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Benzene, Toluene, Ethylbenzene, and Xylenes Occurrence in Relation to Oil and Gas Development in the Denver-Julesburg Basin of Colorado

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BENZENE, TOLUENE, ETHYLBENZENE, AND XYLENES OCCURRENCE IN RELATION TO OIL AND GAS DEVELOPMENT IN THE DENVER-JULESBURG BASIN OF COLORADO

By

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ABSTRACT

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Benzene, Toluene, Ethylbenzene, and Xylenes Occurrence in Relation to Oil and Gas Development in the Denver-Julesburg Basin of Colorado
Thesis directed by Professor Joseph N. Ryan

We quantified the occurrences of benzene, toluene, ethylbenzene, and xylenes (BTEX) in water wells in the Denver-Julesburg Basin and determined the extent to which oil and gas is responsible for contamination. Public environmental sampling records were downloaded with computer scripts between 1988 and 2016 from Colorado Oil and Gas Conservation Commission (COGCC) to find water wells where BTEX compounds were above their detection limits. There were 51 BTEX occurrences in water wells, and for each occurrence, we searched oil and gas wells within a half-mile radius for records on surface casing integrity that could indicate fluid or gas leaks into aquifers. From the first BTEX occurrence in 2001 through 2012, there were 1.7 BTEX occurrences per year. After voluntary regulation by the Colorado Oil and Gas Association in 2012, there were 11 BTEX occurrences per year. We found only eight of the 51 water wells were resolved by the COGCC as having an oil and gas well responsible for the contamination. The COGCC stated poor water quality in five of the water wells was unrelated to oil and gas activity but did not acknowledge the presence of BTEX. Nine water wells had documentation for oil and gas well integrity issues or repairs. The remaining 29 water wells had no explanation for the source of BTEX. Five of the BTEX occurrences were above the respective MCL for Colorado drinking water; two of these occurrences above MCLs had no identified source from the COGCC. Thermogenic methane was present in 26% of the BTEX occurrences, which is another indicator of a gas release from an oil and gas well. Biogenic methane was present in 49% of BTEX occurrences; biogenic methane could be from groundwater contact with coalbeds.

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1. Introduction

1.1. Background

Domestic oil and gas development has surged so the United States reduces its dependence on foreign oil. In response to high demand over the past decade, oil and gas drilling has not only increased, but also shifted to unconventional drilling methods such as horizontal drilling and high-volume hydraulic fracturing that reap greater outputs (U.S. Energy Information Administration, 2018). As with any emerging technology, the direct and indirect effects of these new methods are not fully measured, leading to concern over unknown environmental, health, and safety effects. Specifically, as oil and gas development expands, proximity to domestic water wells is unavoidable. With proper investigation into effects of oil and gas development on groundwater, exposure routes can be minimized.

The western United States is rich in oil and gas resources and has seen an unprecedented increase in drilling. In Colorado, the Denver-Julesburg Basin alone contains over 62,200 oil and gas wells, where 24,500 are listed by the Colorado Oil and Gas Conservation Commission (COGCC) as active or producing, within a 180,000 km^2 area (COGCC, 2016a). In this area, over 65,000 domestic water wells cover the same area (DWR, 2016), or 2.6 water wells for every active oil and gas well. The high density of water wells near oil and gas wells, combined with an uncertainty of environmental pollution and consequent health effects, has led to the public concern of water contamination associated with drilling sites. Should landowners feel their well has been affected, they are able to file complaints and the COGCC will investigate further actions and testing that can be done (COGCC, 2018). A wide variety of compounds associated with oil and gas could degrade water quality, and most cannot be isolated to an oil and gas source, which creates a major complication.

1.2. Effects of Oil and Gas Development on Groundwater

The uncertainty of environmental pollution has led to numerous studies on water risks from oil and gas activity. Two important aspects of water pollution resulting from oil and gas development are (1) surface spills affecting surface water and shallow groundwater and (2) oil and gas well contaminant intrusion into aquifers (Vengosh et al., 2014). The pollution is usually methane or the BTEX compounds, but other organic pollutants have been detected.

