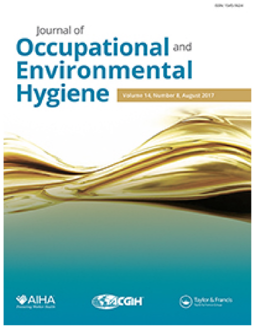

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Noise characterization of oil and gas operations

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ABSTRACT
In cooperation with The Colorado Oil and Gas Conservation Commission, researchers at Colorado State University performed area noise monitoring at 23 oil and gas sites throughout Northern Colorado. The goals of this study were to: (1) measure and compare the noise levels for the different phases of oil and gas development sites; (2) evaluate the effectiveness of noise barriers; and (3) determine if noise levels exceeded the Colorado Oil and Gas Conservation Commission noise limits. The four phases of oil and gas development include drilling, hydraulic fracturing, completion and production. Noise measurements were collected using the A- and C-weighted sound scales. Octave band analysis was also performed to characterize the frequency spectra of the noise measurements.

Noise measurements were collected using noise dosimeters and a hand-held sound-level meter at specified distances from the development sites in each cardinal direction. At 350 ft (107 m), drilling, hydraulic fracturing, and completion sites without noise barriers exceeded the maximum permissible noise levels for residential and commercial zones (55 dBA and 60 dBA, respectively). In addition, drilling and hydraulic fracturing sites with noise barriers exceeded the maximum permissible noise level for residential zones (55 dBA). However, during drilling, hydraulic fracturing, and completion operations, oil producers are allowed an exception to the noise permissible limits in that they only must comply with the industrial noise limit (80 dBA). It is stated in Rule 604.c.(2)A. that: "Operations involving pipeline or gas facility installation or maintenance, the use of a drilling rig, completion rig, workover rig, or stimulation is subject to the maximum permissible noise levels for industrial zones (80dBA)."[8] Production sites were within the Colorado Oil and Gas Conservation Commission permissible noise level criteria for all zones. At 350 ft (107 m) from the noise source, all drilling, hydraulic fracturing, and completion sites exceeded 65 dBC.

Current noise wall mitigation strategies reduced noise levels in both the A- and C-weighted scale measurements. However, this reduction in noise was not sufficient to reduce the noise below the residential permissible noise level (55 dBA).

KEYWORDS
Drilling; fracturing; gas; hydraulic; noise; oil; well site completion

Introduction

One emerging environmental noise concern is noise related to oil and gas operations. The oil and gas industry is rapidly expanding across the U.S. As a result of this advancement, oil and gas operation sites are being developed near communities and within city boundaries. Among other potential environmental concerns such as air and water quality, noise attributed to oil and gas operations is a significant and persistent concern that has proved to be difficult to manage. The state of Colorado established the Colorado Oil and Gas Conservation Commission (COGCC) in 1951 to protect mineral rights owners and to prevent the waste of oil and gas resources.[1] The COGCC promotes the responsible development of oil and gas natural resources in Colorado. The Commission also ensures that oil and gas exploration and production is performed in a manner that protects the health, welfare, and safety of the public and the environment. Each year, the COGCC responds to numerous complaints related to oil and gas activities. From 2008–2012, the COGCC received 1,175 complaints from Colorado residents. The most common complaint was about groundwater (439 complaints) and the second most common involved noise (119 complaints; 10% of all

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complaints).[2] Possible sources of noise attributed to oil and gas development include truck traffic, drilling, hydraulic fracturing, completion activities, production well pumps, and air compressors. These noise sources exhibit different frequencies, durations, and overall sound pressure levels that make it difficult to control all of the noise emitted at one site.[3] The focus of this study was threefold: (1) to characterize and compare the noise levels produced by the different phases of oil and gas development; (2) to evaluate the effectiveness of noise barriers; and (3) to determine if noise levels exceeded the current COGCC noise limits.

