Welcome to my backyard: A seven-part regional analysis of VOCs estimated emission levels from oil and natural gas extraction in Colorado

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Abstract

This study examines the distribution of volatile organic compounds (VOCs) from the natural gas and oil industry across seven regions of Colorado. In particular, this project aims to use Air Pollution Control Division's 2016 air inventory data from the Colorado State Department of Public Health and the Environment to evaluate regions of high producing emitters of VOCs. The research question is as follows: How do VOC estimated emission levels from oil and natural gas compare to the annual throughput of each monitored extraction site, and how do these variables differ among seven regions in the state of Colorado? A two-way analysis of variance (ANOVA) among all seven Colorado regions indicates there is a relationship between region, range of annual throughput, and the log of VOCs estimated emission levels. The overwhelmingly highest area of monitored extraction is the Denver Metro/Northern Front Range region but is not the highest polluting on average from this dataset.

Table of Contents

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Prologue

As a native to the Appalachian Mountain region, my strong connection to the environment stems from my family's relocation to central Pennsylvania in my early childhood. From this early exposure to a mountainous terrain, it was not long before the landscape of mountains and the environment of the Appalachians became close to my heart. Concurrently, the sport of snowboarding became important and altered my childhood. Soon after, my family and I were taking weekly trips up the local ski resort to spend our weekends together on the ski slopes and enjoy the scenery offered by the Appalachian Mountains. The frequent trips led to a passion for the sport through my youth and into my life as a college student. Since becoming interested in this winter sport, I have taken notice of optimal snowboarding years versus the years in which the snow was just not up to par.

In recent years, this passion for observing years of bountiful snowfall has become an important aspect of my life, driven by my desire to preserve such years of great snowfall for future generations to enjoy. It is my hope the powdery winters, in which I first learned to snowboard, exist in the years to come so future generations may enjoy the same winter conditions. Since living in Boulder, Colorado, seasonal changes have solidified my love for winter even further. From sporadic timing of winter my freshman year, with the first snowfall in September, to my junior year where snowboarding was just as substantial in January as it was in May the sudden change in guaranteed winters has begun to dwindle.

The unpredictable seasons, along with the rising mean temperature in the state that has been home to me for four years, have motivated me to investigate into local sources of emissions. Following a climate advocacy internship in the summer of 2017, I decided to work on a project regarding methane and VOCs emissions in Colorado's oil and natural gas industry. Due to a unique childhood celebrating the beauty of the mountains, and an internship displaying the vast amount of work still needed for environmental preservation, the motivation into further research of petroleum production rates in Colorado was instigated.

Acronyms

ACPD-Air Pollution Control Division
BTU-British Thermal Units
CAA-Clean Air Act
CDPHE – Colorado Department of Public Health and the Environment
CH_4- Methane
CO_2-Carbon Dioxide
COGCC-Colorado Oil and Gas Conservation Commission
CU-University of Colorado at Boulder
EPA –The United States Environmental Protection Agency
HAPs-Hazardous air pollutants
IPCC-Intergovernmental panel on climate change
kW-kilowatts
mcf- Million Cubic Feet
NAAQS- National Ambient Air Quality Standards
OCED-Organization for Economic Cooperation and Development
ONG – Oil & Natural Gas
OPEC- Organization of the Petroleum Exporting Countries
PPM- Parts per million
SIP- State Implementation Plan
UNFCCC- United Nations Framework Convention on Climate Change.
USD- United States Dollar
VOCs-Volatile organic compounds
PSD- Prevention of Significant Deterioration
CO-Carbon monoxide
Pb-Lead
NO_2- Nitrogen dioxide
O_3 -Ozone
PM-Particulate matter
SO_2-Sulfur dioxide

Introduction

This study focuses on the relationship of oil and natural gas (ONG) extraction to volatile organic compounds (VOCs) emission levels in the state of Colorado for 2016. Contributing to other publications of emissions data from the ONG industry, VOCs analysis by region was completed to display results from the 2016 monitoring year in a coherent and comprehensive document. I analyze annual throughput, or the extraction rate of crude oil, at each facility reported to the Air Pollution Control Division (APCD) for the 2016 inspection year in Colorado. The APCD is administered by Colorado Department of Public Health and the Environment (CDPHE) to monitor and control local ambient air pollution.

To compare distribution, annual throughput (as an independent variable) and VOCs emission levels (as a dependent variable) are cross-examined by region. The means of distribution of these two variables are compared, along with their variance in each sample group. Eight regions designated are compared based on CDPHE's map (Figure 1.1). The state of Colorado categorizes air sheds geographically based largely on topography, currently designating 8 regions across the state. According to the Colorado 2016 Air Quality Data Report, "In the past, this report has used a five-region classification system. While this served a topographic and climatological purpose, the ACPD has determined the eight-area approach to more accurately reflect local air pollution conditions" (AQDR, 2016).

Annual throughput, in million cubic feet (mcf), is an indication of how much crude oil enters the site of extraction for a given year. Annual throughput for this study is categorized into four levels based on the amount of extraction ranging from zero (all values equal to 0 mcf) to high (HIGH>49.2988128 mcf). VOCs emission levels gauge measurements at the time of inspection for a precursor to an Environmental Protection Agency (EPA) criteria pollutant. The EPA requires measurements for ozone, which is not directly emitted into the atmosphere but is formed when oxides of nitrogen (NOx) and VOCs react in the presence of sunlight (U.S. EPA: Our Nation's Air, 2017). The VOC emissions recorded for the state are measured in U.S tons per year and for this study are log-transformed. The eight regions include Western Slope, Southwestern, South Central, San Louis Valley, Pikes Peak, Eastern High Plains, Denver Metro/North Front Range

(DMNFR), and Central Mountains (Figure 1.1). This study exempts Pikes Peak ONG from extraction and emissions data as they are not reported in the database in 2016.

Figure 1.1: Colorado Department of Public Health and the Environment Map

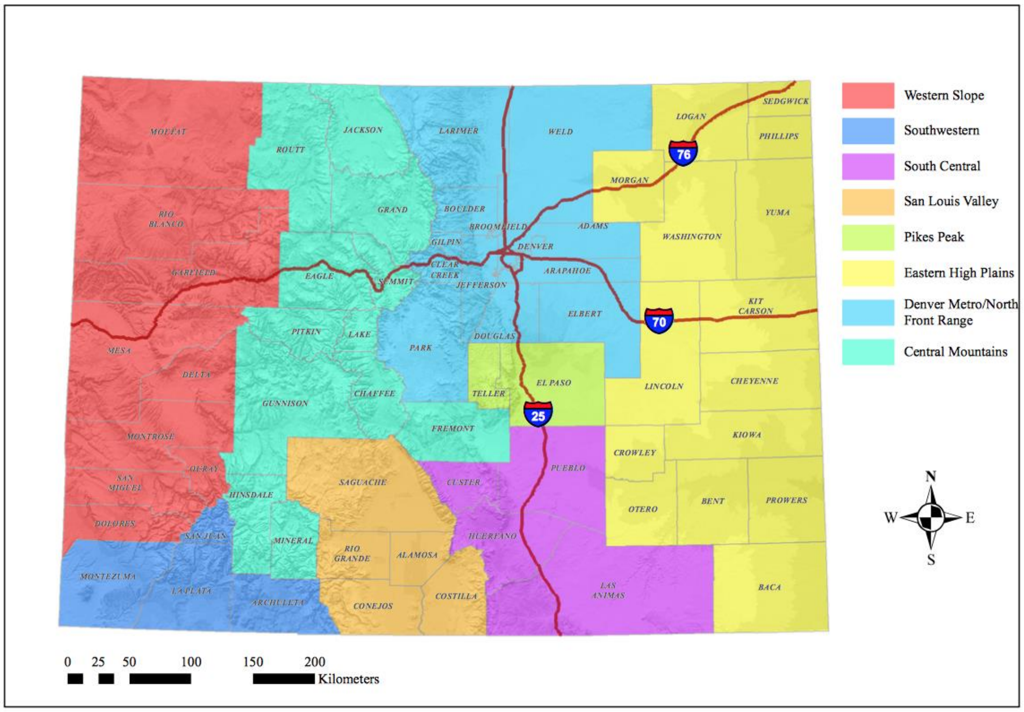


Figure 1.1: Counties and multi-county monitoring regions discussed in this report.

Figure 1.1: Map of Colorado (AQDR, 2016).

The research question for this study is: How do VOC estimated emission levels from oil and natural gas compare to the annual throughput of each monitored extraction site, and how do these variables differ among seven regions in the state of Colorado? The research question provides parameters for measuring the location of extracted ONG, and where it correlates most prominently with the VOCs emissions associated with each site. It is important to note this study does not overview ONG extraction in Colorado, and only explains the data collected from the 2016 monitoring year. This study serves the purpose of displaying an analysis of a dataset publicly available by CDPHE. Specifically, this study focuses on precursors to the EPA criteria pollutant ozone (O_3).

Using air inventory data from CDPHE, a data review of the 2016 APCD reporting year is conducted. Along with the air inventory data provided by CDPHE, the graphical user interface R-Studio Version 1.1.383, was used to perform a two-way analysis of variance (ANOVA) among regions to find where differences occur between the interaction of region and throughput onto VOCs. Summary statistics indicate where highest ONG extraction occurs and counts of sites for each region. Extraction of ONG is a current and relevant subject in the era of transitioning energy sources, as explained further in the paper, allowing for current examination of photochemical precursors to ozone to be relevant and crucial to future ONG exploration. This study aims to examine current methods of energy production and practices Colorado has implemented to provide a reliable source of oil and gas. A study focusing on all types of ozone-producing sources would be extensive and require additional research in all aspects of anthropogenic emissions.

Background

Volatile Organic Compounds

A VOC is any organic compound gas which has a high vapor pressure at ordinary room temperature. A VOC is produced from a hydrocarbon liquid's very low boiling point at mean sea-level and ambient air temperatures on the Earth's surface. Organic compounds contain carbon and include products such as gasoline, alcohol, and solvents. VOCs and oxides of nitrogen (NOx) are important to monitor since they contribute to the formation of photochemical smog and react in the presence of sunlight entering the atmosphere (U.S. EPA. Office of Air and Radiation., 2003). Compounds, emitted from industrial practices and manufacturing, transportation and associated exhaust, solvents, and vapors cause the formation of ozone and ground-level smog noticeable today.

VOC molecules sublimate into the surrounding air due to the volatility of many organic compounds. Volatility allows compounds to release molecules into the surrounding air, making it difficult to recapture these molecules. Although organic compounds are difficult to recapture, there are methods of VOC abatement. According to Jarraya. et al., there are two primary techniques for abatement to occur. The first is destructive using thermal oxidation and catalytic oxidation, which by eliminating the undesirable compounds using machinery and catalysts (Jarraya, I. et al., 2010). The second technique, or the recuperative technique, uses adsorption by adhesion of atoms, absorption through low energy and affordable take-up of VOC waste, and condensation through converting the gas (Jarraya, I. et al., 2010).

VOCs often are noticed in the form of scents and odors of manufactured products, but they are also present in odorless forms. Although ONG industries produce large numbers of VOCs, many come from household products, solvents, and sprays, causing indoor concentrations of VOCs to be generally higher than outdoor environments and the atmosphere. Some sources of VOCs derived from manufactured products are listed in Table 1:

Paint, paint strippers, and other solvents	Moth repellents and air fresheners
Wood Preservatives	Stored fuels and automotive products
Aerosol Sprays	Dry-cleaned clothing
Cleaners and disinfectants	Pesticides

Table 1: Common household sources of VOCs

An example of a VOC is formaldehyde, which is a colorless gaseous pollutant released from agriculture, paint, ONG, wood, and minerals like quartz. The boiling point for formaldehyde is low, approximating around 2°F, causing it to become gas at surface temperatures (United States. Agency for Toxic Substances and Disease Registry, 2008). Formaldehyde, which is highly flammable, is found at ONG extraction sites and has proven to affect the mucous membranes of a person and can make one feel irritated (United States. Agency for Toxic Substances and Disease Registry, 2008). Many VOCs differ in their health implications and vary depending on the concentration, type of VOC, and amount of exposure to an organism.

A VOC produced from ONG extraction in Colorado is benzene, also known as benzol. Benzene, a known human carcinogen, is a colorless liquid with a sweet odor and highly flammable (United States. Agency for Toxic Substances and Disease Registry, 2007). Benzene can release quickly into the air and also dissolves into water, allowing for the transportation of the compound to potable sources. Benzene is made from petroleum and found at sites of ONG extraction (United States. Agency for Toxic Substances and Disease Registry, 2007). Benzene is a monitored compound coming from many of industrial processes and manufacturing. According to the *Agency for Toxic Substances* *and Disease Registry*, “Benzene levels in the air can be elevated by emissions from burning coal and oil, benzene waste and storage operations, motor vehicle exhaust, and evaporation from gasoline service stations” (United States. Agency for Toxic Substances and Disease Registry, 2007). Carcinogens, such as benzene, released from industrial processes continuously allow for hazardous compounds to come into human contact every day. It is alarming to find the same compounds found in Colorado’s air at ONG extraction sites across the state but common compounds, detrimental to human health are found at multiple locations.

VOCs originate from man-made products and also from naturally occurring compounds found in multiple ecosystems. VOCs originating from the ONG industry are considered an anthropogenic source of VOCs and thus are regulated by law as air pollutants. At the federal level, the EPA monitors and regulates organic compounds emitted by industrial sectors, including ONG extraction and refinement. However, the EPA allows states self-jurisdiction of emission compliance in the event state regulations both exceed EPA requirements for air pollutants and comply with federal standards. Colorado’s Regulation No. 7, administered by the Colorado APCD, has been implemented and aligns with federal National Ambient Air Quality Standards (NAAQS) (AQCC Regulation No. 7). The Colorado APCD, therefore, monitors air quality at ONG sites.

According to the EPA, VOCs have the potential for ill health effects including eye, nose, and throat irritation, headaches, loss of coordination, damage to internal organs and the central nervous system (EPA, 2017). Examining VOCs attentively in all sectors is crucial for prevention of human complications by them. This paper provides a platform to assess local extraction sites in terms of VOCs and where they are emitted in Colorado. Shown below, VOCs on a national level have come from an array of industries increasing the number of precursors responsible for ground-level ozone.

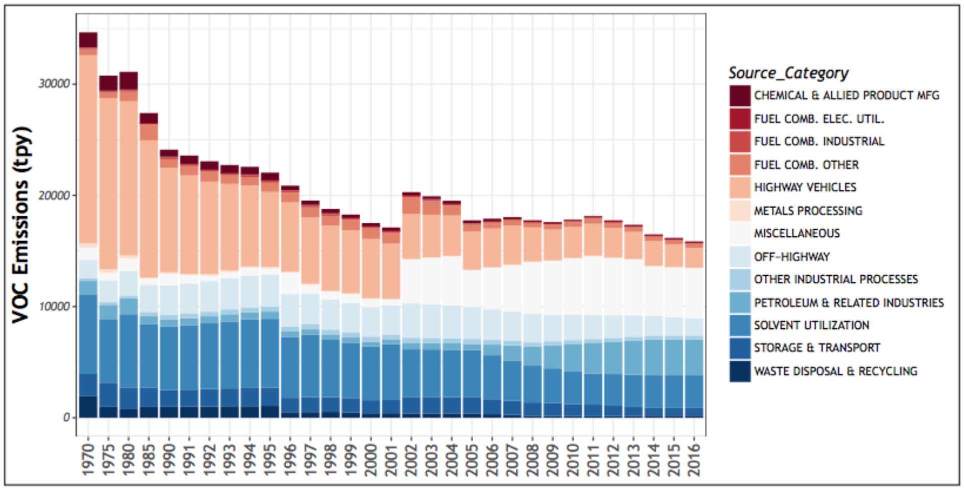


Figure 2: VOC national trends from 1970 to 2016 (U.S. EPA, 2017)

Volatile organic compounds in ONG inspections

In Colorado, levels of VOCs reside in the atmosphere and ambient air around the state, emitted by the ONG industry sector. As described in Regulation No. 7, a VOC refers to “any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, which participates in atmospheric photochemical reactions, except those listed in Section II.B. as having negligible photochemical reactivity” (5 CCR 1001-9). VOCs are emitted from both solids and liquids containing varied amounts of additional chemicals, with some adverse health and environmental effects.

In the ONG sector, pollutants monitored by the APCD are as follows: Ethylbenzene, butadiene, Acrolein, Ethylene glycol, toluene, hexane, Diethanolamine, xylenes, formaldehyde, pentane, Butyl acetate, Methanol, Benzene, Methane, Methanethiol, acetonitrile, acetaldehyde, methylene chloride, hydrogen chloride, hydrogen fluoride, ammonia, hydrogen sulfide, naphthalene, cobalt compounds, nitrogen oxides, nitrilotriacetic acid, lead, particulate matter, and sulfur dioxide. The notion in monitoring VOCs is to keep a record of and supervision on precursors to ground-level ozone in the state. By monitoring compounds, the ACPD can measure ground-level ozone contamination and predict compliance with federal regulations.