1.2.1. Types of Groundwater Contamination from Oil and Gas Development

Surface spills resulting from operator error and equipment failure are common sources of shallow groundwater contamination in areas with hydraulic fracturing (Entrekin et al., 2011; Gross et al., 2013; Drollette et al., 2015; Shores et al., 2017; Armstrong et al., 2017; Maloney et al., 2017). In Colorado, the COGCC requires notification from any surface spill that affects or threatens “any waters of the state, a residence or occupied structure, livestock, or public byway” (COGCC, 2016). For groundwater contamination, BTEX compounds are monitored closely because of their negative health effects. The extent of groundwater remediation is partially driven by reducing the chemicals below the maximum allowable level to restore water quality to safe standards. Surface spills are not the primary topic of this study but are relevant to our knowledge of how actions are taken for contaminant remediation.

Aquifer contamination from stray gas migration is another primary concern of oil and gas development. Currently, stray gas migration is predominantly associated with oil and gas well integrity loss, rather than vertical upward migration of gas between drilled formation layers (Davies et al., 2014; Ingraffea et al., 2014; Jackson, 2014; Darrah et al., 2014; Sherwood et al., 2016). Oil and gas wells are a system of steel piping and cement that is pumped around them to protect against gaseous or dissolved hydrocarbons and fracturing fluids from entering aquifers as

they are pumped to the surface. Leaks that occur in the cement or casings can result in the release of gas into the aquifer.

