies (EPA, ATSDR). These included EPA RFCs (Reference Concentrations), PPRTVs (Provisional Peer-reviewed Toxicity Values) issued under EPA's Superfund program, and ATSDR MRLs (Minimal Risk Levels). When federally issued criteria were not available (which was frequent for acute exposures), we used inhalation criteria that were issued by states with active air-quality programs (California OEHHA [Office of Environmental Health Hazard Assessment], TCEQ [Texas Commission on Environmental Quality]) and were available in early 2018. Where we identified more than one criterion value for a VOC, we selected values according to the following principals. (a) We preferred criteria issued by EPA or ATSDR. (b) Preferred criteria were those intended for risk and hazard analysis (RFCs, MRLs, TCEQ Reference Values) rather than screening-level values tied to specific regulatory programs (PPRTVs, TCEQ ESLs [Effects Screening Levels]). (c) We did not consider welfare-based criteria. (d) We preferred criteria derived using the most current and complete data, and using adequate human databases rather than only animal studies. (e) We preferred criteria derived using state-of-the-science methods (benchmark dose) to extrapolation from no-observed - or lowest-observed-adverse-effect levels. (f) We included criteria based on read-across or structure-activity relationships only if no other values were available (for example, EPA's chronic PPRTV for n-hexane served as a surrogate for 2,2,4- and 2,3,4-trimethylpentane, cyclopentane, and n-octane).

We show in Table 1 the criteria selected for this assessment. We identified suitable values for chronic, subchronic, and acute exposures for 45, 32, and 44 VOCs, respectively. For benzene, which was among the most ubiquitously occurring of the VOCs in the assessment, there were substantial differences in the acute criteria values issued by federal and state agencies. Values ranged from 8 ppb (OEEHA Reference Exposure Level) to 180 ppb (TCEQ ESL). After reviewing the bases and derivations of the values, we chose 30 ppb as the acute non-cancer criterion for benzene (see Appendix C for a complete discussion). The implications of this value's uncertainty are discussed in Supplementary Section D.

As noted above, we calculated HIs for VOCs in various critical-effects groups, calculated as the sum of all VOC HQs in the group. The groups, with chemicals assigned separately for acute, subchronic, and chronic effects, comprised developmental, endocrine, hematological, hepatotoxicity, immune, nephrotoxicity, neurotoxicity, respiratory, and sensory toxicity, as well as "systemic" for nonspecific endpoints such as reduced body weight. We assigned VOCs to specific groups based on effects occurring at or near the criteria levels, and, as shown in Supplementary Section E, a given VOC could be included in more than one group if animal or human data indicated multiple effects at that exposure.

Cancer risks

Among the assessed VOCs, benzene is the only one EPA classifies as a known human carcinogen (EPA 2000). Three other chemicals detected in the monitoring (styrene, isoprene, and ethylbenzene) are identified by the International Agency for Research on Cancer (IARC) as "probably" or "possibly" carcinogenic to humans. We did not include them in the cancer-risk assessment because animal studies are the primary sources of carcinogenicity data, and EPA has not derived exposure-response relationships based on human data for any of them as of publication. In addition, we know (McMullin et al. 2018) O&G operations release other potentially carcinogenic compounds, such as formaldehyde and acetaldehyde, which were not measured by CSU (2016a, 2016b; Hecobian et al. 2019). Exclusion of these compounds means our simulated total cancer risks from O&G operations are underestimated, but the degree of underestimation cannot be assessed accurately.

We used EPA's inhalation unit risk value (IUR) to calculate lifetime cancer risks for benzene exposure. EPA's Integrated Risk Information System issued a benzene IUR for lifetime leukemia risk, defined as $2.2\text{x}10^{-6}$–$7.8\text{x}10^{-6}$ $(\mu g/m^3)^{-1}$, with a central tendency of 5×10^{-6} $(\mu g/m^3)^{-1}$ (EPA 2000). OEHHA (2009) recommends a higher value – 2.9×10^{-5} $(\mu g/m^3)^{-1}$ – but it was derived in 1988 based on a combination of animal and human data and was estimated before the most accurate exposure estimates for the Pliofilm cohort became available.

We estimated ranges of incremental lifetime cancer risk from each well site individually by multiplying the lifetime-average exposure concentration by the three EPA IURs noted above (the lower-bound, central-tendency, and upper-bound values). We calculated exposures as the 70-year time-weighted average of 30–32 years of exposure to O&G benzene emissions (depending on the O&G activity and site) and, after well production has stopped, 38–40 years of no benzene exposure. This approach aligns with the EPA

Table 1. Selected non-cancer criteria values (ppb).

	Chronic criterion value		Subchronic criterion value		Acute criterion value	
Chemical	Value	Source	Value	Source	Value	Source
1,2,3-trimethylbenzene	12	EPA RfC	41	EPA RfC	3000	TCEQ ReV
1,2,4-trimethylbenzene	12	EPA RfC	41	EPA RfC	3000	TCEQ ReV
1,3,5-trimethylbenzene	12	EPA RfC	41	EPA RfC	3000	TCEQ ReV
1,3-diethylbenzene	45	TCEQ ESL	182	EPA PPRTV	450	TCEQ interim ESL
1,4-diethylbenzene	45	TCEQ ESL	182	EPA PPRTV	450	TCEQ interim ESL, surr.
1-butene	2300	TCEQ ReV	NA	NA	27,000	TCEQ ReV
1-pentene	560	TCEQ ReV	NA	NA	12,000	TCEQ ReV
2,2,4-trimethylpentane	124	EPA PPRTV	5740	EPA PPRTV	4100	TCEQ ReV
2,3,4-trimethylpentane	124	EPA PPRTV	5740	EPA PPRTV	4100	TCEQ ReV
2,3-dimethylpentane	2200	TCEQ ReV	6543	EPA PPRTV	8200	TCEQ ReV
2,4-dimethylpentane	2200	TCEQ ReV	6543	EPA PPRTV	8200	TCEQ ReV
2-ethyltoluene	25	TCEQ ESL	204	EPA PPRTV	250	TCEQ interim ESL, surr.
2-methylheptane	390	TCEQ ReV	5740	EPA PPRTV	4100	TCEQ ReV
2-methylhexane	2200	TCEQ ReV	6543	EPA PPRTV	8200	TCEQ ReV
3-ethyltoluene	25	TCEQ ESL	204	EPA PPRTV	250	TCEQ interim ESL, surr.
3-methylheptane	390	TCEQ ReV	5740	EPA PPRTV	4100	TCEQ ReV
3-methylhexane	2200	TCEQ ReV	6543	EPA PPRTV	8200	TCEQ ReV
4-ethyltoluene	25	TCEQ ESL	204	EPA PPRTV	250	TCEQ interim ESL, surr.
benzene	3	ATSDR MRL	25	EPA PPRTV	30	Literature review
cis-2-butene	690	TCEQ ReV	NA	NA	15,000	TCEQ ReV
cis-2-pentene	560	TCEQ ReV	NA	NA	12,000	TCEQ ReV
cyclohexane	1744	EPA RfC	5232	EPA PPRTV	1000	TCEQ interim ESL
cyclopentane	202	EPA PPRTV	9348	EPA PPRTV	5900	TCEQ interim ESL
ethane	NA	NA	NA	NA	NA	NA
ethene	5300	TCEQ ReV	NA	NA	500,000	TCEQ ReV
ethylbenzene	230	EPA RfC	2074	EPA PPRTV	20,000	TCEQ ReV
isobutane	10,000	TCEQ ReV	NA	NA	33,000	TCEQ ReV
isopentane	8000	TCEQ ReV	9087	EPA PPRTV	68,000	TCEQ ReV
isoprene	140	TCEQ ReV	NA	NA	1400	TCEQ ReV, proposed
isopropyl benzene	81	EPA RfC	204	EPA PPRTV	510	TCEQ interim ESL
m + *p*-xylene	23	EPA RfC	91	EPA PPRTV	1700	TCEQ ReV
methylcyclohexane	400	TCEQ ESL	6677	EPA PPRTV	4000	TCEQ interim ESL
n-butane	10,000	TCEQ ReV	NA	NA	92,000	TCEQ ReV
n-decane	190	TCEQ ReV	NA	NA	1000	TCEQ ReV
n-heptane	2200	TCEQ ReV	977	EPA PPRTV	8200	TCEQ ReV
n-hexane	199	EPA RfC	625	EPA PPRTV	5500	TCEQ ReV
n-nonane	3.8	EPA PPRTV	38	EPA PPRTV	3000	TCEQ ReV
n-octane	124	EPA PPRTV	5740	EPA PPRTV	4100	TCEQ ReV
n-pentane	8000	TCEQ ReV	3391	EPA PPRTV	68,000	TCEQ ReV
n-propylbenzene	51	TCEQ ESL	204	EPA PPRTV	510	TCEQ interim ESL
o-xylene	23	EPA RfC	92	EPA PPRTV	1700	TCEQ ReV
propane	NA	NA	NA	NA	NA	NA
propene	1744	OEHHA REL	NA	NA	NA	NA
styrene	235	EPA RfC	NA	NA	5100	TCEQ ReV
toluene	1328	EPA RfC	1328	EPA PPRTV	2000	ATSDR MRL
trans-2-butene	690	TCEQ ReV	NA	NA	15,000	TCEQ ReV
trans-2-pentene	560	TCEQ ReV	NA	NA	12,000	TCEQ ReV

Notes: ppb = parts per billion; RfC = Reference Concentration; MRL = Minimum Risk Level; PPRTV = Provisional Peer-reviewed Toxicity Value; ReV = Reference Value; ESL = Effects Screening Level; REL = Reference Exposure Level; EPA = U.S. Environmental Protection Agency; ATSDR = Agency for Toxic Substances and Disease Registry; TCEQ = Texas Commission on Environmental Quality; OEHHA = California Office of Environmental Health Hazard Assessment; NA = not available; surr. = data for a surrogate compound was used to derive the criterion value.

Superfund approach for conducting site-specific risk assessments for inhaled contaminants (EPA 2009) and has been used when evaluating emissions from sources similar those in this assessment (McKenzie et al. 2012).

Potentially sensitive populations (developmental effects and cancer risks)

Consistent with stated policies of all agencies who derived the health-criteria values, we assumed the non-cancer criteria are adequately protective of all identifiable sensitive groups in the exposed population. In the special case of developmental and reproductive effects, effects in sensitive groups such as pregnant women, children, etc. are specifically taken into account by the issuing agencies when setting numerical criteria values. This is done by (1) using data from human or animal studies during sensitive life stages, and (2) making appropriate dosimetric adjustments where necessary. In this assessment, we calculated HQs and HIs using the same criteria for all age groups, recognizing reproductive and developmental endpoints may not be meaningful for the oldest (60–99-year-old) group, but such effects in the younger groups are adequately captured due to conservatism built into the criteria for these effects.

We also assume no age correction is necessary for the calculation of cancer risks associated with benzene exposure. This is consistent with current practice in the absence of mechanistic evidence that could affect metabolism of the toxic compound or innate sensitivity to exposure. Lifetime exposures were weighted equally over the life stages when exposure takes place for each (hypothetical) individual in the simulation as well as for periods when exposure does not occur.

Results

To identify the potential for adverse health effects, we focused principally on the highest estimated HQs and HIs, particularly at the current 500-ft COGCC Exception Zone Setback for well facilities relative to a building unit. Using the available estimates, we also show distributions of potential HQs and HIs across modeled individuals, placing the highest results into the context of exposures occurring during more typical conditions. We present these HQs, HIs, and lifetime cancer risks to 2,000 ft from the centre of a well pad, and they are incremental metrics, reflecting only the modeled VOCs emitted by the individual hypothetical sites. We do not discuss age stratifications here because age had relatively little impact on exposure distributions. (Exception: at the lower ends of the distributions, we saw 10–20% lower exposures to lower-PEN VOCs for older adults relative to other individuals. We believe this reflects a higher proportion of older adults, relative to other people, who spend substantially more time indoors where concentrations of lower-PEN VOCs are often less than half the outdoor concentrations.) Detailed, stratified results (including by age group for non-cancer effects) are available in Supplementary Sections H and I.

Incremental acute exposures

At 500 ft from each individual development pad, the highest estimated 1-hour exposures exceeded criteria values for four VOCs (benzene, 2- and 3-ethyltoluene, and toluene) at the selected receptors, which were locations more often downwind from the emissions (Table 2). Particularly: maximum acute HQs were > 10 at 500 ft for 2-ethyltoluene (during flowback at the GC sites) and benzene (during drilling and flowback at the NFR site), and also at 2,000 ft for benzene during flowback at NFR. Table 2 also identifies the critical-effect groups with maximum HIs > 1 (hematological, respiratory, and neurotoxicity) and > 10 (hematological) for one or more O&G activities. We provide in Supplementary Section H the HQs and HIs for individual chemicals and critical-effect groups associated with different pad sizes, at all modeled distances and sites. Generally, large pad sizes were associated with somewhat lower HQs and HIs (sometimes ≥ 2 fold) vs. small pads because the plume from a larger source is less concentrated than one from a smaller source (when emission mass is constant).

The HQ and HI ranges shown in Table 2 refer to the maximum values seen at the selected receptors at two distances (500 and 2,000 ft) from the pads. In Figure 5 we show the distributions of acute HQs for benzene during flowback at all modeled distances from individual 1-acre pads, comprising the collections of daily-maximum acute HQs from across the modeled year and set of individuals at the selected receptors. The figure illustrates the large variations (across the modeled individuals and time periods) in the maximum values per distance. At the 500-ft selected receptors, for example, maximum benzene HQs during flowback were factors of 1.6–2.7 higher than median HQs (this difference was a factor of 14–22 during O&G production; see Supplementary Section H). The boxes in the figure, indicating 25th-through-75th-percentile values, indicate a larger spread of acute benzene HQs during flowback at the NFR site (factor of 5.3 spread at the 500-ft receptor) vs. the GC sites (factors of 0.7–0.9 spread).