Process description and background

Each phase of oil and gas development has different contributing noise sources. Drilling and hydraulic fracturing operations have large air compressors, generators, and engines that power the drilling rig and hydraulic fracturing equipment. These compressors, generators, and engines contribute the most noise to drilling and hydraulic fracturing sites. Drilling operations also have mud pumps on site that are used to circulate drilling fluid. Mud pumps on drilling sites can be a substantial noise source. Truck traffic may contribute a significant amount of noise in every phase of oil and gas production.[4]

In an attempt to mitigate noise produced by drilling and fracturing operations, oil and gas operators commonly install noise barriers or noise walls to control the noise. These barriers range from 16–32 ft (4.9–9.8 m) in height. The barriers are commonly constructed from 8-ft high by 20-ft long (2.4 by 6.1 m) acoustic blankets that are mounted on steel frames but some operators choose to use hay bales. The acoustic blankets are rated at a sound transmission class (STC) of 25 and are designed to reduce equipment noise levels by 15 to 22 dBA.[5] While collecting noise measurements, it is important to consider the "sound shadow" that is produced by the installation of these noise walls. The noise or acoustic shadow is an area where acoustic waves do not propagate due to an obstruction such as a noise wall. The acoustic shadow results in decreased sound pressure levels within the shadow.[6] In the scenario involving noise walls, the sound waves can be absorbed by the barrier, reflected back toward the noise source, passed through the barrier, or be diffracted around the barrier.

Those sound waves that are transmitted through the noise wall barrier are frequency dependent. While collecting measurements outside of the perimeter of a noise wall, it is important to take measurements outside of the acoustic shadow to ensure accuracy. The size of the acoustic shadow can vary depending on the frequency of the noise source. Typically, lower frequency noises are not diffracted as sharply at an angle toward the ground as higher frequency noise, resulting in a larger shadow.[7] In order to be effective, the noise wall must be significantly larger compared to the wavelength of the noise. If the noise wall is too short, diffraction of the noise will occur ultimately limiting the effectiveness of the wall.[7]

Table 1. COGCC noise zone regulations.

Zone	7:00 am to next 7:00 pm	7:00 pm to next 7:00 am
Residential/ Agricultural/Rural	55 dBA	50 dBA
Commercial	60 dBA	55 dBA
Light Industrial	70 dBA	65 dBA
Industrial	80 dBA	75 dBA

Oil and gas well sites and production facilities can be located in several zoning areas. The zoning areas include residential/agricultural/rural, commercial, light industrial or industrial. In Colorado, each zoning area has an associated maximum permissible noise level at a distance of 350 ft (107 m) from the noise source. These limits are set forth by the current COGCC aesthetic and noise control regulations. The current maximum permissible noise levels for each zone are listed in Table 1.[8]

Oil and gas operations must comply with the maximum permissible noise levels mandated for the specific zone. However, during drilling, hydraulic fracturing, and completion operations, the oil producers are provided an exception to the permissible noise levels in that they must only comply with the industrial noise limit of 80 dBA. In response to a noise complaint, COGCC regulations require that the noise level be measured at a distance of 350 ft (107 m) from the noise source. If the oil and gas site is located closer than 350 ft (107 m) from an existing occupied structure, noise levels shall be measured 25 ft (7.6 m) from the structure toward the noise source.[8] If noise level measurements at 350 ft (107 m) are impractical due to topography, measurements can be taken at a lesser distance and can be extrapolated to a 350-ft (107 m) equivalent using the inverse square law for noise. The COGCC noise control regulations also briefly address C-weighted sound pressure levels. According to the COGCC noise standard, if a measurement collected 25 ft (7.6 m) from a residence exceeds 65 dBC, further action must be taken to reduce low frequency noise. It has been suggested that below 65 dBC, vibrational issues are minimized and the majority of people do not experience an annoyance or unwanted disturbances from low frequency noise.[9]

Methods and materials

Area noise sampling was performed at 23 oil and gas sites between November 2014 and March 2015 in Northern Colorado. Only sites with perceived low ambient background noise were selected. That is, the sites were located away from major roadways or potentially noisy industrial areas. The aim for this research was to accurately analyze the noise produced by specific oil and gas operations. Therefore, it was important to limit the effect of ambient noise as much as possible. The most common ambient noise sources included busy highways and industrial facilities. The researchers actively selected oil and gas sites located away from these potentially confounding noise sources to ensure measured noise levels could be attributed to oil and gas operations. As a result of the site selection methodology, the number of acceptable sites was limited. Sampling locations included sites owned by various operators, and the researchers did not target sites owned by any specific operator.