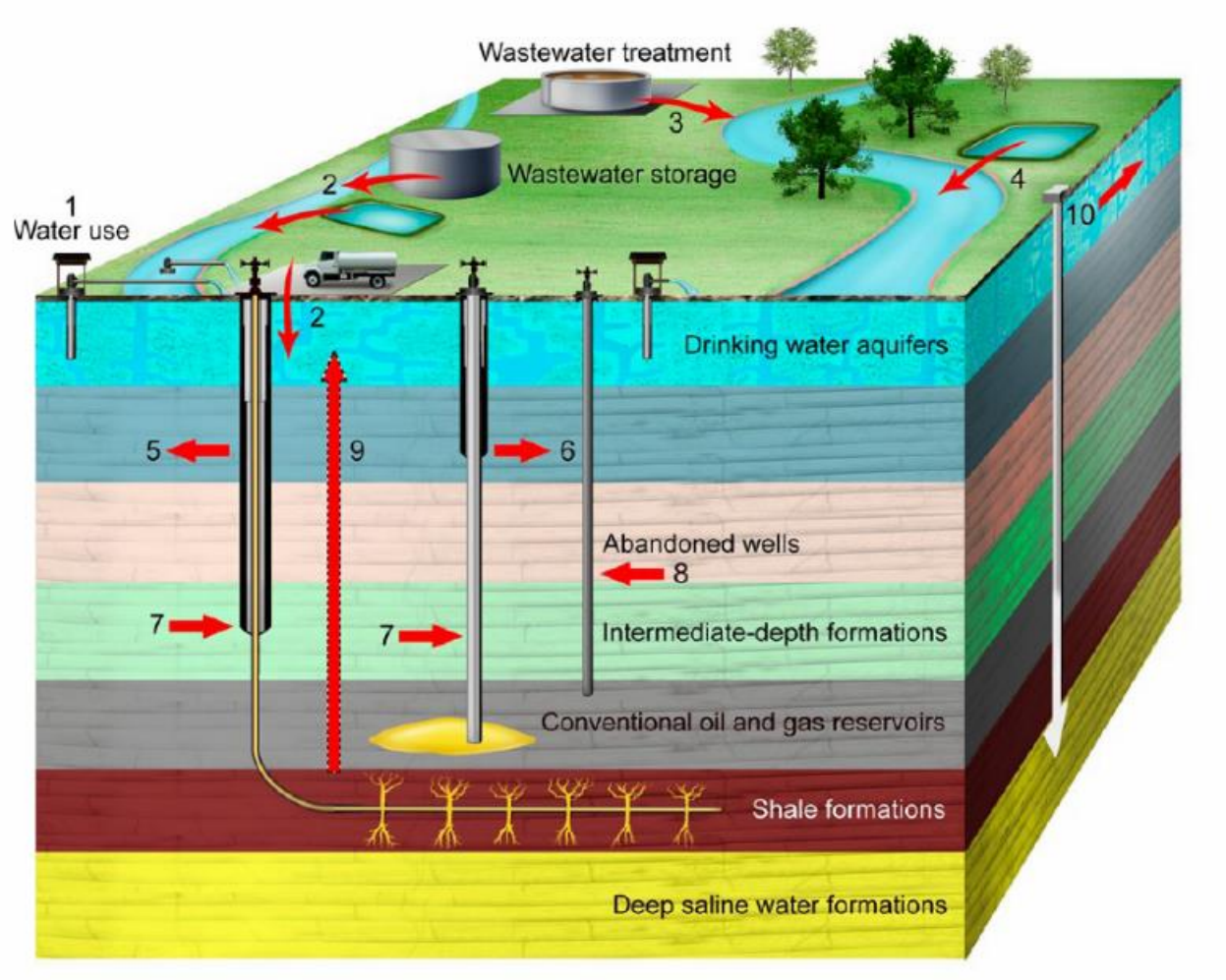

Figure 1 – Possible ways water resources can be affected from the hydraulic fracturing process. The key effects related to groundwater contamination relevant to this study are from (2-4) surface spills or inadequately treated wastes, (4-8) stray gas migration from leaking oil and gas wells, and (10) leaking injection wells (Vengosh et al., 2014).

1.2.2. Methane Contamination from Oil and Gas Development

When assessing the effects of oil and gas drilling on groundwater, methane is a well-studied indicator of water quality degradation (Osborn et al., 2011; Molofsky et al., 2013; Li and Carlson, 2014; Darrah et al., 2014; Moritz et al., 2015; Li et al., 2016; Sherwood et al., 2016;

Wen et al., 2016; McMahon et al., 2017; Nicot et al., 2017). This is because the carbon and hydrogen in methane can differ isotopically by source and indicate whether the source is from a biogenic source associated with microbial activity, or from a thermogenic source common in oil and gas formations. Biogenic methane is a byproduct of microbes and will be more depleted in ^{13}C, with $\delta^{13}C_{CH4}$ values ranging from -110‰ to -50‰. Thermogenic methane originates from the reduction of carbon in anaerobic, high-temperature, high-pressure conditions and results in methane being less depleted in ^{13}C, with $\delta^{13}C_{CH4}$ values ranging from -50‰ to -20‰ (Whiticar, 1999a; Stolper et al., 2014). To identify the source of methane in a landowner's water well, this isotopic signature can be compared to water samples in nearby oil and gas wells to see if the enrichment of stable carbon isotopes ($\delta^{13}C_{CH4}$) is similar. However, there are uncertainties such as in the case of thermogenic methane found in Dimock Township water wells in the Marcellus region. Closer examination of thermogenic methane suspected of being from gas production waters suggested that microbial oxidation changed the signature of methane closer to the subsurface (Molofsky et al., 2013).

Many studies agree that in areas of oil and gas development, dissolved methane is present to an extent, but do not necessarily conclude that the oil and gas development is responsible for the source. In the Marcellus region of Pennsylvania, higher concentrations of dissolved thermogenic methane have been correlated with closer distances to oil and gas, with higher rates of biogenic occurrences occurring in areas farther from oil and gas activity (Osborn et al., 2011; Jackson et al., 2013; Darrah et al., 2014). Jackson et al. (2013) concluded that landowners living within one kilometer of gas wells in the Marcellus region "have drinking water contaminated by stray gases."

