AirWaterGas

NSF Sustainability Research Network

SUMMARY
REPORT
2012 to 2016

Providing research on the impacts of oil and gas development in the Rocky Mountain Region of the United States

Colorado School of PUBLIC HEALTH

Colorado State University

NREL

UCAR

AirWaterGas thanks our partners, collaborators and funders for making our NSF-funded project possible.

Acknowledgements
AirWaterGas is a Sustainability Research Network funded by the National Science Foundation to examine the environmental, social, and economic effects of oil and gas development in the Rocky Mountain region of the United States. This summary report highlights researchers' significant results during the grant period from October 2012 to September 2016.

AirWaterGas thanks the National Science Foundation, our external advisory board, and our collaborators and partners for funding, guiding, and contributing to the many facets of this network's research presented in this summary report.

This report's main goal is to present the network's major findings in a format that is useful to stakeholders addressing concerns and conflicts surrounding recent advances in oil and gas development. Our research efforts were motivated by knowledge gaps inhibiting sound assessment of the benefits, costs, and risks of oil and gas development occurring near populated areas.

We encourage report readers to respond with comments and questions to the network's director, Prof. Joseph Ryan at the University of Colorado Boulder, and to AirWaterGas researchers listed in the publications. Contact information for all of the network researchers is available at the AirWaterGas website *(www.airwatergas.org)*.

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Photography Credits
Front cover collage: drilling rig operator (*Jessica Farris*); wind turbines (*Anne Jordan*); drilling rig at night (*Alex Burke*); natural gas separator (*Alex Burke*); natural gas flare (*Wild Earth Guardians*). *Fronticepiece:* South Platte River (*Marek Uliasz*). *Page 19:* digging a trench for oil and gas pipelines (*Jessica Farris*). *Back Cover*: drill rig and pipes (*Alex Burke*).

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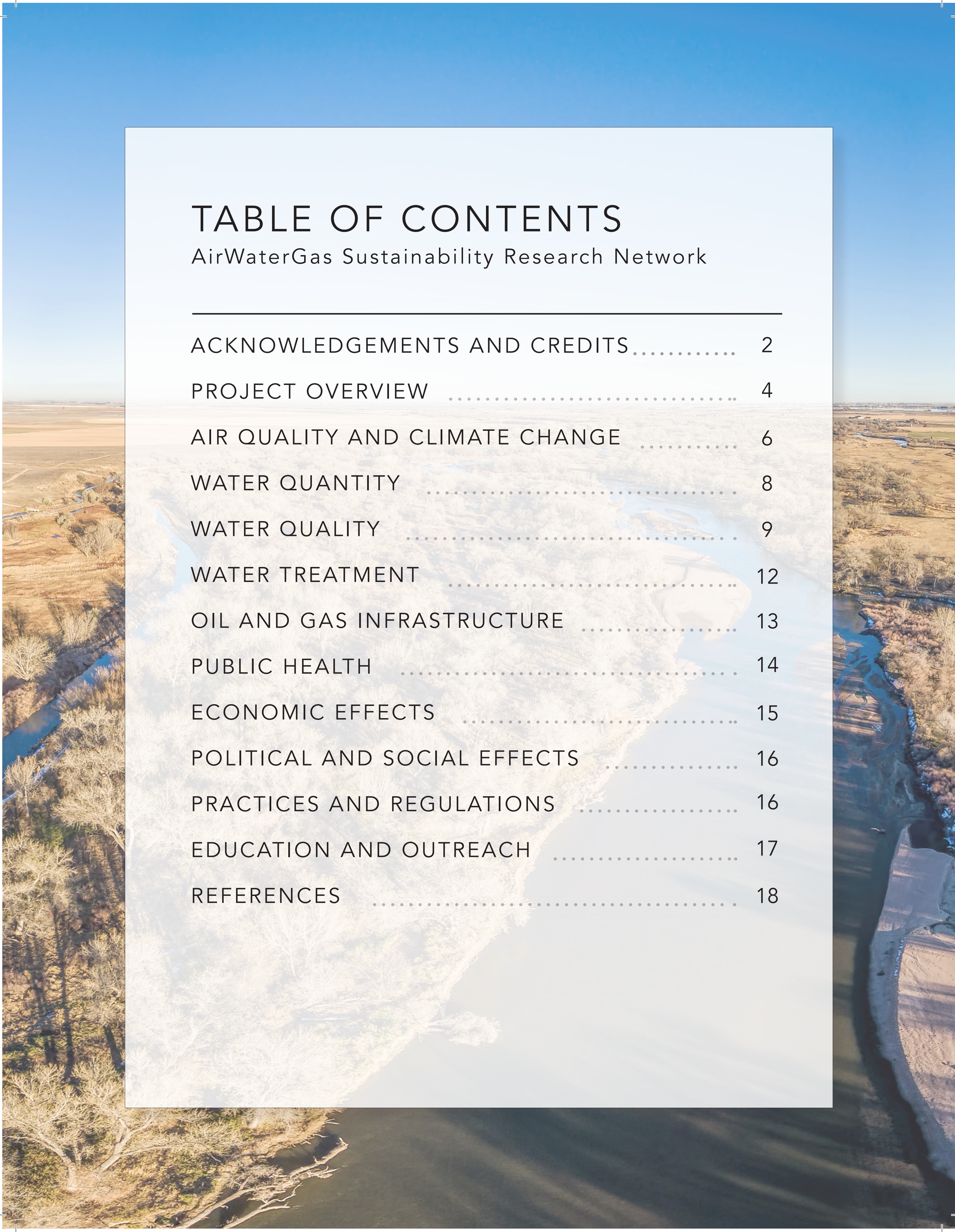