Ozone (O_3)

According to the *2016 Air Quality Data Report* from the APCD, "O_3 is an atmospheric oxidant composed of three oxygen atoms" (AQDR, 2016). Ozone typically is not emitted directly into the air, but instead formed at ground-level via photochemical reactions among NOx and VOCs in the presence of sunlight. In Colorado, emissions from industrial facilities, motor exhaust, gasoline vapor, along with ONG extraction are major sources of NOx and VOCs.

Ozone is a natural gas occurring in the Earth's stratosphere and also near the Earth at ground level (U.S. EPA. Office of Air and Radiation., 2003). Depending on where ozone is found, the gas can determine if the type of ozone is "good" or "bad" for the human population, vegetation, and ecosystems. The "bad" type of ozone resides in the troposphere, or the layer closest the Earth's surface. The ground-level ozone occurring in the troposphere layer is considered "bad" because it is harmful to breathe, damages vegetation, and is the main ingredient in urban smog (U.S. EPA. Office of Air and Radiation., 2003).

Above the troposphere, which ranges about six miles up, the second layer of the atmosphere is reached known as the stratosphere. The stratosphere extends from 6 to 30 miles up and here the "good" type of ozone resides (U.S. EPA. Office of Air and Radiation., 2003). In the stratosphere, ozone is present to help protect Earth from the sun's ultraviolet (UV) rays and provide a barrier for living organisms (U.S. EPA. Office of Air and Radiation., 2003). Ozone is produced naturally in this layer of the atmosphere for protection of the sun's UV rays and is influenced from man-made chemicals "…including chlorofluorocarbons (CFCs), hydro chlorofluorocarbons (HCFCs), halons, methyl bromide, carbon tetrachloride, and methyl chloroform" (U.S. EPA. Office of Air and Radiation., 2003).

In Colorado, statewide average O_3 design values have fluctuated around the standard and in recent years have been upward in regard to ozone concentrations (Table 2). As stated in the *2016 Air Quality Data Report*, the "APCD believes the upward trend can be linked to the recent oil and gas development in Colorado and the uptick in the overall economy since about 2010, although global declines in oil prices in 2014 have slowed oil and gas development somewhat" (AQDR, 2016).

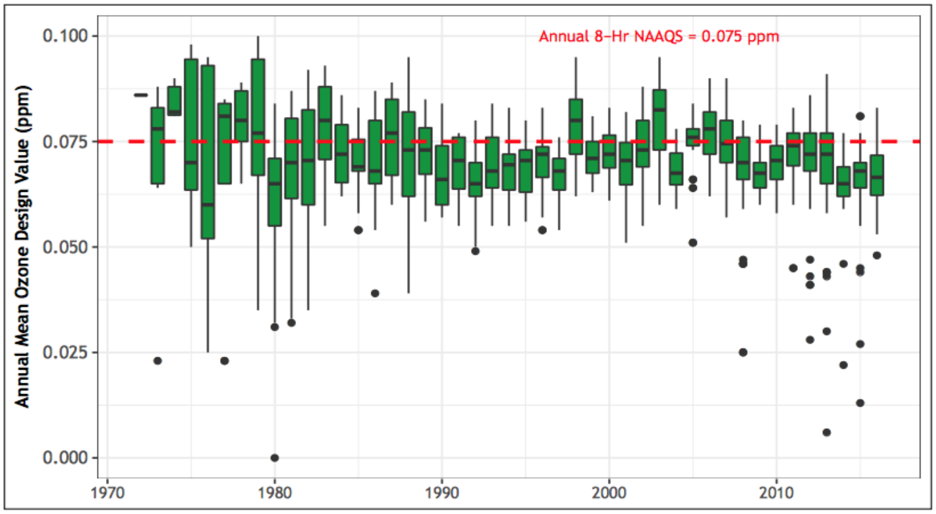


Table 2: Statewide historical record of 8-hr ozone design values. The box plot shows the mean design value statewide for each year, as well as the interquartile range (box) of values observed at monitoring sites throughout the state and minimum and maximum values.

The effects of ozone are numerous and widely spread from their ability to possess both human health and environmental effects. According to the EPA, "ozone exposure can impair those by reducing lung function and causes respiratory symptoms, such as coughing and shortness of breath" (U.S. EPA Basic Information about Ozone, 2017) Additionally, ozone exposure also aggravates lung conditions diseases, such as emphysema and asthma, causing patients who suffer from such diseases to have increased medication use, hospital visits, and doctor consultations (U.S. EPA Basic Information about Ozone, 2017). Ozone exposure has the potential to increase the risk of premature mortality from respiratory causes and breathing in polluted airborne substances. Therefore, ozone can be associated with non-accidental mortality, which includes respiratory associated deaths and impairments (U.S. EPA Basic Information about Ozone, 2017).

According to the EPA, "ozone damages vegetation by injuring leaves, reducing photosynthesis, impairing reproduction and growth and decreasing crop yields. Ozone damage to plants may alter ecosystem structure, reduce biodiversity, and decrease plant uptake of CO_2" (U.S. EPA Basic Information about Ozone, 2017). The environmental effects of ozone cannot only reduce current mechanisms of pollution control, such as the uptake of CO_2 through photosynthesis but also affects the richness and biodiversity indices of certain species exposed. In addition to all the negative effects of ozone on the atmosphere, ozone also promotes global warming since ozone is a greenhouse gas that contributes to the warming of the Earth's atmosphere (U.S. EPA Basic Information about Ozone, 2017).

Off-gassing

VOC off-gassing, is the process of releasing gases and airborne particles trapped, dissolved, frozen, or absorbed in some matter. VOC off-gassing is due to ONG extraction and occurs where a geological material containing airborne particles, stored in rock, is brought up from the earth's subsurface and released into ambient air. Material made of rock, oil, clay, gas, and silt removed from the Earth's subsurface originated in intense heat and pressure. This material stores organic compounds which react with the Earth's surface-level pressure and temperatures.

In ONG extraction, the variety of compounds released strongly depends on the geologic material brought up to the surface and its potency. Drill site locations influence the type of compounds released, due to the concentration of VOCs stored in the rock. VOC off-gassing like the scent of a new car, also occurs on a larger scale at ONG extraction sites. The geologic material brought up at these extraction sites contain VOCs which has not been exposed to surface temperature pressures before. VOC off-gassing particular to petroleum products is associated with the toxic geologic material, the release of precursors to ground-level photochemical smog, and visual air pollution.

Literature Review

Understanding the distribution of ONG and pollutants across extraction sites is necessary for a continual projected rate of ONG development for at least the next decade. ONG production in the United States is expected to increase for the next 10 to 15 years and spur industrial production and thereby extraction (U.S. EIA, 2014). Expected use of anthropogenic resources calls for research on the production of ONG along with its associated implications.

ONG production, including shale gas development, produces volatile organic compounds (VOCs), hazardous air pollutants (HAPs) including benzene, and additional greenhouse gases such as methane which can impose risks onto those proximal to site extraction (Brantley et al., 2015). Pollutants such as VOCs and HAPs pose serious health risks for both the general public and employees that operate drill extraction sites. VOCs and HAPs are dangerous due to their negative influence on the human population and are required components to ground-level ozone. Due to the harmful properties of VOCs and health implications they generate, monitoring divisions such as the APCD, require that inspectors precisely monitor and quantify VOCs emitted from each ONG facility.

Colorado and Energy Production

Colorado has a large industrial sector and population heavily dependent on fossil fuels extraction and production. As stated by Lisa M. McKenzie et at., “Colorado is the sixth and seventh largest producer of natural gas and oil, respectively, in the United States” (McKenzie, 2016). However, in recent history, Colorado has shown movement towards clean and cost-effective renewable energy methods through agreements such as the U.S. Climate Alliance, which Governor Hickenlooper signed onto in the summer of 2017. The U.S. Climate Alliance commitment aligns with the Paris Climate Agreement, or the provisions set to reduce global emissions and GHGs, which has been signed by large contributors such as China, India, and Russia. According to *Energy and Global Climate Change: The Road from Paris to Denver* authored by Jeffery Logan, “Governor John Hickenlooper has an executive plan to cut Colorado’s power sector emissions 35% by 2030 compared to 2012 levels” (Logan, 2016). The provisions set by the Paris Climate Agreement lay out a plan of action for participating countries and their subsequent emissions by the year 2025 while considering the increase in emissions from developing countries. According to National Renewable Energy Laboratory (NREL), Colorado, within the parameters of the United States Climate Alliance, “plans to reduce U.S. economy-wide GHG emissions by 26- 28% by 2025 from 2005 levels” (Logan, 2016). The agreement allowed for Colorado to continue ONG extraction, but conventional and unconventional methods are being reevaluated to cut emissions in the state.

ONG extraction in Colorado is closely tied to the presence of viable oil reserves and feasibility of extraction. Aligning with large profitable basins, the majority of ONG production in Colorado occurs on the Eastern Plains of the state and Weld County while most natural gas production occurs on Colorado’s Western Slope (Figure 3) (Lewandowski et al., 2014). The top five producers in Colorado are depicted in green while the counties shaded in blue indicate the occurrence of oil production, according to county-level production data from the Colorado Oil and Gas Conservation Commission (COGCC).

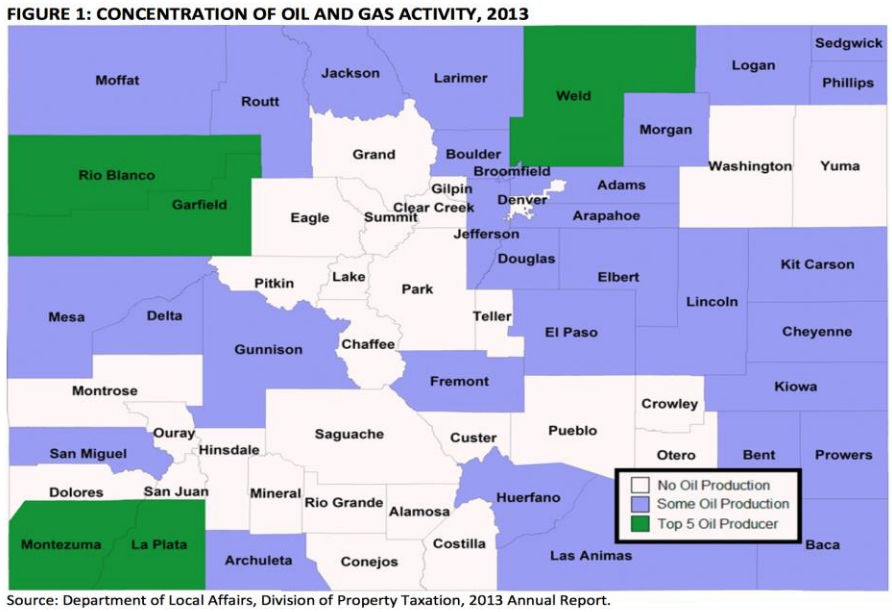


Figure 3: ONG extraction in Colorado by county. (Lewandowski et al., 2014).

Due to the location of the Denver-Julesburg Basin, the northeastern part of the state is an ideal drilling region, as seen from the majority of blue stated shaded. The Denver-Julesburg basin is a geologic structural basin located in eastern part of Colorado underlying southeast Wyoming, Western Nebraska, and Western Kansas. The deepest part of the basin is under Denver, while gradually ascending to the surface as it reaches Kansas. The Denver-Julesburg basin is a large oil reserve that underlies populated areas of Colorado, including the Front Range of the Rocky Mountains, and consists of a large asymmetric syncline of Paleozoic, Mesozoic, and Cenozoic rock layers (Eisele et al., 2016). ONG companies responsible for hydraulic fracturing are incentivized economically and focus drilling based on seismic data displaying viable reserves in basins such as the Denver-Julesburg basin.

As referenced in *Population Size, Growth, and Environmental Justice Near Oil and Gas Wells in Colorado* “between 2000 and 2012, more than 20,000 O&G wells were started in three major Colorado O&G basins: the Denver Julesburg Basin (DJB), Piceance Basin (PB), and San Juan Basin (SJB)” (McKenzie et al., 2016). An increase in the drilling of petroleum basins is important to consider in Colorado because both drill sites and residential areas can exist in the same municipality. Colorado is well known historically for conventional extraction of oil through vertical drilling procedures. From much advancement in the ONG industry, new technologies have emerged that allow for alternative methods of oil extraction to take place.

Crude Oil

According to Regulation No. 7, crude oil is defined "as hydrocarbon liquids that remain liquid at standard conditions (a temperature of 68 degrees Fahrenheit and pressure of 29.92 inches Mercury) and are formed by condensation from, or produced with, natural gas, and which have an American Petroleum Institute gravity (API gravity) of 40 degrees or greater" (5 CCR 1001-9). Crude oil is produced from a source rock which generates hydrocarbons from organic matter. Organic-rich sediments that have matured through time, with increasing layers of sediment and burial, are often referred to as tight oil formations. Tight oils are often noted for their ability to generate oil in formations of low permeability, creating an environment in which migration of oil can occur. Maturation of rock formations in addition to the level of permeability is a key component into the migration and occurrence of an oil reservoir.

Natural Gas

Thermally mature hydrocarbons released into porous media can migrate to the surface due to buoyancy, known as secondary migration. The less dense material will rise to the surface through migration when the surrounding material has a higher density (Dembicki Jr, Harry, and Michael J. Anderson., 1989). Natural gas is made of methane (CH_4) with differing quantities of alkanes, carbon dioxide, nitrogen, hydrogen, sulfide, or helium, also present.

As a naturally occurring fossil fuel, natural gas has seen ample benefits in industries including automobiles, plastics, and electricity. Natural gas is classified as either dry or wet with a scale used to determine the amount of methane (CH_4) comprising the gas. The scale is an indication of whether or not methane is the primary constituent of the gas and to what percentage other gasses are present. A dry natural gas means the product is mainly composed of methane and has smaller amounts of other constituents, such as ethane or butane. In contrast, a wet natural gas is composed of many constituents other than methane including ethane, propane, butane, and pentane to name a few.

Based on the percentage of methane constituting the gas reservoir, the gas can be categorized as a methane gas or be stored and sold separately. Natural gas primarily consists of methane, which is a greenhouse gas and in April 2013, the EPA has estimated 2,545 Gg of CH_4 emissions have been attributed to natural gas production activities (Allen, David T., et al. 2013). A recent advancement in liquefied natural gas has made this product highly concentrated, easy to transport, and safer due to a non-pressurized state for storage. Natural gas liquids such as ethane, propane, butane, and pentane can be used to make refrigerants and common household products. The plastic industry relies heavily on the use of these liquids, derived from extraction of ONG to make household products.

During a drill operation on a well pad where oil is located, natural gas is often found in addition to petroleum. As an economic advantage to the drilling company, the natural gas associated with the petroleum reservoir, also known as “associated gas,” is removed and can be used for various purposes in the energy grid (Elvidge, Christopher D., et al. 2009). Although most natural gas production involves extracting from wells drilled into underground gas reservoirs, some natural gas is generated as a by-product of oil production. When both oil and natural gas are found in one reserve, the natural gas is economically viable and useful for capture instead of allowing this gas to freely be released into the air through venting

Extraction of conventional sources

Extraction of conventional oil is done through a borehole vertically drilled into an oil reservoir, removing the hydrocarbon liquid via hydrostatic pressure. Natural pressure from the well and from pumping operations remove ONG from the underlying rock secured by a cap rock. Pressure from the well generally decreases over time and produced water from drilling is returned to the reservoir to increase pressure. Conventional wells use artificial lift and gas injections to retrieve more ONG beyond what is naturally pressurized, applying methodologies such as beam and hydraulic pumping. After production has reached a point of natural production and ONG cannot be obtained to maximize profit, the well is usually capped and extraction ceases.

Conventional methods of extraction use geologic surveys of underlying rock structures and seismic reflection data to determine a drill site and designated depth. Determining drill locations requires the presence of a source rock, or a rock which has the ability to produce oil, indicating generation of an oil reserve to extract from. A cap rock structure is ideal for the trapping of ONG in an impermeable layer of strata. Oil migration is critical in conventional ONG extraction, which is a process of oil migrating upward toward the surface allowing reservoirs to contain plentiful supplies and movement of oil into a singular region or regions. To determine where a source rock is located, seismic reflection data is commonly used and seismic waves can mark where oil is potentially trapped. Migratory oil, which might not have come from a singular source rock, may be found because it is less dense than surrounding rock formations.

Extraction of non-conventional sources

An extraction practice in Colorado, hydraulic fracturing, also known as fracking, is where a high-pressure water mixture is injected into the rock to release oil or gas stored in the pores of rock (Finkel, 2015). In fracking, a drill is inserted into the earth’s subsurface and a borehole doubled-cased in concrete is used to keep the opening exposed. After drilling, horizontal fractures are blasted into the underlying rock with fluids to increase the surface area of exposed rock, and therefore oil, to the borehole opening.