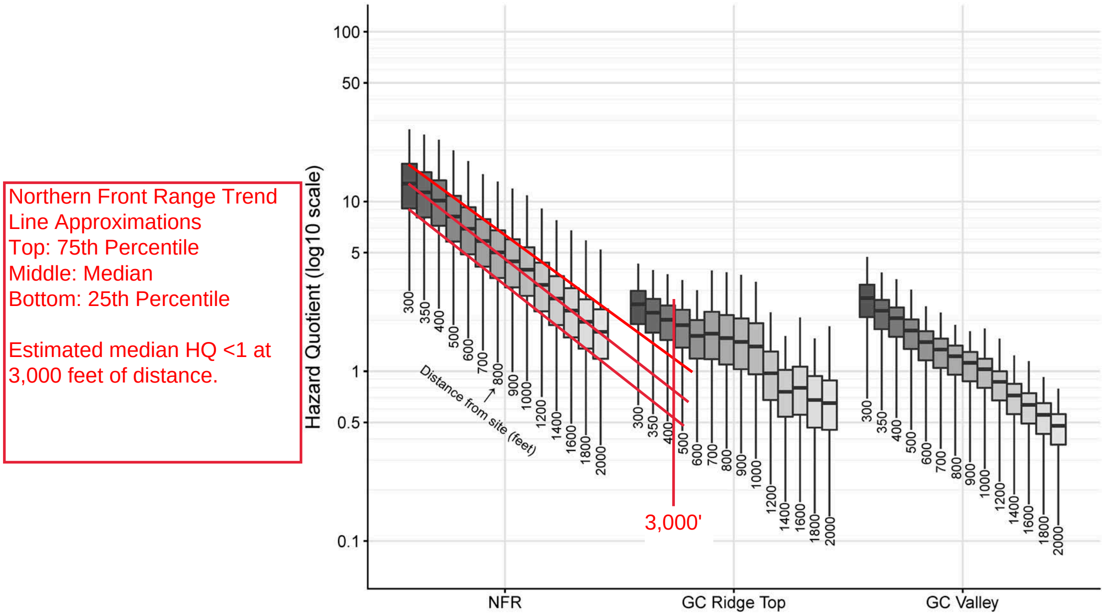
In Figure 5, the generally small differences in HQ distributions between the GC sites result from differences in meteorology (we used the same emissions data at both sites). The acute benzene HQs during flowback are much higher at the NFR site relative to the GC sites; while there are differences in meteorology between the sites, the higher HQs at the NFR site result primarily from higher emissions (see Figure A-1, Supplementary Section A). Figure 5 also illustrates the dependence of HQs on distance. As anticipated, HQs at distances < 500 ft (inside the Colorado setback requirement) were usually higher than those at 500 ft. At these closer locations, as shown in Supplementary Section H, HQs and HIs reached as high as 27, with maximum HQs > 1 for 4-ethyltoluene, n-decane, n-propylbenzene, and m + *p*-xylene, and maximum HIs > 1 for respiratory and sensory groups, during fracking or flowback at the GC sites (plus the VOCs and groups already mentioned as having values > 1 at 500 ft). Finally, Figure 5 illustrates how the distributions of acute benzene HQs during flowback vary between the three hypothetical sites: median HQs at 500 ft were similar for the two GC sites (within about 30% of each other), while at the NFR site they were approximately 5 times higher. Additionally, the pattern of decreasing HQs with increasing distance differs between sites, owing primarily to

Table 2. Overview of the largest acute non-cancer hazard quotients for the highest exposed hypothetical individuals at 500 and 2,000 feet from the well-pad centre.

			500 ft from well pad			2,000 ft from well pad		
Range of HQs or HIs	HQ or HI?	O&G activity	GC: ridge top (BarD)	GC: valley (Rifle)	NFR	GC: ridge top (BarD)	GC: valley (Rifle)	NFR
≥10	HQ	Drilling	none	none	benzene ^{1}	none	none	none
		Fracking	none	none	none	none	none	none
		Flowback	2-ET ^{1,3,5}	2-ET ^{1,3}	benzene ^{1,3,5}	none	none	benzene ^{3}
		Production	none	none	none	none	none	none
	HI	Drilling	none	none	hematological ^{1}	none	none	none
		Fracking	none	none	none	none	none	none
		Flowback	none	none	hematological ^{1,3}	none	none	hematological ^{3}
		Production	none	none	none	none	none	none
Between 1 and 10	HQ	Drilling	benzene ^{1,3,5} toluene ^{1,3,5}	benzene ^{1,3,5} toluene ^{1,3,5}	benzene ^{3,5} toluene ^{1,3,5}	benzene ^{1,3,5} toluene ^{1,3}	benzene ^{1,3,5}	benzene ^{1,3,5}
		Fracking	benzene ^{1,3,5}	benzene ^{1,3,5}	none	benzene ^{1,3,5}	benzene ^{1,3,5}	none
		Flowback	3-ET ^{1,3,5} benzene ^{1,3,5}	2-ET ^{5} 3-ET ^{1,3} benzene ^{1,3,5}	none	2-ET ^{1,3,5} benzene ^{1,3,5}	2-ET ^{1,3,5}	benzene ^{1,5}
		Production	benzene	benzene	benzene	none	none	none
	HI	Drilling	hematological ^{1,3} neurotoxicity ^{1,3}	hematological ^{1,3} neurotoxicity ^{1,3}	hematological ^{3} neurotoxicity ^{1,3}	hematological ^{1,3} neurotoxicity ^{1,3}	hematological ^{1,3}	hematological ^{1,3}
		Fracking	hematological ^{1,3} neurotoxicity ^{1,3} respiratory ^{1}	hematological ^{1,3} neurotoxicity ^{1,3}	none	hematological ^{1,3}	hematological ^{1,3}	none
		Flowback	hematological ^{1,3} neurotoxicity ^{1,3}	hematological ^{1,3} neurotoxicity ^{1,3}	neurotoxicity ^{1,3}	hematological ^{1,3} neurotoxicity ^{1,3}	none	hematological ^{1} neurotoxicity ^{3}
		Production	hematological	hematological	hematological	none	none	none

Notes: Not showing chemicals with hazard quotients less than 1 or critical-effect groups with hazard indices less than 1. Corresponds to ages 0–17 years (results for other age groups are nearly identical). Numbers in superscript indicate the size of development well pad (in acres) associated with that entry (well-pad sizes are not shown for production activities because they were all modeled as 1 acre).

HQ = hazard quotient; HI = hazard index; O&G = oil and gas; GC = Garfield County; NFR = Northern Front Range; ft = feet; ET = ethyltoluene.



Northern Front Range Trend Line Approximations
Top: 75th Percentile
Middle: Median
Bottom: 25th Percentile

Estimated median HQ <1 at 3,000 feet of distance.

Figure 5. Distributions of daily-maximum acute non-cancer hazard quotients for benzene (across the hypothetical population) at distances from the centre of the 1-acre well pad during flowback activities. The bottom and top of the boxes are the 25th and 75th percentiles, respectively; the line inside the box represents the median; and the bottom and top whiskers are the minima and maxima. Notes: log10 = logarithm base 10; NFR = Northern Front Range; GC = Garfield County; GC Ridge Top refers to the BarD site; GC Valley refers to the Rifle site.

differences in meteorological conditions, with the GC ridge-top site showing the least (relative) decrease in acute HQ 500-to-2,000 ft.

VOC emissions, and thus the acute HQs, were generally much lower during O&G production vs. development. Benzene was the only chemical with a maximum acute HQ > 1 during production (2.9 and 1.6 at 150 and 500 ft, respectively, at the NFR site; corresponding HQs at the GC ridge-top site were 2.6 and 1.4, and 2.7 and 1.1 at the GC valley site). HQs were < 1 beyond 600 ft (183 m) from the pad at the GC sites and beyond about 1,200 ft (366 m) for NFR. Hematological toxicity (driven by benzene) was the only critical-effect group with HIs > 1 at any site and distance associated with production.

Incremental subchronic exposures

We did not calculate subchronic HQs or HIs for O&G activities lasting > 1 year; potential adverse effects from such long-term exposures are adequately captured by comparison to the generally more health-protective chronic criteria. For O&G development, estimated subchronic exposures to individual VOCs were below subchronic criteria at 500–2,000 ft from all modeling sites. For combined exposures at 500 ft, maximum HIs were > 1 (up to 2.2) for the hematological and neurotoxicity groups at the GC sites during fracking (all pad configurations at the ridge-top site; 1- and 3-acre pads at the valley site), and these HIs > 1 extended to 800 ft (244 m) from the pads and were higher at distances inside the Colorado setback requirement. This can be seen in Figure 6, where distributions of subchronic HIs are plotted for neurotoxicity at the selected receptors during fracking activities at a hypothetical 1-acre pad. The HIs composing the distributions are from across the modeled year (different periods of the year with durations corresponding to assumed activity durations) and the set of individuals. The span of subchronic neurotoxicity HIs during fracking was close to one order of magnitude at all sites and distances. M + *p*-xylene and n-nonane contributed the most to neurotoxicity effects, while m + *p*-xylene and benzene contributed the most to hematological effects, with m + *p*-xylene having an HQ near 1 at both GC sites for the 1-acre scenario. At locations < 500 ft from the pad, maximum HQs or HIs were > 1 for benzene, m + *p*-xylene, n-nonane, and the respiratory group (in addition to those already mentioned as being > 1 at 500 ft) during fracking and flowback activities individually and during all development activities in sequence (not shown), with maximum HQs near 2 and maximum HIs near 4.3 (we provide in Supplementary Section H the HQs and HIs for individual chemicals and critical-effect groups associated with different pad sizes, at all modeled distances and sites).

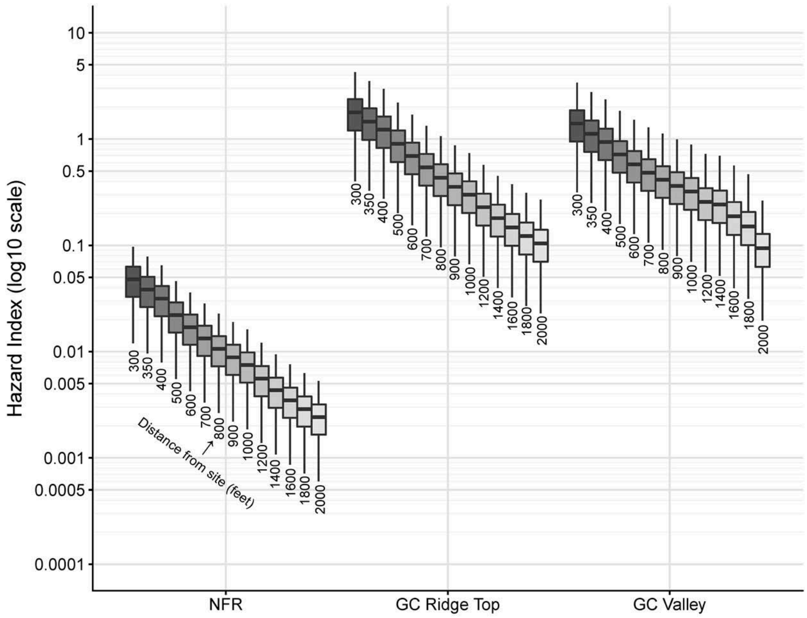


Figure 6. Distributions of subchronic non-cancer hazard indices for the neurotoxicity critical-effect group (across the hypothetical population) at distances from the centre of the 1-acre well pad during fracking activities. The bottom and top of the boxes are the 25th and 75th percentiles, respectively; the line inside the box represents the median; and the bottom and top whiskers are the minima and maxima. Notes: log10 = logarithm base 10; NFR = Northern Front Range; GC = Garfield County; GC Ridge Top refers to the BarD site; GC Valley refers to the Rifle site.

Incremental chronic exposures – non-cancer

We evaluated chronic non-cancer hazards for two sets of scenarios: those involving O&G production only (the modeled individual is not present for well development), and those involving development and production activities (the individual is present for all activities). During production, emissions are generally much lower than during the highest-emission development activities. Thus, notwithstanding the more demanding chronic health criteria, maximum chronic HQs and HIs were < 1 for production activities at 500 ft from each site, falling to < 0.1 at 2,000 ft. Only at the closest receptor (150 ft, much closer than setback requirements) were the chronic HQs > 1 (1.1–1.2) for benzene during production. At this distance during production, chronic HIs ranged 1.4–1.8 for hematological effects and 1.1–1.3 for neurotoxicity. We provide in Supplementary Section H the HQs and HIs for individual chemicals and critical-effect groups, at all distances.

Figure 7 illustrates the variability in chronic HIs for hematological effects during production at the selected receptors. The distributions are from across the modeled individuals, with modeled exposure durations defined as 1 year (assumed to reflect a 30-year average over the duration of production). The span of HIs was about a factor of 6–8 at all sites and distances. In contrast to the acute and subchronic results, generally the variability in chronic HI was < 15% between sites.

For the combined development-production scenario, long-term exposure varies with pad size; larger pads have longer development periods resulting in higher duration-weighted-average exposures. For 1-acre pads (a single well) and 3-acre pads (8 wells at NFR sites; 16 wells at GC sites), development is completed within weeks to months, so the resulting weighted-average chronic exposures were very similar to those for production alone and were below criteria in all cases.

For 5-acre pads (32 wells), at the GC sites the estimated development time exceeds 1 year, with flowback lasting over a year. During these development scenarios, all chronic HQs were < 1 at ≥ 500 ft, while maximum chronic HIs were > 1 at 500 ft for hematological and neurotoxicity effects (2.1 and 1.5, respectively, at the GC ridge-top site; 1.9 and 1.2 at the GC valley site). Benzene and n-nonane emissions from flowback contributed the bulk of the hematological and neurotoxicity HIs.

Chronic exposures – incremental lifetime cancer risks

We calculated 70-year incremental lifetime cancer risks associated with exposures to benzene for the 30–32-year combined development-production scenario, utilizing central-tendency and maximum chronic-exposure estimates. Risks were 8–14% higher at the 3-acre pads and 19–40%

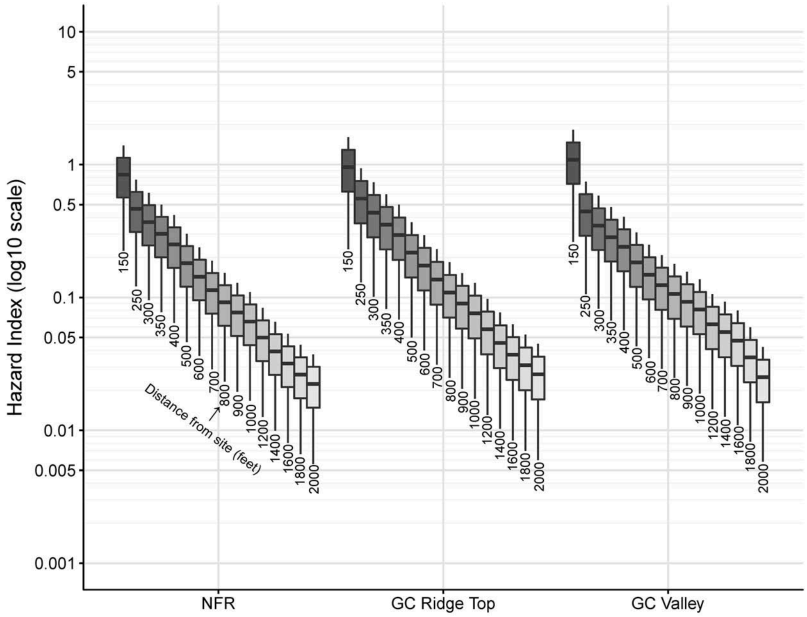


Figure 7. Distributions of chronic non-cancer hazard indices for the hematological critical-effect group (across the hypothetical population) at distances from the centre of the 1-acre well pad during production activities. The bottom and top of the boxes are the 25th and 75th percentiles, respectively; the line inside the box represents the median; and the bottom and top whiskers are the minima and maxima. Notes: log10 = logarithm base 10; NFR = Northern Front Range; GC = Garfield County; GC ridge top refers to the BarD site; GC Valley refers to the Rifle site.

higher at the 5-acre pads vs. the 1-acre pad, owing to longer durations of development at the larger sites. In areas < 500 ft from the well pad (inside the setback zone), maximum risks (maximum exposures with upper-bound IUR) reached 1.4×10^{-5} (for 1-acre sites) to 1.6×10^{-5} (for 5-acre sites), while central-tendency risks (average exposures with central-tendency IUR) were $5.2\text{x}10^{-6}$–$6.1\text{x}10^{-6}$.