In oil and gas basins in Texas and Arkansas, studies showed no correlation between methane and distances to oil and gas wells or the density of oil and gas wells (Warner et al., 2013; Wen et al., 2016; Nicot et al., 2017). Studies have also been critical of methane occurrences in Pennsylvania and Colorado as well, concluding that biogenic methane is far more widespread in oil and gas producing regions and that thermogenic methane occurrences are relatively rare (Molofsky et al., 2013; Li and Carlson, 2014). Additionally, Molofsky et al. (2013) have suggested higher methane concentrations in shallow groundwater were natural and explained by topographic factors.

In Colorado, two studies have identified the number of methane occurrences in the Denver-Julesburg basin. Li and Carlson (2014) first analyzed thermogenic methane occurrences in the Wattenberg Field of the Denver-Julesburg Basin and found no correlation between methane concentration and distance to oil and gas wells. Density of the oil and gas wells in relation to water wells also had no significance. This finding was based off analysis of 176 water wells. This is in contrast with Sherwood et al. (2016) who used public records and documents of 924 sampled water wells in the Denver-Julesburg Basin to identify 42 (4.5%) with thermogenic methane. Investigation by the COGCC identified 11 oil and gas wells with wellbore failures causing the contamination. Sherwood et al. included more detailed analysis on other possible sources of methane, specifically coalbeds in contact with water of the Laramie-Fox Hills aquifer which could explain more widespread biogenic methane occurrences.

We know that thermogenic methane is an indicator of oil and gas and several studies have examined how failures are occurring. Gaseous hydrocarbons may travel upward through the casing annulus through a variety of casing leaks or inadequate cementing. Gas pressure can be vented at the surface, but if unvented, it will build pressure known as a sustained casing pressure

on the surface casing. This is also referred to as a sustained annular pressure or Bradenhead pressure. If gas escapes into the outermost annulus of the well, and that annular is hydraulically connected to the surrounding formation, the buildup of pressure displaces annular liquid. Gas can escape the well into the surrounding environment if the casing pressure exceeds the formation fluid pressure at the bottom of the surface casing. This type of high casing pressure is referred to as the critical pressure (Lackey et al., 2017). The oil and gas wellbore leaks that resulted in water contamination often occurred in wells constructed before 1993, a regulatory period where surface casings were not set deep enough below the bottom of aquifers and led to direct gas migration into the aquifer (Llewellyn et al., 2015; Fleckenstein et al., 2015; Sherwood et al., 2016). Lackey et al. (2017) observed that modern unconventional oil and gas wells in Colorado develop sustained casing pressure more frequently than older wells, however, they have been constructed with deeper surface casings and more production casing cement coverage which reduces their risk for groundwater contamination.

1.2.3. Organic Chemicals Associated with Hydraulic Fracturing Fluid and Produced Water

A common environmental and public health concern comes from the chemicals used for hydraulic fracturing. The chemicals involved with hydraulic fracturing are commonly environmental and public health concerns. Hydraulic fracturing fluid contains about 1% chemical additives to the water and proppant, the median oil and gas well uses 5,700,000 L of water (U.S. EPA, 2016). After the fluid is injected, it returns to the surface with hydrocarbons and is known as flowback water. We do not have a comprehensive understanding of every chemical used in hydraulic fracturing that could be affecting groundwater.

Studies in Colorado have been characterizing the water chemistry of hydraulic fracturing fluid and produced waters to be used as tracers for environmental contamination. In a study

examining the fate and transport of chemicals commonly used in hydraulic fracturing fluids, Rogers et al. (2015) provided a framework to identify organic compounds of concern. The framework examined the persistence, mobility, and toxicity of commonly-used chemicals and used these parameters as a scale for elevated exposure potential. The framework ranked chemicals inside or outside a zone of potential elevated exposure based on their transport time to the average setback distance in the United States and time to degrade to 10% of their original concentration.