The high-pressure fluid injected into the borehole to pry open the multiple fractures made in the rock formation below is “overwhelmingly comprised of water, but the other additives, including friction reducer, biocide, surfactant, acid, and scale inhibitor, have the potential to remain in shale layers and contaminate nearby water supplies after drill removal” (Stephenson, 2017). These chemicals used in the pressurized fluid is an argument made in the opposition of fracking and environmental effects it has on ecosystems and aquifers. This process is conducted to stimulate movement in ONG residing in the rock formation, subsequently extending flow back to expel fracture fluids and solids at a high-pressure rate (Finkel, 2015). The ability and advancement in drilling horizontal to the earth’s surface has allowed a secondary revolution of ONG to emerge as more potential reservoirs can be accessed.

According to the COGCC, it is estimated that fracking used 32 billion gallons of water in Colorado between 2010 and 2015 (Minor, 2014). According to a study by Stephenson "fracking may use a small portion of Colorado's total water supply, there are still approximately 250 liters of water that can disappear down a fracking well every second during a high-volume frack" (Stephenson, 2017). Due to geologic formations and oil basins in Colorado, incentives to drill locally have increased along the Front Range where oil exists.

Well location

Improved understanding of well locations and near-source concentration of air pollutants around ONG wells are important for multiple reasons. Initially, well pads serve as the collection and storage location of product extraction, where producing wells may deliver natural gas, condensate, oil, and water to the surface. Additionally, the petroleum products "extracted products from shale gas consists of VOCs and other HAPs, which have potential air quality impact at local and regional scales" (Brantley et al., 2015).

Exposure of VOCs and HAPs can occur near a drill site, which can have health implications for the local environment and air quality for those proximal to extraction sites, according to an article on VOCs by Brantley et al. Understanding the distribution associated with the ONG industry is crucial to human health hazards and complications. According to a Denver-Julesburg Basin and Texan shale study, "methane and benzene emissions from ONG operations in the Colorado Denver–Julesburg Basin (DJB) have been found to be underestimated, emphasizing the need for air monitoring at and near such facilities to better characterize ONG source contribution" (Eisele et al., 2016).

Regulatory Action

The Clean Air Act

The Clean Air Act (CAA), implemented in 1963, and amended multiple times after, is a federal law passed in the United States to initiate control and monitoring of air pollution. The CAA was passed to improve air quality across the United States during a period of high air pollution and smog levels. The CAA today is "comprehensive federal law that regulates air emissions from stationary and mobile sources. Among other things, this law authorizes EPA to establish NAAQS to protect public health and public welfare and to regulate emissions of hazardous air pollutants" (U.S. EPA: Laws & Regulations-Summary of Clean Air Act, 2017). National air standards listed under the CAA are currently used to control pollutants found in the ONG industry.

The CAA of 1970 after amendments occurred resulted in a shift of the U.S. government's role in air pollution monitoring and regulation by implementing state and federal regulations to limit emissions from stationary and mobile sources (42 U.S.C. §7401). The adoption of legislation occurred concurrently with the establishment of the National Environmental Policy Act, which eventually formed into the EPA. In 1977, major amendments occurred again to the CAA concerning the provision for the "Prevention of Significant Deterioration (PSD) of air quality in the areas attaining the NAAQS" (U.S. EPA: Clean Air Act Overview, 2017). The amendments contained requirements pertaining to sources in non-attainment areas for NAAQS. In 1990 a major set of amendments occurred primarily focusing on the federal government's responsibility and increased authority in regulation.

The CAA requires the EPA to set NAAQS for specific pollutants to protect human health and the environment. Six common air pollutants, also referred to as the EPA "criteria pollutants", include carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO_2), ozone (O_3), particulate matter (PM), and sulfur dioxide (SO_2) (U.S. EPA: Our Nation's Air, 2017). While some of these pollutants are released directly into the atmosphere, others are formed in the atmosphere from chemical reactions. Ground-level ozone is one example of a GHG which is formed from emissions of NOx and VOCs reacting in sunlight.

Ground-level ozone is of concern at ONG extraction sites from these compounds being released through off-gassing and federal compliance is required. Colorado complies with EPA regulations at inspection by monitoring these pollutants and therefore abides by the NAAQS for six criteria pollutants. Although monitoring takes place, it does not mean Colorado consistently complies with federal standards in terms of meeting the allowance for these pollutants or precursors to the formation of them.

Regulation No. 7

Under Colorado state law, Regulation No. 7 (*Control of Ozone via Ozone Precursors and Control of Hydrocarbons via Oil and Gas Emissions*) administered by the APCD with regulatory action and oversight of ONG development in the state. Regulation No. 7 is enforced across Colorado, in areas complying with NAASQ standards along with nonattainment areas. Since ozone is a direct resultant of the ground-level VOCs from ONG extraction, Regulation No. 7 was implemented to record, monitor, and comply with the CAA and federal standards of ozone pollution (5 CCR 1001-9).

In Regulation No. 7, ozone control areas are designated to distinguish regions in compliance with ozone NAAQS and areas that exceed this limit, referred to as nonattainment. In Regulation No. 7, the 8-hour Ozone Control Area is based on EPA's review of the air quality criteria for ozone and related photochemical oxidants. Nonattainment in Colorado is currently based on the 2015 ozone standard, which the EPA revised the primary and secondary ozone standard levels to 0.070 parts per million (ppm). The 8-hour Ozone Control Area in Colorado is "met at an air quality monitor when the 3-year average of the annual fourth-highest daily maximum 8-hour average ozone concentration is less than or equal to 0.070 ppm" (5 CCR 1001-9). Based on these criteria, the 8-hour ozone nonattainment area includes "counties of Adams, Arapahoe, Boulder (including some of Rocky Mountain National Park), Douglas, and Jefferson; the cities and counties of Denver and Broomfield; and portions of Larimer and Weld Counties" (5 CCR 1001-9).

Nonattainment can be of concern since these areas across the United States are federally violating a standard that exists for the sole protection of human, ecosystem, and atmospheric health. When an area is in violation of these national standards, the population and surrounding forms of life are put at risk of the effects of ozone and their health may be impaired. A national baseline is used in order to keep consistency in ground-level containments and exposure of these compounds to sensitive life forms in proximity to polluting industries.

The primary purpose of Regulation No. 7 as it is applied to the ONG industry is to have a practical, effective, and overseen practice of VOCs emissions while collecting air inventory data (5 CCR 1001-9). The implementation of the regulation intends reduce ozone levels in Colorado from ONG emissions and byproduct VOCs from drilling practices. Particularly, the ozone control standard applies to the Front Range of Colorado in the Denver Metropolitan and Northern Front Range region. All ONG facilities must comply with Regulation No. 7, in both nonattainment and attainment areas, in ordered to be granted a valid extraction permit for the leasing year.

Regulation No. 7 entails requirements for both existing sources and new sources that have developed following its implementation. It has unique designations and procedures for both. The state utilizes Regulation No. 7 monitoring quarterly, monthly, biannually, or annually, depending on categorization of the facility and size of extraction. Monitoring methods are described extensively in the regulation so as to comply with state and federal ambient air standards.

The following is an example section from Regulation No. 7 (5 CCR 1001-9), including the general emission limitations on all existing sources. It shows the complexity and detailed specifications of the regulation:

- Existing sources of VOCs which are not subject to specific emission limitations set forth in Reg. 7, and which have the potential to emit 100 tons per year or more of VOC, shall utilize Reasonably Available Control Technology (RACT).
- Potential to emit of such sources shall be based on design capacity or maximum production rate, whichever is greater, 8760 hours/year operation, and before add-on controls.
- Owners or operators of such sources with potential emissions of 100 tons per year or more, but with actual emissions less than 100 tons per year may obtain a federally enforceable permit limiting emissions to actual rates by restricting production capacity or hours of operation, thus avoiding RACT requirements.
- Sources with potential emissions of 100 tons per year or more but with actual emissions of less than 50 tons per year, on a rolling 12-month total, may avoid RACT and permit requirements if the owner or operator submits revised Air Pollutant Emission Notices (APENs) by April 1 of each year, which demonstrate that the 50 tons per year threshold has not been exceeded and maintains records on site which include monthly VOC use and monthly VOC emissions.
- Existing sources that are modified – undergo any physical change, or changed in the method of operation of a stationary source which increase VOC or NOx emissions – on or after March 30, 2008, shall utilize RACT control technologies pursuant to Regulation Number 7 and Regulation Number 3, Part B, Section III.D.2. upon recommencing operation.

As shown, Regulation No. 7 often refers to sections which describe additional procedures of the inspection and monitoring process. Baseline requirements for ONG sources and associated VOCs are stated in the regulation for existing sources in Colorado to abide by to be acceptable under the ACPD jurisdiction. All existing facilities must meet the APCD credentials to produce and extract ONG.

Regulation No. 7, in recent years, has also been subjected to changes and repeals based on monitoring practices and revisions in the industry. On November 16, 2017, Colorado's Air Quality Control Commission (CAQCC) strengthened existing ONG control measures to comply with federal requirements and to improve ground-level ozone levels. The revision was driven by Colorado's obligation under the federal CAA to include provisions implementing Reasonably Available Control Technology (RACT) requirements in Colorado's Ozone State Implementation Plan (SIP) (R7 fact sheet. FINAL.12.26.2017). RACT is an EPA air pollution control standard used to determine the type of air pollution control technology for a specific pollutant to a designated limit. A SIP is a United States state plan for complying with the federal CAA administered by the EPA. A SIP is a developed by state agencies and approved by the EPA in order for states to get back on track with pollution control. SIPs consist of narratives, rules, technical documentation, and agreements that an individual state will use to clean up polluted areas. The revisions were completed to include provisions in the SIP allowing for transparent requirements for the RACT detection of current facilities and their associated VOCs.

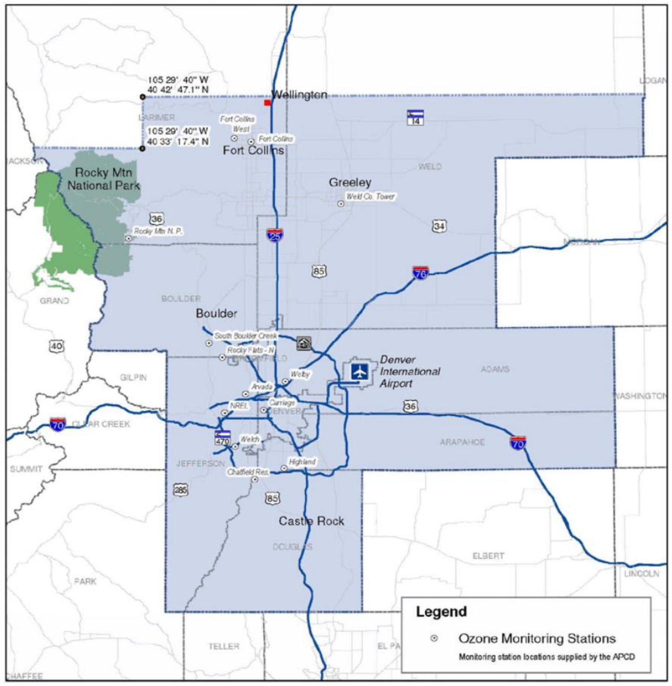
The revisions include requirements for compressors, pneumatic controllers, pneumatic pumps, equipment leaks at natural gas processing plants, and fugitive emissions at well production facilities and natural gas compressor stations. The revisions are intended for the Denver Metro North Front Range (DMNFR) ozone nonattainment area in Colorado's Ozone SIP (R7 fact sheet., 2017). These requirements relied heavily on prior guidelines described in the regulation and affected specific sections of Regulation No. 7 as deemed necessary. Changes made to Regulation No.7 affect the DMNFR nonattainment area (federally enforceable), while other changes only applied to state regulation. It is evident that as technological advancements progress in the extraction industry, the subsequent regulations have to be updated to modernized ONG practices.

Nonattainment Area & History

A nonattainment area, is an area's air quality below the NAAQS and therefore exceeds federal air quality standards. A nonattainment zone does not meet national primary or secondary ambient air standards. NAAQS primary standards in nonattainment refer to public health and apply to hazardous materials causing human health effects. Secondary standards pertain to the effects onto secondary nonhuman populations such as animals and plants. Primary and secondary standards pertain to the CAA amendments of 1970. The objective is to reduce the levels of ozone pollution and various precursors to smog, while implementing a nation-wide secure baseline standard for air quality.

Due to poor air quality in Colorado's Front Range, from sectors such as ONG extraction, designation by the EPA as a nonattainment zone for the 1997 8-hour ozone standard occurred in April 2004. The 1997 8-hour ozone standards regulate 0.08ppm of O_3 over the annual's fourth-highest daily maximum 8-hr concentration, averaged over 3 years. During 2004, the state of Colorado and Regional Air Quality Council (RAQC) committed to implement control measures on ground-level ozone sooner than required by the CAA, deferring the effective date of nonattainment classification until November of 2007 (History of Ozone, 2018). The commitment to control ozone measures was included in the Denver Early Action Compact. As long as the Early Action Areas met certain milestones and criteria regarding pollutants, the EPA deferred the effective date of nonattainment designations for those areas violating the 8-hour standard.

On November 20, 2007 the EPA deferral expired, and the DMNFR areas were designated as "Marginal" nonattainment in terms of the 1997 ozone standards, with an 8-hour federal ozone standard in effect (History of Ozone, 2018). The nonattainment classification was a result of violation of federal ozone standards, for the years 2005-2007. The 8-hour ozone nonattainment area consists of nine counties–including "the counties of Adams, Arapahoe, Boulder, Broomfield, Denver, Douglas, Jefferson, and a portion of Larimer and Weld" (CDPHE: Technical Support Document, 2009) (Figure 4).



Denver-Boulder-Greeley-Fort Collins, Colorado
Eight-Hour Ozone Control Area

Figure 4: Map on Nonattainment Area. https://www.colorado.gov/pacific/sites/default/files/AP_PO_ozone-nonattainment-area-map.pdf

Following nonattainment classification, a detailed Ozone Action Plan was developed by the APCD, partnered with the RAQC and North Front Range Metropolitan Planning Organization. The new plan required greater reduction in ozone levels than in the 2004 Ozone Early Action Compact and was submitted by the governor to the EPA on June 18, 2009 (History of Ozone, 2018). In 2009, Colorado evaluated a measure of a new ozone standard issued in March of 2008 by the EPA, changing the limit from 80 parts per billion to 75 parts per billion of ozone averaged over an 8-hour period. During this time, Colorado was able to state no areas outside the non-attainment zone violated the protocol (History of Ozone, 2018). The 2008 standard is “met at an air quality monitor when the 3-year average of the annual fourth-highest daily maximum 8-hour average ozone concentration is less than or equal to 0.075 ppm” (U.S. EPA: Eight-Hour Average Ozone Concentration, 2017).

In 2012, the DMNFR area was re-classified as a “Marginal” nonattainment area pertaining to the 2008 ozone standard by the EPA effective July 20, 2012 (History of Ozone, 2018). This “Marginal” classification was a result of not meeting 2008 ozone standards set by the federal government. For Colorado, the year 2013 was the fourth year that the DMNFR was above the standard for ozone. In early 2014, the Air Quality Control Commission (AQCC) adopted regulatory changes to reduce VOC emissions from the ONG sector. The revisions adopted planned to reduce VOC emissions by 93,000 tons per year in Colorado in addition to reductions of oxides of nitrogen (NOx), which the AQCC approved revisions in the regional haze plan of 2011 (History of Ozone, 2018). These changes allowed for a forecast of more than 35,000 tons per year of NOx reductions in the state of Colorado by 2018.

On October 1, 2015, the EPA revised the ozone standard to 70 ppb, an additional decrease in ppb from the 2008 ozone standard. The DMNFR region currently does not meet the ozone standard of 75 ppb, let alone 70 ppb (History of Ozone, 2018). As stated in *History on Ozone*, "as a result, the APCD and the RAQC engaged in an extensive planning and implementation effort, using both voluntary and mandatory air pollution control measures to reduce ground-level ozone" (History of Ozone, 2018). The standards brought about in 2015 are currently under EPA review. In 2016, the DMNFR region increased from a "Marginal" to a "Moderate" ozone attainment area for the 2008 8-hour Ozone standard.

Colorado's "Marginal" ozone nonattainment area failed to attain the 2008 8-hour Ozone NAAQS on May 4, 2016 (History of Ozone, 2018). Since the re-classification, the division and Regional Air Quality Council have produced a SIP to reduce ozone levels in this region. Colorado now is faced with complying with the 2008 ozone standard by 2018, which has provisions to meet this requirement in the SIP. The commission approved the SIP on November 17, 2016 while the rest of Colorado was in compliance with ozone standards (History of Ozone, 2018).