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PROJECT OVERVIEW

AirWaterGas Sustainability Research Network

The United States has experienced an unprecedented boom in oil and gas development during the past decade. The use of horizontal drilling and hydraulic fracturing have allowed the withdrawal of oil and gas from previously inaccessible resources like shale and tight sand formations. The increase in oil and gas production has boosted the U.S. economy, reduced U.S dependence on foreign oil and improved air quality by reducing electricity generation from coal. The benefits to our nation have not been without costs. Concern about potential negative impacts to air quality, water quality, water supplies and public health in oil- and gas-producing communities has fueled political debates and highlighted the need for cutting-edge research.

AirWaterGas *(www.airwatergas.org)* is a network of researchers funded by the National Science Foundation to investigate the effects of oil and gas development on the Rocky Mountain region of the United States. This five-year project (October 2012 to September 2017) brings together more than two dozen researchers from seven universities and three federal research centers.

The main goals of AirWaterGas researchers have been to (1) conduct research on the environmental, social, and economic effects of oil and gas development; (2) develop frameworks to address trade-offs associated with the practice and regulation of oil and gas development; and (3) engage with stakeholders in oil and gas development to better understand and address issues of concern. The network focused on oil and gas development in the Rocky Mountain region to assess some of its unique conerns, and to take advantage of the variety of oil and gas basins, and

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For a full listing of journal articles produced by AirWaterGas researchers, please visit the AirWaterGas website *(www.airwatergas.org/publications)*.

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abundance of relevant data available in Colorado. AirWaterGas research teams have assessed the effects of oil and gas development by focusing on their specific fields that have been used to organize this report. This report highlights significant results and findings of these researchers during the network's first four years (October 2012 to September 2016). Still in progress over the network's last year is the integration of research findings into decision-making frameworks that better guide practices, regulation, and policy for oil and gas development.

In this last network year, researchers are also conveying their findings directly to stakeholders – affected communities, local governments, state regulators and oil and gas operators – in formats and forums more accessible than peer-reviewed journal articles that are the usual products of academic research. This report includes citations to the major AirWaterGas researchers' publications to assure readers that the findings have undergone rigorous review by appropriate experts in each field. For a full listing of AirWaterGas researchers' publications, please visit our website *(www.airwatergas.org/publications)*.

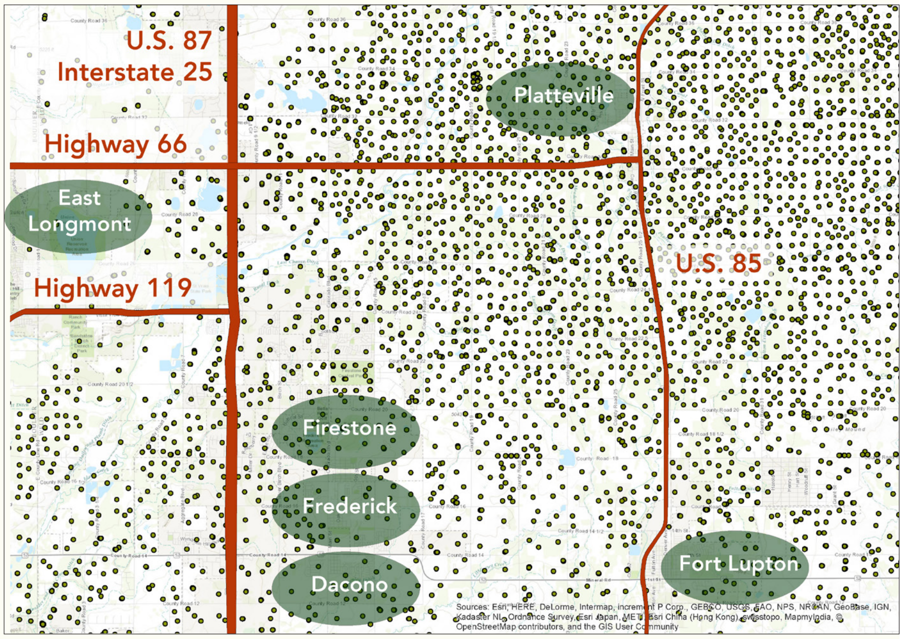

Figure 1: Hundreds of oil and gas wells are found within 20 square miles near Platteville, Colo., in the Denver-Julesburg (DJ) Basin. Green dots represent active wells as of mid-2015. Over half of Colorado's active wells are located in the DJ Basin *(Graphic adapted from COGCC Data)*.