Before collecting noise measurements, the researchers met with oil and gas personnel at each site to ensure that the site was operating at maximum capacity to obtain the "worst-case" noise level measurements (i.e., operations were running at 100%). The researchers used model 706RC Larson Davis noise dosimeters (Provo, Utah) and a Larson Davis sound-level meter/octave-band analyzer (SLM/OBA) model 824 (Provo, Utah) to collect the noise measurements at each oil and gas site. The noise monitoring instruments were pre- and post-calibrated at 94 dB and 114 dB to maintain data quality and assure accuracy. In addition, the following environmental conditions were measured: ambient temperature, humidity, and wind speed. Noise data were not collected when temperatures were below 20°F or when the wind speed exceeded 10 miles per hour (mph). Also, measurements were not collected when there was snow on the ground due to mitigating effects. Global positioning system (GPS) coordinates were recorded for each noise measurement to identify measurement locations. All data were downloaded and analyzed using Larson Davis Blaze Software (Provo, Utah) and Noise at Work Software (Den Haag, Netherlands). GPS coordinates and the Noise at Work software were also used to develop noise contour maps when feasible. Noise contours of potential zones of noncompliance were identified on the maps and can be used to identify areas where a residence or business may be at risk for excessive noise. The noise data were compared to the maximum permissible noise levels for each land-use zone as stated in the COGCC Aesthetic and Noise Control Regulations.[8] The average noise dosimeter and SLM/OBA equivalent sound pressure levels (L_{eq}) for each oil and gas site type were calculated and compared to COGCC regulations.

Noise dosimeter measurements at unmitigated sites

Four noise dosimeters were used at each site to collect a minimum L_{eq} of 15-min located 350 ft (107 m) from the most significant noise source at each site in each cardinal direction (i.e., north, south, east, west). The distance of 350 ft (107 m) was used based on the current COGCC Aesthetic and Noise Control Regulations.[8] The most significant noise source was centrally located at each oil and gas site and included the machine or group of machines that contributed the greatest amount of noise originating from the site. The noise dosimeters met the American National Standards Institute Standard ANSI S1.4, 1983[10] specifications for use as sound-level meters. Noise measurements were collected using the A- and C-weighting scales, slow response, and a three-decibel exchange rate. The dosimeters were attached to tripods at a height of 5 ft (1.5 m) per the methods outlined in the Noise Manual.[6] The sampling times ranged from 20–45 minutes. Larson Davis Blaze Software (Provo, Utah) was used to obtain the 15-min L_{eq} that represented the highest L_{eq} for the sampling period.

Sound level meter measurements at unmitigated sites

The SLM/OBA was used to collect 5-sec L_{eqs} at specified distances from the noise source in each cardinal direction during the site maximum operating capacity. Octave band measurements were taken to identify the major frequency noise levels at each site. The researchers attempted to collect SLM/OBA measurements at 117 yd (107 m), 58.5 yd (53.5 m), 29 yd (26.5 m), 14 yd (12.8 m), and as close as possible from the most significant noise source (in each cardinal direction) to develop a noise map for each site. A Nikon 550 Rangefinder (Tokyo, Japan) was used to precisely record the distances of measurement points.

Noise measurements at mitigated sites

Noise measurements were collected at three drilling sites and one hydraulic fracturing site with noise wall mitigation in place using the noise dosimeters and SLM/OBA time of collection and distances as described above. All four sites had the same noise wall mitigation that included noise blankets mounted on a steel frame. Noise measurements were collected inside and outside of the noise walls. 5-sec L_{eq} measurements were collected with the SLM/OBA starting at 10 ft (3 m) from the inside of the wall and then halving the distance until the researchers could collect measurements as close as possible to the noise source. 15-min L_{eq} measurements were also collected 10 ft (3 m) from the inside of the wall in each cardinal direction using the noise dosimeters. At a distance of 350 ft (107 m) in each cardinal direction outside of the noise walls, researchers collected 15-min L_{eq} measurements using the noise dosimeters. To avoid the acoustic

Table 2. Noise levels at drilling sites 350 ft (107 m) from source.