During 2017, the EPA delayed classification designating the nonattainment areas for the 2015 standard in Colorado. Since the delay of the 2015 ozone standard, the 2008 standard is still in place for Colorado, which is now outdated by a decade. Colorado has until July 2018 to meet this standard, and with present data collected by the division, it does not look promising that Colorado will comply with this deadline (History of Ozone, 2018). If Colorado does not meet this standard, the ozone nonattainment area could be bumped-up again to "Serious" classification making it a hazard in terms of ozone pollution. Currently the APCD is preparing for potential reclassification and working to comply with the EPA on meeting the ozone standards.

Implementation of regulating ozone has become more stringent. In particular, the limitations allowed between the 1997, 2008, and 2015 regulation have lessened in acceptable ppm and is based on high ozone daily amounts with the availability of sunlight. The evolution of the nonattainment areas shows a transition of air pollution across the Front Range of Colorado and displays how the regulation of ozone standards is becoming increasingly stricter, while not properly reducing the ppb expected.

Instrument monitoring methods

The APCD monitoring methods operate with two procedures to conduct site inspections (5 CCR 1001-9). First, the division uses an infrared camera, applicable under Regulation No. 7, at sites to determine for leaks and optical gas imaging reports. Secondly, the inspectors also use audio and visual methods that includes a see-sight-smell procedure conducted at the time of facility inspection. These methods are used to monitor the leakages among facilities to gauge if a company is violating air pollution protocols.

Approved Instrument Monitoring method

Under EPA regulations, in order to collect data on VOCs, methods that meet regulation Approved Instrument Monitoring Method (AIMM) must be used. An AIMM is required for monitoring storage tanks and components at well production facilities and natural gas compressor stations. An AIMM can be “an infrared camera designed for and capable of detecting hydrocarbon and VOC emissions (examples include the FLIR GF300/320 cameras and the OPGAL EyeCGas camera), EPA Reference Method 21, or other instrument-based monitoring device or method approved by the division” (AQCC, 5 CCR 1001-9, Section XVII.A.2).

The use of an infrared camera allows the inspection to capture live optical images of VOCs radiating from sources while detecting for leaks. Alternative methods of monitoring VOCs may be used with submission of an alternative monitoring method formed approved by the division, but for the purpose of this study, the standard monitoring methods are discussed.

Audio-Visual-Olfactory

The second method of VOCs detection among the APCD is the Audio-visual-olfactory method (5 CCR 1001-9). Using the principles listed below from Regulation No. 7 (5 CCR 1001-9, Section XVII.C.), the audio-visual-olfactory method uses sense to detect immediate leaks and release points of emissions:

- An audio inspection of the storage tank and associated equipment to determine if you can hear any noises indicating the presence of emissions.
- A visual inspection to determine if there are any emissions visible to the naked eye from the tank or associated equipment (this is different than “visible emissions” which is defined as smoke observable for 1 minute in any 15-minute period).
- An olfactory inspection to determine if you can smell any odors indicating emissions from the tank or associated equipment.

EPA METHOD 21 - Determination of volatile organic compounds leaks

Method 21 is used to regulate leaks of VOCs from large individual sources. The EPA, has developed Method 21 to regulate leaks from processing equipment at a ONG facility. Since this is an additional methodology in the monitoring process for leakages detected, the two primary inspection methods are carried out and Method 21 is only necessary if a leak occurs. Types of equipment applicable under EPA Method 21 are sources including “valves, flanges and other connections, pumps and compressors, pressure relief devices, process drains, open-ended valves, pump and compressor seal system degassing vents, accumulator vessel vents, agitator seals, and access door seals” (U.S. EPA: Method 21:1.2 *Scope*).

Under section 6.0 (*Equipment and Supplies*) of the Method 21, the specifications list the criteria for a monitoring instrument to be approved. Specifications include parameter such as VOC instrument detectors shall respond to the compounds being processed, including “catalytic oxidation, flame ionization, infrared absorption, and photoionization” (U.S. EPA: Method 21:6.0). Requiring the response of the detector proves a leak will appear when the instrument is properly handled. Additionally, the monitoring instrument utilized should measure leak definition concentrations specified in regulation meaning it can identify pollutants the state has required (U.S. EPA: Method 21:6.2). There are additional specifications which can be found in the methodology itself regarding the detection of VOCs which are not discussed in this paper.

Regions

Eastern High Plains (EHP)

The Eastern High Plains region includes the counties of Sedgwick, Phillips, Logan, Morgan, Washington, Cheyenne, Yuma, Lincoln, Kit Carson, Kiowa, Crowley, Otero, Baca, Bent, and Prowers. The Eastern High Plains region encompasses the fifteen counties on the plains of eastern Colorado. The EHP is located on the eastern side of the state which is semiarid and often windy in weather patterns. The area's population is approximately 134,298, according to estimates calculated from the 2010 U.S. Census Bureau data (AQDR, 2016).

South Central (SC)

The South Central region includes the following counties: Las Animas, Huerfano, Custer, and Pueblo. According to the 2016 Air Quality Data Report, the South Central population is approximately 190,505, according to estimates calculated from the 2010 U.S. Census Bureau data (AQRD, 2016). The South Central region contains rolling semiarid plains to the east and has a mountainous landscape to the west. All of this area currently complies with federal air quality standards and previously completed particulate matter monitoring in this region but found low concentrations and therefore discontinued (AQDR, 2016). The South Central region consists of plateaus, canyons, and high valleys. This region is in compliance with all federal air quality standards.

Denver Metro/North Front Range (DMNFR)

The DMNFR region includes the counties of Adams, Arapahoe, Denver, Douglas, Jefferson, Gilpin, Boulder, Broomfield. Clear Creek, Larimer, Weld, Clear Creek, Elbert. The DMNFR comprises of 13 counties and the largest population in Colorado approximating 3,810,228, according to estimated calculated in the 2010 U.S. Census Bureau Data. The DMNFR includes parts of Rocky Mountain National Park, along with other wilderness areas. This region has been in compliance with all NAAQS, except for ozone since 2002 (AQDR, 2016). According to the *2016 Air Quality Data Report* by the APCD, “The area has been exceeding the EPA’s current ozone standards since the early 2000s, and in 2007 was formally designated as a “nonattainment” area” (AQDR, 2016). After more stringent ozone standards were implemented in 2008, the designation was re-affirmed in 2012 when the EPA designated the region as a “Marginal” nonattainment area.

Western Slope (WS)

The Western Slope region includes the following counties: Moffat, Rio Blanco, Mesa, Garfield, Delta, Montrose, San Miguel, Ouray, Dolores. The Western Slope region consists of the Rockies Mountains to the east with plateaus, valleys, mesas, and canyons on the western side of the region. The population of this region is approximately 315,467, according to estimates calculated from the 2010 U.S. Census Bureau data and all this region complies with federal air quality standards (AQDR, 2016).

San Louis Valley (SLV)

The San Louis Valley region includes the following counties: Saguache, Rio Grande, Conejos, Alamosa, and Costilla. The San Louis Valley is an alpine valley situated in the Sangre de Cristo Mountains on the northeast and the San Juan Mountains of the Continental Divide to the west. The San Louis Valley is semiarid and contains croplands of potatoes, lettuce, and barely which require water irrigation. The population of this area is approximately 46,372, according to U.S. Census Bureau estimates (AQDR, 2016). In 2016, this region proved to exceed federal limits of particulate matter.

Southwest (SW)

The Southwest region includes the following counties: San Juan, La Plata, Montezuma, and Archuleta. The population of this region is approximately 96,170, according to estimates calculated from the 2010 U.S. Census Bureau data. The Southwest region consists of mountains, plateaus, high valleys, and canyons and the region is home to Mesa Verde National Park. Agriculture and tourism from around the state is the dominant industries in this region, but ONG has become increase more important (AQDR, 2016). Currently all of this area complies with federal air quality standards.

Central Mountains (CM)

The Central Mountain region includes the counties of Routt, Jackson, Grand, Eagle, Summit, Pitkin, Lake, Chaffee, Gunnison, Fremont, Hinsdale, Mineral. The Central Mountains region consists of 12 counties in the central area of the state. The Continental Divide passes through much of this region and consists of mountains and valleys as the dominant feature in this region's landscape. The population of this region is approximately 235,528, according to estimates calculated from the 2010 U.S. Census Bureau data (AQDR, 2016).

Pikes Peak (PP)

The region of Pikes Peak includes the counties of El Paso and Teller. According to the 2016 Air Quality Data Report by the APCD, "the area has a population of approximately 713,337, according to estimates calculated from the 2010 U.S. Census Bureau data" (AQDR, 2016). The region had no data inputs for 2016 monitoring year and therefore was exempt in this study. Due to the ACPD not obtaining data for the Pikes Peak Region, the study is not reflective of VOCs or annual throughput in the Pikes Peak region of the state. The Pikes Peak region, exempt from this study, was not run against any of the other sample regions and therefore did not conclude any significant differences among VOCs and throughput.

Methods

The methodologies used for this study come from literature by Mertens, W., Pugliese, A., & Recker, J. (2017). *Quantitative data analysis: A companion for accounting and information systems research* (Mertens, 2017). By using previous methodologies, tests were run according to their description and practice. The R-Studio script attached is the code to identify the facilities and their levels of extraction, in addition to comparing the annual throughput range along with region to log of VOCs. The R-Studio Version 1.1.383 software provided a platform to run analyses and determine difference in means of distribution of production and emissions across the state. The database collected from CDPHE includes annual facility inspection reports for the 2016 monitoring year. The database includes a column definitions sheet explaining each criteria pollutant potentially appearing for an ONG monitoring report. The database is categorized by individual piece of equipment, facility, county and was obtained through a personal connection at the APCD.

For comprehensive purposes, the database does not include portable sources of emissions to keep consistency among regions. The study also excludes the following units: *process-unit/year, parts processed, seals in operation (annual basis), ton input to process, tons burned, tons cement produced, tons handled, tons of waste treated, tons processed, tons solvent consumed, valves in operation, vehicle miles by haul trucks, vehicle miles traveled, wells/year in operation, Error: select from list, facility annual, flanges in operation, tons product, barrels waste liquid, barrels processed, tons raw material, gallons paint consumed, hours of operation, million BTU/year heat input, tons handled, vehicles processed, and each year operating*. In the entire database, 251 rows of portable sources and 271 unrecognized unit rows of inputs were removed, since they do not pertain to the annual throughput of extraction or VOCs estimated emissions levels in this study. Prior to exemption of the 525 input rows for portable sources and unrecognized units, there was a total of 28169 inputs in the entire datasheet. This study included and analyzed 27644 rows of inputs from CDPHE.

Following a map based on CDPHE geographical division of the state, Colorado is divided into eight regions based on air sheds and topography, with only seven regions of inputs included in the study (AQDR, 2016). The regions utilized in this study are listed with their aggregated counties above followed by a brief description of each area and its topography. The counties excluded from this study include: Gilpin, Clear Creek, Park, Douglas, Teller, El Paso, Pueblo, Custer, Conejos, Alamosa, Costilla, San Juan, Ouray, Eagle, Summit, Saguache, Lake, Chaffee, Hinsdale, and Mineral. The remaining counties in Colorado were considered. Since this study focuses on inspections only, results are an approximate representation of the overseen values of annual throughput and VOCs estimated emissions while not representing total ONG production for the entirety of Colorado.

The information collected from CDPHE was the facility’s identification number, county, region, annual throughput (units: million cubic feet) and VOCs estimated emission levels (U.S. tons per year), along with various criteria pollutants inspected in a monitoring year. These pollutants were not included in this document. Imperial units are kept consistent to provide a comprehensive result for the units originally used in monitoring. By aggregating data into one platform, all inputs of annual throughput were standardized in million cubic feet with the rational for all units of annual throughput, in a homogenous unit, extracted at each site. In the Excel workbook, the standardization of units from thousand gallons to million cubic feet is found from the following equation:

$$Standardization = \frac{\frac{((throughput\ cell) \times 1000)}{7.48052}}{1000000}$$

where the throughput cell is the starting cell in the spreadsheet of annual throughput, 1000 is used to convert throughput to thousands of gallons, 7.48052 is used to convert gallons to cubic feet, and 1000000 to convert cubic feet to million cubic feet. The units for VOCs were originally in U.S. tons per year and therefore VOCs standardization had previously occurred.

Following standardization of annual throughput, a method of categorizing annual throughput occurred in order to run statistical tests properly. Requiring two categorical variables for a two-way ANOVA, annual throughput was made statistically categorical by K-means. K-means is a clustering method that partitions a given dataset into a set of *k* groups. It classifies objects in the dataset into multiple groups (clusters), such that objects in the same cluster are as similar as possible. The categorical levels to annual throughput are Zero, Low, Medium, and High. K-means determined that class intervals of annual throughput would be: Zero equals 0 values, Low is 0>LOW< 0.15337889, Medium is 0.15337889>MEDIUM<49.2988128, and High is 49.2988128>HIGH.

First, a Wilcoxon Rank Sum Test, or Mann-Whitney-Wilcoxon Test, was used to first determined if a significant difference occurs between VOCs and throughput. A Wilcoxon Rank Sum Test is a nonparametric alternative to the two-sample t-test, which is based solely on the order in which the observations from the two samples fall. By running this non-parametric test, one can conclude if a significant difference occurs for the sample means of throughput and VOCs. Using a Mann-Whitney-Wilcoxon Test one can determine whether the population distributions are identical without assuming them to follow the normal distribution. Following a Wilcoxon Rank Sum Test, a one-way ANOVA on ranks was run between VOCs and region. Since this dataset was not normally distributed, a non-parametric ANOVA on ranks was run, referred to as a Kruskal-Wallis, between VOCs and regions. A Kruskal-Wallis test is a non-parametric alternative to the one-way ANOVA F-test. This statistical test can determine whether a statistically significant difference occurs between two or more groups of an independent variable on a continuous or ordinal dependent variable. A Kruskal-Wallis test is used to determine whether a statistically significant difference occurs in VOCs between independent groups of the factor region.

To determine differences between the logs of VOCs estimated emission levels to the annual throughput and region, a two-way ANOVA statistical test was run. An ANOVA is a statistical method that utilizes the mean differences between groups that have been split on two independent variables called factors. Factors in this study were region and annual throughput onto and one dependent continuous variable of VOCS, or the response variable, so therefore a two-way analysis is best fit. A two-way ANOVA is used to understand the interaction between the two independent variables onto the dependent variable. Additionally, for feasibility and to comprehend true values, evaluating logs of VOCs was executed and inputs were cleaned to represent only data points which have valid log of VOC. Zeros were removed from both annual throughput and VOCs to validate correctness onto logs of VOCS. 9415 sites had a throughput where VOCs were greater than zero and 9352 sites had a VOC where VOCs were greater than zero.

Following the occurrence of significant differences produced from the two-way ANOVA, I ran a Tukey honest significant difference (Tukey HSD) test to locate between what two regions and ranges of throughput the difference occurs. VOCs estimated emissions by the CDPHE is an accurate measure of what the overseeing air pollution division, APCD, can project for the active year of extraction from OGN facilities.

Results

As categorized by regions provided by the APCD map (Figure 1.1) each region displays results found from using the graphical user interface R-Studio Version 1.1.383. In total, there were 10665 sites analyzed in this dataset. After aggregation, there were 64 sites in the CM, 7630 sites in DMNFR, 401 sites in EHP, 1 site in SLV, 692 sites in SC, 180 sites in SW, and 1697 in WS. Since the ACPD monitors by equipment, I found pieces of equipment distributed by 211 in the Central Mountains, 19043 in the DMNFR, 1026 in the Eastern High Plains, 1 in the San Louis Valley (therefore excluding a standard deviation from this region), 1090 in South Central, 389 in Southwest, and 5883 in the Western Slope. The total annual throughput and VOCs estimated emission levels by region are listed below (Table 3).

REGION	ANNUAL THROUGHPUT	VOCS ESTIMATED EMISSION LEVELS
EASTERN HIGH PLAINS	232478.5	1923.2468
SOUTH CENTRAL	473523.57	451.7179
DMNFR	35304156.1	32947.5017
WESTERN SLOPE	2260625.9	12793.469
SAN LOUIS VALLEY	12.63	1.66
SOUTHWEST	371742.64	304.175
CENTRAL MOUNTAINS	28872.56	1671.0136
PIKES PEAK	N/A	N/A

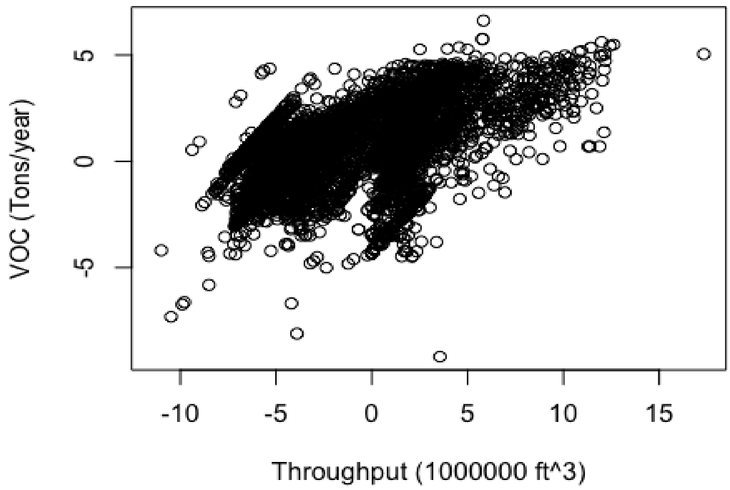
Table 3: 2016 Totals for monitored annual throughput and VOCs

Summary statistics listed below show the means and standard deviations for each monitored region showing the disproportionality among equipment readings (Table 4).