All risk estimates fell to $\leq 8.2 \times 10^{-6}$ at 500 ft, with central-tendency risks $\leq 3.1 \times 10^{-6}$ and falling to $\leq 1.0 \times 10^{-6}$ by 1,200 ft. All risks fell to $\leq 1.0 \times 10^{-6}$ between 500 ft (average exposures using lower-bound IUR at 1- and 3-acre sites) and 2,000 ft (maximum estimates at all sites).

Figure 8 summarizes the cancer risks calculated at all distances from the GC ridge-top site, assuming a 1-acre pad and utilizing the three IURs (including the lower bound). For this scenario, estimated incremental lifetime cancer risks at 500 ft ranged from 1.1×10^{-6} (average exposure, lower-bound IUR) to 6.8×10^{-6} (maximum value). As shown in the full results presented in Supplementary Section I, maximum estimated lifetime cancer risks at 500 ft were 5.7×10^{-6} and 5.6×10^{-6} at the GC valley and NFR sites, respectively, decreasing with distance in a manner similar to that for the GC ridge-top site. Also, estimated cancer risks increased slightly with size of development pad, owing to longer durations of development activities.

Uncertainties and limitations

In this section, we summarize the major uncertainties and limitations of our assessment. See Supplementary Section F for additional analyses of the uncertainties and sensitivities of the assessment to various methodological choices and input parameters, and Supplementary Section G for a discussion of sensitivity analyses conducted on modeling inputs.

We estimate the emission rates, which directly and proportionally affect risk estimates, represented the highest uncertainty in the assessment, having perhaps ≥ 0.5 orders of magnitude of potential influence on the results. Emission measurements were at a limited number of sites, so we cannot be certain that they are representative of the full, real-world distribution of O&G emission and dispersion scenarios, particularly at the upper tail (as with any assessment, there is considerable uncertainty at the extreme tails of the data and outputs). O&G emissions can be highly variable with respect to configuration and operational practices, and the measurements reflected this high variability (as seen previously in Adgate, Goldstein, and McKenzie 2014; Allen 2016; Brantley, Thoma, and Eisele 2015; McMullin et al. 2018; Thompson et al. 2017). When we estimated 1-hour-avearge emission rates, there was uncertainty in assuming the means were similar to

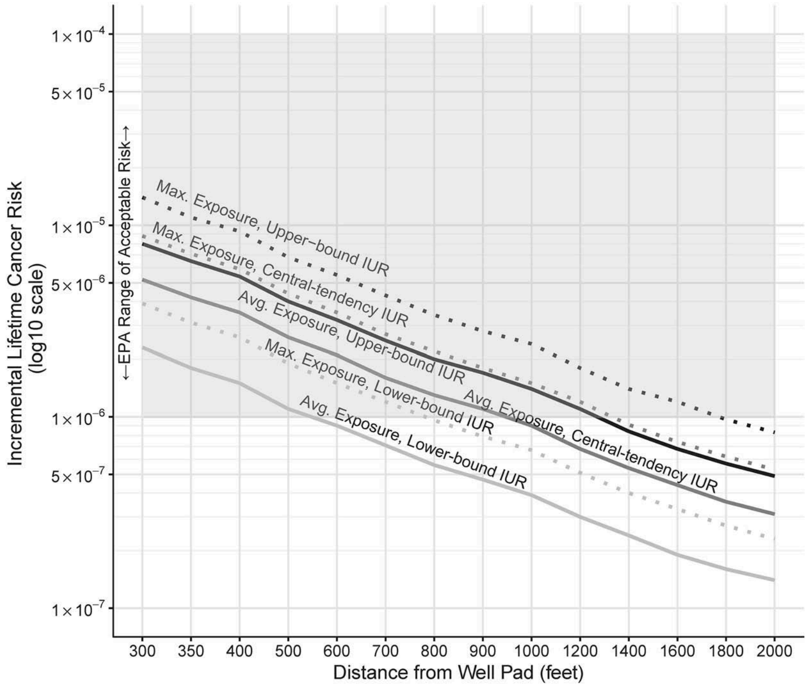


Figure 8. Incremental lifetime cancer risks from benzene exposure for average- and maximum-exposed hypothetical individuals at distances from the centre of the well pad during all activities in sequence at the Garfield County ridge-top site (1-acre development pad, 1-acre production pad). X-axis is not to scale. Grey box indicates the U.S. Environmental Protection Agency's range of acceptable cancer risk. Notes: Avg. = average; max. = maximum; IUR = inhalation unit risk.

those of the 3-minute measurements and fitting the values to a lognormal distribution.

The limited sampling and high variability in measured emissions necessitated use of stochastic methods to capture the resulting variabilities in exposure and generalize the results to different O&G-activity durations and geographic and meteorological settings. While these meteorology settings included several years of hourly meteorology in different locations, including wind speeds as low as 0.2 meters per second, we may not have captured all possible weather conditions (an estimated 2–3-fold uncertainty).

These uncertainties and limitations particularly affect the interpretation of "maximum" HQs and HIs. Maximum exposures, as defined in this assessment, occur only at the most-exposed locations during atypical times when simulations created a confluence of very conservative meteorological conditions, unusually high emissions, and personal activities leading to exposures far above average. Maximum exposures also assume individuals reside at the most-exposed locations. While these conditions are possible according to our assumptions and input data (and indeed they are the health-protective focus of our assessment), as outputs in the upper tails of our modeling results, they are not representative of "typical" exposures. Distributions of typical exposures will generally be shifted toward lower values, sometimes much lower, at other receptors. Additional analyses with site-specific monitoring and meteorological data would better characterize the relationship between the highest and typical exposures during well development and production (analyses such as McKenzie et al. 2012; Colborn et al. 2014 but including information on acute timescales and, in the case of Colborn et al. 2014, with measurements within a half-mile of the well-pad centre).

Previous studies and reviews suggested O&G emissions can contribute to exceedances of regulatory or guidance levels of health and ecological welfare on a local and regional scale (e.g., Shonkoff, Hays, and Finkel 2014; Thompson et al. 2017). While our study has the advantage of helping to understand the contribution of a single O&G facility toward an individual's exposure, multiple O&G facilities are increasingly intermingled with residential and recreational areas. The large numbers of chemical exposures experienced by any individual, across short and especially long (chronic) time scales, and their variable and sometimes compounding effects on human health, are complex and uncertain.

Another limitation of our analysis is that we used a limited number of generic well-pad configurations to represent several variations in possible release conditions, but risk estimates (particularly those close to the well pad) can be sensitive to the exact locations and specifications of the emission sources (e.g., we estimated a < 3-fold potential risk-assessment uncertainty related to the AERMOD dispersion modeling, including source characterization). We did not utilize decline curves to account for variations in emissions during O&G production (as they are uncertain and dependent on the site and operator), nor did we utilize algorithms for downwash due to any obstructions that might be present (e.g., sound walls at development sites). Additional monitoring campaigns and modeling efforts near a variety of well-pad configurations and structures would provide important additional data on potential health risks.

Considering these limitations, the exposure concentrations we generated, while representative of higher-end values that would be seen at the modeling sites as-configured, do not constitute real-time measurements. We believe the exposure distributions are realistic, providing reliable summary statistics for the time frames examined, but new studies collecting additional exposure data would add to the body of knowledge. There is also some degree of uncertainty (probably < 2 fold) associated with applying APEX to estimate personal exposures, but on aggregate, these APEX-related uncertainties are small compared to those associated with emission estimation, air modeling, and health-criteria values.

There is an unavoidable degree of uncertainty associated with the values of health criteria and cancer slope factors used to estimate HQs, HIs, and lifetime cancer risks. The level of uncertainty associated with such values is generally estimated to be about one order of magnitude, and the toxic effects of some chemicals are currently less well understood than others like benzene. The HI estimates did not include examination of synergistic effects.

A final limitation of this study is it does not include all airborne chemicals previously detected near O&G sites. The canister sampling methodology used to characterize emissions measured only hydrocarbons; levels of polar oxygen-, sulfur-, and nitrogen-containing compounds were not quantified, though some (formaldehyde and acetaldehyde) have been frequently observed near O&G sites, and they are known or suspected human carcinogens (McMullin et al. 2018). We also did not calculate cancer risks for several chemicals in our assessment (styrene, isoprene, and ethylbenzene) classified by IARC or EPA as “possible” or “probable” human carcinogens, but for which human exposure-response models were not available. Exclusion of chemicals from our analysis results in lower estimates of HIs and total cancer risks than if we had included them.

Conclusions

Our study coupled stochastic dispersion modeling of emission rates with probabilistic risk-assessment methods to illustrate the potential non-cancer hazards and cancer risks associated with air emissions of certain VOCs from individual sites of O&G development and production in Colorado under plausible highest-exposure scenarios. The results will help in evaluating the efficacy of setback distances in protecting public health from such emissions. The emission studies (CSU 2016a, 2016b; Hecobian et al. 2019) utilized here were among the first of their kind in the US to use the TRM near individual facilities to characterize per-facility emission rates from individual phases of O&G development and production. Their measurements are likely comparable to similar sites elsewhere. The measurements were source-attributable because the facility’s emission plume was identified with a mobile tracker, and other nearby chemical signals were removed via an upwind background monitor. This is in contrast to typical monitoring data (e.g., those used by Colborn et al. 2014; Gilman et al. 2013; Halliday et al. 2016; Long, Briggs, and Bamgbose 2019; McKenzie et al. 2018, 2012; McMullin et al. 2018; Swarthout et al. 2013; Thompson, Hueber, and Helmig 2014) which measure the ambient air both within and outside the plume (depending on conditions) and cannot necessarily differentiate a target source of emissions from other nearby emissions. Our stochastic approach to dispersion modeling, whereby we combined the on-site-measured emissions data with multiple datasets of variable meteorology, has the advantage of generating thousands of credible and representative short- and long-term VOC air-concentration scenarios at hundreds of possible exposure locations – many more than can be reasonably observed with monitoring. These include myriad acute (1-hour) scenarios that have been understudied to-date in O&G risk assessments. Further, rather than assuming constant exposure to outdoor air (as was done, for example, by McKenzie et al. 2012; McMullin et al. 2018), we estimated individual exposures across MEs using the state-of-the-science APEX model with time-activity-pattern data (including surveys from Coloradans) and distributions of ME PENs based on chemical volatility. From these data, we derived detailed distributions of acute, subchronic, and chronic exposures for each modeled site, pad size, and exposure distance. We compared these exposures to toxicity criteria issued by federal and state agencies, chosen so as to generally prefer federal criteria based on the most current and complete data available and state-of-the-science methods.

Acute exposures were of greatest concern, primarily during O&G development and for a limited set of VOCs and critical-effect groups, sometimes at distances out to 2,000 ft from the well pad. While most acute HQs and HIs were < 1 for most VOCs and critical-effect groups, our results suggest the potential for HQs and HIs > 1, sometimes > 10, for several VOCs (particularly benzene and 2-ethyltoluene) and critical-effect groups (particularly neurological and hematological effects), during O&G development (particularly drilling and flowback). Benzene HQs, and hematological HIs driven by benzene emissions, were slightly > 1 during O&G production. These findings support increased concern for adverse effects in the exposed individuals, although the exact probability or severity of adverse effects cannot be estimated. Our results contrast somewhat with those of McMullin et al. (2018), who utilized ambient monitoring data and found all acute exposures to outdoor air were below criteria, except for the conservative "all-VOC" HI estimate (which we did not calculate) which was 1.2. However, nearly all monitoring data utilized by McMullin et al. (2018) were > 500 ft from the closest wells, and observations ≤ 500 ft were limited to regions of O&G activity rather than site-specific studies and were targeting either the lower-emitting production activities or were 24-hour integrated measurements rather than 1-hour averages. However, as in our study, McMullin et al. (2018) found benzene to be among the chemicals of highest relative concern and most VOCs corresponded to acute exposures far below criteria levels.

Nearly all HQs and HIs for subchronic effects were < 1 at ≥ 500 ft from the well pads. During fracking, subchronic HIs for hematological and neurotoxicity effects slightly exceeded 1 at 800 ft from the two GC locations. These findings were generally similar to those of McKenzie et al. (2012), who utilized ambient monitoring data close to well sources and found higher-end subchronic exposures to outdoor air (for people living within 0.5 miles of wells) that slightly exceeded criteria values for 1,3,5-trimethylbenzene (which had among the highest subchronic HQs in our study as well, though below criteria) and that lead to HIs ≤ 4 for several critical effects (particularly neurotoxicity and hematological).

Emissions during well production did not lead to chronic exposures above criteria levels at ≥ 250 ft from well pads. Chronic exposures due to well development lasting > 1 year resulted in chronic HIs for hematological and neurological effects that slightly exceeded 1 at 500 ft from 5-acre pads. These findings generally match those of McMullin et al. (2018) and McKenzie et al. (2012), who found for constant exposure to outdoor air that all chronic HQs, and all HIs for individual critical-effect groups, were below criteria levels.

Our largest estimated incremental cancer risks associated with benzene exposure were $< 2.0 \times 10^{-5}$ at all distances. We estimated central-tendency risks (average exposure, central-tendency IUR) to be $2.1\text{x}10^{-6}$–$3.1\text{x}10^{-6}$ (depending on pad size) at the 500-ft location most often downwind from the pad, decreasing to $< 1.0 \times 10^{-6}$ by 1,000–1,200 ft. The largest risk estimates fell below 1.0×10^{-6} by 2,000 ft. McKenzie et al. (2012) estimated similar benzene cancer risks ($3.3\text{x}10^{-6}$–$8.7\text{x}10^{-6}$, depending on the concentration used for constant exposure to outdoor air); risk estimates due to other chemicals were smaller than for benzene. McMullin et al. (2018) estimated benzene cancer risks in a higher range ($1.0\text{x}10^{-5}$–$3.6\text{x}10^{-5}$) due to constant exposure to outdoor air, which are similar to levels we estimated inside the 500-ft setback (up to 1.6×10^{-5}); here, too, risk estimates were highest for benzene.

These findings provide important information related to potential health hazards associated with O&G development and production activities in Colorado, and they shed light on the specific activities and chemicals of most concern for further analyses of such risks. These include, in particular, benzene and 2-ethyltoluene emissions during drilling and flowback, and hematological effects during most development phases. To a lesser degree, these also include 3-ethyltoluene and toluene emissions and neurotoxicity and respiratory effects during drilling and flowback; hematological and neurotoxicity effects during fracking (driven primarily by benzene, m + *p*-xylene, and n-nonane emissions); and hematological and neurotoxicity effects during extended development phases at large multi-well sites (driven primarily by benzene and n-nonane emissions). Acute exposures were of greatest concern: acute HQs and HIs were generally much higher than subchronic and chronic HQs and HIs, with acute values > 1 in some cases as far out as 2,000 ft from the well pad (our maximum modeled distance).