Photos: A Weld County, Colo., well pad *(Jessica Farris)*. Natural gas equipment catches over-spray from a Greeley, Colo., irrigation pivot *(Alex Burke)*. Colorado School of Mines (CSM) graduate student Victoria Frank explains a sequencing-batch membrane bioreactor produced water treatment process to CSM President Paul Johnson *(Tzahi Cath)*.

Contact information for AirWaterGas researchers is available at the network's website *(www.airwatergas.org)*.

AIR QUALITY AND CLIMATE CHANGE

How is oil and gas development affecting air quality?

AirWaterGas research on the effects of oil and gas development on air quality and climate is led by scientists from the National Oceanic and Atmospheric Administration, University of Colorado Boulder, and the National Renewable Energy Laboratory. These researchers have added to our understanding of the effects of oil and gas development on ozone formation and the contribution of the oil and gas sector to greenhouse gas emissions.

Oil and gas development is a primary source of the volatile organic compounds (VOCs) and nitrogen oxides that create ground-level ozone. Improved emissions data have helped AirWaterGas researchers and their partners determine the cause of high ozone levels in sparsely populated areas of the Rocky Mountain West. The occurrence of high ozone levels in Utah's Uinta Basin and in southwestern Wyoming was especially surprising to the atmospheric science research community because it occurred in winter, whereas high surface ozone is typically a summertime problem. Field studies have shown that winter temperature inversions in these basins can allow VOCs generated by oil and gas development to build up and produce ozone when they combine with nitrogen oxides in chemical reactions driven by sunlight reflected from the snow (Oltmans et al., 2014).

> Utilizing innovative technology, AirWaterGas researchers have discovered that the levels of methane, benzene, and other oil- and gas-related hydrocarbons over the northeastern Colorado Front Range were several times higher than had been estimated using oil and gas facility inventories.
>
> (Pétron et al., 2014)

As a greenhouse gas, emissions of methane are estimated to be as much as 80 times more potent than carbon dioxide. Reducing methane emissions has therefore become a national priority. Utilizing innovative technology, AirWaterGas researchers have discovered that the levels of methane, benzene and other oil- and gas-related hydrocarbons over the northeastern Colorado Front Range were several times higher than had been estimated using oil and gas facility inventories (Pétron et al., 2014). AirWaterGas research has contributed to a body of measurement studies across the country that found a relatively small number of facilities – "super emitters" – account for a disproportionate amount of methane emissions from the oil and gas sector. Further research is needed to examine the effect of state and federal air quality regulations and new industry practices in reducing these emissions.

AirWaterGas researchers are also modeling different scenarios for future oil and gas production and our nation's energy system to understand the trade-offs of energy choices that we are making. In the Rocky Mountain region, forecasted costs of electricity production from wind and natural gas are similar. This means the price of natural gas and any potential fees on greenhouse gas emissions could strongly influence which choice is most economical (McLeod et al., 2014). AirWaterGas researchers are undertaking detailed modeling of emissions from the region's electricity generation and oil and gas production systems to investigate how these choices could affect future air quality.

AirWaterGas researchers are also working to bring low-cost air quality sensors into the hands of communities that are experiencing oil and gas development. These tools are helping educate the public about the benefits and costs of oil and gas development and may one day allow local communities to conduct their own scientific investigations of emissions and exposure.