	REGION	MeanVOC	SDVOC	MeanTHROUGH	SDTHROUGH	COUNT
1	CENTRAL MOUNTAINS	7.9194958	18.283941	136.8368	136.8368	211
2	DMNFR	1.7301634	5.993712	1853.9178	1853.9178	19043
3	EASTERN HIGH PLAINS	1.8745096	4.568092	226.5872	226.5872	1026
4	SAN LOUIS VALLEY	1.6600000	NA	12.6300	12.6300	1
5	SOUTH CENTRAL	0.4144201	1.719452	434.4253	434.4253	1090
6	SOUTHWEST	0.7819408	4.495528	955.6366	955.6366	389
7	WESTERN SLOPE	2.1746505	8.954257	384.2641	384.2641	5883

Table 4: Summary statistics by region

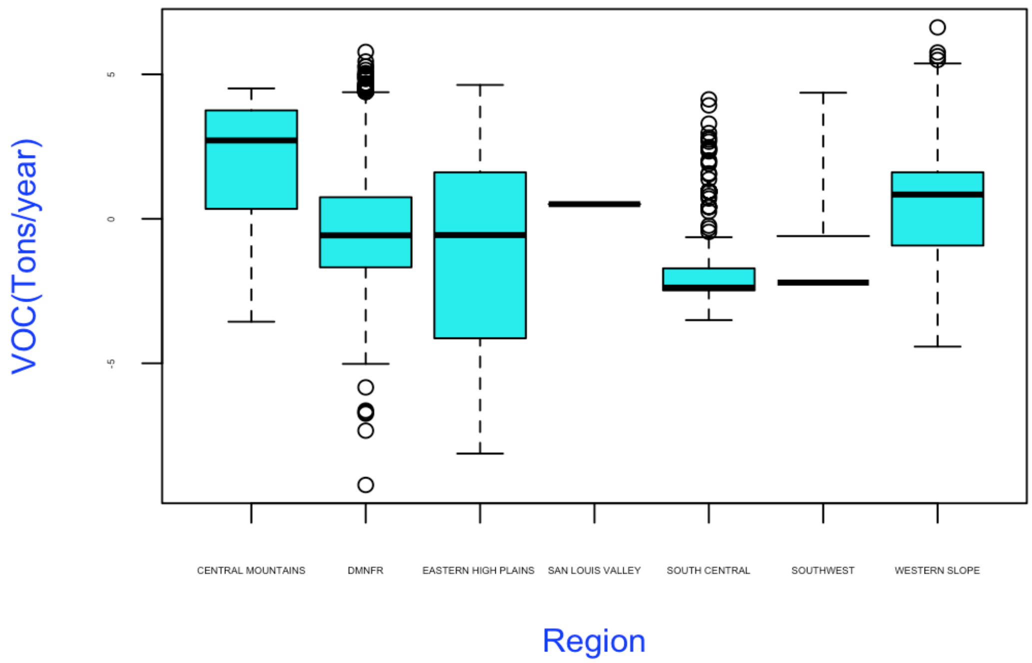
Shown below is the plot of a log-transformed distribution of VOCs and log-transformed annual throughput excluding zeros from the database. Since this dataset included an array of inputs that were zero, and by being unable to take the log of the value zero, this plot represents the log of throughput compared to the log of VOCs recorded that has a value which exists. This plot is representative of all sites monitored in Colorado and is not categorized by region (Plot 1).



Plot 1: Log-transformed plot of VOCs by annual throughput

By using non-parametric statistical tests, this study was based not solely on parameterized families of probability distributions, but instead on a distribution-free account of analysis while considering zeros. From the Wilcoxon-Rank Sum Test, which is a nonparametric alternative to the t-test, a significant difference occurred between VOC and throughput prior to log-transformation (p-value < 0.05 ($2.2e^{-16}$), W= 74597000). At 0.05 significance level, we conclude that VOCs estimated emission levels and annual throughput are *nonidentical* populations.

A Kruskal-Wallis rank sum test showed a significant difference occurring between region and VOCs with a p-value <0.05 ($2.2e^{-16}$), degrees of freedom = 6, and a chi-squared = 917.28. This non-parametric one-way analysis of variance determined there is a statistically significant difference in VOCs between the seven independent groups of region. The figure below illustrates VOCs by region, which have been log transferred in order for differences to appear (Plot 2). By log-transforming VOCs, only those values which are non-zero values will appear, since the log can only occur for a numerical value other than zero.



Plot 2: Boxplot of log-transformed VOCs by region

Two- Way Analysis of Variance (ANOVA)

A two-way analysis of variance (ANOVA) was calculated on region and annual throughput range (Zero, Low, Medium, and High) to the logs of VOCs estimated emission levels. The ANOVA was aggregated by site to determine differences based on site instead of equipment. The analysis proved all three combinations of independent variables onto the dependent were significant. From the ANOVA, I conclude that:

1) The p-value of region is <0.05 ($2e^{-16}$), which indicates that the levels of region are associated with significant different logs of VOCs.

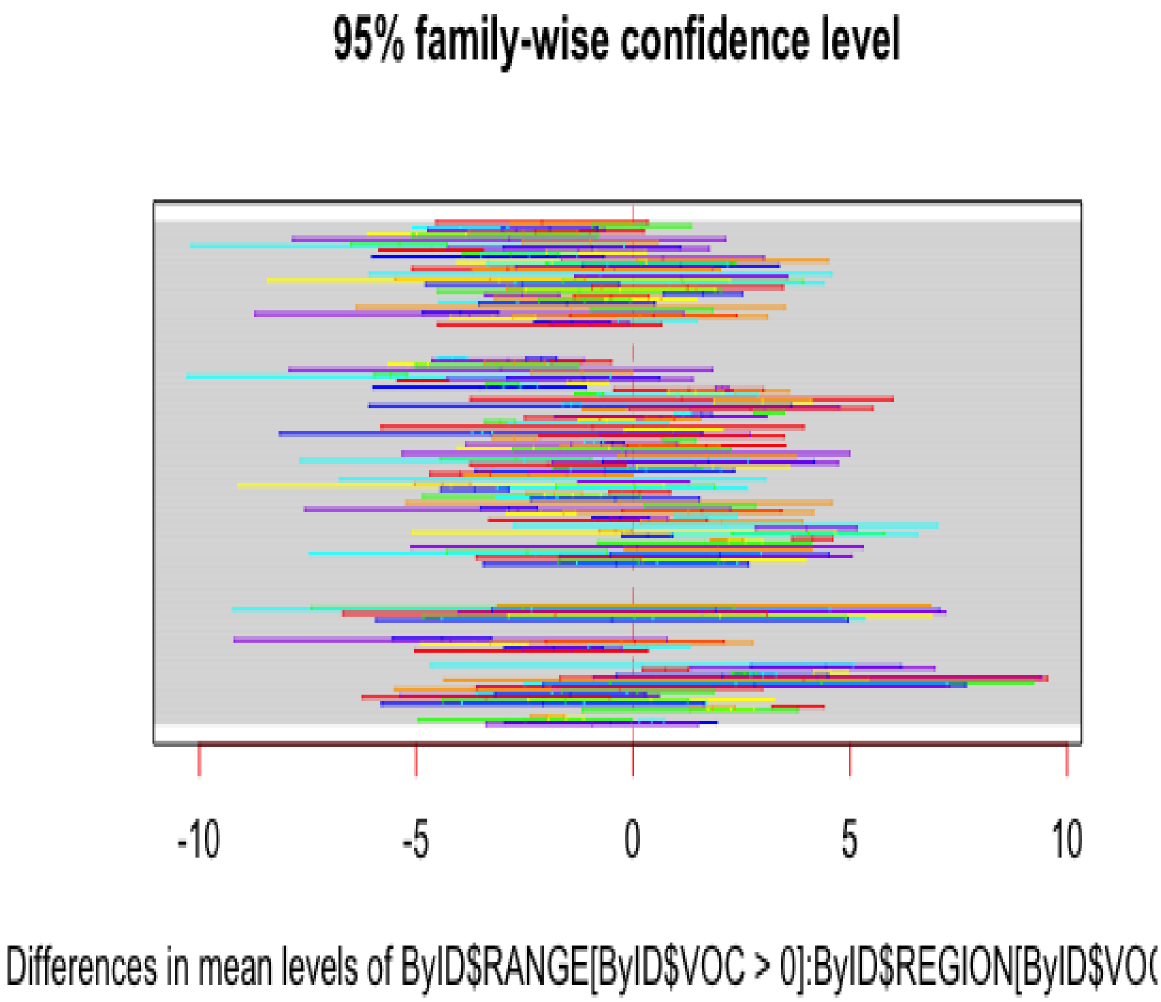
2) The p-value of annual throughput (range of zero, low, medium, and high) is <0.05 ($2e^{-16}$), which indicates the categorical levels of annual throughput are associated with significant different logs of VOCs.

3) The p-value for the interaction between annual throughput (range) and region is <0.05 ($2e^{-16}$), which indicates the relationship between the category of annual throughput and the log of VOCs depends on region.

The two-way ANOVA test was able to determine the previous salient points and proved a significant difference between both the independent factors and response factor.

Since the two-way ANOVA can only explain that a difference occurs between those variables, a Tukey HSD test was also run to determine where those significant differences occur. Shown below is a difference in means plot for the Tukey HSD test, while the actual values for all comparisons are listed in Appendices (Plot 3).

Tukey Honest Significant Difference



Plot 3: Tukey HSD plot

Table 5: Tukey HSD results for Range and VOCs>0 by site

Range 1	**Range 2**	**diff**	**lwr**	**upr**	**P-adj**
Low	**High**	3.40786894	3.5581655	3.2575724	0
Medium	**High**	2.70503392	2.8616682	2.5483997	0
Zero	**High**	2.63095576	3.3963162	1.8655953	0
Medium	**Low**	0.70283502	0.6266857	0.7789843	0
Zero	**Low**	0.77691318	0.0238919	1.5299345	0.0401244
Zero	**Medium**	0.07407816	0.6802336	0.82839	0.9943642

Table 6: Tukey HSD results for Region and VOCs>0 by site

Region 1	**Region 2**	**diff**	**lwr**	**upr**	**P-adj**
DMNFR	CM	1.1019798	1.6107966	0.59316305	0
EHP	CM	2.3348806	2.8805901	1.78917118	0
SLV	CM	0.9942046	4.8857054	2.89729618	0.9890856
SC	CM	3.4881022	4.0161435	2.96006088	0
SW	CM	2.61104	3.2352153	1.98686473	0
WS	CM	0.5651471	1.0818658	0.04842849	0.0215119
EHP	DMNFR	1.2329008	1.4410952	1.02470644	0
SLV	DMNFR	0.1077752	3.7508936	3.96644396	1
SC	DMNFR	2.3861224	2.5422433	2.2300015	0
SW	DMNFR	1.5090602	1.8766753	1.14144508	0
WS	DMNFR	0.5368327	0.4248317	0.64883372	0
SLV	EHP	1.340676	2.5230306	5.20438264	0.9488231
SC	EHP	1.1532216	1.4047728	0.90167032	0
SW	EHP	0.2761594	0.6933466	0.14102784	0.4457102
WS	EHP	1.7697335	1.5429108	1.99655619	0
SC	SLV	2.4938976	6.3551484	1.36735323	0.4771501
SW	SLV	1.6168354	5.4924031	2.2587323	0.8825179

WS	SLV	0.4290575	3.4306612	4.28877618	0.9999011
SW	SC	0.8770622	0.4832678	1.27085655	0
WS	SC	2.9229551	2.7427403	3.10316983	0
WS	SW	2.0458929	1.6674163	2.42436945	0

Discussion

This study strived to answer the research question: How do VOC estimated emission levels from oil and natural gas compare to the annual throughput of each monitored extraction site, and how do these variables differ among seven regions in the state of Colorado? From inferences, these three variables are contingent upon one another and factors, such as oil throughput and region, show the VOCs emission will vary depending on how much one extracts and where you are located in the state. These variables are specifically compared showing the levels of these factors and how they influence VOC rates across the state in the Appendices. To answer the research question, there is a trend in the location of a drill site, along with how much a company will extract, to produce the VOCs we record today.

The relationship of region and range of annual throughput onto VOCs estimated emission levels was examined providing interesting results. From annual throughput means and standard deviations, one can see the DMNFR is the overwhelmingly highest oil extraction region in this dataset (*M=1853.92, SD=1853.92*), followed by Southwest, South Central, Western Slope, Eastern High Plains, Central Mountains, and San Louis Valley in descending order. The amount of crude oil being run through a given facility is highest in the DMNFR, most likely due to Weld County's oil production and monitored sites. DMNFR is consistent with other studies in predicting oil extraction in Colorado and approximating high levels of oil reserves found in the Denver-Julesburg Basin (Pétron, G. et al., 2012). One can decipher this result instinctively since the Denver-Julesburg Basin is a profitable oil reserve for Colorado, providing a large region for extraction in the northern part of the state.

Since the majority of hydraulic fracturing occurs in the DMNFR region, it is also inevitable the highest amount of crude oil of annual throughput would occur in this region. Specifically, conclusions can be drawn about the amount of extraction in the

DMNFR and explicitly state this region consists of the most amount of oil extraction in Colorado. It is important to note the means of annual throughput are for the numeric values existing in the dataset, including zeros. The summary statistics were calculated separately of the range of annual throughput and therefore are in the units of million cubic feet.

The means of VOCs indicate the Central Mountains is the highest (M=7.92, SD=18.28) followed by the Western Slope, Eastern High Plains, DMNFR, San Louis Valley, Southwest, and South Central, respectively. Although one might expect means of VOCs and annual throughput to correlation directly, the difference between VOCs means and means of annual throughput indicates highest extraction region does not correlate to the highest VOCs estimated emission levels for each region. The Central Mountains proved to contain the most polluting mean of VOCs while the DMNFR region came in with a much smaller mean value of VOCs. Since the Central Mountains is the highest polluting region averaged by monitoring sites, one can conclude this region regardless of the amount of ONG being extracted, contains the highest polluting locations. One explanation for the polarity between means of regions could be due to the DMNFR sites consisting of numerous inputs valued at zero, while the Central Mountains had fewer inputs, but ones that had higher VOCs estimated emission levels.

Type of equipment inspected can also influence the number of VOCs produced, showing more extraction taking place in DMNFR, but more polluting equipment per site in the Central Mountains. This indicates the equipment being used, aggregated by site, could potentially be outdated leading to higher VOC levels. Additionally, the sheer number of inputs of sites can alter means, which are not completely representative of air pollution of VOCs. As shown in the database, the number of VOCs coming from the DMNFR is drastically higher than any other region, but the value is correlated to the 19,043 inputs. No other region had over 6,000 inputs and therefore this dataset is mainly comprised of DMNFR inputs. Therefore, when calculating means of VOCs and annual throughput for each region, the DMNFR region obviously contains more equipment inputs for extraction sites and could skew the average of a total region to disguise itself as producing less than regions with fewer inputs.

The ANOVA test concludes a few characteristics about the factors of region and range of annual throughput onto VOCs. First, the levels of the region are associated with significantly different logs of VOCs. Comprehensively interpreting this result means that between each region, a significant difference occurs in means of the log of VOCs estimated emission levels. One could expect this result solely based on this report representing a monitoring year and not an oversight of total VOCs estimated emission levels in Colorado. If all regions were equally monitored in sites and the count across all regions were even, a determination that between each region, a significant difference in means of logs of VOCs estimated emission levels would indicate one region is significantly producing more VOCs than another.

Secondly, the ANOVA determines the categorical levels of annual throughput are associated with significantly different logs of VOCs. In laymen terms, the categorical factor of annual throughput, with levels of zero, low, medium, and high, are all associated with statistically significant different logs of VOCs. This determination shows the annual throughput category is related to different levels of logs of VOCs, which could suggest significant different levels of VOCs depend on the amount of crude oil extracted by the facility. This indicates annual throughput categories vary in relation to different levels of logs of VOCs. An important finding is VOCs estimated emission levels are primarily influenced by annual throughput across the state, meaning this variable has the most impact on VOCs estimated emission levels.