Site Number	5-sec Leq (dBA)	5-sec Leq (dBC)	15-min Leq (dBA)	15-min Leq (dBC)
		Drilling Sites without Walls		
1	64	78	64	79
2	64	80	63	79
3	66	80	65	80
4	64	77	65	No Data
Mean (SD)	65 (1.0)	79 (1.4)	65 (1.0)	79 (0.6)
		Drilling Sites with Walls		
5	58	75	60	76
6	58	73	56	70
7	52	67	59	69
Mean (SD)	57 (3.5)	73 (4.2)	59 (2.1)	73 (3.8)

Table 3. Noise levels at hydraulic fracturing sites 350 ft (107 meters) from source.

Site Number	5-sec L_{eq} (dBA)	5-sec L_{eq} (dBC)	15-min L_{eq} (dBA)	15-min L_{eq} (dBC)
		Hydraulic Fracturing Sites without Walls		
8	65	79	66	79
9	69	80	72	82
10	66	77	66	77
11	72	82	70	81
Mean (SD)	69 (3.2)	80 (2.1)	70 (3.0)	80 (2.2)
		Hydraulic Fracturing Sites with Walls		
12	59	73	59	74

shadow created by the 32 ft (9.8 m) tall noise walls, a distance of 350 ft (107 m) from the walls was chosen.

It was observed that noise measurements collected within 100 yards (91.4 m) outside of the noise wall had the potential to be skewed due the acoustic shadow. At several sites, the site orientation and operating equipment were located in such a way that the exact distances described above could not be achieved. For example, on some sites the researchers were limited on how close they could get to the noise source due to safety factors. Measurements were collected using the same protocol for mitigated sites as unmitigated sites to allow for data comparison between the two types of sites.

Results

The results of the 5-sec and 15-min L_{eqs} for each oil and gas site type are presented in Tables 2–5. On average at a

Table 4. Noise levels at completions sites without walls at 44–77 and 117 yd (107 m) from source.

Site Number	5 Second L_{eq} (No. of measurements)	5 Second L_{eq} (No. of measurements)	15 Minute L_{eq} (No. of measurements)	15 Minute L_{eq} (No. of measurements)
13	73 dBA (4)	82 dBC (4)	73 dBA (3)	82 dBC (3)
14	65 dBA (1)	76 dBC (1)	62 dBC (1)	77 dBC (1)

Table 5. Noise levels at production sites without walls 350 ft (107 m) from source.

Site Number	5-sec L_{eq} (dBA)	5-sec L_{eq} (dBC)
15	59	74
16	51	69
17	41	58
18	42	61
19	41	58
20	46	63
21	55	65
22	44	64
23	41	62
Mean (SD)	47 (6.8)	64 (5.1)

distance of 350 ft from the noise source, including all four of the following cardinal directions.

- The A-weighted 15-min L_{eqs} for drilling sites without walls were 5 dBA lower than hydraulic fracturing sites without walls.
- The C-weighted 15-min L_{eqs} for drilling sites without walls were 1 dBC lower than hydraulic fracturing sites without walls.
- The A-weighted 15-min L_{eqs} for drilling sites with walls were the same as the hydraulic fracturing site with walls.
- The C-weighted 15-min L_{eqs} for drilling sites with walls were 1 dBC lower than the hydraulic fracturing site with walls.
- The average A-weighted L_{eq} measurements collected at production sites were at least 15 dBA lower than the A-weighted 15-min L_{eq} measurements collected at drilling, hydraulic fracturing, and completion sites.

The differences in A- and C-weighted noise measurements between drilling and hydraulic fracturing sites are depicted in Figure 1. The current COGCC permissible noise limit of 65 dBC is indicated by the solid horizontal line. The current COGCC permissible noise limit of 55 dBA for residential zones during the daytime is indicated by the dotted horizontal line. It is clear that the

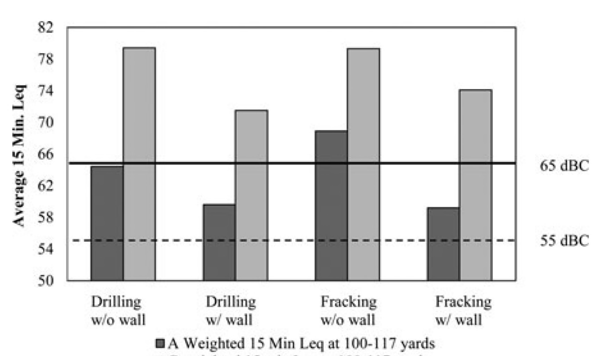

Figure 1. Measured sound levels at drilling and hydraulic fracturing sites with and without sound walls.