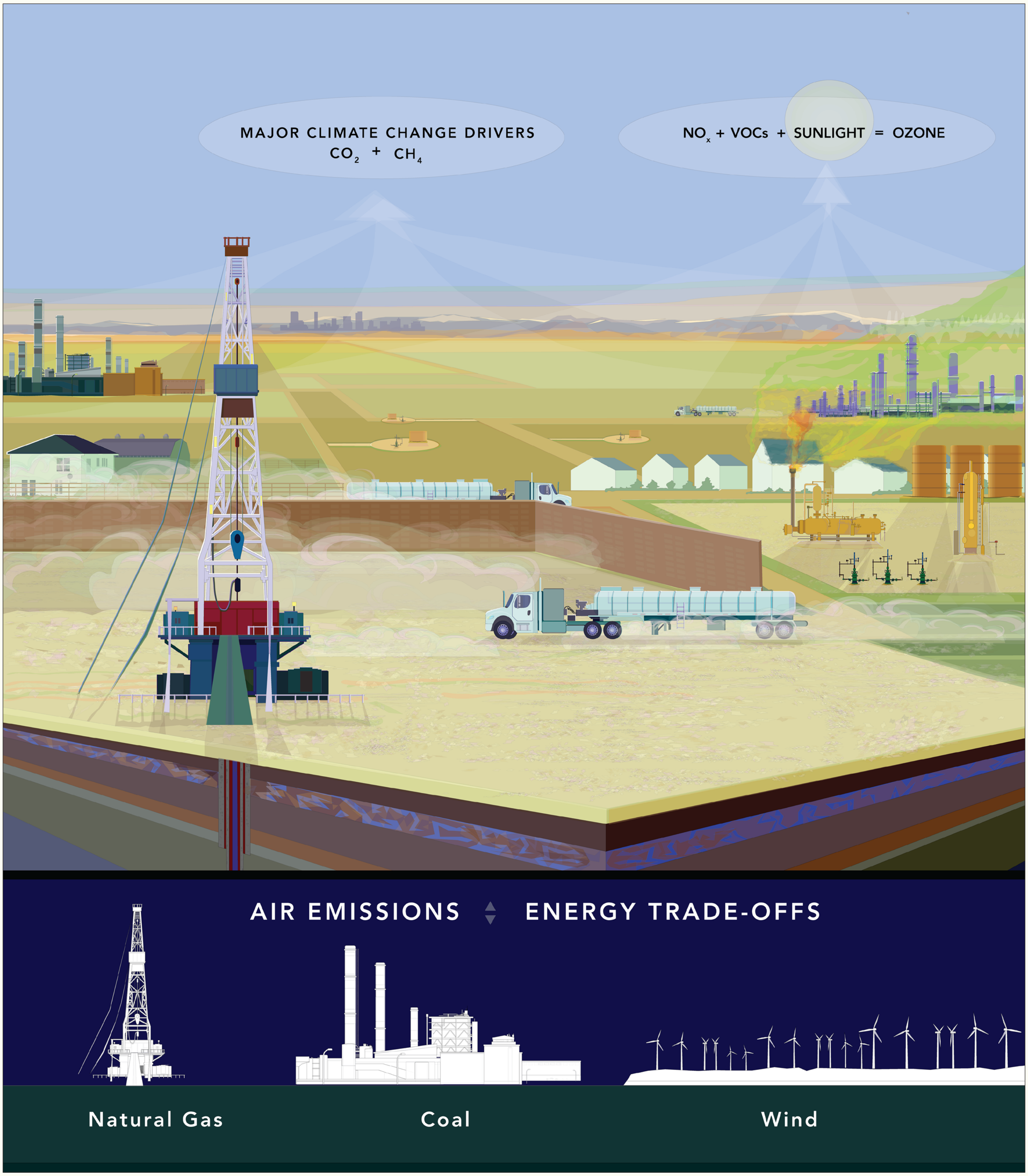

Figure 2: AirWaterGas researchers are linking energy system and emissions models to examine how the Rocky Mountain region's air quality might be affected by the future mix of coal, natural gas, and renewables used to generate electricity. Natural gas and wind are both expected to be cost-competitive in this region, but electricity generation from wind offers more benefits for reducing emissions of greenhouse gases and other air pollutants (McLeod et al., 2014) *(Science illustration by Jenn Paul Glaser / Scribe Arts for Our Planet, Oceans and Fisheries).*

WATER QUANTITY

Where is the oil and gas industry getting the water used in the hydraulic fracturing process? How much water is being used?

AirWaterGas researchers at Colorado State University are studying current water use trends for oil and gas development throughout Colorado and are also projecting future water use. Depending on the length of the horizontal wellbore and the basin where the well is located, two to five million gallons of water are needed to hydraulically fracture a well in Colorado. The annual average water use for oil and gas development from 2011 to 2013 was about 1% of total water use in Weld County and 2% in Garfield County (Oikonomou et al., 2016).

These figures exemplify the regional disparity of water delivery and use, particularly since Colorado trade associations estimate that the industry's use of water statewide is only 0.13%. In Weld County, most oil and gas companies prefer to lease water from municipalities, private water service companies and irrigation and reservoir companies. The industry is also drilling wells into non-tributary freshwater aquifers. These water sources are not administered by the state's priority system and have been legally disconnected from the surface water's hydrologic cycle. In Garfield County, gas companies tend to own water rights they obtained during the 1950s, 1960s and 1970s for oil shale development. The results of this research highlight a need for an adjustment of reporting requirements to better track water consumption by the oil and gas industry (Oikonomou et al., 2016).

Depending on the length of the horizontal wellbore and the basin where the well is located, two to five million gallons of water are needed to hydraulically fracture a well in Colorado.

Photos: A large array of condensate tanks rests in a Greeley, Colo., cornfield *(Alex Burke)*. Roughnecks work on a drill rig in Weld County, Colo *(Lisa Gardner)*.

WATER QUALITY

What is in hydraulic fracturing fluid?

More than 20 states require oil and gas operators to report most of the chemicals they use during the hydraulic fracturing process via a national database registry, FracFocus. However, the registry had limited utility because data could not be compared across wells. AirWaterGas researchers from the University of Colorado Boulder created a program that made all FracFocus data searchable.

The increased usability of FracFocus data allowed the screening of 659 organic compounds used in hydraulic fracturing fluids and identification of the nine chemicals of most concern based on their toxicity, mobility, persistence, and frequency of use.

This research and expanded utility of the FracFocus database will provide regulators and the general public with better tools to understand and recommend what chemicals are used for hydraulic fracturing and what chemicals should be avoided – especially when drilling near domestic drinking water supplies (Rogers et al., 2015).

> The increased usability of FracFocus data allowed the screening of 659 organic compounds used in hydraulic fracturing fluids and identification of nine chemicals of most concern based on their toxicity, mobility, persistence, and frequency of use.