Lastly, the ANOVA indicates the interaction between the range of annual throughput and region is significant, showing a relationship between the category of annual throughput and the log of VOCs depends on region. Therefore, depending on the annual throughput compared to VOCs, this interaction will be different among all seven regions included in this study. Different regions produce varying amounts of annual throughput and VOCs, so when cross-examined by region a statistical difference will be encountered when going from one to another. The topography, geologic underlying rock, and extraction practices are all variations to determine how polluting and profitable a region will be. An area where the geologic material is extracted efficiently will make for a high producing region while allowing for these precursors to be exposed.

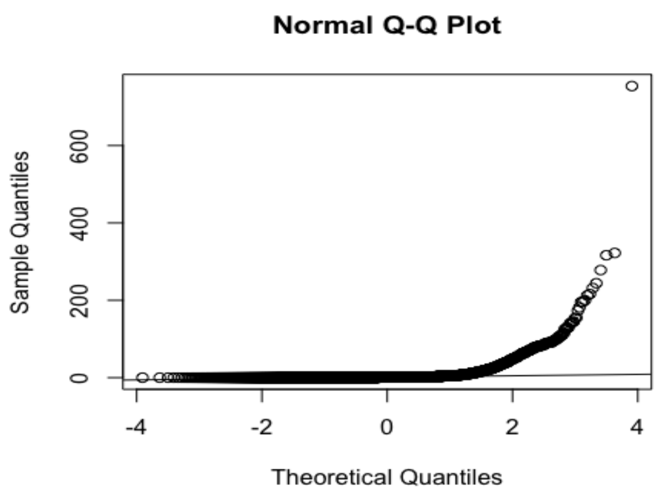
By analyzing the sums of squares from the ANOVA, one can determine which independent variable has more of an effect on the dependent variable. In this case, the sums of square for a region (5952) was less than the sums of square for range (6154) determining that range has more of an influence on VOCs than region does. It is important to note that VOCs would be more influenced by the range of annual throughput than it would be region. Consequently, this proves VOCs are not usually determined off of one location of high air pollutants, but all drill sites pollute and those with higher annual throughput will be indicative of VOCs.

The Tukey HSD test was able to determine between which range category in addition to a region will prove a significant difference onto the log of VOCs. The Tukey HSD results follow this paper in the Appendices and show the significant relationships between range and region onto the log of VOCs. In total, I found that there were 378 combinations of range and regions were conducted. Out of the 378 combinations, 231 were applicable in this dataset and had values to be compared. The remaining 147 combinations did not contain inputs for specific ranges of annual throughput or regions that could be compared, and therefore were unfeasible in statistically comparing. From the 231 valid combinations, 104 proved to be significantly differently while 127 did not. For more information on specific differences between region and range onto the log of VOCs refer to the Appendix.

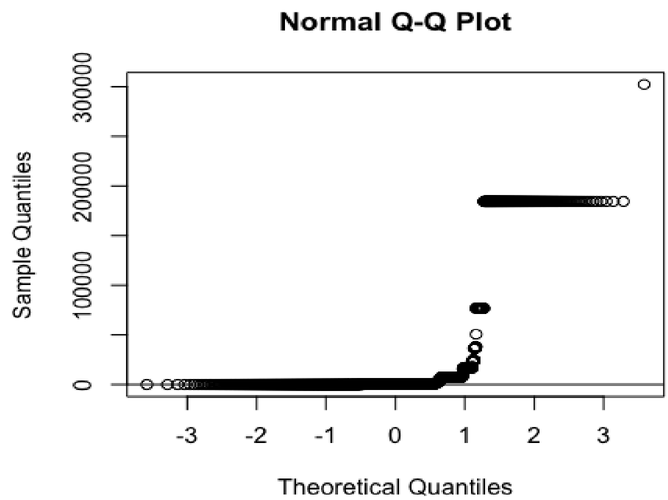
A big component of the significant differences values for all runs of the Tukey HSD could be related to the vast amount of data inputs in this database. Since there were 27,643 data inputs for the air inventory data, it is difficult to determine if a difference occurs because of the number of inputs or if the means truly do statistically compare differently. One way to confirm if a true difference occurs would be with a correlation coefficient, or a number between -1 and 1 to represent the linear dependence of the two variables, which could not be determined with the ANOVA test run in this study. This study still concludes that significant differences do truly occur between the variables, but a correlation coefficient could explain to what degree those differences are accurate.

Another factor influencing this dataset would be the abnormal distribution inputs. Since much of the dataset consists of zero, the distribution of annual throughput and VOCs estimated emission levels by extraction site before log transformation is not normally distributed, shown by the Q-Q plot (Plot 4 & Plot 5). The quantile-quantile plot is a probability plot, which is a graphical method for comparing two probability distributions by plotting their quantiles against each other. If the two distributions being compared were similar, the points on the Q-Q plot will approximately lie on the line y=x. If this dataset was parametric and was normally distributed, it would follow the horizontal line and show the graphical representation of these two variables onto one another. Since the point do not follow the line for both VOCs and annual throughput, non-parametric statistics are used.

Plot 4: Q-Q plot of VOCs estimated emission levels by site



Plot 5: Q-Q plot of annual throughput by site



In particular, the regulations being implemented and prioritized are not sufficiently defined and explicit. Revisions occurring to Regulation No. 7, along with violation in nonattainment areas in Colorado, show the regulation is lagging and only a parameter to meet. Although an infrared camera and auditory-visual-olfactory inspection are required upon inspection to register VOCs, the increased classification in severity for the nonattainment area indicates the difference between federal air regulations and those being produced in the DMNFR. The potential upcoming designation of “Serious” classification for the 8-hour nonattainment area has shown ozone to be a continuous issue in the nonattainment area and extraction practices of ONG contribute directly to this ground-level smog. With current inventory data, the APCD has determined the “Serious” classification is bound to happen for Colorado and therefore increasing federal air violations by multiple degrees.

One factor influencing the increase in classification could be due to the variety of unrecognized VOCs being extracted from drill sites. For example, with an automobile in Colorado, all emitted compounds are recognized and measured. Additionally, to stop excessive pollution from transportation such as a car, required pollutants are monitored and analyzed on a two-year basis in order to be issued a valid registration. VOCs emitted from driving can be reduced by simply refraining to drive. In the ONG industry, these components are not entirely recognized and depending on the location of a drill site, an array of VOCs can be present. One finds this with different VOCs being emitted from extraction sites across the United States. Geologic material differs with regions and the VOCs contained in this material is expected to vary. The baseline for VOCs in Colorado depends on the size of extraction, location, and the material being processed and refined. VOC from ONG is much more difficult to refrain from releasing due to continued extraction, regardless of VOCs emitted, without the proper monitoring in place.

VOCs ranging from both transportation and energy alter differently, but if abatement is a statewide objective, then all industries must be considered, along with their complementary practices. For ONG, Colorado must consider the reality to refrain from exposing ozone precursors to the environment, through reducing the amount of extraction occurring in the state. Colorado is unique in terms of energy production in the United States, which means specific regulations and rules must not only be in place but harsh incentives not to extract and ultimately refrain from releasing toxins to the environment must develop. Other states do not face the same ONG extraction issues as Colorado, meaning a state such as Colorado is a beneficial place to start this abatement on a national level.

Not only does Colorado continuously strive to meet EPA regulations, but the regulations put in place to control ground-level ozone do not to combat the root of the problem. The upcoming classification in July 2018 will justify the current ozone levels exceeding federal standards, concluding the severity of the problem from ONG. The increase in classification for previous years shows this pattern of regulations not sufficiently resolving the precursors to air pollution results in ozone, while current practices of hydraulic fracturing and extraction continuing to occur. The only way to truly combat this issue of nonattainment ozone would be to reduce the practice of ONG in the nonattainment region.

No regulation will solve this issue. Extraction alone is a major contributor to ozone, while regulation is only a financial incentive to reduce pollutants. Many stakeholders, in addition to the state, seek regulation as the best remediation practice. Since it is near to impossible to completely halt the ONG extraction practices occurring, Colorado has much work in terms of developing strategies and techniques to reduce these undesired pollutants.

From this research, the disconnect between the APCD and the COGCC is apparent and there is a need for future interaction between these departments. Although monitoring occurs, the COGCC is the responsible agency in the development of Colorado's ONG aligning with public health, safety, and environmental protection in the state. The APCD is on the receiving end of emissions and only monitors the emission component of the ONG industry. A combination of strategies, developed from both of these departments, is necessary for VOC trend levels to decrease and provide a habitable surface level environment for the local population. Currently, there is little interaction between these departments with no future plan to coordinate similar interventions of the ONG industry.

Additionally, the results from this study indicate that such mechanisms for VOC abatement have not been developed to a sufficient degree. The community, as well as the APCD, are relying on methods that use sight-see-smell procedures when other technologies, which could be more expensive but accurate, are available. There has been a future discussion of aerial technologies, but the state department has yet to fully fund these activities and show improvements in their monitoring methods. In 2016, the APCD is very much relying on human senses to predict VOC rates for the monitoring year, allowing for leaks to and sites to easily go unnoticed. The practice of monitoring pollutants is a difficult, convoluted process that will include many trial and error scenarios. One monitoring method will always need to be utilized, but using a combination of monitoring methods with proven reliability is a valid route the APCD can implement.

The APCD also includes in their database inputs missing for certain VOCs, such as benzene, indicating that not all individual VOCs are recorded for the monitoring year. A compound such as benzene, as stated previously in this paper, is harmful to human health and exposure can have serve effects. The APCD has benzene listed for certain sites, but there are additional inputs missing for other sites of VOCs and only aggregates total VOCs instead of specific compounds. Due to aggregation, there could be flaws in each compound being monitored precisely and uninformed records for each pollutant.

The APCD, although having limited inspection options with only 12 inspectors for the entire monitoring year, could implement a process to record each pollutant precisely and consistently for every inspection year. Due to only some pieces of equipment monitored with benzene, this is additional proof every site polluting benzene is not considered every year, causing harm to those in proximity.

Conclusion

In conclusion, discussion points produced from this study are only a subset of the entire ozone issue Colorado faces today. This study aimed to examine monitored VOCs across Colorado to determine where extraction is occurring, and how do those air pollutants vary across regions. Noticeably, it is apparent the implementation of regulations for ozone we see today have not been prioritized and are only used to keep up with extraction rates and VOCs releasement. The ACPD regulates these air pollutants and precursors to ozone, but it has been evident that increased regulation is not the solution to ground-level ozone.

Since this study only examines VOCs estimated emission levels to region and range of annual throughput for the 2016 year, a future study could investigate how region and range of throughput correlation to other criteria pollutants the EPA monitors. Additionally, a future study could incorporate multiple years of APCD inventory data to see how ozone formation across Colorado has changed with the regulations implemented. This study was able to produce findings of VOCs to annual throughput and region for a shot in time of 2016, but not over the extensive history of ozone in Colorado. Another study could incorporate how pollution affects ozone and what this means for the population residing in the Front Range of Colorado. Since ONG production is very high in areas incorporating population, one must consider how ozone directly affects humans in proximity. Furthermore, this study examines VOCs only in ONG extraction while not considering VOCs emitted from transportation.

This study proposes future research into publically available data collected by the APCD. A starting point to monitoring pollutants can be drawn from this study and produced an origin for monitoring EPA criteria pollutants. The state of Colorado can begin to investigate into future ozone levels based on recordings from the 2016 monitoring year. From here, the APCD can start to produce records that can be publically viewed on both extraction and pollutants which everyone can grasp. Due to difficult laymen interpretation of state air inventory data, the future of publishing studies with feasible interpretation is crucial in reducing ground-level ozone from all sectors.

Some limitations during this study were the allotted time, relying heavily on coherent APCD inventory data, properly converting all units, and running statistical tests with the outlier's present. The air inventory data is only a starting point for an actual depiction of true ozone levels, which means this data is always varying with time. Furthermore, the conversion of all units to standardize was used, but within the dataset, there could have a few inputs exaggerated after conversion. This study aimed to use non-parametric statistical tests to accurately represent the abnormal distribution of the state, which could also have led to some insecurities. Although recognizing these potential margins of error, the validity of this study still holds true to the results and conclusions produced.

Appendices

R-Studio Script to run statistical tests

1. #Initializations---------------
   CDPHE3=read.csv(file.choose("Downloads/CDPHE3.csv"))
   head(CDPHE3)
   str(CDPHE3)
   require(plyr)
   library(nlme)
   install.packages("lme4")
   library(lme4)
   require(classInt)

2. #Aggregating the data by site
   ByID=ddply(
3. 13CDPHE3,
4. .(ID,REGION),
5. summarize,
6. "THROUGHPUT"=sum(STANDARDIZATION),
7. "VOC"=sum(VOC)
8.)

9. ByID

10. summary(ByID)
11. #First Plots-------------
12. #Just plotting Throughput and VOCs without transformation
13. plot(ByID$VOC~ByID$THROUGHPUT)

14. #THROUGHPUT vs. VOCs (log-transformed) (NOTICE NO ZEROS (-Inf))
15. PLOT1=plot(log(ByID$VOC)~log(ByID$THROUGHPUT), xlab="Throughput (1000000 ft^3)",ylab="VOC (Tons/year)")

16. #Wilcoxon Rank Test between VOC and throughput
17. #non-parametric
18. wilcox.test(ByID$VOC,ByID$THROUGHPUT)

19. #First ANOVAS and Kruskal-Wallis (non-parametric)------------------
20. #ANOVA between VOC and REGION (each site is one record)
21. VOCREGION.kruskal=kruskal.test(ByID$VOC~ByID$REGION)
22. VOCREGION.kruskal

23. #Spearman's rank correlaiton (for reference, not necessary)

```
24. VOCREGIONspear=cor.test(ByID$THROUGHPUT,ByID$VOC,method="spear
    man")
25. VOCREGIONspear

26. #Boxplot showing the VOCs by region (log transformed so that differences can be
    seen)
27. PLOT2=boxplot(log(ByID$VOC)~ByID$REGION,
    xlab="Region",ylab="VOC(Tons/year)", cex.axis=0.30, col.lab="blue",
    col="cyan2")

28. #TWO-WAY ANOVAS---------------------
29. #Defining throughput into 4 categorical classes for ANOVA
30. RANGE2<- classIntervals(log(CLEAN), 3, style="kmeans")
31. RANGE2

32. for(i in 1:length(ByID$VOC)){
33. if(ByID$THROUGHPUT[i]<0.000000000000000001){
34. ByID$RANGE[i]="ZERO"
35. } else if (ByID$THROUGHPUT[i]>0 & ByID$THROUGHPUT[i]<0.15337889)
    {
36. ByID$RANGE[i]="LOW"
37. } else if (ByID$THROUGHPUT[i]>0.15337889 &
    ByID$THROUGHPUT[i]<49.2988128){
38. ByID$RANGE[i]="MEDIUM"
39. } else if (ByID$THROUGHPUT[i]>49.2988128){
40. ByID$RANGE[i]="HIGH"
41. }
42. }


43. #Remove zeroes from throughput for log transforming
44. CLEAN=ByID$THROUGHPUT
45. length(ByID$THROUGHPUT)
46. CLEAN=CLEAN[which(CLEAN>0)]
47. length(CLEAN)

48. #Remove zeroes from VOC for log transforming
49. CLEANVOC=ByID$VOC
50. length(ByID$VOC)
51. CLEANVOC=CLEANVOC[which(CLEANVOC>0)]
52. length(CLEANVOC)


53. #Two-way Analysis of Variance (ANOVA)
```

54. VOCREGION_RANGE.aov<-aov(log(CLEANVOC)~ByID$RANGE[ByID$VOC>0]*ByID$REGION[ByID$VOC>0])

55. hist(VOCREGION_RANGE.aov$residuals)
56. summary(VOCREGION_RANGE.aov)
57. plot(VOCREGION_RANGE.aov)

58. TukeyHSD(VOCREGION_RANGE.aov)

59. tuk<-TukeyHSD(VOCREGION_RANGE.aov)

60. plot(TukeyHSD(VOCREGION_RANGE.aov))

61. plot(TukeyHSD(VOCREGION_RANGE.aov,
```
        xlab="Difference in Means",
        ylab="Comparison",
        axis.adjust= 0,
        adjust.x.spacing = 5))
```

62. plot(TukeyHSD(VOCREGION_RANGE.aov,
```
        xlab="Difference in Means",
        ylab="Comparison",
        axis.adjust= 0,
        adjust.x.spacing = 5), yaxt = 'n', col=c('red', 'orange', 'yellow',
                                   'green', 'cyan', 'blue', 'purple'))
```

63. options(max.print = 100000000)

64. #This shows that data are not normally distributed
65. qqnorm(ByID$VOC)
66. qqline(ByID$VOC)

67. qqnorm(ByID$THROUGHPUT[ByID$THROUGHPUT])
68. qqline(ByID$THROUGHPUT)
69. #Big outlier in this one, but it's still not normal even if excluded