Relative to monitoring studies, we have high confidence that these chemical signals are attributed directly to O&G activities on the target well pad, due to the TRM used to derive on-site O&G emissions during specific O&G activities. We also have high confidence that the estimated exposures reasonably represent some real-life exposures that could be experienced by people living near O&G

facilities, due to the stochastic approaches to dispersion and ME assessment allowing the generation of thousands of acute-to-chronic exposure scenarios for individuals across the 2,000-ft radius. These approaches and findings can be used to further evaluate data needs and to support refinement of setback distances.

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UNIVERSITY OF CALIFORNIA

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October 1, 2021

RE: Response to CalGEM Questions for the California Oil and Gas Public Health Rulemaking Scientific Advisory Panel

Director Shabazian and Supervisor Ntuk,

Please find attached the responses from the California Oil and Gas Public Health Rulemaking Scientific Advisory Panel to the written questions sent by the California Geologic Energy Management Division (CalGEM) on August 31, 2021.

We would be glad to answer any further questions that may arise.

Best Regards,

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CalGEM Questions for the California Oil and Gas Public Health Rulemaking Scientific Advisory Panel

CalGEM requests the California Oil and Gas Public Health Rulemaking Scientific Advisory Panel assistance with the following questions:

1. ***How would the panel characterize the level of certainty that proximity to oil and gas extraction wells and associated facilities in California causes negative health outcomes? Is there a demonstrated causal link between living near oil and gas wells and associated facilities and health outcomes?***

We have focused our review on epidemiological studies carried out in multiple oil and gas regions, including Colorado, which has a similar regulatory context as California. Given that similar environmental health hazards and risks are intrinsic to both conventional and unconventional oil and gas development (OGD), including exposure pathways, chemicals associated with hydrocarbon reservoirs, use of ancillary equipment, and non-chemical stressors (See section on "Similarities and Differences Between Unconventional and Conventional OGD"), the California Oil and Gas Public Health Rulemaking Scientific Advisory Panel (Panel) concludes that the full body of epidemiologic literature is relevant to assess the human health hazards, risks and impacts of upstream OGD in California.

Our Panel concludes with a high level of certainty[1] that the epidemiologic evidence indicates that close residential proximity to OGD is associated with adverse perinatal and respiratory outcomes, for which the body of human health studies is most extensive in California and other locations.

Studies on Oil and Gas Development and Perinatal Outcomes

Perinatal outcome studies provide the largest [19 studies][2] and strongest body of evidence linking OGD exposure during the sensitive prenatal period with adverse health effects. The majority of studies that examine perinatal effects found increased risk of adverse birth outcomes in those most exposed to OGD (measured using metrics including, but not limited to proximity, well density, and production volume). It should also be noted that adverse perinatal outcomes, including preterm births, low birth weight, and small-for-gestational age births

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[1] In this document, the statement, "a high-level of certainty" is based on the professional judgement of all California Oil and Gas Public Health Rulemaking Scientific Advisory Panel (Panel) members in their assessment of the scientific evidence. In terms of panel process, all Panel members agree with the responses to the questions in this document. Any Panel member could have written a dissenting opinion, but no one requested to do so. This document reflects the perspective of the Panel members and not necessarily the opinions of their employers or institutions.

[2] Apergis et al., 2019; Busby & Mangano, 2017; Caron-Beaudoin et al., 2020; Casey et al., 2016; Currie et al., 2017; Cushing et al., 2020; Gonzalez et al., 2020; Hill, 2018; Janitz et al., 2019; Ma, 2016; McKenzie et al., 2014, 2019; Stacy et al., 2015; Tang et al., 2021; Tran et al., 2020, *Forthcoming*; Walker Whitworth et al., 2018; Whitworth et al., 2017; Willis et al., 2021.

increase the risk of mortality and long-term developmental problems in newborns (Liu et al., 2012; Vogel et al., 2018) as well as longer term morbidity through adulthood (Baer et al., 2016; Barker, 1995; Carmody & Charlton, 2013; Frey & Klebanoff, 2016)**.**

Perinatal Outcomes Associated with Conventional and Unconventional Oil and Gas Development

While many perinatal outcome studies outside of California focus on unconventional OGD (e.g., high-volume hydraulic fracturing), a recent review of the literature (Deziel et al., 2020), highlighted the need for an updated assessment of the health effects associated with OGD more generally, as both conventional and unconventional OGD operations present health risks, especially to those living in close proximity. This bolsters conclusions reached by the authors of the 2015 independent scientific study of hydraulic fracturing and well stimulation in California led by the California Council on Science and Technology (CCST) (Long et al., 2015) pursuant to Senate Bill 4 (2013, Pavley). Recent studies in California have reported associations between exposure to OGD and adverse birth outcomes, considering wells under production using enhanced oil recovery including cyclic steam injection, steam flooding and water flooding -- methods that do not meet the definition of unconventional development (Gonzalez et al., 2020; Tran et al., 2020, *Forthcoming*). Similar findings regarding adverse birth outcomes have been reported while examining unconventional OGD in Colorado, Oklahoma, Pennsylvania and Texas (Apergis et al., 2019; Casey et al., 2016; Cushing et al., 2020; Gonzalez et al., 2020; Hill, 2018; McKenzie et al., 2019; Stacy et al., 2015; Walker Whitworth et al., 2018; Whitworth et al., 2017). In the California independent scientific study on well stimulation pursuant to Senate Bill 4 (2013, Pavley), the authors concluded that while hydraulic fracturing introduces some specific human health risks, the majority of environmental risks and stressors are similar across conventional and unconventional oil and gas operations (Long et al., 2015; Shonkoff et al., 2015). Further, a handful of epidemiological studies explicitly examine potential differences in associations between conventional or unconventional oil or natural gas development and adverse outcomes. For example, Apergis et al. (2019) reported statistically significant reductions in infant health index within 1 km of both conventional and unconventional drilling sites in Oklahoma. <u>In summary, the Panel concludes with a high level of certainty that human health studies focused on unconventional and conventional OGD are relevant to consider in the California context where conventional development is most prevalent.</u>

Consistency Across Perinatal Epidemiology Studies

<u>We have a high level of certainty in the findings in the body of epidemiological studies for perinatal health outcomes because of the consistency of results across multiple studies that were conducted using different methodologies, in different locations, with diverse populations, and during different time periods</u> (see **Table 1** below). Most of these studies entail rigorous, high quality analyses (i.e., study designs that establish temporality based on large sample sizes, control for potential individual and area-level confounders, apply rigorous statistical

modelling techniques, and conduct sensitivity analyses to assess the robustness of effects). A variety of pollutants (e.g., $PM_{2.5}$ and air toxics) and other OGD stressors are associated with these same adverse birth outcomes (Dzhambov & Lercher, 2019; Nieuwenhuijsen et al., 2017; Shapiro et al., 2013), which further strengthens the evidence of the link between OGD and adverse perinatal outcomes. Therefore, the totality of the epidemiological evidence provides a high level of certainty that exposure to OGD (and associated exposures) cause a significant increased risk of poor birth outcomes.

Further, imprecision in exposure assessment or non-differential exposure misclassification in some of the epidemiological studies is more likely to attenuate observed relationships, thus leading to an underestimate of the true adverse impacts of OGD on birth outcomes (**Figure 1**). In environmental epidemiologic studies, researchers often use surrogates to estimate exposures or assign individuals to exposure categories; these surrogates have some measurement error associated with them. When these errors in assigning or classifying participant exposures are similar between exposed and unexposed or those with or without the health outcome, this is referred to as non-differential exposure misclassification. This type of "noise" in the data tends to dilute or attenuate the true exposure-response relationship, as illustrated by the hypothetical dashed line in **Figure 1**, which has a shallower slope compared to the hypothetical "true" solid line.

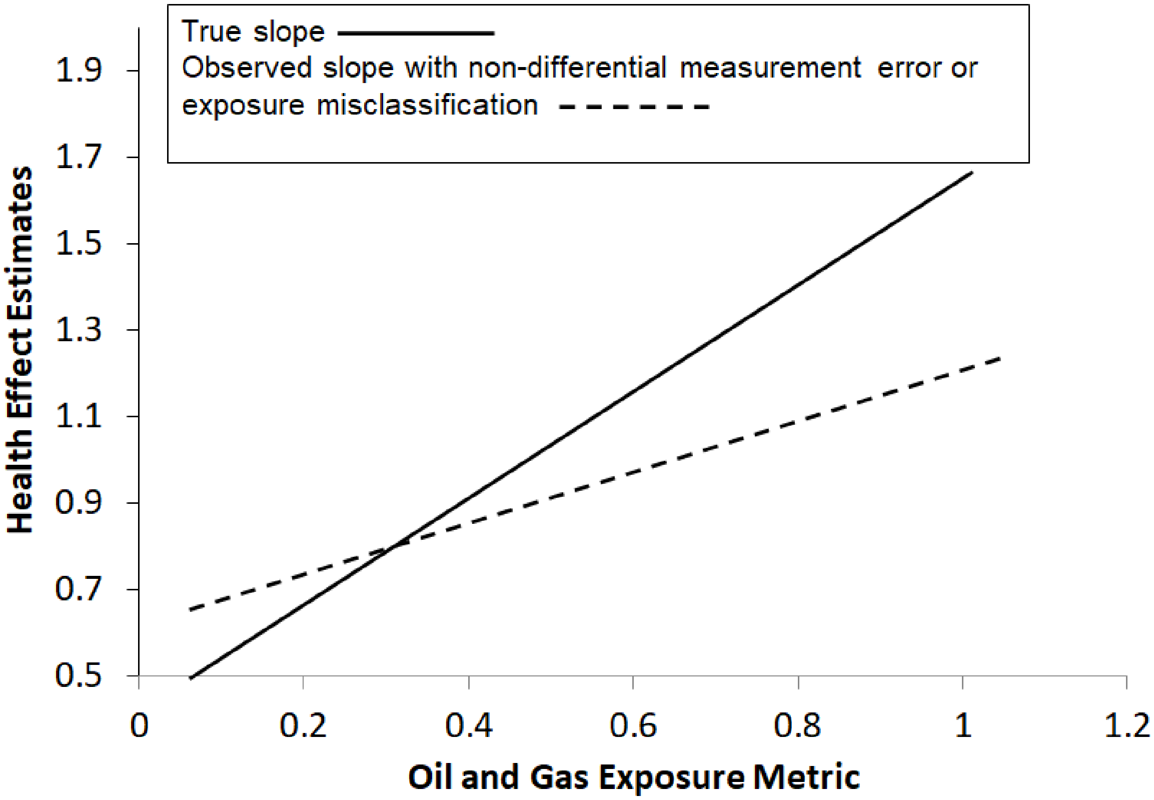

Figure 1. Effect of imprecise exposure estimates on a hypothetical exposure-response relationship (Source: Adapted from Seixas & Checkoway, 1995).

Respiratory Risks and Impacts from Oil and Gas Development

Respiratory health outcomes are the second most studied health outcomes in the epidemiological literature examining OGD, with eight peer-reviewed studies published to date. Two peer-reviewed studies in California found an association between OGD and self-reported and physician-diagnosed asthma, reduced lung function, and self-reported acute respiratory symptoms (e.g., recent wheeze) (Johnston et al., 2021; Shamasunder et al., 2018). Six studies in other oil and gas regions (Pennsylvania and Texas) reported an association between OGD and asthma exacerbations, asthma hospitalizations, and respiratory symptoms (Koehler et al., 2018; Peng et al., 2018; Rabinowitz et al., 2015; Rasmussen et al., 2016; Willis et al., 2018, 2020).

Epidemiological studies, by design, often use aggregate measures of exposure to account for multiple potential stressors and pathways associated with OGD (e.g., air pollution, noise pollution, groundwater and/or drinking water contamination). Many criteria air pollutants (e.g., particulate matter, ozone, nitrogen oxides) and hazardous air pollutants emitted from OGD have a well-established body of scientific literature indicating that exposure to these pollutants causes an increased risk of development and exacerbation of respiratory disease (Bolden et al., 2015; Ferrero et al., 2014). We reiterate the relevance of studies on both conventional and unconventional OGD for respiratory health outcomes. For example, (Willis et al., 2020) found that both conventional and unconventional natural gas development at the ZIP code level was associated with pediatric asthma hospitalizations in Texas.

Comparing The Body of Perinatal and Respiratory Outcome Studies Against The Bradford Hill Criteria for Causation

Below, we demonstrate how the body of epidemiological studies on the relationship between OGD and perinatal and respiratory outcomes meets the nine Bradford Hill Criteria for Causation (Hill, 1965; Lucas & McMichael, 2005). The Bradford Hill Criteria are used to evaluate the strength of epidemiological evidence for determining a causal relationship between an exposure and observed effect. These criteria are widely used in the field of epidemiology and public health practice to guide decision-making. After considering these criteria, the Panel concludes with a high level of certainty that there is a causal relationship between close geographic proximity to OGD and adverse perinatal and respiratory outcomes (**Table 1**).

Table 1. Application of the Bradford Hill Criteria for Causation to the peer-reviewed epidemiological literature on oil and gas development and perinatal and respiratory health outcomes.

Criteria for Causation (Bradford-Hill)	Description of Criteria	Perinatal Health Studies	Respiratory Health Studies
Strength of Association	Environmental studies commonly report modest effects sizes (i.e., relative to active tobacco smoking or alcohol consumption). A small magnitude of association can support a causal relationship, a larger association may be more convincing.	Reported effect sizes are in ranges similar to other well-established environmental reproductive and developmental hazards, such as $PM_{2.5}$ (Dadvand et al., 2013; C. Li et al., 2020). Some studies, particularly those in California, have found stronger effect estimates for OGD exposures among socially marginalized groups (Cushing et al., 2020; Gonzalez et al., 2020; Tran et al., 2020, *Forthcoming*).	Reported effect sizes are in ranges similar to other well-established environmental respiratory hazards. For example, effect sizes in reductions in lung function by Johnston et al. (2021) are similar in magnitude to reductions in lung function associated with secondhand smoke exposure among women (Eisner, 2002) and reductions in lung function among adults living near busy roadways (e.g., (Kan et al., 2007).
Consistency	Consistent findings observed by different persons in different places with different samples strengthens the likelihood of an effect.	Adverse birth outcomes have been observed in multiple studies using multiple methods in different populations at different times and locations (e.g., California, Pennsylvania, Colorado, Texas). While there is some variation in findings by specific perinatal outcomes, the overall body of evidence is highly consistent in supporting the association between OGD and adverse perinatal outcomes.	Various respiratory health outcomes are evaluated in the literature. For asthma -- the most commonly studied respiratory health outcome -- studies across California, Pennsylvania and Texas consistently show an association between OGD and asthma-related metrics (asthma prevalence, exacerbations, pediatric hospitalizations) (Koehler et al., 2018; Rasmussen et al., 2016; Shamasunder et al., 2018; Willis et al., 2018, 2020) .