Photo: Groundwater microcosm vials simulate a surface spill of produced water to a shallow aquifer *(Jessica Rogers).*

A primary research question about the hydraulic fracturing process is whether the newly created fractures could function as a pathway to allow hydraulic fracturing fluid, methane or salty groundwater located deep underground to flow into and contaminate a drinking water aquifer.

AirWaterGas researchers from the University of Colorado Boulder developed a numerical model of hydraulic fracturing fluid migration underground. The model showed that the combined

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influence of the hydraulic fracturing fluid being absorbed by the shale (imbibition) and well suction significantly reduce the risk of aquifer contamination because the hydraulic fracturing fluid is either sequestered in the underground shale or is removed by the suction on the well. Of the small amount of fluid that escapes above the shale layer, most will remain at great depth because of the previous influence of well suction on the flow field.

Also, most oil and gas development from shale occurs thousands of feet below drinking water aquifers. Without a permeable pathway, the hydraulic fracturing fluid cannot travel far enough to reach aquifers (Birdsell et al., 2015a). However, when developing shale closer to the surface or where rocks above the deeper shale are highly permeable, hydraulic fracturing fluid migration to aquifers remained more likely.

AirWaterGas researchers at the University of Colorado Boulder have shown that large-scale transport of hydraulic fracturing fluid between a deep shale layer and a shallow drinking water aquifer is unlikely through natural geologic pathways, but other work suggests that hydrocarbon transport along faulty oil and gas wells is the primary pathway of concern. Oil and gas wellbores are a system of nested steel casings and cement. If either the cement or steel lose their structural integrity, hydrocarbons from the target formation can escape upwards along the wellbore. In Colorado, where wellheads are sealed at the surface, these fugitive hydrocarbons can collect and build a pressure known as surface casing pressure. Oil and gas wells with surface casing pressure have compromised structural integrity and pose a risk for releasing stray gas into the surrounding aquifer or atmosphere.

The Colorado Oil and Gas Conservation Commission (COGCC) maintains the only publicly available oil and gas database in the country with surface casing pressure data. To assess the rate at which Colorado oil and gas wells lose their structural integrity and potentially contaminate groundwater, researchers analyzed surface casing pressure data for 10,365 oil and gas wells in the Wattenberg Field, the most densely drilled region in Colorado. They found that deviated wells (wells drilled at an angle but not fully horizontal), and horizontal wells develop surface casing pressure more frequently than vertical wells (Lackey et al., 2016). Consequently, since deviated drilling expanded in 2003, the number of wells installed in the Wattenberg Field that developed surface casing pressure has increased. Since 2010, the industry primarily has installed horizontal wells in the Wattenberg Field, which develop surface casing pressure as frequently as deviated wells. However, the horizontal wells have been consistently built to exceed current regulations; thus they pose a lower risk of causing a stray gas migration incident than legacy deviated and vertical wells that would violate current regulations if drilled today (Lackey et al., 2016).

Another AirWaterGas study found that insufficient casing or cementing of a wellbore in Colorado's Denver-Julesburg Basin was the main cause of methane migration from oil and gas wells into water wells. Using publicly available data from the COGCC, AirWaterGas researchers identified 42 Colorado drinking water wells that contained thermogenic stray gas (thermogenic gas can be identified as originating from underlying oil- and gas-producing formations, as opposed to other possible biogenic sources, such as microbes). The incidence rate was about two cases per year over the past 15 years (Sherwood et al., 2016). The COGCC determined the cause for roughly one-third of the thermogenic methane occurrences was due to improper casing of nearby oil and gas wells. None of the water wells with thermogenic stray gas could be specifically attributed to recent horizontal well drilling or hydraulic fracturing. Therefore, an assessment of the risk of thermogenic methane release should address the full history and life cycle of both conventional vertical well and unconventional oil and gas operations.