Rosenblum et al. (2017) characterized dissolved organic carbon (DOC) in hydraulic fracturing fluid and the changes over time as produced water returned to the surface in the Wattenberg Field, the region of the greatest oil and gas production in the Denver-Julesburg Basin in northeastern Colorado. Dissolved organic carbon was primarily composed of hydrophilic compounds that were both volatile and non-volatile. Volatile compounds included the BTEX compounds and related substituted benzenes and ketones. The substituted benzenes are relatively unstudied, and their environmental effects are not well understood. Ketones were found at similar levels to BTEX compounds. Some of the ketones indicated subsurface reactions (2-hexanone), where others are presumed to be directly from the hydraulic fracturing fluid (2-butanone, 4-methyl-2-pentanone). The latter two chemicals present health risks and are suggested to be monitored for with surface spills.

Surfactants such as polyethylene glycols (PEGs), polypropylene glycols (PPGs), linear alkylethoxylates, and triisopropanolamine have been studied in the Wattenberg Field as “fingerprints” that could monitor water quality from spills of hydraulic fracturing fluid of produced water (Thurman et al. 2014; Thurman et al. 2017; Rosenblum et al. 2017). The authors characterize these chemicals because they can show a strong signal in waters affected by oil and

gas. As seen with the PEGs and PPGs, effective tracers must have a strong signal when diluted and be mobile so that early detection is possible.

An important case study revealed groundwater contamination directly from hydraulic fracturing in Pavillion, Wyoming. DiGiulio and Jackson (2016) clearly showed that hydraulic fracturing contaminated drinking water sources by dumping drilling and production fluids into unlined pits, and operating oil and gas wells without adequate surface casings to protect aquifers. Monitoring wells showed elevated levels of natural gas, glycols, phenols, ketones, and BTEX. The glycols, substituted benzenes, and two ketones could be traced from water wells to sources originating from oil and gas wells (Rosenblum et al., 2017). The groundwater contamination at Pavillion shows that specific oil and gas activities can directly cause groundwater contamination, but due to the lack of pre-drilling water quality information, specific contaminant migration pathways are difficult to legally resolve (EPA, 2016).

In standard baseline groundwater quality monitoring testing, samples do not test for specific hydraulic fracturing fluid chemicals. Basic water parameters tested vary by state, but in Colorado they are (COGCC, 2016):

- pH
- Specific conductance
- Total dissolved solids (TDS)
- Dissolved gases (methane, ethane, propane)
- Alkalinity
- Major anions and cations
- Other elements and metals
- Bacteria
- Total petroleum hydrocarbons (TPH)
- BTEX

Thurman et al. (2014) showed that certain chemical additives can be “fingerprinted” to hydraulic fracturing fluids. While this is useful on a case-by-case basis, tracers like PEGs and PPGs are uncommonly tested for in water quality monitoring. To draw conclusions about the

risks of oil and gas development on a national scale, we need to study widely-tested compounds that pose known health risks. Unlike these additives, BTEX compounds are being measured with all samples for standard baseline water quality monitoring. The Agency for Toxic Substances and Disease Registry state that BTEX poses an urgent health risk with inhalation and high concentrations in water. In addition to the known health risks, we also have a detailed understanding of their fate and transport properties that we use to predict their behavior in groundwater and thus use for remediation and reducing human exposure (Schwarzenbach et al., 2016).

1.2.4. Benzene, Toluene, Ethylbenzene, and Xylenes Contamination

Human activities are the primary sources of BTEX in groundwater and these have historically been surface spills or storage tank leaks (Meehan, 1993; USEPA, 2017). Concerns of leaking oil and gas wells have more recently come into focus as evident with methane migration studies (Osborn et al., 2011; Molofsky et al., 2013; Li and Carlson, 2014; Darrah et al., 2014; Moritz et al., 2015; Sherwood et al., 2016; Wen et al., 2016; McMahon et al., 2017; Nicot et al., 2017). Oil and gas effects on water quality can therefore be divided into sources that affect shallow groundwater, and sources that affect deep aquifers.