Criteria for Causation (Bradford-Hill)	Description of Criteria	Perinatal Health Studies	Respiratory Health Studies
Specificity	Causation is likely if there is no other likely explanation.	All peer-reviewed birth outcome studies included in our review controlled for other potential confounders by (i) accounting or adjusting for other individual-level or area-level factors (e.g., other air pollution sources, neighborhood socioeconomic status) in the analysis (Casey et al., 2016; McKenzie et al., 2014; Tran et al., 2020, *Forthcoming*). Other studies applied statistical modeling approaches such as difference-in-difference that accounts for temporal and spatial trends that may confound observed effects (Willis et al., 2021).	Most respiratory health studies have controlled for other potential explanatory or confounding factors by (i) accounting or adjusting for other individual-level (e.g., smoking status) or area-level factors (e.g., other air pollution sources) in the analysis (Johnston et al., 2021; Koehler et al., 2018; Peng et al., 2018; Rabinowitz et al., 2015; Rasmussen et al., 2016; Willis et al., 2018, 2020), or in the study design, such as utilizing a difference-in-difference methodology (Peng et al., 2018; Willis et al., 2018).
Temporality	Exposure precedes the disease.	Most birth outcomes studies have proper temporal alignment between exposure and outcome and use a retrospective cohort, case control or other study design that allows retroactive assessment of exposures to OGD occurring before the onset of disease. They do not consider exposure that occurred at the time of disease or oil and gas wells drilled after the disease.	Some respiratory health studies do not allow for assessments of exposure that predate disease. However, of the studies with the proper temporal alignment (Johnston et al., 2021; Koehler et al., 2018; Peng et al., 2018; Rasmussen et al., 2016; Willis et al., 2018), authors report statistically significant associations between OGD and oral corticosteroid medication orders, asthma hospitalizations and asthma-related emergency department visits.

Criteria for Causation (Bradford-Hill)	**Description of Criteria**	**Perinatal Health Studies**	**Respiratory Health Studies**
Biological Gradient (Dose-Response)	Greater exposure leads to a greater likelihood of the outcome.	Some studies have found dose-response relationships based on oil and gas production volume categories or metrics of inverse distance weighting and/or oil and gas well density in California and elsewhere (Casey et al., 2016; McKenzie et al., 2014, 2019; Tang et al., 2021; Tran et al., 2020).	Larger reductions in lung function observed with decreased distance from active oil development sites (Johnston et al., 2021).
Plausibility	The exposure pathway and biological mechanism is plausible based on other knowledge.	Individual health-damaging chemical pollutants are well-understood to be emitted from OGD (e.g., $PM_{2.5}$, benzene) and established as contributing to increased risk for the same adverse perinatal outcomes observed in the epidemiology studies. Stressors associated with OGD (e.g., psychosocial stress; (Casey et al., 2019) can also contribute to increased adverse perinatal outcomes.	Many air pollutants associated with OGD are well-known to contribute to respiratory morbidity and mortality, including exacerbations of existing respiratory conditions (Guarnieri & Balmes, 2014).
Coherence	Causal inference is possible only if the literature or substantive knowledge supports this conclusion.	In particular, the body of peer-reviewed literature is converging towards singular directions for adverse perinatal outcomes.	The body of peer-reviewed literature points in a singular direction for adverse respiratory health outcomes.

Criteria for Causation (Bradford-Hill)	Description of Criteria	Perinatal Health Studies	Respiratory Health Studies
Experiment	Causation is a valid conclusion if researchers have seen observed associations in prior experimental studies.	N/A- Human population-based experimental studies are not available due to ethical issues.	N/A- Human population-based experimental studies are not available due to ethical issues.
Analogy	For similar programs operating, similar results can be expected to bolster the causal inference concluded.	Pollutants well known to be emitted during OGD including benzene, toluene and 1,3 butadiene are listed as reproductive or developmental toxicants under Prop 65 and thus are recognized as such by the State of California (CalEPA OEHHA, 2021). EPA's current Integrated Science Assessments of particulate matter and tropospheric ozone conclude that the evidence is suggestive of, but is not sufficient to infer, a causative relationship between birth outcomes, including preterm birth and low birth weight, and $PM_{2.5}$ and long term ozone exposures (US EPA, 2019, 2020). Additionally, increased stress during pregnancy can alter fetal growth and length of gestation (Fink et al., 2012).	EPA's current Integrated Science Assessments of particulate matter and tropospheric ozone conclude that there is: a casual relationship between respiratory outcomes, including asthma and short term ozone exposure; and likely a causal relationship between respiratory outcomes, including asthma and: short and long term $PM_{2.5}$ exposure; and long term ozone exposure (US EPA, 2019, 2020).

Similarities and Differences Between Unconventional and Conventional Oil and Gas Development

Though definitions of conventional and unconventional OGD may differ across different regulatory and policy landscapes, the majority of OGD in California is often considered conventional, involving vertical drilling at shallower depths into target geologies that hold migrated hydrocarbons. These attributes of development are often considered in contrast to unconventional OGD, which can involve horizontal directional drilling in deeper wells to access source rock formations by increasing the permeability of these tight formations using mostly hydraulic fracturing. In addition, these unconventional operations are often accompanied with greater masses of material inputs (e.g., water, chemical additives, proppants) and a greater magnitude of liquid and solid waste outputs (e.g., flowback fluids and produced water). It should be noted, however, that hydraulic fracturing that takes place in California often uses fluids (gels) with higher concentrations of well stimulation chemicals than those fluids used in high-volume slick water hydraulic fracturing of source rock in other parts of the United States (Long et al., 2015).

However, many environmental and health hazards and risks are intrinsic to both conventional and unconventional OGD (Hill et al., 2019; Jackson et al., 2014; Lauer et al., 2018; Stringfellow et al., 2017; Zammerilli et al., 2014). $PM_{2.5}$ and nitrogen oxides emissions result from the use of diesel-powered equipment and trucks and hazardous air pollutants such as benzene, toluene, ethylbenzene and xylene (BTEX) occur naturally in oil and gas formations, regardless of the type of extraction method employed. Noise pollution, odors, and landscape disruption are inherent to OGD. Investigations in other oil and gas states have noted radioactivity on particles downwind from unconventional oil and gas wells (Li et al., 2020b) and in sediment downstream of water treatment plants that treat waste from conventional as well as unconventional oil and gas operations (Burgos et al., 2017; Lauer et al., 2018).

In California, policy, regulatory and scientific emphasis has been placed on well stimulation activities, including hydraulic fracturing, matrix acidizing and acid fracturing. The 2015 Independent Scientific Assessment on Well Stimulation in California, which focused primarily on well stimulation activities pursuant to Senate Bill 4 (2013, Pavley), reported the following key conclusion: *“The majority of impacts associated with hydraulic fracturing are caused by the indirect impacts of oil and gas production enabled by the hydraulic fracturing”* (Long et al., 2015). Indirect impacts relevant to human health for the purposes of the study included: “proximity to any oil production, including stimulation- enabled production, could result in hazardous emissions to air and water, and noise and light pollution that could affect public health” (Long et al., 2015). Additionally, a recent evaluation of chemical usage during OGD in California found significant overlap in chemical additives used for well stimulation (including hydraulic fracturing) and those used in routine activities, such as well maintenance (Stringfellow et al., 2017).

2. *What are the air pollutants released from these activities that cause negative health outcomes? How do we know exposure to these is likely from oil and gas extraction wells and associated facilities, as opposed to other sources?*

The wells, valves, tanks and other equipment used to produce, store, process and transport petroleum products at both unconventional and conventional OGD sites are associated with emissions of toxic air contaminants, hazardous air pollutants and other health-damaging non-methane VOCs (Helmig, 2020; Moore et al., 2014). Diesel engines used to power on-site equipment and trucks at unconventional and conventional OGD sites directly emit health-damaging hazardous air pollutants, fine particulate matter ($PM_{2.5}$), nitrogen oxides and volatile organic compounds (VOCs) (CalEPA OEHHA, 2001). Many VOCs and nitrogen oxides are precursors to ground level ozone (O_3) formation, another known health harming pollutant. Hazardous air pollutants that are known to be emitted from OGD sites include benzene, toluene, ethylbenzene, xylenes, hexane and formaldehyde--many of which are known, probable or possible carcinogens and/or teratogens and which have other adverse effects for non-cancer health outcomes (CalEPA OEHHA, 2008, 2009; Moore et al., 2014). In the San Joaquin Valley Air Pollution Control District, OGD activities are responsible for the majority of emissions of multiple toxic air contaminants including acetaldehyde, benzene, formaldehyde, hexane and hydrogen sulfide (**Figure 2**) (Brandt et al., 2015; Long et al., 2015).

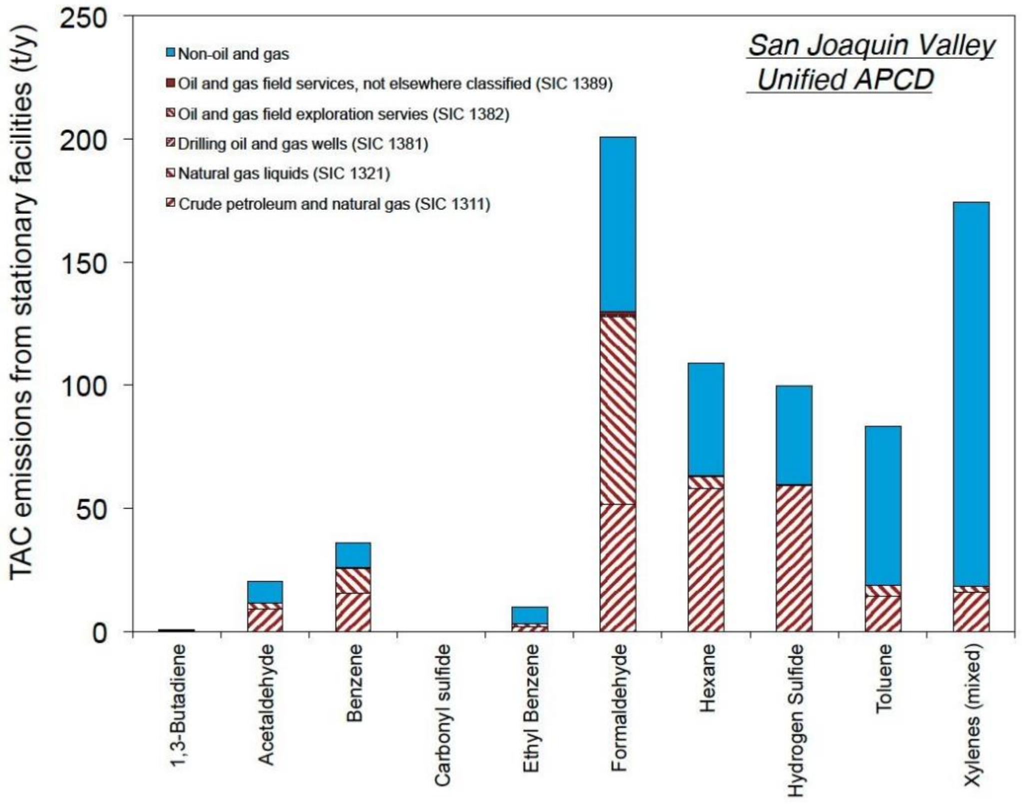

Figure 2. **Toxic Air Contaminant emissions from stationary facilities in the San Joaquin Valley Air Pollution Control District (Source: (Brandt et al., 2015).**

A recently published study using statewide air quality monitoring data from California investigated whether drilling new wells or increasing production volume at active wells resulted in emissions of $PM_{2.5}$, nitrogen dioxide (NO_2), VOCs, or O_3 (Gonzalez et al., 2021)**.** To assess the effect of oil and gas activities on concentrations of air pollutants, the authors used daily variation in wind direction as an instrumental variable and used fixed effects regression to control temporal factors and time-invariant geographic factors. The authors documented higher concentrations of $PM_{2.5}$, NO_2, VOCs, and O_3 at air quality monitoring sites within 4 km of pre-production OGD well sites (i.e., wells that were between spudding and completion) and 2 km of production OGD well sites, after adjusting for geographic, meteorological, seasonal, and time trending factors. In placebo tests, the authors assessed exposure to well sites downwind of the air monitors and observed no effect on air pollutant concentrations. **Table 2** summarizes the increases in each pollutant for each additional upwind well site by distance.

Table 2. Summary of air pollutant concentrations measured between 2006-2019 at 314 air quality monitoring sites in the EPA Air Quality System for California (Gonzalez et al., 2021*).*

Distance	$PM_{2.5}$ µg/m^3*	NO_2 ppb	VOCs (ppb C)*	O_3 (ppb)
Estimated increase for each additional upwind pre-production well site				
Within 2 km	2.35 (0.81, 3.89)	2.91 (0.99, 4.84)	No increase	no increase
2-3 km	0.97 (0.52, 1.41)	0.65 (0.31, 0.99)	No increase	0.31 (0.2, 42)
3-4 km	no increase	no increase	no increase	0.14 (0.05, 0.23)
Estimated Increase for each 100 BOE of total oil and gas upwind production volume				
1 km	1.93 (1.08, 2.78)	0.62 (0.37, 0.86)	0.04 (0.01, 07)	no increase
1-2 km	no increase	no increase	no increase	0.11 (0.08, 0.14)

*No $PM_{2.5}$ or VOC monitoring sites with 1 km of pre-production well sites; BOE, barrels of oil equivalents.

These multiple stressors, along with other physical factors such as noise and vibration, are consistently found in exposure studies to be measurably higher near oil and gas extraction wells and other ancillary infrastructure in California. As such, the Panel concludes with a high level of certainty that concentrations of health-damaging air pollutants, including criteria air pollutants and toxic air contaminants, are more concentrated near OGD activities compared to further away.

3. ***Does the evidence evaluated clearly support a specific setback? If so, what is this setback distance and what oil and gas extraction activities would it specifically apply to? What is the supporting evidence?***
    a. ***How does this evidence justify the recommended setback distance, as opposed to another distance?***

Existing epidemiologic studies were not designed to test and establish a specific “safe” buffer distance between OGD sites and sensitive receptors, such as homes and schools. Nevertheless, studies consistently demonstrate evidence of harm at distances less than 1 km, and some studies also show evidence of harm linked to OGD activity at distances greater than 1 km. In addition, exposure pathway studies have demonstrated through measurements and modelling techniques, the potential for human exposure to numerous environmental stressors (e.g., air pollutants, water contaminants, noise) at distances less than 1 km (e.g., Allshouse et al., 2019; Holder et al., 2019; McKenzie et al., 2018; DiGiulio et al., 2021; Soriano et al., 2020), and that the likelihood and magnitude of exposure decreases with increasing distance.

   b. ***What are the health benefits from this setback? Can the panel quantify them or recommend a methodology CalGEM can use to quantify them? Can the panel establish that these health benefits can only be achieved with the setback? Or can they also be achieved with mitigation controls?***

Figure 3 presents a hierarchy of strategies to reduce human health hazards, risks and impacts from OGD activities. **Table 3** presents the advantages and disadvantages of each strategy from an environmental public health perspective.