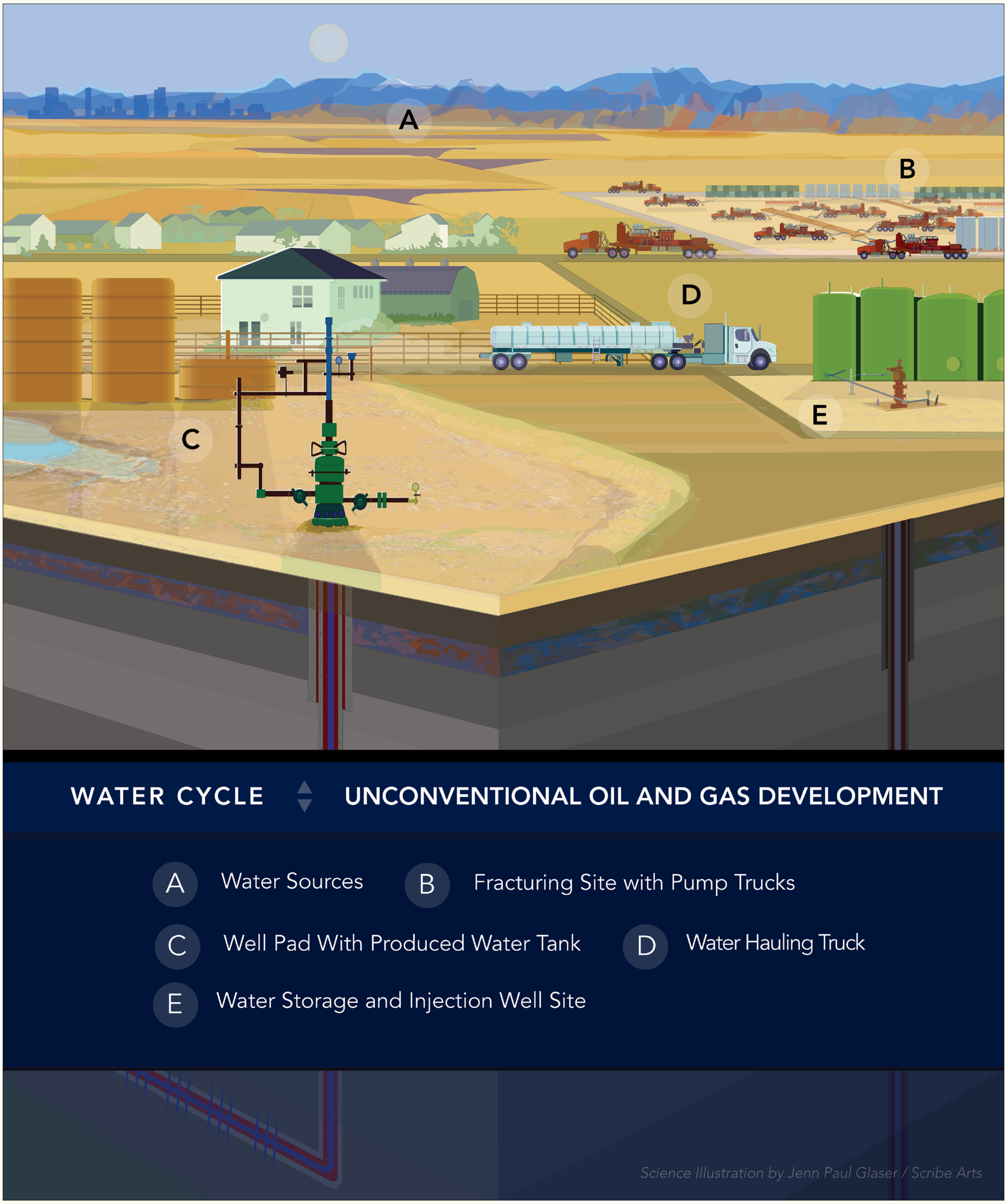

Figure 3: Two to five million gallons of water from municipalities, agriculture, and other sources (A) are used in combination with sand and chemicals injected at high pressure to hydraulically fracture a well (B). A portion of this water will return to surface along with salty water from the underground formation, and will be stored in tanks on the well pad (C). This water is collected and trucked (D) to wastewater injection operations, where it is pumped many thousands of feet underground (E) (*Science illustration by Jenn Paul Glaser / Scribe Arts for Our Planet, Oceans and Fisheries*).

WATER TREATMENT

Can water use in oil and gas development be made more sustainable through treatment or reuse?

During the hydraulic fracturing process, some two to five million gallons of water-based solution will be forced down the borehole. Roughly 20 to 40% of the water injected into the well will return to the surface. This is known as flowback water.

Produced water is another source of water that flows to the surface through the borehole. Produced water is naturally occurring water found in the shale formation, and it will typically flow for the well's entire lifespan.

The transition between flowback and produced water is not readily identifiable, but each will probably have a different chemical composition and flowrate. Both flowback and produced water typically have high levels of total dissolved solids, which makes them extremely salty.

AirWaterGas researchers at the Colorado School of Mines and the University of Colorado Boulder are developing on-site techniques for treatment of hydraulic fracturing flowback and produced water because the current practice of injecting the wastewater into deep wells may not be sustainable. One particular concern is a growing body of research showing that injecting wastewater into deep wells may cause earthquakes (induced seismicity).

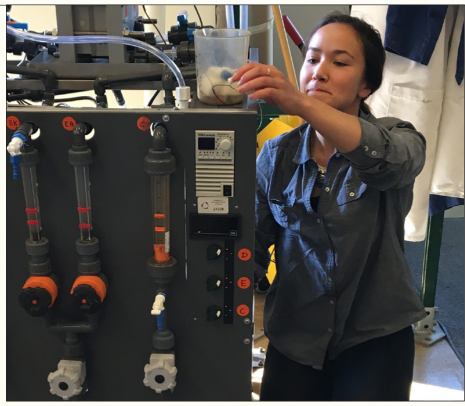

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Photo: Colorado School of Mines graduate student Amanda Yoshino works with the electrodialysis system used to desalinate pre-treated produced water to produce irrigation water (*Tzahi Cath*).

The research task requires examination and optimization of physical/chemical, biologically based, and membrane-based treatment technologies. Using results from the development of treatment technology, researchers are developing a decision support tool that will allow industry to select sustainable processes for the treatment and beneficial reuse of reclaimed water from the oil and gas industry.