A- and C-weighted noise levels were reduced when noise walls were installed at drilling and fracturing sites. With the installation of noise walls, noise levels at drilling sites were reduced from 65 dBA to 59 dBA and 79 dBC to 73 dBC at 350 ft from the noise source (see Table 2). Noise levels at fracturing sites were reduced from 70 dBA to 59 dBA and 80 dBC to 74 dBC at 350 ft from the noise source (see Table 3). With the noise walls in place, the average C-weighted noise levels were measured at 74 dBC for fracturing sites and 73 dBC for drilling sites at 350 ft from the noise source (see Tables 5 and 3). These C-weighted noise levels still exceeded the maximum permissible noise level of 65 dBC per COGCC Aesthetic and Noise Control Regulations.[8]

It is important to note that Site 13 was configured in such a way that noise measurements could not be collected at 350 ft (107 m) from the most significant noise source. Due to the site configuration, noise measurements were collected between 44 and 77 yards (40–70 m) from the most significant noise source in each cardinal direction. As a result, the average noise measurements between the two completion sites could not be compared to one another. Additionally, only 5-sec L_{eq} measurements from the SLM were obtained from production sites. The noise levels at production sites were below the gain detection settings for the noise dosimeters that were used to collect 15-min L_{eq} measurements. The gain was adjusted to 20 dB which limited the instruments' measurement range from 53–123 dB. Noise levels lower than 53 dB were not collected by noise dosimeters.

Octave band analysis

One-third octave band noise data were collected at each site using the SLM/OBA (see Table 6). The dominant sound frequencies at each oil and gas site were at or below 125 Hz. This is at the low end of the frequency spectrum, indicating that the noise sources emitted predominantly lower noise frequencies.

Noise contour maps

Noise contour maps were developed using the Noise at Work Software to create a visual representation of noise contours at drilling and fracturing sites. Individual average noise level measurements collected using the SLM at various distances in each cardinal direction were used to create the maps illustrating the average overall noise levels at a typical oil and gas site in each phase. GPS coordinates were used in conjunction with Google Earth® and the Noise at Work Software to create detailed noise maps overlapping with individual sites. This technique allowed the researchers to provide the COGCC and operators a way of visualizing the noise contours at specific sites. This information can be used to identify areas of concern regarding noise at different types of oil and gas sites and it can be used to determine how the noise travels beyond the confines of the site. An example of a noise contour map created using Noise at Work Software with Google Earth® is provided in Figure 2. Using noise contour maps, the propagation of sound can be easily visualized.

Table 6. Dominant octave center band frequencies during each phase of operation.

Operation Phase	Dominant Octave Center Band Frequency
Drilling	63 Hz
Hydraulic Fracturing	125 Hz
Completion	125 Hz
Production	16–31.5 Hz

Discussion

The researchers determined that there was a difference in noise levels between the different phases of oil and gas development. Given the limited number of available sampling sites, the researchers could not determine if these differences were statistically significant. It was concluded, however, that hydraulic fracturing sites had the highest noise levels while sites in the production phase had the lowest noise levels. Hydraulic fracturing sites appeared to have the highest noise levels at the noise source, however, as the distance from the noise source increased, the average noise levels for hydraulic fracturing sites become very similar to the average noise levels of drilling sites. At a distance of 117 yd, drilling and hydraulic fracturing sites with sound wall installations had almost identical A- and C-weighted sound levels. Hydraulic fracturing sites had considerably higher sound levels in the A- and C-weighted scale when sound walls were not installed. This finding suggests that at a distance, sound walls mitigate the sound of the louder hydraulic fracturing sites to a level similar to that of drilling sites. During the hydraulic fracturing phase, large trucks, and specialized machinery pump hydraulic fracturing fluid, comprised of mostly sand and water, into the hole created during the drilling phase. The hydraulic fracturing fluid is pumped at 10,000 psi more than a mile below the surface.[13] The high pressure fluid is pumped into the well to separate (fracture) the shale rock structure to stimulate the release of natural gas or oil. Each phase of oil and gas development has different contributing noise sources. Hydraulic fracturing operations have large air compressors, generators, and engines that power the hydraulic fracturing equipment. These compressors, generators, and engines contribute to the noise