Historically, the first remediations of BTEX in groundwater were from leaking underground storage tanks (UST) after the SDWA during the 1990s. In the 1950s and 1960s, an estimated 2,000,000 gasoline storage tanks were made of steel and a reported 160,000 corroded and leaked into the environment (USEPA, 1993). During releases, gasoline rises to the top of the water table, where a fraction of soluble components (BTEX) dissolves into the water (Meehan, 1993). This is the same process by which surface spills of hydraulic fracturing fluid or produced water can contaminate shallow groundwater. Surface spills are widespread in areas of oil and gas

activity, typically releasing flowback water and produced water (Maloney et al., 2017). BTEX compounds are abundant in petroleum products and often occur in spills of petroleum products. After a reported spill in Colorado, the parameters listed are tested in groundwater. Total petroleum hydrocarbons and the BTEX compounds are indicators of water impacts and can be monitored during remediation efforts. Gross et al. (2013) and Shores et al. (2017) have both reported that the BTEX contaminants can reach drinking water limits in groundwater and that more precautions need to be implemented for surface level oil and gas operations.

Sources of BTEX that infiltrate aquifers are less common in available literature because studies have primarily focused on sources of methane. However, the BTEX compounds may move between gas and water interfaces similarly to methane transport. Rice et al. (2017) suggest that thermogenic methane serves as a precursor to BTEX found in groundwater. They explain that it is likely transported in the aqueous phase because BTEX is unlikely to appear in dry gas reservoirs. This is contrasted by Li et al. (2016), who stated that BTEX and total petroleum hydrocarbons (TPH) were not found in their previous study of the Wattenberg Field (Li and Carlson, 2014), but that if BTEX or TPH were found in contaminated waters, it would be from aqueous phase fluids. They analyzed the ionic compositions of deep aquifer water samples (polluted and unpolluted by thermogenic methane) and compared them to produced water from nearby horizontal oil and gas wells. The study used a dataset of 672 groundwater samples from the Laramie-Fox Hills aquifer in the Wattenberg field, and concluded that leaking well casings may result in stray gas, but not aqueous phase transport.

Methane and BTEX compounds are somewhat soluble in water (properties listed in Appendix 1), but the BTEX compounds are significantly more volatile than methane based on their Henry's Law constants, which range from 0.20 to 0.32, whereas for methane, it is 0.037.

Additionally, methane and the BTEX compounds are unlikely to adsorb to organic carbon in soil due to their relatively low octanol-water partition coefficients (Zytner, 1994; Schwarzenbach et al., 2016).

When describing case studies of thermogenic methane in the Denver-Julesburg Basin, Sherwood et al. (2016) noted when BTEX would appear above the MCL in specific case studies. Noting when BTEX occurred on a case-by-case basis showed that the COGCC recognized BTEX was co-occurring with thermogenic methane and that a specific oil and gas well was responsible.

We have an in-depth understanding of BTEX fate and transport (chemical properties in Appendix 2) with surface spills or leaks because of the immediate risks to the public health, but studies have not examined BTEX transport in deep aquifers. These compounds are tested in every baseline sample, but little knowledge exists on the reported samples of BTEX tested in aquifers.

1.3. Non-Oil and Gas Well Sources of Benzene, Toluene, Ethylbenzene, and Xylenes in Groundwater

In natural waters, it is important to identify whether BTEX can occur from sources other than oil and gas development. These alternative sources could be from rarer natural occurrences, or non-oil and gas related human activities that release hydrocarbons into the water. Understanding the natural concentrations of the BTEX compounds are important because it can be insightful to where a source of contamination may originate.