In order to assure proper treatment, reuse, or disposal of produced water and flowback wastewater, the contaminants in the water need to be accurately characterized and quantified (Lester et al., 2015).

AirWaterGas researchers conducted a multi-laboratory, round-robin comparison testing five different methods to characterize the chemical composition of different types of flowback water: raw fracturing flowback, treated fracturing flowback, raw produced water and treated produced water. A follow up round-robin test will be conducted focusing on organic matter and hydrocarbons in the wastewater.

OIL AND GAS INFRASTRUCTURE

How fail-proof are Colorado's oil and gas wells?

AirWaterGas researchers from the Colorado School of Mines analyzed data from 17,948 wells drilled in the Wattenberg Field, Colo., between 1970 to 2013 for possible barrier failures that would allow migration of hydrocarbons or hydraulic fracturing fluid into an aquifer (Fleckenstein et al., 2015). They determined that three independent events must occur for migration of hydrocarbons into an aquifer: failure of the cemented surface casing, failure of the cemented production casing and failure of the annular hydrostatic pressure.

An additional two independent events must occur for contamination of an aquifer during the hydraulic fracturing process: failure of the stimulation pressure monitoring and failure of the annular pressure monitoring.

No evidence of aquifer contamination by hydraulic fracturing operations through wellbores was discovered in the Wattenberg Field.
However, a total of 10 wells in the study area exhibited signs of hydrocarbon migration to freshwater aquifers.

These events were found to only be associated with older wells, with surface casing which was not extended through the entire series of fresh water aquifers in the study area.

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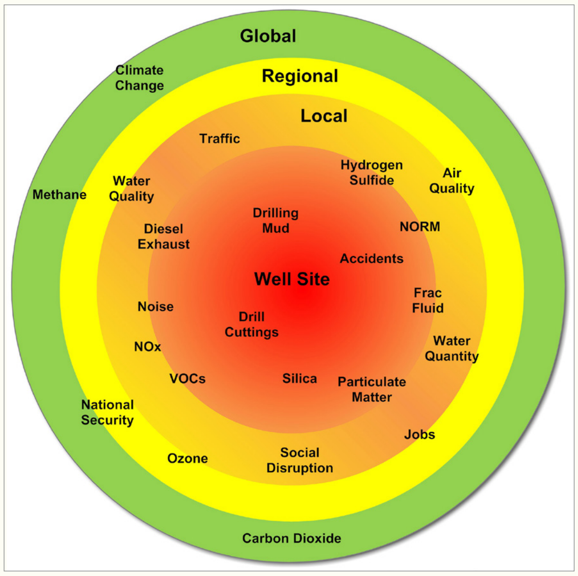
An additional two independent events must occur for contamination of an aquifer during the hydraulic fracturing process: failure of the stimulation pressure monitoring and failure of the annular pressure monitoring.

Photo: One of 800 well pads scattered across 10,000 acres of a large cattle ranch in Weld County, Colo. (*Jessica Farris*).

PUBLIC HEALTH

How is oil and gas development affecting the health and welfare of nearby communities?

Oil and gas development results in hazards, emissions and pollutants that can affect the health of residents living nearby oil and gas development. A team from the Colorado School of Public Health is focusing on human health impacts stemming from exposure to contaminants in air and water, as well as nonchemical stressors that affect residents, such as noise, traffic, fires and explosions.



AirWaterGas researchers conducted a review of published studies to evaluate risks to public health from chemical and nonchemical stressors associated with oil and gas development. The review describes likely exposure pathways and potential health effects, and identifies major uncertainties to address with future research (Adgate et al., 2014). The review found that no comprehensive population-based studies of the public health effects of oil and gas development exists in the peer-reviewed scientific literature and notes that comprehensive health studies will take many years and millions of dollars to conduct.

Researchers estimated that at least 378,000 people in Colorado live within one mile of an oil and gas well.

Figure 4: Chemical and non-chemical stressors from oil and gas operations vary by spatial scales. (Adgate et al., 2014).

AirWaterGas researchers studied Colorado's population living in oil and gas development areas. Researchers estimated that at least 378,000 people in Colorado live within one mile of an oil and gas well. The population living within a mile of these oil and gas wells is growing at a faster rate than the overall population. They found that the growing population around the wells appears to be a result of homes being built near the wells in some areas and wells being drilled near homes in other areas. In populations living nearest to wells, they found possible environmental injustices regarding income, distribution of risks and benefits resulting from oil and gas development, and participation in decision-making processes concerning oil and gas development (McKenzie et al., 2016).

In parallel with AirWaterGas-funded research, the Colorado School of Public Health team has been conducting epidemiological studies on associations between oil and gas development and health outcomes. One recent study by Colorado School of Public Health researchers considered the incidence prevalence of birth defects and the proximity of the mother's residence to natural gas development in rural Colorado (McKenzie et al., 2014). Researchers found a positive association between greater density and proximity of natural gas wells within a 10-mile radius of the mother's residence and greater prevalence of congenital heart defects and possibly neural tube defects. While not conclusive, this research speaks to the need for additional studies on the potential health effects associated with oil and gas development near homes and schools.