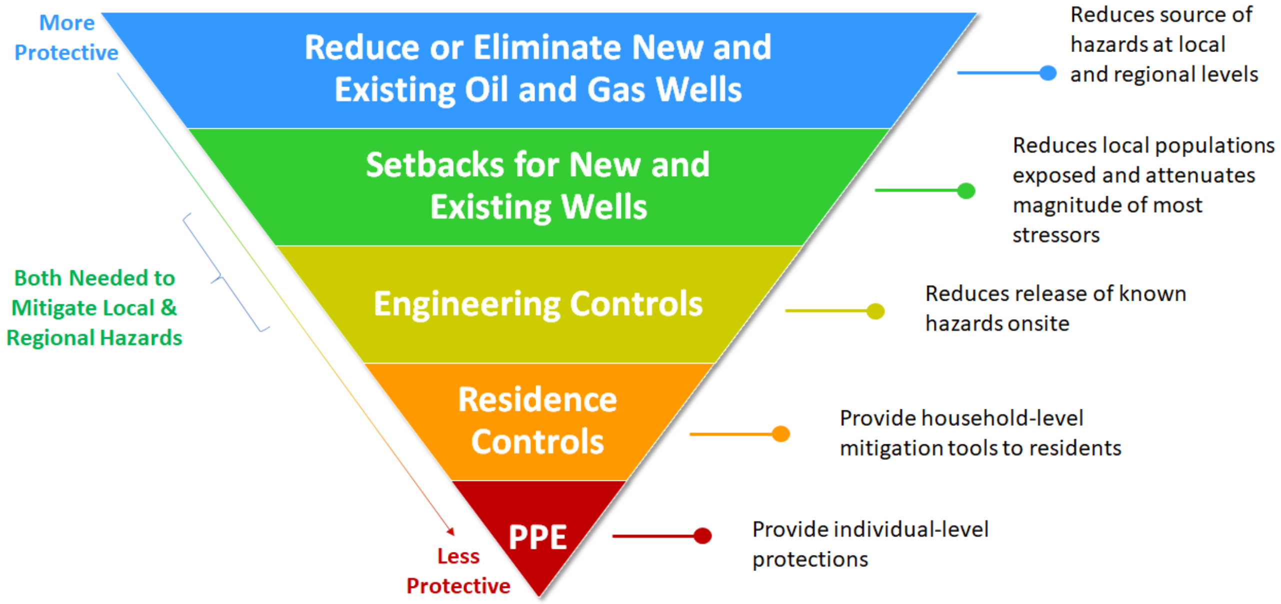

Figure 3. Hierarchy of strategies to reduce or eliminate public health harms for OGD activities. Note: the use of the term “wells” includes the ancillary infrastructure used to develop, gather and process oil and gas in the upstream oil and gas sector.

At the top of Figure 3 is the most health protective strategy: to stop drilling and developing new wells, phase out existing OGD activities and associated infrastructure, and properly plug remediate legacy wells and ancillary infrastructure.

If the development of oil and gas is to continue, the greatest health benefits would be gained from a strategy that includes the next two controls in the hierarchy depicted in Figure 3: the elimination of new and existing wells and ancillary infrastructure within scientifically informed setback distances and the deployment of engineering emission controls and associated monitoring approaches that lead to rapid leak detection and repair for new and existing wells and ancillary infrastructure. Because air pollutant concentrations and noise levels decrease with increasing distance from a source, adequate setbacks can reduce harm to local populations by reducing exposures to air pollutants and noise directly emitted from the OGD activities. However, setbacks do not reduce harms from OGD contributions to regional air pollutant levels, such as secondary particulate matter and ozone, or greenhouse gases, such as methane, which are nearly always co-mingled with health-damaging air pollutants (Michanowicz et al., *Forthcoming*). Engineering controls that reduce emissions at the well site are also necessary to reduce these harms.

Engineering controls include cradle-to-grave noise and air pollution emission mitigation controls on OGD infrastructure including new, modified and existing infrastructure, and proper abandonment of legacy infrastructure, prioritizing those nearest to residential sites and schools and those associated with the highest emissions, leaks and other environmental hazards.

However, engineering controls can fail and engineering solutions may not be available for or economically feasible to handle all of the complex stressors generated by OGD, including multiple sources and types of air pollution, noise pollution, light pollution, water pollution, and other stressors. <u>Therefore, neither setbacks or engineering controls alone are sufficient to reduce the health hazards and risks from OGD activities -- both approaches are needed in tandem</u>.

Finally, we note that while outside of CalGEM's jurisdiction, setbacks for new construction of housing or schools at a certain distance from existing or permitted OGD sites (commonly referred to as reverse setbacks), should be considered.

Table 3. Advantages and Disadvantages of Oil and Gas Development Control Strategies from an Environmental Public Health Perspective.

Control Strategy	Description	Advantage	Disadvantage
Elimination	Eliminate or reduce new and existing wells and ancillary infrastructure in combination with proper plugging and abandonment of wells and other legacy infrastructure.	Eliminates the source of nearly all environmental stressors (e.g., air and water pollutants, noise); protects local and regional populations	None.
Setbacks	Increase the distance between OGD hazards and sensitive receptors.	Reduces risk of exposures to populations living near OGD sites; environmental stressors are generally attenuated with increasing distance.	Setbacks alone without coupled engineered mitigation controls allow continued release of hazards and therefore does not adequately address air pollutant and greenhouse gas emissions from OGD and their impacts on regional air quality and the climate.
Engineering Controls	Reduces or eliminates release of specific hazards on site.	Reduces or eliminates certain hazards and therefore can have local and regional environmental public health benefits.	Tends to be disproportionately focused on air pollutant emissions. Often not feasible to apply engineering solutions to multiple, complex stressors each requiring different control technologies (e.g. noise, air and water impacts, social stressors) and lacks the important factor of safety provided by a setback when engineering controls fail.
Residence Controls	Provides households with devices to reduce hazard at the home (e.g., water filter, light-blocking shades, air filters).	Reduces intensity of certain hazards to nearby communities at the household level.	Places burden on individuals and households to use devices properly and to maintain and regularly replace controls to maximize effectiveness. Not feasible to apply devices to address numerous, complex stressors.
Personal Protective Equipment	Provide individuals with devices to reduce exposure (e.g., respiratory masks, ear plugs, eye masks).	Reduces intensity of exposure of certain hazards to nearby individuals.	Places burden on individuals to use PPE consistently and properly and is not feasible for the complex stressors.

Attributable Risk Calculations

One method to estimate health harms from OGD is to use the measures of association from the epidemiologic literature and population counts to calculate the excess number of specific health outcomes. This is what is known as an attributable risk method. We may be able to derive these estimates in the final report for birth outcomes using estimates of population counts for women of reproductive age in California living near OGD sites. We will also attempt to derive similar estimates for respiratory outcomes by using age appropriate population counts near OGD sites. This attributable risk method can allow us to estimate the number of adverse perinatal or respiratory cases that are attributable to OGD exposures and could be attenuated through the implementation of elimination or setback strategies.

c. Can the panel quantify or recommend a methodology CalGEM can use to quantify the health benefits associated with mitigation controls?

The Panel was not tasked to estimate health benefits of various setbacks and mitigation strategies, which pose significant methodological challenges and would require considerable time and effort. Among the challenges is the need to consider the benefits of reducing multiple stressors -- multiple air pollutants and other chemicals, noise, vibration, light, subsurface contamination, etc.

Known Health Benefits of Reducing Air and Noise Pollution

There is a significant body of literature and available tools that address the potential health benefits that can be achieved by reducing air and noise pollution exposures. The National Institute of Environmental Health Sciences has linked air pollution and specifically $PM_{2.5}$ to respiratory disease, cardiovascular disease, cancer, and reproduction harm and provides references supporting these links (NIEHS (National Institute of Environmental Health Sciences), 2021). Schraufnagel et al. (2019) examined in detail the health benefits of air pollution reductions in different geographic regions. Friedman et al. (2001) showed that improvements in air quality in preparation for the 1996 Atlanta Olympics resulted in significantly lower rates of childhood asthma events, including reduced emergency department visits and hospitalizations. Avol et al. (2001) demonstrated that children in southern California who moved to communities with higher air pollution levels had lower lung function growth rates than children who moved to areas with lower air pollution levels. Gauderman et al. (2015), examining the impact of reductions in $PM_{2.5}$ and nitrogen dioxide in the Los Angeles air basin, found that children who grew up after air quality improvements had less than ½ the chance of having clinically low lung function results. Ha et al. (2014) found $PM_{2.5}$ exposures in all trimesters to be significantly and positively associated with the risk of all adverse birth outcomes.

In an analysis of noise exposure reductions. Based on sound levels measured and/or modeled across the US together with an EPA exposure- response model for levels exceeding EPA standards, Swinburn et al. (2015) found that a 5-dB noise reduction scenario in communities with noise exceeding EPA standards would reduce the prevalence of hypertension by 1.4% and coronary heart disease by 1.8%. The types of health-benefit studies noted here provide a basis for conducting a health-benefits analysis using a tool such as US EPA's Environmental Benefits Mapping and Analysis Program—Community Edition (BenMAP-CE) (US EPA, 2021).

Possible Approaches to Quantify Health Benefits

CalGEM could obtain estimates of the health benefits achieved from different mitigation strategies individually or in combination with tools such as the Community Multiscale Air Quality Model (CMAQ) (Binkowski & Roselle, 2003) and/or other exposure assessment tools and link model output to EPA's BenMAP-CE (US EPA, 2021). However, these models and approaches are only focused on air quality and noise. It should also be noted that a significant drawback of using BenMAP-CE for this application is that it only considers impacts from criteria air pollutants and not from toxic air contaminants or other emerging air pollutants.

BenMAP-CE estimates the number and economic value of health impacts resulting from changes in air pollution concentrations. BenMAP-CE estimates benefits in terms of the reductions in the risk of premature death, heart attacks, and other adverse health effects. BenMAP-CE requires as input, pollutant concentrations at a scale that matches with population data. These concentrations can be obtained from a model such as CMAQ (Binkowski & Roselle, 2003) or from a monitoring network. BenMAP-CE takes the concentration fields for a base case and then for a pollution reduction (or increase) to assess health benefits (or detriments). BenMAP-CE then estimates changes in health endpoints, allowing the user to specify the concentration–response function and either use built-in population and baseline mortality rates or specify them as inputs.

It should be noted that in order to use a model such as BenMAP-CE to assess health benefits of setbacks and mitigation controls at well sites across California would involve a significant level of time and effort in data collection and model executions. In addition, these models are limited to characterizing the health benefits of criteria air pollutant reductions, but do not account for other OGD related exposures such as toxic air contaminants, other chemical exposures and exposures to other stressors through other environmental pathways (e.g., water and noise). Additionally, and importantly, the lack of spatially resolved emissions data from upstream OGD introduces challenges when assessing local- and sub-regional scaled health impacts that would be required for calculating benefits of specific policies such as setbacks and emission control. As such, attempts to quantify benefits using BenMAP-CE are likely to underestimate them.

4. ***CalGEM is aware of health risk assessments, health impact assessments, air exposure studies, and workforce safety studies that have been conducted but were not evaluated as part of your preliminary advice. How do these studies align with your causation determination, any recommended setback distance, and recommendations on health benefits quantification?***

The Panel determined early in its deliberations that it would limit the studies assessed in its report to those in the peer-reviewed scientific literature. This criterion ensures that studies have been evaluated by scientists who have not been involved with the study but have expertise in the relevant topic area and/or the methods used to carry out analyses, prior to publication. The peer-review process helps to ensure that high quality data and scientific interpretations are at the core of the science-policy decision-making process. Authors of peer reviewed studies are more likely to have been questioned about their methods, data interpretations, and conclusions, leading to greater confidence in the results.

In addition, the Panel was not tasked with assessing occupational studies. If CalGEM staff are aware of any peer-reviewed studies that were not included in our preliminary advice, we encourage them to send the Panel references so that we can evaluate them for inclusion in the final report. We intend to scan the literature again to assess whether relevant studies have been published since we completed the draft report. Should additional peer-reviewed studies be identified, the Panel will evaluate them to determine if they align with the scope of the report and should be added.

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Springtime for Home Rule over Oil and Gas

BY DANIEL E. KRAMER

This article discusses Colorado SB 19-181, which makes sweeping changes to the regulation of oil and gas extraction operations.

On April 3, 2019, the Colorado General Assembly passed SB 19-181, Protect Public Welfare Oil and Gas Operations (the Act), which makes sweeping revisions to several statutes governing oil and gas extraction operations. The Governor signed the bill into law on April 16, making the Act effective on that date. The changes encompass state agency rulemaking, the process for allowing oil and gas to be exploited without the consent of the mineral rights holder, financial guarantees to ensure the cleanup and reclamation of wells, and the essential mission of the Colorado Oil and Gas Conservation Commission (the Commission). But arguably the most pivotal change was the legislature's placement of the regulation of the surface impacts of oil and gas exploration firmly in the control of local communities, as coequals with the state.

This shift to local control abrogated the Colorado Supreme Court precedent that, in the event of a conflict between state and local laws on oil and gas, the state law prevails and the local law subsides.[1] Now, the state statute itself makes state laws the floor, not the ceiling, for local regulation. The General Assembly has effectively reinstituted a sort of legislative home rule over the subject, bucking the national trend of state legislatures favoring intrastate preemption on oil and gas regulation issues and reversing a decades-long process of eroding local control.

The Court's recent elaborations of Colorado intrastate preemption doctrine may well still hold for other matters,[2] but not for oil and gas.

SB 19-181: Changes in Local Control

In its 2016 decision overturning the City of Longmont's ban on hydraulic fracturing, the

Colorado Supreme Court set forth its test for whether a local oil and gas regulation would pass scrutiny under the existing statutory scheme. Boiled down, the question was whether the local law conflicted with the state law, which, in practical terms, meant whether the local law would materially impede the state's interest in oil and gas production.[3] The Court extended its previous tests to find preemption where it determined that the local restriction upset "exhaustive" and "pervasive" state regulations that implied a state interest in uniform regulation of the subject.[4]

Eliminating Preemption

By passing SB 19-181, the legislature has abrogated those holdings. The Act created new CRS § 34-60-131:

> **34-60-131. No land use preemption.** Local governments . . . have regulatory authority over oil and gas development, including as specified in section 34-60-105(1)(b). A local government's regulations may be more protective or stricter than state requirements.[5]

Now, the statute itself helps define what constitutes a conflict between the state act and local regulations. There is no question that local governments may properly regulate oil and gas. While local ordinances cannot reduce the minimum state standards for protecting health, safety, welfare, and the environment, they now can clearly regulate above and beyond state regulations. This is true regardless of those state regulations' complexity or thoroughness. The heightened local standards will be in harmony with the Act itself and cannot be considered to conflict with it.[6] As preemption is largely a matter of statutory interpretation[7]—putting the state and local laws side by side to determine whether they can coexist[8]—heightened local standards for oil and gas regulation will no longer be preempted by the state law.