In some groundwater wells with BTEX present, the water from the aquifer may be in contact with coalbed seams. In Colorado, coalbed seams are often cited as sources of methane in water wells because they are found at shallower depths than shale formations and have a methane biogenic in origin (Sherwood et al., 2016). Dahm et al. (2011) characterized produced

waters of coalbed methane wells in the San Juan Basin and Raton Basin and found BTEX co-occurs with methane at varying concentrations by basin.

Another source of toluene that has been reported in water wells is from PVC piping glue or epoxy. The BTEX compounds are detectable at high concentrations from pipe leaching when water has been stagnant for 72 h (AWWA, 2002). The presence of new piping could result in positive detections of BTEX compounds if not thoroughly purged to flush the system. Groundwater sampling standard operating procedures include purging water from the piping system, but trace concentrations could still be present.

1.4. Purposes of the Study

The Denver-Julesburg Basin has a 60-year history of oil and gas development and an extensive archive of data collected from 1988 through the present. Oil and gas development still remains a public concern in this region because of the unknown pathways by which chemicals can affect water quality. Despite the ability to trace specific chemical additives in hydraulic fracturing fluid, those chemicals are not being measured. The chemicals of concern that are being measured are constituents of oil and gas such as TPH and BTEX. Of these two constituents, BTEX compounds are federally regulated by the Safe Drinking Water Act.

The primary purpose of this study is to quantify the occurrences of BTEX in the Denver-Julesburg Basin and describe the rate of occurrences within the time period of 1988 through 2016. Within this region, our study will investigate the extent of BTEX contamination in domestic water wells and examine the role of oil and gas development in the observed contamination. We will examine documented violations and reported issues for each oil and gas well within a half-mile (0.80 km) radius of BTEX occurrences. For all case studies, we will check for correlation between BTEX concentrations and distances to the nearest “culprit” oil and

gas well. We hypothesize that the concentrations of the BTEX occurrences in the Denver-Julesburg Basin will decrease with distance from suspect oil and gas wells because with distance, BTEX is subject to degradation and dispersion. We will use the quantity of occurrences to project estimates to the Wattenberg Field, a sub-region of the Denver-Julesburg Basin where oil and gas development is most active.

Lastly, we hypothesize that if thermogenic methane is detected in drinking water wells, so could BTEX because of the co-occurrence with natural gas. We expect that the occurrence rate of BTEX should match the occurrence rate of thermogenic methane if they follow similar pathways.

2. Methods

Quantifying the occurrences of benzene, toluene, ethylbenzene, and xylenes (BTEX) compounds in the Denver-Julesburg Basin requires compiling environmental sampling data from public archives, refined and filtered, then interpreted. The interpreted data was used to document each specific case of a BTEX occurrence and the possible sources or contamination or lack of. Python computer scripting was used for all data analysis and filtering unless otherwise noted.

2.1. Data Collection

Two datasets were compiled for this study. The first dataset of environmental sampling records of water wells was downloaded in bulk as a single file from the Colorado Oil and Gas Conservation Commission. The second dataset was water well information available from the Colorado Division of Water Resources (DWR) which provided water well information used for quality control on sampling data.

The COGCC Oil and Gas Information Systems (COGIS) is a database organized by the state to present information on well facilities, gas production, inspections, incidents, and water quality sampling. Water quality samples have been collected in both water wells and oil and gas wells because of baseline sampling, landowner requests, or known issues with nearby oil and gas facilities. The data included every chemical analyzed and recorded, sample dates, locations, facility IDs, facility types, and specific information from third party laboratories. All of these data comprised the first dataset, downloaded in bulk from the COGCC website (COGCC, 2017).

The second dataset consisted of DWR water well information and was downloaded in bulk as a single file which includes the construction date, permit and receipt numbers, depths, and owners (COGCC, 2017). These data were used as quality control to verify the existence and location of each water well with a BTEX occurrence.