70. #Non-parametric anovas (not log-transformed, 0s included)
71. kruskal.test(ByID$VOC~ByID$RANGE)
72. kruskal.test(ByID$VOC~ByID$REGION)

```
#Means and SD for each REGION------------------------
require("plyr")
ByREGION=ddply(CDPHE3,
.(REGION),
summarise,
MeanVOC = mean(VOC),
SDVOC = sd(VOC),
MeanTHROUGH=mean(STANDARDIZATION),
SDTHROUGH=mean(STANDARDIZATION),
COUNT=length(VOC)
)


ByREGION

plot(ByREGION)
```

Table 7: Tukey HSD results by region and range

REGION 1	REGION 2	Difference	Upper	Lower	P-adj
LOW: CM	HIGH: CM	2.10138522	4.53214824	0.329377795	0.2198028
MEDIUM: CM	HIGH: CM	1.41891769	2.7965667	0.041268686	0.0340047
ZERO: CM	HIGH: CM	NA	NA	NA	NA
HIGH: DMNFR	HIGH: CM	0.19252202	0.94082708	1.325871116	1
LOW: DMNFR	HIGH: CM	3.97570662	5.06492313	2.886490106	0
MEDIUM: DMNFR	HIGH: CM	1.92161109	3.01638025	0.826841927	0
ZERO: DMNFR	HIGH: CM	2.69088326	4.72460551	0.657161006	0.0003152
HIGH: EHP	HIGH: CM	1.00342159	2.25116817	0.244324992	0.3637159
LOW: EHP	HIGH: CM	2.53497805	3.78764382	1.28231228	0
MEDIUM: EHP	HIGH: CM	4.9880188	6.12117163	3.854865967	0
ZERO: EHP	HIGH: CM	2.94826599	5.08322961	0.813302362	0.0001056
HIGH: SLV	HIGH: CM	NA	NA	NA	NA
LOW: SLV	HIGH: CM	NA	NA	NA	NA
MEDIUM: SLV	HIGH: CM	2.85485486	7.83643665	2.126726934	0.9409605
ZERO: SLV	HIGH: CM	NA	NA	NA	NA
HIGH: SC	HIGH: CM	0.99163372	2.54908017	0.565812718	0.8373966
LOW: SC	HIGH: CM	NA	NA	NA	NA
MEDIUM: SC	HIGH: CM	5.39701935	6.50063654	4.293402158	0
ZERO: SC	HIGH: CM	5.19425392	10.17583571	0.212672132	0.0286962
HIGH: SW	HIGH: CM	0.95109367	2.98481592	1.08262858	0.9957897
LOW: SW	HIGH: CM	1.26294805	4.27290932	1.74701323	0.9992611
MEDIUM: SW	HIGH: CM	4.65247473	5.84231761	3.462631848	0
ZERO: SW	HIGH: CM	NA	NA	NA	NA
HIGH: WS	HIGH: CM	0.85157026	1.98994533	0.286804801	0.5281458
LOW: WS	HIGH: CM	2.82446177	3.92618324	1.722740295	0
MEDIUM: WS	HIGH: CM	2.39773881	3.50659622	1.2888814	0
ZERO: WS	HIGH: CM	3.34112893	6.00389641	0.678361462	0.0010738
MEDIUM: CM	LOW: CM	0.68246753	1.65057385	3.015508911	0.9999994
ZERO: CM	LOW: CM	NA	NA	NA	NA
HIGH: DMNFR	LOW: CM	2.29390724	0.0962618	4.491552679	0.02827
LOW: DMNFR	LOW: CM	1.8743214	4.04953585	0.300893057	0.2255621
MEDIUM: DMNFR	LOW: CM	0.17977413	1.99822606	2.357774321	1
ZERO: DMNFR	LOW: CM	0.58949803	3.36099429	2.181998221	1
HIGH: EHP	LOW: CM	1.09796363	1.16080525	3.356732507	0.9925749
LOW: EHP	LOW: CM	0.43359283	2.69508279	1.827897131	1
MEDIUM: EHP	LOW: CM	2.88663358	5.08417781	0.689089348	0.0003758
ZERO: EHP	LOW: CM	0.84688077	3.69349893	1.999737401	0.9999991
HIGH: SLV	LOW: CM	NA	NA	NA	NA
LOW: SLV	LOW: CM	NA	NA	NA	NA
MEDIUM: SLV	LOW: CM	0.75346964	6.07900458	4.572065309	1
ZERO: SLV	LOW: CM	NA	NA	NA	NA
HIGH: SC	LOW: CM	1.1097515	1.33377152	3.553274512	0.9973127

LOW: SC	LOW: CM	NA	NA	NA	NA
MEDIUM: SC	LOW: CM	3.29563413	5.47809517	1.113173083	0.0000077
ZERO: SC	LOW: CM	3.0928687	8.41840365	2.232666243	0.9319542
HIGH: SW	LOW: CM	1.15029155	1.6212047	3.921787807	0.9993866
LOW: SW	LOW: CM	0.83843717	2.71191946	4.388793803	1
MEDIUM: SW	LOW: CM	2.55108951	4.77839537	0.323783649	0.0064836
ZERO: SW	LOW: CM	NA	NA	NA	NA
HIGH: WS	LOW: CM	1.24981496	0.95042664	3.450056557	0.946393
LOW: WS	LOW: CM	0.72307655	2.90457958	1.458426493	0.9999912
MEDIUM: WS	LOW: CM	0.29635359	2.48146916	1.888761982	1
ZERO: WS	LOW: CM	1.23974371	4.50095452	2.021467092	0.9998723
ZERO: CM	MEDIUM: CM	NA	NA	NA	NA
HIGH: DMNFR	MEDIUM: CM	1.61143971	0.70647925	2.516400162	0
LOW: DMNFR	MEDIUM: CM	2.55678893	3.40582712	1.707750735	0
MEDIUM: DMNFR	MEDIUM: CM	0.5026934	1.35884336	0.353456566	0.9237539
ZERO: DMNFR	MEDIUM: CM	1.27196556	3.18782032	0.643889187	0.7732568
HIGH: EHP	MEDIUM: CM	0.4154961	0.62917839	1.460170584	0.9997093
LOW: EHP	MEDIUM: CM	1.11606036	2.16660535	0.06551537	0.0219322
MEDIUM: EHP	MEDIUM: CM	3.56910111	4.47381575	2.664386467	0
ZERO: EHP	MEDIUM: CM	1.5293483	3.55235174	0.493655145	0.5039586
HIGH: SLV	MEDIUM: CM	NA	NA	NA	NA
LOW: SLV	MEDIUM: CM	NA	NA	NA	NA
MEDIUM: SLV	MEDIUM: CM	1.43593717	6.37057296	3.498698625	0.9999994
ZERO: SLV	MEDIUM: CM	NA	NA	NA	NA
HIGH: SC	MEDIUM: CM	0.42728397	0.97275627	1.827324202	0.9999984
LOW: SC	MEDIUM: CM	NA	NA	NA	NA
MEDIUM: SC	MEDIUM: CM	3.97810166	4.84553704	3.110666273	0

ZERO: SC	MEDIUM: CM	3.77533623	8.70997202	1.159299559	0.4764453
HIGH: SW	MEDIUM: CM	0.46782402	1.44803073	2.383678773	1
LOW: SW	MEDIUM: CM	0.15596964	2.77564086	3.087580145	1
MEDIUM: SW	MEDIUM: CM	3.23355704	4.20833872	2.258775358	0
ZERO: SW	MEDIUM: CM	NA	NA	NA	NA
HIGH: WS	MEDIUM: CM	0.56734743	0.34389953	1.478594392	0.8661183
LOW: WS	MEDIUM: CM	1.40554408	2.2705663	0.540521854	0.0000006
MEDIUM: WS	MEDIUM: CM	0.97882112	1.85291379	0.104728448	0.0095693
ZERO: WS	MEDIUM: CM	1.92221124	4.49608068	0.651658188	0.5319439
HIGH: DMNFR	ZERO: CM	NA	NA	NA	NA
LOW: DMNFR	ZERO: CM	NA	NA	NA	NA
MEDIUM: DMNFR	ZERO: CM	NA	NA	NA	NA
ZERO: DMNFR	ZERO: CM	NA	NA	NA	NA
HIGH: EHP	ZERO: CM	NA	NA	NA	NA
LOW: EHP	ZERO: CM	NA	NA	NA	NA
MEDIUM: EHP	ZERO: CM	NA	NA	NA	NA
ZERO: EHP	ZERO: CM	NA	NA	NA	NA
HIGH: SLV	ZERO: CM	NA	NA	NA	NA
LOW: SLV	ZERO: CM	NA	NA	NA	NA
MEDIUM: SLV	ZERO: CM	NA	NA	NA	NA
ZERO: SLV	ZERO: CM	NA	NA	NA	NA
HIGH: SC	ZERO: CM	NA	NA	NA	NA
LOW: SC	ZERO: CM	NA	NA	NA	NA
MEDIUM: SC	ZERO: CM	NA	NA	NA	NA
ZERO: SC	ZERO: CM	NA	NA	NA	NA
HIGH: SW	ZERO: CM	NA	NA	NA	NA
LOW: SW	ZERO: CM	NA	NA	NA	NA
MEDIUM: SW	ZERO: CM	NA	NA	NA	NA
ZERO: SW	ZERO: CM	NA	NA	NA	NA
HIGH: WS	ZERO: CM	NA	NA	NA	NA
LOW: WS	ZERO: CM	NA	NA	NA	NA
MEDIUM: WS	ZERO: CM	NA	NA	NA	NA
ZERO: WS	ZERO: CM	NA	NA	NA	NA

LOW: DMNFR	HIGH: DMNFR	4.16822863	4.49599265	3.840464614	0
MEDIUM: DMNFR	HIGH: DMNFR	2.11413311	2.45990205	1.768364157	0
ZERO: DMNFR	HIGH: DMNFR	2.88340527	4.63185111	1.134959438	0.0000003
HIGH: EHP	HIGH: DMNFR	1.19594361	1.88725264	0.504634572	0.0000001
LOW: EHP	HIGH: DMNFR	2.72750007	3.42764875	2.027351385	0
MEDIUM: EHP	HIGH: DMNFR	5.18054082	5.63338956	4.727692069	0
ZERO: EHP	HIGH: DMNFR	3.140788	5.00602427	1.275551737	0.0000002
HIGH: SLV	HIGH: DMNFR	NA	NA	NA	NA
LOW: SLV	HIGH: DMNFR	NA	NA	NA	NA
MEDIUM: SLV	HIGH: DMNFR	3.04737687	7.91945998	1.824706233	0.8605324
ZERO: SLV	HIGH: DMNFR	NA	NA	NA	NA
HIGH: SC	HIGH: DMNFR	1.18415574	2.34461947	0.023692012	0.038528
LOW: SC	HIGH: DMNFR	NA	NA	NA	NA
MEDIUM: SC	HIGH: DMNFR	5.58954136	5.96237853	5.216704203	0
ZERO: SC	HIGH: DMNFR	5.38677594	10.25885904	0.514692833	0.0118123
HIGH: SW	HIGH: DMNFR	1.14361569	2.89206152	0.604830148	0.7976982
LOW: SW	HIGH: DMNFR	1.45547006	4.28051936	1.369579234	0.9835113
MEDIUM: SW	HIGH: DMNFR	4.84499674	5.42530935	4.264684135	0
ZERO: SW	HIGH: DMNFR	NA	NA	NA	NA
HIGH: WS	HIGH: DMNFR	1.04409228	1.50985448	0.578330074	0
LOW: WS	HIGH: DMNFR	3.01698378	3.38417154	2.649796027	0

MEDIUM: WS	HIGH: DMNFR	2.59026083	2.97833479	2.202186863	0
ZERO: WS	HIGH: DMNFR	3.53365095	5.98545993	1.081841974	0.000032
MEDIUM: DMNFR	LOW: DMNFR	2.05409553	1.9075739	2.200617156	0
ZERO: DMNFR	LOW: DMNFR	1.28482336	0.43534386	3.004990578	0.5316375
HIGH: EHP	LOW: DMNFR	2.97228502	2.35598915	3.588580899	0
LOW: EHP	LOW: DMNFR	1.44072857	0.81453323	2.066923902	0
MEDIUM: EHP	LOW: DMNFR	1.01231218	1.3393969	0.68522747	0
ZERO: EHP	LOW: DMNFR	1.02744063	0.81131404	2.866195303	0.9554064
HIGH: SLV	LOW: DMNFR	NA	NA	NA	NA
LOW: SLV	LOW: DMNFR	NA	NA	NA	NA
MEDIUM: SLV	LOW: DMNFR	1.12085176	3.74115464	5.982858157	1
ZERO: SLV	LOW: DMNFR	NA	NA	NA	NA
HIGH: SC	LOW: DMNFR	2.98407289	1.86667033	4.101475455	0
LOW: SC	LOW: DMNFR	NA	NA	NA	NA
MEDIUM: SC	LOW: DMNFR	1.42131273	1.62359959	1.219025879	0
ZERO: SC	LOW: DMNFR	1.21854731	6.0805537	3.643459091	1
HIGH: SW	LOW: DMNFR	3.02461295	1.30444573	4.744780164	0
LOW: SW	LOW: DMNFR	2.71275857	0.09487673	5.520393865	0.0754101
MEDIUM: SW	LOW: DMNFR	0.67676811	1.16531202	0.188224207	0.0000971
ZERO: SW	LOW: DMNFR	NA	NA	NA	NA
HIGH: WS	LOW: DMNFR	3.12413635	2.77939463	3.468878074	0

LOW: WS	LOW: DMNFR	1.15124485	0.95956994	1.342919757	0
MEDIUM: WS	LOW: DMNFR	1.57796781	1.34880886	1.807126754	0
ZERO: WS	LOW: DMNFR	0.63457768	1.79714592	3.066301284	0.9999999
ZERO: DMNFR	MEDIUM: DMNFR	0.76927217	2.4929607	0.95441637	0.9979596
HIGH: EHP	MEDIUM: DMNFR	0.9181895	0.29213238	1.544246619	0.000019
LOW: EHP	MEDIUM: DMNFR	0.61336696	1.24917158	0.022437657	0.0767495
MEDIUM: EHP	MEDIUM: DMNFR	3.06640771	3.4115328	2.721282626	0
ZERO: EHP	MEDIUM: DMNFR	1.0266549	2.86870421	0.815394413	0.9566871
HIGH: SLV	MEDIUM: DMNFR	NA	NA	NA	NA
LOW: SLV	MEDIUM: DMNFR	NA	NA	NA	NA
MEDIUM: SLV	MEDIUM: DMNFR	0.93324377	5.79649711	3.93000958	1
ZERO: SLV	MEDIUM: DMNFR	NA	NA	NA	NA
HIGH: SC	MEDIUM: DMNFR	0.92997736	0.19283847	2.052793201	0.3012112
LOW: SC	MEDIUM: DMNFR	NA	NA	NA	NA
MEDIUM: SC	MEDIUM: DMNFR	3.47540826	3.70572735	3.245089166	0
ZERO: SC	MEDIUM: DMNFR	3.27264283	8.13589618	1.590610514	0.7497369
HIGH: SW	MEDIUM: DMNFR	0.97051742	0.75317112	2.694205956	0.9513969
LOW: SW	MEDIUM: DMNFR	0.65866304	2.15113106	3.46845714	1
MEDIUM: SW	MEDIUM: DMNFR	2.73086364	3.23166506	2.23006222	0
ZERO: SW	MEDIUM: DMNFR	NA	NA	NA	NA
HIGH: WS	MEDIUM: DMNFR	1.07004083	0.70813785	1.431943807	0

LOW: WS	MEDIUM: DMNFR	0.90285068	1.12390765	0.681793708	0
MEDIUM: WS	MEDIUM: DMNFR	0.47612772	0.73037315	0.221882294	0
ZERO: WS	MEDIUM: DMNFR	1.41951785	3.85373365	1.014697961	0.9289648
HIGH: EHP	ZERO: DMNFR	1.68746166	0.13721754	3.512140866	0.1202911
LOW: EHP	ZERO: DMNFR	0.15590521	1.67214134	1.983951755	1
MEDIUM: EHP	ZERO: DMNFR	2.29713554	4.04545416	0.548816925	0.0003735
ZERO: EHP	ZERO: DMNFR	0.25738273	2.77346149	2.25869603	1
HIGH: SLV	ZERO: DMNFR	NA	NA	NA	NA
LOW: SLV	ZERO: DMNFR	NA	NA	NA	NA
MEDIUM: SLV	ZERO: DMNFR	0.1639716	5.32039864	4.992455437	1
ZERO: SLV	ZERO: DMNFR	NA	NA	NA	NA
HIGH: SC	ZERO: DMNFR	1.69924953	0.34970681	3.748205869	0.2985809
LOW: SC	ZERO: DMNFR	NA	NA	NA	NA
MEDIUM: SC	ZERO: DMNFR	2.70613609	4.4354578	0.976814389	0.0000023
ZERO: SC	ZERO: DMNFR	2.50337067	7.6597977	2.653056371	0.9927058
HIGH: SW	ZERO: DMNFR	1.73978959	0.69097343	4.170552602	0.6269466
LOW: SW	ZERO: DMNFR	1.42793521	1.86333347	4.719203891	0.9987082
MEDIUM: SW	ZERO: DMNFR	1.96159147	3.74717506	0.17600789	0.0131017
ZERO: SW	ZERO: DMNFR	NA	NA	NA	NA
HIGH: WS	ZERO: DMNFR	1.83931299	0.08760513	3.591020857	0.025989
LOW: WS	ZERO: DMNFR	0.13357851	1.86169102	1.594534001	1