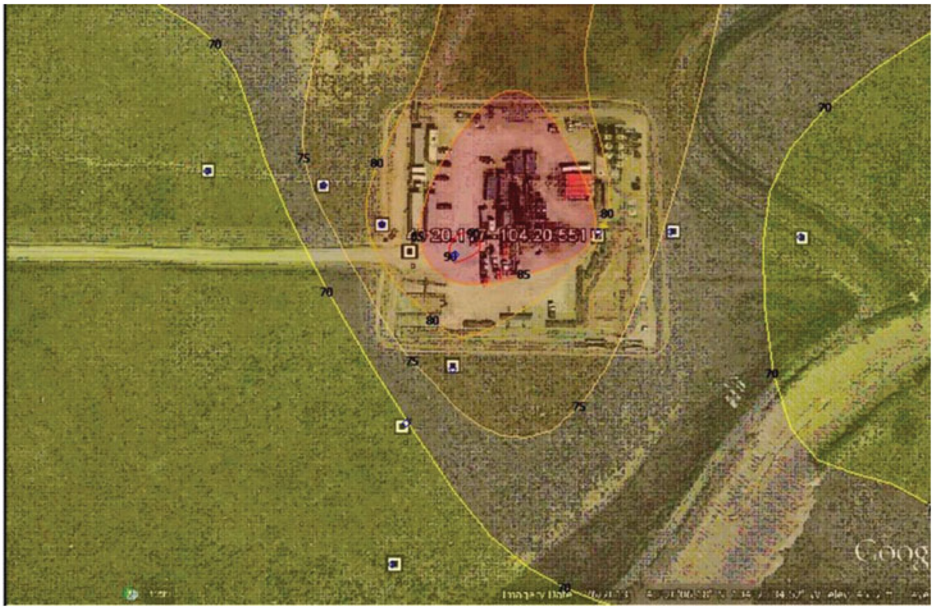

Figure 2. Noise contour map of a hydraulic fracturing site.

at hydraulic fracturing sites. Truck traffic appears to contribute a significant amount of noise in every phase of oil and gas production. However, hydraulic fracturing sites have a heavier volume of truck traffic due to the continual flow of sand and other materials in the fracturing process. The amount and types of heavy equipment involved in the hydraulic fracturing process and the fracturing itself appear to make hydraulic fracturing the loudest phase of oil and gas production.

Considering that the accuracy of the noise monitoring instruments was ±1 or 2 dB, it was difficult to conclude that hydraulic fracturing sites were significantly louder than drilling sites at 350 ft (107 m) on average. Four of four (100%) of the A-weighted, 15-min L_{eqs} at 350 ft (107 m) for drilling sites without noise wall installations exceeded the current COGCC regulations for residential and commercial zones. Three of three (100%) of the A-weighted, 15-min L_{eqs} at 350 ft (107 m) for drilling sites with noise wall installations exceeded the current COGCC regulations for residential zones. No A-weighted 15-min L_{eq} at 350 ft (107 m) for drilling sites with or without noise wall installations exceeded the current COGCC limit for light industrial or industrial zones. Two of four (50%) of the A-weighted 15-min L_{eqs} at 350 ft (107 me) for hydraulic fracturing sites without walls exceeded the current COGCC limit for light industrial zones, while four of four (100%) of the A-weighted L_{eqs} for the same hydraulic fracturing sites exceeded the limits for residential and commercial zones. The hydraulic fracturing site with the noise wall installation had an A-weighted 15-min L_{eq} that exceeded the current COGCC limit for residential zones but not commercial zones.

The C-weighted noise level measurements were higher than the A-weighted noise measurements at every oil and gas site. This indicated a low frequency noise issue at oil and gas sites, which was confirmed with the octave band analysis. The dominant frequency at every oil and gas site was in the low frequency range, with the highest dominant frequency at 125 Hz at hydraulic fracturing and completion sites. While noise levels were decreased when noise wall installations were present, the C-weighted noise level measurements with walls continued to exceed 65 dBC.

A very limited amount of research has been performed regarding environmental noise from the oil and gas industry, making this an interesting but challenging area of research. Researchers from Behrens and Associates[12] as well as Earthworks[11] investigated environmental noise from oil and gas operations using different methodologies to obtain noise measurements as compared to the current study. Some researchers collected measurements at different distances from the noise source while other researchers measured completely different types of sites and equipment.[11,12] This made it difficult to compare the results of the current study and earlier studies to one another.