ECONOMIC EFFECTS

How can the economic value and market and non-market costs of oil and gas development be quantified to provide a cost-benefit accounting?

Conversations about oil and gas economics are often cast solely in terms of jobs, tax revenue, and the cost of energy. Colorado State University economists are working to quantify the economic value of market and non-market costs such as the economic cost of impacts on public health, air quality, and water quality. The goal is to enable comprehensive conversations about regulations of oil and gas development rather than just having an economy versus public health and environment debate. This cost-benefit accounting research will be used to build a framework for a model that will assess the total costs and benefits of an oil and gas policy (such as setbacks from homes). The model will consider the direct economic effects of oil and gas regulations (access to resources, employment, oil and gas revenue) as well as the non-market economic effects (air quality, greenhouse gas emissions, water quality, public health, habitat fragmentation, greenhouse gases).

These researchers also conducted a study examining the effects of hydraulically fractured oil and gas wells on house prices in Weld County, Colorado (Bennett and Loomis, 2015). Within the city of Greeley, active drilling within a half mile of a well during the time a buyer was deciding about a purchase reduced the price of the house by 1% per well on average. This price effect was not found in the county's rural areas. Once active drilling finished, there was no statistically significant negative effect on house prices. Employment in the oil and gas industry has a statistically significant but very small (less than 1% of the purchase price) positive effect on house prices (Bennett and Loomis, 2015).

Conversations about oil and gas economics are often cast solely in terms of jobs, tax revenue, and cost of energy. Colorado State University economists are working to quantify the economic value of market and non-market costs such as the economic cost of impacts on public health, air quality and water quality.

Photo: Oil and gas operations as seen from a Frederick, Colo., neighborhood *(Honey Lindburg).*

POLITICAL AND SOCIAL EFFECTS

What are the changing beliefs of people involved in Colorado's hydraulic fracturing issues?


Photos: AirWaterGas researchers presenting results at the University of Colorado Denver School of Public Affairs (*John Merritt*). Farmlands and oil and gas development (*Anne Jordan*). Drill pipes on a drill site in Weld County, Colo. (*Katya Hafich*).

AirWaterGas researchers at the University of Colorado Denver School of Public Affairs studied policy actors involved or knowledgeable about oil and gas development in Colorado. Researchers conducted interviews, administered surveys and analyzed news articles (Heikkila and Weible, 2015).

The researchers found divergent views on the risks and benefits and positions related to oil and gas development. On average, respondents reported the political debate around oil and gas worsening over the past two years despite acknowledging a greater availability of scientific and technical information on the subject. Respondents overall also cited interactions with state government as a valuable resource for achieving their goals.

PRACTICES AND REGULATIONS

How can regulations and non-regulatory agreements governing oil and gas development be made more accessible to the public?

The AirWaterGas practices and regulations team has created several web-based tools to share information on management of air, water and other resources impacted by oil and gas development.

These AirWaterGas tools include a searchable best management practices (BMP) database *(www.oilandgasbmps.org)* for the Intermountain region and the LawAtlas comparative air quality, water quality and water quantity law databases *(http://lawatlas.org/oilandgas)*, which cover 17 states and four federal agencies.

Researchers have recently added non-regulatory, voluntary negotiated agreements, known as memoranda of understanding (MOU) between local governments and operators to the BMP database. MOUs allow operators and local governments to negotiate restrictions on siting and operations of oil and gas development despite the fact that Colorado has preempted local governments from directly regulating most aspects of oil and gas development *(www.oilandgasbmps.org/resources/MOU.php)*.

The MOU project has also conducted a stakeholder assessment regarding the use and potential use of MOUs to address oil and gas development within Colorado's regulatory framework.

EDUCATION AND OUTREACH

How can researchers help bring good science to the public debate about oil and gas development?

The education and outreach team seeks to develop evidence-based resources to create more productive and substantive education and conversations about unconventional oil and gas development.

AirWaterGas researchers are working with K-12 educators and interested citizens through several initiatives, including a project-based learning program for students in rural areas to learn about air quality and a community small grant program.

AirWaterGas also conducted two teacher professional development programs for Colorado secondary science teachers, including a year-long program with a curriculum development component and a second online course highlighting curriculum developed in the first program.

Each resource gives the public access to scientists in different settings such as the classroom, online learning, in-person workshops, and community lectures.

By building and fostering mutually beneficial partnerships that bridge the gap between scientists and the public, AirWaterGas researchers will continue to look for new ways and new opportunities to bring scientific information about the costs and benefits of oil and gas development to the public.

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Photos: ***Top left:*** An AirWaterGas undergraduate student shows Platteville Elementary School students how to filter water samples for water quality analysis (*Katya Hafich*). ***Left:*** A next-generation air quality monitor developed by AirWaterGas researchers (*Casey Cass*). ***Right:*** Greeley High School students measure truck emissions (*Casey Cass*).

Learn More About AirWaterGas

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