MEDIUM: WS	ZERO: DMNFR	0.29314445	1.43952615	2.025815045	1
ZERO: WS	ZERO: DMNFR	0.65024568	3.62731022	2.326818859	1
LOW: EHP	HIGH: EHP	1.53155646	2.40482591	0.65828701	0
MEDIUM: EHP	HIGH: EHP	3.98459721	4.67558443	3.293609987	0
ZERO: EHP	HIGH: EHP	1.94484439	3.88172273	0.007966062	0.0474774
HIGH: SLV	HIGH: EHP	NA	NA	NA	NA
LOW: SLV	HIGH: EHP	NA	NA	NA	NA
MEDIUM: SLV	HIGH: EHP	1.85143326	6.75139093	3.048524402	0.999886
ZERO: SLV	HIGH: EHP	NA	NA	NA	NA
HIGH: SC	HIGH: EHP	0.01178787	1.26063793	1.284213668	1
LOW: SC	HIGH: EHP	NA	NA	NA	NA
MEDIUM: SC	HIGH: EHP	4.39359776	5.03500161	3.752193905	0
ZERO: SC	HIGH: EHP	4.19083233	9.09079	0.709125336	0.238969
HIGH: SW	HIGH: EHP	0.05232792	1.77235128	1.877007123	1
LOW: SW	HIGH: EHP	0.25952646	3.13238129	2.613328376	1
MEDIUM: SW	HIGH: EHP	3.64905314	4.42953637	2.868569903	0
ZERO: SW	HIGH: EHP	NA	NA	NA	NA
HIGH: WS	HIGH: EHP	0.15185133	0.54766692	0.851369581	1
LOW: WS	HIGH: EHP	1.82104018	2.45917668	1.182903669	0
MEDIUM: WS	HIGH: EHP	1.39431722	2.04469615	0.743938288	0
ZERO: WS	HIGH: EHP	2.33770734	4.84444997	0.169035286	0.1105515
MEDIUM: EHP	LOW: EHP	2.45304075	3.15287168	1.753209819	0
ZERO: EHP	LOW: EHP	0.41328794	2.35333888	1.526763008	1
HIGH: SLV	LOW: EHP	NA	NA	NA	NA
LOW: SLV	LOW: EHP	NA	NA	NA	NA
MEDIUM: SLV	LOW: EHP	0.31987681	5.22108943	4.581335811	1
ZERO: SLV	LOW: EHP	NA	NA	NA	NA
HIGH: SC	LOW: EHP	1.54334432	0.26609438	2.820594265	0.0023623
LOW: SC	LOW: EHP	NA	NA	NA	NA
MEDIUM: SC	LOW: EHP	2.8620413	3.51296287	2.211119726	0
ZERO: SC	LOW: EHP	2.65927587	7.56048849	2.241936745	0.9683879
HIGH: SW	LOW: EHP	1.58388438	0.24416217	3.411930927	0.215906
LOW: SW	LOW: EHP	1.27203	1.60296476	4.147024764	0.9982235
MEDIUM: SW	LOW: EHP	2.11749668	2.90582026	1.329173097	0
ZERO: SW	LOW: EHP	NA	NA	NA	NA
HIGH: WS	LOW: EHP	1.68340779	0.97515234	2.391663233	0
LOW: WS	LOW: EHP	0.28948372	0.93718596	0.358218523	0.9979121
MEDIUM: WS	LOW: EHP	0.13723924	0.52252795	0.79700643	1
ZERO: WS	LOW: EHP	0.80615089	3.3153457	1.703043926	0.9999953

ZERO: EHP	MEDIUM: EHP	2.03975281	0.1746358	3.904869829	0.014077
HIGH: SLV	MEDIUM: EHP	NA	NA	NA	NA
LOW: SLV	MEDIUM: EHP	NA	NA	NA	NA
MEDIUM: SLV	MEDIUM: EHP	2.13316394	2.73887351	7.005201396	0.9985002
ZERO: SLV	MEDIUM: EHP	NA	NA	NA	NA
HIGH: SC	MEDIUM: EHP	3.99638508	2.83611303	5.156657123	0
LOW: SC	MEDIUM: EHP	NA	NA	NA	NA
MEDIUM: SC	MEDIUM: EHP	0.40900055	0.78124067	0.036760428	0.0130667
ZERO: SC	MEDIUM: EHP	0.20623512	5.07827258	4.66580233	1
HIGH: SW	MEDIUM: EHP	4.03692513	2.28860651	5.785243749	0
LOW: SW	MEDIUM: EHP	3.72507075	0.90010019	6.550041318	0.0003426
MEDIUM: SW	MEDIUM: EHP	0.33554407	0.24438513	0.915473277	0.9345876
ZERO: SW	MEDIUM: EHP	NA	NA	NA	NA
HIGH: WS	MEDIUM: EHP	4.13644854	3.67116412	4.601732955	0
LOW: WS	MEDIUM: EHP	2.16355703	1.79697552	2.530138547	0
MEDIUM: WS	MEDIUM: EHP	2.59027999	2.20277959	2.977780389	0
ZERO: WS	MEDIUM: EHP	1.64688987	0.80482839	4.098608123	0.7529356
HIGH: SLV	ZERO: EHP	NA	NA	NA	NA
LOW: SLV	ZERO: EHP	NA	NA	NA	NA
MEDIUM: SLV	ZERO: EHP	0.09341113	5.10377881	5.290601071	1
ZERO: SLV	ZERO: EHP	NA	NA	NA	NA
HIGH: SC	ZERO: EHP	1.95663226	0.19284804	4.106112562	0.1402813
LOW: SC	ZERO: EHP	NA	NA	NA	NA
MEDIUM: SC	ZERO: EHP	2.44875336	4.29607495	0.601431776	0.0003013
ZERO: SC	ZERO: EHP	2.24598794	7.44317788	2.951202004	0.9987891
HIGH: SW	ZERO: EHP	1.99717232	0.51890644	4.513251077	0.3925928

LOW: SW	ZERO: EHP	1.68531794	1.66945374	5.04008962	0.988236
MEDIUM: SW	ZERO: EHP	1.70420874	3.60430143	0.195883945	0.160857
ZERO: SW	ZERO: EHP	NA	NA	NA	NA
HIGH: WS	ZERO: EHP	2.09669572	0.22840133	3.964990114	0.0092254
LOW: WS	ZERO: EHP	0.12380422	1.72238546	1.969993902	1
MEDIUM: WS	ZERO: EHP	0.55052718	1.29992977	2.400984119	0.9999991
ZERO: WS	ZERO: EHP	0.39286295	3.43998565	2.654259752	1
LOW: SLV	HIGH: SLV	NA	NA	NA	NA
MEDIUM: SLV	HIGH: SLV	NA	NA	NA	NA
ZERO: SLV	HIGH: SLV	NA	NA	NA	NA
HIGH: SC	HIGH: SLV	NA	NA	NA	NA
LOW: SC	HIGH: SLV	NA	NA	NA	NA
MEDIUM: SC	HIGH: SLV	NA	NA	NA	NA
ZERO: SC	HIGH: SLV	NA	NA	NA	NA
HIGH: SW	HIGH: SLV	NA	NA	NA	NA
LOW: SW	HIGH: SLV	NA	NA	NA	NA
MEDIUM: SW	HIGH: SLV	NA	NA	NA	NA
ZERO: SW	HIGH: SLV	NA	NA	NA	NA
HIGH: WS	HIGH: SLV	NA	NA	NA	NA
LOW: WS	HIGH: SLV	NA	NA	NA	NA
MEDIUM: WS	HIGH: SLV	NA	NA	NA	NA
ZERO: WS	HIGH: SLV	NA	NA	NA	NA
MEDIUM: SLV	LOW: SLV	NA	NA	NA	NA
ZERO: SLV	LOW: SLV	NA	NA	NA	NA
HIGH: SC	LOW: SLV	NA	NA	NA	NA
LOW: SC	LOW: SLV	NA	NA	NA	NA
MEDIUM: SC	LOW: SLV	NA	NA	NA	NA
ZERO: SC	LOW: SLV	NA	NA	NA	NA
HIGH: SW	LOW: SLV	NA	NA	NA	NA
LOW: SW	LOW: SLV	NA	NA	NA	NA
MEDIUM: SW	LOW: SLV	NA	NA	NA	NA
ZERO: SW	LOW: SLV	NA	NA	NA	NA
HIGH: WS	LOW: SLV	NA	NA	NA	NA
LOW: WS	LOW: SLV	NA	NA	NA	NA
MEDIUM: WS	LOW: SLV	NA	NA	NA	NA
ZERO: WS	LOW: SLV	NA	NA	NA	NA
ZERO: SLV	MEDIUM: SLV	NA	NA	NA	NA
HIGH: SC	MEDIUM: SLV	1.86322113	3.12459934	6.8510416	0.9999079
LOW: SC	MEDIUM: SLV	NA	NA	NA	NA

MEDIUM: SC	MEDIUM: SLV	2.54216449	7.40741726	2.323088276	0.9802034
ZERO: SC	MEDIUM: SLV	2.33939907	9.21463512	4.535836983	0.999985
HIGH: SW	MEDIUM: SLV	1.90376119	3.25266585	7.060188223	0.9999262
LOW: SW	MEDIUM: SLV	1.59190681	4.02169992	7.205513536	0.9999997
MEDIUM: SW	MEDIUM: SLV	1.79761987	6.68315359	3.087913843	0.9999308
ZERO: SW	MEDIUM: SLV	NA	NA	NA	NA
HIGH: WS	MEDIUM: SLV	2.00328459	2.86997011	6.876539295	0.9994802
LOW: WS	MEDIUM: SLV	0.03039309	4.83443001	4.89521619	1
MEDIUM: WS	MEDIUM: SLV	0.45711605	4.40932807	5.323560164	1
ZERO: WS	MEDIUM: SLV	0.48627408	5.92162542	4.949077264	1
HIGH: SC	ZERO: SLV	NA	NA	NA	NA
LOW: SC	ZERO: SLV	NA	NA	NA	NA
MEDIUM: SC	ZERO: SLV	NA	NA	NA	NA
ZERO: SC	ZERO: SLV	NA	NA	NA	NA
HIGH: SW	ZERO: SLV	NA	NA	NA	NA
LOW: SW	ZERO: SLV	NA	NA	NA	NA
MEDIUM: SW	ZERO: SLV	NA	NA	NA	NA
ZERO: SW	ZERO: SLV	NA	NA	NA	NA
HIGH: WS	ZERO: SLV	NA	NA	NA	NA
LOW: WS	ZERO: SLV	NA	NA	NA	NA
MEDIUM: WS	ZERO: SLV	NA	NA	NA	NA
ZERO: WS	ZERO: SLV	NA	NA	NA	NA
LOW: SC	HIGH: SC	NA	NA	NA	NA
MEDIUM: SC	HIGH: SC	4.40538562	5.53683018	3.273941067	0
ZERO: SC	HIGH: SC	4.2026202	9.19044067	0.78520027	0.2671204
HIGH: SW	HIGH: SC	0.04054005	2.00841628	2.089496392	1
LOW: SW	HIGH: SC	0.27131432	3.2915896	2.748960958	1
MEDIUM: SW	HIGH: SC	3.660841	4.87653914	2.445142866	0
ZERO: SW	HIGH: SC	NA	NA	NA	NA
HIGH: WS	HIGH: SC	0.14006346	1.0253093	1.305436221	1
LOW: WS	HIGH:SC	1.83282804	2.96242358	0.703232502	0.0000006
MEDIUM: WS	HIGH: SC	1.40610509	2.54266157	0.269548603	0.001454
ZERO: WS	HIGH: SC	2.34949521	5.02391599	0.324925567	0.1927161

MEDIUM: SC	LOW: SC	NA	NA	NA	NA
ZERO: SC	LOW: SC	NA	NA	NA	NA
HIGH: SW	LOW: SC	NA	NA	NA	NA
LOW: SW	LOW: SC	NA	NA	NA	NA
MEDIUM: SW	LOW: SC	NA	NA	NA	NA
ZERO: SW	LOW: SC	NA	NA	NA	NA
HIGH: WS	LOW: SC	NA	NA	NA	NA
LOW: WS	LOW: SC	NA	NA	NA	NA
MEDIUM: WS	LOW: SC	NA	NA	NA	NA
ZERO: WS	LOW: SC	NA	NA	NA	NA
ZERO: SC	MEDIUM: SC	0.20276543	4.66248734	5.068018194	1
HIGH: SW	MEDIUM: SC	4.44592568	2.71660397	6.175247382	0
LOW: SW	MEDIUM: SC	4.1340713	1.32081798	6.947324623	0.0000179
MEDIUM: SW	MEDIUM: SC	0.74454462	0.22468556	1.264403682	0.0000384
ZERO: SW	MEDIUM: SC	NA	NA	NA	NA
HIGH: WS	MEDIUM: SC	4.54544909	4.15760227	4.933295899	0
LOW: WS	MEDIUM: SC	2.57255758	2.31118129	2.833933876	0
MEDIUM: WS	MEDIUM: SC	2.99928054	2.70929412	3.289266953	0
ZERO: WS	MEDIUM: SC	2.05589041	0.38231753	4.494098357	0.2656983
HIGH: SW	ZERO: SC	4.24316025	0.91326678	9.399587289	0.3146037
LOW: SW	ZERO: SC	3.93130587	1.68230085	9.544912602	0.6728676
MEDIUM: SW	ZERO: SC	0.54177919	4.34375452	5.427312909	1
ZERO: SW	ZERO: SC	NA	NA	NA	NA
HIGH: WS	ZERO: SC	4.34268366	0.53057104	9.215938361	0.1704185
LOW: WS	ZERO:SC	2.36979216	2.49503095	7.234615256	0.992345
MEDIUM: WS	ZERO:SC	2.79651511	2.06992901	7.66295923	0.939192
ZERO: WS	ZERO:SC	1.85312499	3.58222635	7.28847633	0.9999844
LOW: SW	HIGH: SW	0.31185438	3.60312306	2.979414305	1
MEDIUM: SW	HIGH: SW	3.70138106	5.48696464	1.915797475	0
ZERO: SW	HIGH: SW	NA	NA	NA	NA
HIGH: WS	HIGH: SW	0.09952341	1.65218446	1.851231271	1
LOW: WS	HIGH: SW	1.8733681	3.60148061	0.145255585	0.0161582
MEDIUM: WS	HIGH: SW	1.44664514	3.17931574	0.28602546	0.2850366
ZERO: WS	HIGH: SW	2.39003526	5.3670998	0.587029274	0.3674565
MEDIUM: SW	LOW: SW	3.38952668	6.23771021	0.541343148	0.0031893
ZERO: SW	LOW: SW	NA	NA	NA	NA
HIGH: WS	LOW: SW	0.41137779	2.41569157	3.238447141	1
LOW: WS	LOW: SW	1.56151372	4.37402391	1.250996468	0.9585582
MEDIUM: WS	LOW: SW	1.13479076	3.95010391	1.680522383	0.9996314
ZERO: WS	LOW: SW	2.07818089	5.79123273	1.634870953	0.9545596
ZERO: SW	MEDIUM: SW	NA	NA	NA	NA

HIGH: WS	MEDIUM: SW	3.80090447	3.2108364	4.390972536	0
LOW: WS	MEDIUM: SW	1.82801296	1.31219057	2.343835357	0
MEDIUM: WS	MEDIUM: SW	2.25473592	1.72384299	2.785628843	0
ZERO: WS	MEDIUM: SW	1.31134579	1.16708378	3.789775368	0.9767906
HIGH: WS	ZERO: SW	NA	NA	NA	NA
LOW: WS	ZERO: SW	NA	NA	NA	NA
MEDIUM: WS	ZERO: SW	NA	NA	NA	NA
ZERO: WS	ZERO: SW	NA	NA	NA	NA
LOW: WS	HIGH: WS	1.9728915	2.35531071	1.590472298	0
MEDIUM: WS	HIGH: WS	1.54616855	1.94868439	1.143652706	0
ZERO: WS	HIGH: WS	2.48955867	4.94369495	0.035422397	0.041625
MEDIUM: WS	LOW: WS	0.42672296	0.14403688	0.709409037	0.0000077
ZERO: WS	LOW: WS	0.51666717	2.95401763	1.920683295	1
ZERO: WS	MEDIUM: WS	0.94339012	3.38397445	1.497194197	0.9998264

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