An unpublished COGCC study, performed in 2015, addressed both A-weighted and C-weighted noise levels.[4] The COGCC study followed similar protocol as the current study. Measurements were collected at 350 ft (107 m) from the noise source at drilling and hydraulic fracturing sites with and without noise wall installations. The only difference in protocol was that the COGCC personnel collected measurements over a one-hour period

Table 7. Comparison of COGCC and CSU noise results.

Site Type Measured at 350 ft	COGCC Study Mean Noise Level	CSU Study Mean Noise Level	COGCC Study Mean Noise Level	CSU Study Mean Noise Level
Drilling Site without Wall	62 dBA	65 dBA	76 dBC	79 dBC
Drilling Site with Wall	54 dBA	59 dBA	72 dBC	73 dBC
Fracturing Site without Wall	69 dBA	70 dBA	80 dBC	80 dBC
Fracturing Site with Wall	59 dBA	59 dBA	76 dBC	74 dBC

compared to the current study that used 15-min measurements. In general, the COGCC monitoring results were within ±2 dB of the current study results. A comparison of the results between the COGCC study and the current study are presented in Table 7. The largest discrepancy was between the A-weighted noise levels for drilling sites with noise wall installations. The COGCC reported an average one-hour noise level of 54 dBA for drilling sites with noise walls while the current study reported an average 15-min noise level of 59 dBA for drilling sites with noise walls. The difference in these observations may be a result from the differing sampling periods. The CSU researchers coordinated with the oil and gas operators to ensure that the site was operating at full capacity during the 15-min sampling period. COGCC researchers used an hour-long sampling period without coordinating with operators. Thus, drilling operations may not have been running at full capacity during their measurements. The COGCC reported similar decreases in noise levels between sites with and without noise wall installations. In both the COGCC and the current study data, there was a greater reduction in A-weighted noise than C-weighted noise when noise walls were in place. It can be concluded that the COGCC one-hour noise measurement data support the current study's 15-min noise level measurement protocol for drilling and fracturing sites. The similarities between the one-hour COGCC results and the 15-min measurement results in the current study may indicate that noise at oil and gas operations are in a relatively steady state. Once a site is operational, there may not be much variation in the noise that is produced.

Study limitations

A very limited number of oil and gas sites appeared on Google Earth® to create the noise contour maps. Future evaluations using the noise contour software should employ aerial images of each specific site. This way, a noise contour map can be created on top of a layered image of each oil and gas site, not just the sites that appear on Google Earth®. Another limitation in this study was that the gain setting of the noise dosimeters was set at a range that the 15-min L_{eq} measurements from production sites was not recorded (i.e., the production sites produced noise below the threshold of the dosimeter). Instead of using the dosimeters, 5-sec L_{eq} measurements were collected at production sites using the SLM/OBA. Additionally, the inverse square law for noise was used to predict noise attenuation over certain distances. The inverse square law assumes the attenuation of noise in a free field. In reality, the noise most likely did not travel in a free field. There may have been some attenuation of noise due to topography and other environmental factors.

Noise measurements were collected during five-second and 15-min intervals. Even though sampling occurred while oil and gas operations were running at full capacity to obtain a "worst-case" noise scenario, variability in noise levels throughout the day or night could not be determined. Without a 24-hr sampling period, community noise parameters such as L_{90} values and the community noise equivalent level could not be calculated. It would be useful in future studies to measure the average noise level over a 24-hr period for a comprehensive evaluation. With the limited number of active oil and gas sites in the Northern Colorado area that were acceptable to sample, the researchers were able to sample twenty-three sites in total during the study time frame. Ideally, to evaluate consistency, a greater number of fracturing sites with walls and completion sites should be measured. It would also be valuable to sample oil and gas sites in different parts of Colorado with diverse topography during different times of the year to investigate any variations in noise levels. Finally, the contribution of oil and gas operations to overall noise pollution in areas with other predominant noise sources was not assessed in this study.