Express Local Powers

The bill grants a long list of regulatory powers over oil and gas to local governments, some preexisting and some new:

I. Land use;
II. The location and siting of oil and gas facilities and oil and gas locations . . .;

III. Impacts to public facilities and services;
IV. Water quality and source, noise, vibration, odor, light, dust, air emissions and air quality, land disturbance, reclamation procedures, cultural resources, emergency preparedness and coordination with first responders, security, and traffic and transportation impacts;
V. Financial securities, indemnification, and insurance as appropriate to ensure compliance with the regulations of the local government; and
VI. All other nuisance-type effects of oil and gas development.[9]

Land use controls over oil and gas facilities are an example of a power that previously was within the authority of local government, so long as the controls did not conflict with state statute.[10] On the other hand, controls over local financial securities and noise, for example, had been held to be preempted.[11] Siting of facilities, meanwhile, had been a perennial source of contention without much guidance from the courts. And the phrase "nuisance-type effects" in subparagraph VI is potentially so broad that it is hard to say yet just how much it expands existing powers.[12]

In addition to these enumerated powers, the bill contains a catch-all provision: Local governments may also regulate to "protect and minimize adverse impacts to public health, safety, and welfare and the environment," although this can only be done "to the extent necessary and reasonable."[13]

In fact, both the catch-all minimization of adverse impacts and the list of enumerated powers are limited in two other ways: the statutory authorization extends only to the regulation of "surface impacts," rather than pure underground engineering, and the regulations may only be exercised "in a reasonable manner."[14]

Defining "Necessary" and "Reasonable"

The words "necessary" and "reasonable" are not defined and leave much to interpretation. While "necessary" applies only to the catch-all minimization of adverse impacts, the full list is subject to the "reasonable manner" limitation. Where the application of the statute to a particular local regulation may be ambiguous, the courts may consider the words of a Senate sponsor of the legislation before the final legislative vote on the bill:[15]

> [A] question has repeatedly come up about the, quote, "necessary and reasonable"

standard language that we added in the Senate. There have been several requests to further define it, but unfortunately that's proved to be difficult. I will say, though, that it's the sponsors' intent to have that phrase interpreted together, and in the context of, the bill as a whole, which is (1) a clear desire to prioritize health and safety when it comes to oil and gas operations, permitting, and supervision, without consideration of profitability from the state regulatory authority, the COGCC, and (2) an ability for local governments to do the same, and be more protective than the state if they choose. "Necessary and reasonable" is not intended to mean regulatory authorities can only make a land use decision or enact a regulation once all other options are exhausted. Instead, it is meant to be a guardrail against a regulatory or land use decision without reasonable justification. State and local governments should not be able to impose requirements, limitations, or decisions that defy explanation. However, they should be entitled to deference and allowed to use the precautionary principle to determine if a regulation or a land use decision is necessary and reasonable. Each locality's application of "necessary and reasonable" may be different depending on its circumstances, and should be examined on a case-by-case basis.[16]

How strict a local regulation can be while remaining "reasonable" will ultimately be decided by the courts. SB 19-181 did not finally settle the bounds of local authority, and litigation will continue to define the rules of engagement. But SB 19-181 dramatically changed the location of the battlefield, propelling local jurisdictions into a much stronger position. Rather than argue over whether it is interfering with the state's manner of regulation—which the state has the inherent advantage of *defining*—the local government now need only show that its method of regulation is reasonable.

Since local land use decisions already cannot be arbitrary and capricious,[17] "reasonable" may not prove to be a very high bar. A local government could demonstrate reasonableness through rough proportionality,[18] by more or less matching the strictness of the regulation to the severity of the oil and gas operation's potential surface impact. Reasonableness might also be demonstrated by the industry's ability to comply with similar regulations elsewhere, or the general application of similar regulations to other heavy industry. Conversely, unreasonableness probably could not be established based solely on the cost of a regulation to an operator, especially given the Act's removal of cost-effectiveness as a consideration elsewhere.[19]

> "SB 19-181 did not finally settle the bounds of local authority, and litigation will continue to define the rules of engagement. But SB 19-181 dramatically changed the location of the battlefield, propelling local jurisdictions into a much stronger position."

In addition to the courts, another new entity could also indirectly weigh in on the reasonableness of a local regulation. The Act creates a process for a local government or operator to request review of a local decision by a technical review board, with members appointed by the Commission director.[20] The board has authority to make a nonbinding report on the impacts of the decision to the recovery of the resource, whether the decision would require unavailable or impracticable technologies, and whether the operator is proposing to use best management practices.[21] While the local government can simply ignore an unfavorable report,[22] nothing in the Act would prevent a report from becoming evidence in a suit challenging the legality of the decision. However, because the reports will cover particular local decisions on particular applications, the reports would presumably receive judicial review only under CRCP 106(a)(4), which allows limited judicial review where a governmental body has exceeded its jurisdiction or abused its discretion.[23] The operator cannot force the technical review until after the decision is made, so the report would not likely be part of the administrative record, and thus not part of the judicial review.[24]

In sum, while courts will ultimately need to interpret "necessary" and "reasonable" on a case-by-case basis to define the outer boundaries of local power, SB 19-181 nevertheless firmly establishes local control, coequal with the state, over the surface impacts of oil and gas exploration. Local communities, through their elected representatives, will now be able to write wide-ranging and strict rules for using land within their jurisdictions, with much less risk of those rules being overturned.

Is There Authority for Local Bans?

This new local authority does not necessarily mean that local governments will now be able to entirely ban practices such as drilling or fracking. In advancing the bill in the Senate, one of its sponsors, the majority leader, cast doubt on whether the new local authority could extend to complete bans.[25]

However, the bill contains a potential sleeper provision. The preexisting law on minerals regulation, known colloquially as HB 1041 and officially as the Areas and Activities of State Interest Act (the AASIA), allowed local governments to regulate mineral resource areas, much as they can regulate water projects.[26] The key difference is that previously, local governments had to seek the Commission's approval to regulate mineral resources. The Act removes that prerequisite.[27] While the bill sections described above sketch the outer bounds of local land use authority, those sections do not seem to limit local government authority under the AASIA. The Act's amendments to the AASIA might even allow a local government to go so far as to prohibit oil and gas activity where it determines that "extraction and exploration would cause significant danger to public health and safety,"[28] the sponsor's words notwithstanding.

Local Enforcement and Implementation

Enforcement mechanisms for local regulations have also been strengthened. Before, local governments could require inspections of oil and gas facilities if the Commission was willing to execute an intergovernmental agreement to that effect.[29] And local governments could not charge fees or fines except in limited circumstances.[30] Now, local power to impose inspections, fees, and penalties has been liberalized and broadened, without much limitation.[31]

While the enactment and enforcement of local regulations will continue to generate headlines, for the most part the Act's effect will play out behind the scenes, in negotiations between local governments and operators over memoranda of understanding covering the specifics of each operator's activity within each jurisdiction. These negotiations take place against the backdrop of the community's regulations and the state of the law. Whereas the industry was once able to use preemption law as leverage to get the deal it wanted, now the lever has a different fulcrum. Negotiating positions, and ultimately the deals that result, will begin to change accordingly.

SB 19-181: Changes at the State Level

SB 19-181's broad changes to the Oil and Gas Conservation Act extend well beyond matters of local authority, making statewide changes by altering the Commission's fundamental purpose and composition.

The Commission's mission has changed from fostering the development of oil and gas to regulating it.[32] And where the Commission previously had only to *consider* concerns for health, safety, welfare, and the environment in making its decisions,[33] now its decisions must be "subject to the protection" of those concerns,[34] effectively making them criteria for approval of state permits and providing a new substantive means of challenging Commission decisions. The Commission is also explicitly authorized to make decisions that keep recoverable resources in the ground as necessary to protect health, safety, welfare, and the environment.[35]

The Commission will shrink from nine voting members to five by July 2020, including a decrease from three to one who must have substantial experience in the industry.[36] The Commission will also be "professionalized," meaning members will be paid as employees and barred from outside employment.[37]

Local prerogatives will factor into the Commission's own processes as well. To receive a state drilling permit, the operator must prove that the local jurisdiction has either approved of the siting of the facility, or does not regulate oil and gas siting at all.[38]

The Act directs the Commission to undertake a series of rulemakings, including to

- regulate oil and gas operations to protect and minimize adverse impacts to public health, safety, welfare, the environment, and wildlife;
- require operators to consider alternative locations in to-be-defined situations, to address the cumulative impacts of oil and gas development;
- conform its regulation of flowlines and shut-in wells to minimize safety and environmental risks;
- revamp financial assurances requirements and address the growing problem of orphan wells;
- revisit engineering requirements to ensure wellbore integrity; and
- introduce new professional certification requirements for the industry.[39]

In the interim, until the new rules specified in the first three bullet points are adopted, the Commission's director can delay approval of a

> "While the enactment and enforcement of local regulations will continue to generate headlines, for the most part the Act's effect will play out behind the scenes, in negotiations between local governments and operators over memoranda of understanding covering the specifics of each operator's activity within each jurisdiction."

drilling permit pursuant to "objective criteria," if the Commission needs to consult with the local government or to determine whether health, safety, welfare, and the environment will be protected.[40] The Air Quality Control Commission will also have to adopt new rules to minimize various emissions, require leak detection and regular inspections, and continuously monitor some facilities' emissions.[41]

The Act removes limits on state permit and filing fees[42] and replaces them with a requirement that fees be sufficient to cover costs.[43]

Other statewide changes include the parameters of forced pooling, which is the mechanism by which an operator can effectively obtain a lease, by operation of law, from a nonconsenting mineral interest owner. Previously, any operator could obtain such a statutory lease, but now operators will be subject to a threshold requirement that they already have rights in at least 45% of the interests to be pooled together for the purposes of production.[44] The royalty rate for statutory leases has also increased marginally, from 12.5% to either 13% or 16%, depending on the type of well.[45] As with a drilling permit, the Commission can no longer approve a forced pooling application until the operator proves that the local jurisdiction has either approved of the siting of the facility, or does not regulate oil and gas siting at all.[46]

Broader Implications for Home Rule and Local Control

While the changes embedded in SB 19-181 may seem important enough on their own, the evolution of home rule in Colorado puts their significance into high relief. Colorado voters passed the Home Rule Amendment to the Colorado Constitution in a pair of votes in 1902 and 1912,[47] part of a wave of similar Progressive-era reforms around the country. Support for the constitutional amendment was probably due to a confluence of factors, including the general distrust of corrupt state governments, especially "[o]nce state invasion of city authority became a common occurrence" in the late 19th century.[48] Also, philosophies of localism began to pervade the public consciousness, rooted in both the desire of smaller towns to be free of bigger-city influence and the urging of socially minded reformers for the freedom to enact progressive policies on a local level.[49] Noted attorneys and jurists began to extol the "absolute right" of local self-government as "part of the liberty of a community, an expression of community freedom, the heart of our political institutions."[50] But as many commentators have noted, in Colorado and elsewhere, home rule has failed to live up to its hype,[51] as courts have often constrained the ability of home rule cities and towns to experiment in areas where the state has also expressed an interest.

Doctrinally, this traces to the constitutional language that home rule authority extends only to "local and municipal matters."[52] Courts have been inconsistent on whether a matter must be "solely" or "purely" local in nature, or only "predominantly" so, for a home rule municipality to regulate an issue.[53] The problem of how to classify an issue as a "state issue" or a "local issue" was never clearly resolved,[54] and the problem became more complex in 1961 with the advent of a third category: issues of mixed state and local concern.[55] In this zone, when state and local laws conflict, the local laws give way.[56] Given the proliferation of both state and local laws since that development, it should not be surprising that court holdings that matters are of mixed concern, resulting in preemption, have been steadily on the rise.[57] At the same time, state legislatures across the country have increasingly taken the matter into their own hands, expressly preempting local authority on a wide variety of subjects.[58]

There is no doubt that SB 19-181 makes dramatic changes to oil and gas industry regulation on the local level in Colorado. But only time will tell whether SB 19-181 presages Colorado's rejection of the national trend, represents a subtler inflection point, or is a mere blip. It does not change the law of home rule or preemption for any other issue, and does not disturb home rule doctrine regarding oil and gas, which jurisprudence is rooted in the constitution, not statutes. And SB 19-181 is not limited to home rule cities and towns, but applies to counties and statutory municipalities as well.

Nevertheless, given the political dynamics surrounding the failure of home rule to justify local restrictions in the courts,[59] the issue elections over the past seven years,[60] and the candidate campaigns in the 2018 statewide elections,[61] SB 19-181 clearly represents the intent of the people to legislatively enact, for at least one issue,[62] a variant of home rule not based in the constitution. The result is a more muscular, albeit issue-specific, home rule power that echoes the voters' intentions behind the original constitutional enactments.

Conclusion

With the enactment of SB 19-181, members of local communities will be able, much more than before, to control their own destinies in the area of oil and gas regulation. For this issue, over the coming years, we may witness a rare thing: a home rule renaissance.

The views and opinions expressed in this article are those of the author and do not reflect the opinions of his employer or anyone else.

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NOTES

1. *City of Longmont v. Colo. Oil & Gas Ass'n*, 369 P.3d 573, 579 (Colo. 2016).
2. *See generally* Kramer, "Colorado Preemption Law: The Evolving Meaning of 'Conflict,'" 48 *Colo. Law.* 38 (Apr. 2019). The article went to print as the General Assembly deliberated on SB 19-181. With this Act now the centerpiece of oil and gas preemption law, readers might consider these April and July articles as before and after photos.
3. *City of Longmont*, 369 P.3d at 583. While this might sound like a factual inquiry, the Supreme Court recently held this to be a facial matter of "assess[ing] the interplay between the state and local regulatory schemes." *Id. See also Colo. Oil & Gas Conservation Comm'n v. Martinez*, 433 P.3d 22, 32 (Colo. 2019) (while environmental protection was part of the Commission's interest, it was not a "condition precedent" to oil and gas development; instead, the Commission's principal objective was to ensure production proceeded economically).
4. *City of Longmont*, 369 P.3d at 584–85.

5. SB 19-181, § 17. The caption refers to “land use” preemption, but the body of the section prevents preemption of all local regulations that are stricter or more protective than the state’s. *See* SB 19-181, § 4, amending CRS § 29-20-104(1)(h) (referenced by CRS § 34-60-105(1)(b) and containing the list of express local powers, of which land use is only the first. SB 19-181, § 11.). *See also People v. Rieger*, 436 P.3d 610, 613 (holding that the word “including” in a statute “denotes that the examples listed are not exhaustive or exclusive”).

6. *Colo. Min. Ass’n v. Bd. of Cty. Comm’rs of Summit Cty.*, 199 P.3d 718, 730 (Colo. 2009) (“[L]ocal land use regulations could be consistent with the Oil and Gas Conservation Act if the local and state regulations could be harmonized.”).