Conclusion

Each phase of oil and gas operations demonstrated different average noise levels at 350 ft (107 m) from the noise source. The highest noise level measurements in the A- and C-weighted scales, on average, were collected at hydraulic fracturing sites. At a distance of 350 ft (107 m) from the noise source, drilling and hydraulic fracturing sites had similar noise measurements. The greatest difference between drilling and hydraulic fracturing sites was a 5 dBA lower A-weighted average 15-min L_{eq} at drilling sites without walls than hydraulic fracturing sites without walls 350 ft (107 m) from the noise source. Drilling and hydraulic fracturing sites were within 1 dBC of each other with and without noise walls at a distance of 350 ft (107 m) from the noise source. The average A-weighted noise level measurements collected at production sites were at least 15 dBA lower than the A-weighted 15-min L_{eq} measurements collected at all drilling, hydraulic fracturing, and completion sites. The average C-weighted noise level measurements collected at production sites were at least 8 dBC lower than the C-weighted 15-min L_{eq} measurements collected at all drilling, hydraulic fracturing, and completion sites.

Oil and gas sites with noise wall installations had lower noise levels in both the A- and C-weighted measurement scales than those without noise wall installations. However, this reduction in noise was not sufficient to reduce the noise below the residential permissible noise level (55 dBA). On average, production sites without mitigation did not exceed current COGCC noise regulations. It is recommended that additional measures be taken to further reduce noise levels at drilling and hydraulic fracturing sites. It is essential to control low-frequency noise present in the C-weighted measurements. If the C-weighted noise is controlled, the A-weighted noise will be reduced as well.

It is important to highlight that every drilling and hydraulic fracturing site with and without noise walls had average noise measurements at 350 ft (107 m) that exceeded the current COGCC residential daytime and night time noise limits. Every drilling and hydraulic fracturing site without noise walls exceeded the current COGCC commercial daytime and night-time limits. 75% of drilling sites without walls and 100% of hydraulic fracturing sites without walls exceeded the current COGCC light industrial night-time limits. A lower proportion of production sites exceeded the COGCC limits for A-weighted noise levels. Regarding C-weighted noise level measurements, every drilling, hydraulic fracturing, and completion site exceeded the current COGCC limit of 65 dBC. The average C-weighted noise level at production sites was 64 dBC. A slight increase of 1 dB places the average production site at the current COGCC limit of 65 dBC. Considering the accuracy of the type one and type two noise measuring instruments that were used, it could not be concluded that the average production site was below the current COGCC limit of 65 dBC.

Recommendations

There are a plethora of sources on an oil and gas site that contribute to noise. While oil and gas operators commonly use different mitigation techniques, oftentimes those techniques aren't enough to significantly decrease the noise level. There are several possible mitigation techniques that may be used in addition to installing sound walls to further abate the noise at oil and gas sites to help achieve the permissible noise levels. Several techniques aside from sound wall installations are listed below. This list is not a comprehensive list of all possible mitigation techniques that can be used to reduce sound levels at oil and gas sites.

- Motor vehicles used to access well sites generate noise. Remote automated monitoring systems can be used to eliminate some traffic to and from well sites.
- Sound barriers and partial enclosures can be constructed next to or around specific noise generating equipment.
- Sound-insulating buildings (full enclosures) may be constructed around permanent noise producing structures such as compressors and pump-jacks.
- Installing silencers on engines and compressors may help to minimize the noise impact of these sources.
- Rig orientation may be a key control method. Directing the noise sources away from residential areas may reduce the noise propagated toward the residential areas (e.g., pointing the exhaust side of machinery away from neighbors).
- The use of electric rigs and equipment may reduce sound levels. However, additional research is needed to assess the effectiveness of electric rigs in terms of reducing sound levels.

It is recommended that the oil and gas industry continue to collaborate with private and government entities to work toward reducing sound levels produced by oil and gas operations, specifically drilling and hydraulic fracturing operations.

There has been little research on evaluating and characterizing environmental noise produced by oil and gas operations. With the increase in hydraulic fracturing in the U.S., it is important to continue to evaluate the community and environmental impacts of noise resulting from these sites. This study has opened the door for additional researchers to evaluate and further understand environmental noise in the oil and gas industry. Further research to control low-frequency noise produced by oil and gas operations is essential. Also, there is a need for additional sound surveys to be conducted encompassing a larger sample size of oil and gas sites. In future studies, it would be beneficial to collect sound measurements over a longer period of time to understand how noise may fluctuate between day-time and night-time levels.

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