7. “Express and implied preemption are primarily matters of statutory interpretation.” *City of Longmont*, 369 P.3d at 582 (internal quotation marks omitted). Even the more context-dependent operational conflict species of preemption was sensitive to interpretation of the statute and administrative regulations. *See id.* at 584–85.

8. *Id.* at 583 (Analysis of whether a conflict exists “requires us to assess the interplay between the state and local regulatory schemes. In virtually all cases, this analysis will involve a facial evaluation of the respective statutory and regulatory schemes . . . .”); *id.* at 582 (local oil and gas ordinance can “coexist” with a state statute absent a conflict).

9. SB 19-181, § 4.

10. *City of Longmont*, 369 P.3d at 583–84.

11. *Bd. of Cty. Comm’rs of Gunnison Cty. v. BDS Int’l, LLC*, 159 P.3d 773, 779 (Colo.App. 2006) (financial requirements); *Town of Frederick v. N. Am. Res. Co.*, 60 P.3d 758, 765 (Colo.App. 2002) (noise). *See also* SB 19-181, § 5 (removing a prohibition on counties regulating oil and gas noise).

12. Even for the word “nuisance” itself, “[i]t is not practicable to give other than a general definition.” *Black’s Law Dictionary*, Nuisance (10th ed. Thomson Reuters 2014) (quoting Joyce and Joyce, *Treatise on the Law Governing Nuisances* 22 (Matthew Bender & Co. 1906)).

13. SB 19-181, § 4.

14. *Id.*

15. *Union Pac. R. Co. v. Martin*, 209 P.3d 185, 188 (Colo. 2009). *See People v. Zapotocky*, 869 P.2d 1234, 1238 (Colo. 1994) (using sponsor’s statements as an interpretive aide because, “if the intended scope of the statutory language is unclear, a court may apply other rules of statutory construction and look to pertinent legislative history”).

16. Statement of Sen. Foote at 1:13:08, http://coloradoga.granicus.com/MediaPlayer.php?view_id=42&clip_id=13895.

17. CRCP 106(a)(4); *Ross v. Fire and Police Pension Ass’n*, 713 P.2d 1304, 1309 (Colo. 1986) (“‘No competent evidence’ [under CRCP 106(a)(4)] means that the ultimate decision of the administrative body is so devoid of evidentiary support that it can only be explained as an arbitrary and capricious exercise of authority.”).

18. *Cf. Krupp v. Breckenridge Sanitation Dist.*, 19 P.3d 687, 693–94 (Colo. 2001) (“Because a service fee is designed to defray the cost of a particular governmental service, the amount of the fee must be reasonably related to the overall cost of the service. Mathematical exactitude is not required, however, and the particular mode adopted by the governmental entity in assessing the fee is generally a matter of legislative discretion.” (emphasis added) (citation omitted)); *id.* at 695 (“No precise mathematical calculation is required for the rough proportionality test, but the governmental entity must make some sort of individualized determination that the required dedication is related both in nature and extent to the impact of the proposed development.” (internal quotation marks omitted)).

19. SB 19-181, § 12, CRS § 34-60-106(2)(d); § 10, CRS § 34-60-104.5(3)(b)(II).

20. SB 19-181, § 4, CRS § 29-2-104(1)(i); § 10, CRS § 34-60-104.5(3).

21. SB 19-181 § 10, CRS § 34-60-104.5(3)(b).

22. SB 19-181, § 4, CRS § 29-20-104(3)(b).

23. “C.R.C.P. 106(a)(4) is the exclusive remedy for reviewing quasi-judicial decisions.” *JJR 1, LLC v. Mt. Crested Butte*, 160 P.3d 365, 369 (Colo.App. 2007).

24. CRCP 106(a)(4)(I) (“Review shall be limited to a determination of whether the body or officer has exceeded its jurisdiction or abused its discretion, based on the evidence in the record before the defendant body or officer.”). While the period to seek judicial review under Rule 106(a)(4) is tolled until the technical report comes out, the local government would have already made its decision based on the record in front of it at the time. *See* SB 19-181, § 4, CRS § 29-20-104(3)(c).

25. *See, e.g.*, statement of Sen. Fenberg at 1:10:19, http://coloradoga.granicus.com/MediaPlayer.php?view_id=42&clip_id=13895.

26. CRS § 24-65.1-201(1)(a).

27. SB 19-181, §§ 1 to 2.

28. CRS § 24 65.1-202(1)(a). Weld County has also expressed interest in using AASIA powers, apparently in an attempt to preempt the updated state laws. Weld County News Release, “Process begins to officially designate unincorporated Weld County as an oil and gas local-control county” (May 1, 2019). As one county commissioner put it, “We believe that 181 gives us the power of pre-emption over the state on land-use powers. If it pre-empts the state one way, it pre-empts the state the other way.” “In ‘new era’ of oil and gas regulation, Colorado communities waste no time writing own rules,” *Denv. Post* (May 6, 2019), www.denverpost.com/2019/05/06/colorado-oil-and-gas-local-regulations-181. It is unclear what authority, in either SB 19-181 or the AASIA, could allow a local government to supplant a more protective state standard. *See* SB 19-181, § 17, CRS § 34-60-131 (allowing local regulations to be more protective or stricter than the state’s).

29. CRS § 34-60-106(15).

30. *Id.*; *Town of Frederick v. N. Am. Res. Co.*, 60 P.3d 758, 765–66 (Colo.App. 2002).

31. SB 19-181 § 4, CRS § 29-20-104(2).

32. SB 19-181, § 6, CRS § 34-60-102(1)(a)(I).

33. *See Martinez*, 433 P.3d at 32.

34. SB 19-181, § 6, CRS § 34-60-102(1)(b).

35. SB 19-181, § 7, CRS § 34-60-103(11)(b), (12)(b), (13)(b); § 12, CRS § 34-60-106(2.5)(b).

36. SB 19-181, § 9, CRS § 34-60-104.3(2)(a). The makeup of the Commission will also change in the interim, with the replacement of two slots reserved for industry members with technical experts. SB 19-181, § 8, CRS § 34-60-104(2)(a)(I).

37. SB 19-181, § 9, CRS § 34-60-104.3(2)(b).

38. SB 19-181, § 12, CRS § 34-60-106(1)(f)(I)(A). *See also* COGCC Operator Guidance, SB 19-181: Hearings and Permitting Groups at 3 (Apr. 19, 2019). However, the COGCC director indicated at a public meeting on May 15, 2019 that he may revisit whether a final determination by the local government will be necessary in circumstances where the local government requests concurrent state and local review.

39. SB 19-181, § 12, CRS § 34-60-106(11)(c), (13), (18)–(20).

40. SB 19-181, § 12, CRS § 34-60-106(1)(f)(III). During the debate on the bill, this provision was characterized by some as a moratorium.

41. SB 19-181, § 3.

42. SB 19-181, § 12, CRS § 34-60-106(7)(a).

43. SB 19-181, § 12, CRS § 34-60-106(7)(b).

44. SB 19-181, § 14, CRS § 34-60-116(3)(b)(I).

45. SB 19-181, § 14, CRS § 34-60-116(7)(c).

46. SB 19-181, § 14, CRS § 34-60-116(1)(b). *See also supra* note 38.

47. Hayes and Hartl, “Home Rule in Colorado: Evolution or Devolution,” 33 *Colo. Law.* 61 (Jan. 2004). For more background on the home rule amendment, *see* Broadwell, “Municipal Home Rule in the 1990s,” 28 *Colo. Law.* 95 (Sept. 1999); McCullough, “A Primer on Municipal Home Rule in Colorado,” 18 *Colo. Law.* 443 (Mar. 1989); Bueche, A History of Home Rule (Colo. Municipal League Nov. 2009); Colo. Municipal League, Home Rule Handbook (2017).

48. Frug, “The City as a Legal Concept,” 93 *Harv. L. Rev.* 1059, 1115–16 (1980); Barron, “Reclaiming Home Rule,” 116 *Harv. L. Rev.* 2255, 2293 (2003). *See also* Fox, “Home Rule in an Era of Local Environmental Innovation,” 44 *Ecology L.Q.* 575, 588–89 (2017) (“Home rule was also designed to combat the dangers of state control that had been evidenced in targeted special legislation, which interfered with appropriate city governance.”) (citing Frug and Barron, *City Bound: How States Stifle Urban Innovation* 37 (Cornell Univ. Press 2008)).

49. Barron, *supra* note 48 at 2292–320.

50. Frug, *supra* note 48 at 1113–14 (quoting *People ex rel. Le Roy v. Hurlbut*, 24 *Mich.* 44, 93 (1871); Eaton, “The Right to Local Self-Government” (pts. 1–3), 13 *Harv. L. Rev.* 441, 570, 638 (1900), (pts. 4–5), 14 *Harv. L. Rev.* 20, 116 (1900); McQuillin, *The Law of Municipal Corporations*, vol. 1, § 268 Rise and Progress of Municipal Institutions at 679 (2d ed. Callaghan

and Company 1928)).

51. *See, e.g.*, Frug, *supra* note 48 at 1117 (Home rule "has not successfully created an area of local autonomy protected from state control."); Baker and Rodriguez, "Constitutional Home Rule and Judicial Scrutiny," 86 *Denv. U. L. Rev.* 1337, 1342 (2009) ("While constitutional home rule on paper points to a delineated realm of local sovereignty, the record of home rule in the state courts in this regard is more mixed.").

52. Colo. Const. art. XX, § 6.

53. *Compare, e.g.*, *Webb v. City of Black Hawk*, 295 P.3d 480, 486 (Colo. 2013) ("solely" and "purely") *with City and Cty. of Denver v. State*, 788 P.2d 764, 767 (Colo. 1990) ("In fact, there may exist a relatively minor state interest in the matter at issue but we characterize the matter as local to express our conclusion that, in the context of our constitutional scheme, the local regulation must prevail. Thus, even though the state may be able to suggest a plausible interest in regulating a matter to the exclusion of a home rule municipality, such an interest may be insufficient to characterize the matter as being even of 'mixed' state and local concern.").

54. Frug, *supra* note 48 at 1117 ("[T]he courts have grappled with determining what matters are of 'state concern' and what matters are 'purely local' in nature."). *See also City and Cty. of Denver*, 788 P.2d at 767–68 ("Those affairs which are municipal, mixed or of statewide concern often imperceptibly merge. . . . We have not developed a particular test which could resolve in every case the issue of whether a particular matter is 'local,' 'state,' or 'mixed.' Instead, we have made these determinations on an ad hoc basis, taking into consideration the facts of each case.").

55. *Woolverton v. City and Cty. of Denver*, 361 P.2d 982, 985–90 (Colo. 1961), *overruled*, 484 P.2d 1204.

56. *City of Aurora v. Martin*, 507 P.2d 868, 869–70 (Colo. 1973).

57. *See, e.g.*, *City of Longmont*, 369 P.3d at 581; *City of Fort Collins v. Colo. Oil & Gas Ass'n*, 369 P.3d 586, 591 (Colo. 2016); *Ryals v. City of Englewood*, 364 P.3d 900, 908–09 (Colo. 2016); *Webb*, 295 P.3d at 492; *MDC Holdings, Inc. v. Town of Parker*, 223 P.3d 710, 720 (Colo. 2010); *City of Commerce City v. State*, 40 P.3d 1273 (Colo. 2002); *City and Cty. of Denver v. Qwest Corp.*, 18 P.3d 748, 751 (Colo. 2001); *Town of Telluride v. Lot Thirty-Four Venture, L.L.C.*, 3 P.3d 30, 39 (Colo. 2000).

58. *See generally* Briffault, "The Challenge of the New Preemption," 70 *Stan. L. Rev.* 1995, 1997 (June 2018) ("This decade has witnessed the emergence and rapid spread of a new and aggressive form of state preemption of local government action. . . . [T]he real action today is the *new preemption*: sweeping state laws that clearly, intentionally, extensively, and at times punitively bar local efforts to address a host of local problems.") (emphasis in original); Scharff, "Hyper Preemption: A Reordering of the State–Local Relationship?" 106 *Georgetown L.J.* 1469, 1471, 1473 (2018) ("In recent years, state legislators have sought to limit local policymaking by passing increasingly broad state preemption statutes. . . . This new brand of preemption statutes, which I call 'hyper preemption,' seeks not just to curtail local government policy authority over a specific subject, but to broadly discourage local governments from exercising policy authority in the first place."); Schragger, "The Attack on American Cities," 96 *Tex. L. Rev.* 1163, 1164 (May 2018) ("American cities are under attack. The last few years have witnessed an explosion of preemptive state legislation challenging and overriding municipal ordinances across a wide range of policy areas."). These scholars have emphasized the apparent "partnership between the private interests that seek to avoid local regulation and legislators at the state level, exemplified by organizations such as the American Legislative Exchange Council (ALEC)." *Id.* at 1170. *See also* Briffault at 1997; Scharff at 1484 ("[M]any of these preemption ordinances are drafted by the American Legislative Exchange Council (ALEC), a business- backed think tank for conservative lawmakers that provides model legislation.").

59. *See, e.g.*, *City of Longmont*, 369 P.3d at 581; *City of Fort Collins*, 369 P.3d at 591; *Colo. Oil & Gas Ass'n v. City of Thornton*, Case No. 2017CV31640 (Adams Cty. Dist. Ct. Apr. 24, 2018); *Colo. Oil & Gas Ass'n v. City and Cty. of Broomfield*, Case No. 2014CV30232 (Broomfield Cnty. Dist. Ct. June 3, 2016); *Colo. Oil & Gas Ass'n v. City of Lafayette*, Case No. 13CV31746 (Boulder Cty. Dist. Ct. Aug. 27, 2014).

60. "All four Colorado oil, gas ballot measures withdrawn as promised," *Denv. Post* (Aug. 5, 2014), www.denverpost.com/2014/08/05/all-four-colorado-oil-gas-ballot-measures-withdrawn-as-promised; Aguilar, "Prop 112 fails as voters say no to larger setbacks for oil and gas," *Denv. Post* (Nov. 6, 2018), www.denverpost.com/2018/11/06/colorado-proposition-112-results.

61. Aguilar, "'Let's get real, guys': Oil and gas rules front and center for Colorado lawmakers following Prop 112's defeat," *Denv. Post* (Nov. 12, 2018), www.denverpost.com/2018/11/12/oil-gas-setback-legislature-regulation-prop-112.

62. This approach has already begun to spread to other spheres of regulation. The General Assembly followed up with an act allowing local governments to establish a local minimum wage, HB 19-1210. It also considered, but did not adopt, a bill allowing local governments to control residential rents, SB 19-225. The Colorado Supreme Court had previously held rent control to be a matter of mixed state and local concern. *Town of Telluride*, 3 P.3d at 39. And while there was no case on point, a local minimum wage previously "probably would not be viable" based on home rule, given the prior express preemption in state statute. Dalmat, "Bringing Economic Justice Closer to Home: The Legal Viability of Local Minimum Wage Laws under Home Rule," 39 *Colum. J.L. & Soc. Probs.* 93, 113 (2005).