2.2. Data Refinement and Quality Control

Python coding was used for database refinement. It is a high-level programming language that has the ability to use modular packages for specific tasks. The locations of sample results were confined to the Denver-Julesburg Basin using the keyword tag “Denver Basin” from the merged COGCC datasets. To ensure all wells were within the Denver-Julesburg Basin, we used ArcGIS Pro to intersect the perimeter of the Denver-Julesburg Basin with water well location point data and discard data points outside of the region. The perimeter of the Denver-Julesburg Basin was provided by the COGCC as a shapefile for download. Data collection from water quality testing began in the late 1980s. From the available data, we chose the start date of the study to be January 1, 1988 and the end date to be December 31, 2016.

The study investigates BTEX occurrences in water wells that may have human exposure potential in domestic wells, community wells, or irrigation wells. To refine the dataset of all water samples to reflect this, the COGCC water well facility types in Table 1 were selected. We chose to exclude groundwater monitoring wells because they are installed after an issue has been identified for remediation purposes and do not have human exposure pathways. Similarly, the sampling results were filtered for the BTEX measurements under the sampling parameters listed in Table 2. A total of 1,585 water wells met these criteria.

Water wells with the correct location data and possible human exposure were then refined to samples with BTEX concentrations above their recorded detection limit for the compounds. If no detection limit was recorded for an individual sample measurement, the highest detection limit recorded for baseline sampling of the compound was substituted.

Table 1 – Water well facility types are labeled by the Colorado Division of Water Resources to organize water wells in the online database (DWR, 2016). We used the following well facility types to filter water wells based on routes of possible human exposure.

Parameter	**Well Description**
“GROUNDWATER”	Household use only
“GROUND WATER”	Household use only
“GW”	Groundwater, household use only
“DOMESTIC WELL”	Withdraws from deeper sources having minimal impact on surface water, or land is 35 acres or more
“DOM”	Withdraws from deeper sources having minimal impact on surface water, or land is 35 acres or more
“MUNICIPAL”	For residential subdivisions
“COMMERCIAL”	For commercial business operations
“STOCK OR IRRIGATION”	Withdraws from deeper sources having minimal impact on surface water, or land is 35 acres or more
“IRR”	For crop irrigation
“IRRIGATION”	For crop irrigation

Table 2 – Parameters used to filter the dataset for the BTEX compounds. The *meta* and *para* xylene isomers were only available together and not individually.

Parameter	Description
“BENZENE”	Benzene
"TOLUENE"	Toluene
"ETHYLBENZENE"	Ethylbenzene
"TOT XYLENES"	All cumulative xylene isomers in sample
"m-+p-XYLENE"	*meta* and *para* xylene isomers
"o-XYLENE"	*ortho* xylene isomer

The refined list of water wells with BTEX above detection limits was manually cross-checked with DWR permit information to verify the completion status and location of each well. The permit and receipt of a DWR water well are required by the state and issued for all water wells, whether they are in-construction, constructed, or abandoned. If a COGCC groundwater sample did not have a well permit or receipt number to confirm the completion status, we searched neighboring completed water wells within a half-mile radius and matched records based

on the applicant name and completion date, and well depths if possible. Water wells without permit or receipt numbers were not considered in this study.

Each occurrence of BTEX in a groundwater sample corresponds to an aquifer that the well withdraws from. We used the DWR Aquifer Determination Tool to identify the aquifer that each of the water wells with a BTEX occurrence withdraws from. By knowing the aquifer, we can look at sources that may infiltrate that depth and speculate on the contamination source of the water well (Colorado Division of Water Resources, 2017). Using the Aquifer Determination Tool is also important for consistency because permit records do not necessarily have well depths that match their corresponding aquifer. The surface elevation and location data were entered into the aquifer determination tool for each water well with Python scripts. The aquifer determination tool requires location data in the form of "section," "township," and "range" as well as the measured distance from section lines. If the aquifer could not be determined through the tool, we listed the aquifer in the permit file document.

2.3. ArcGIS Data Analysis

ArcGIS Pro was used for data visualization and spatial analysis of oil and gas wells in relation to the water wells with elevated BTEX concentrations, which is shown in Figure 1. We used the WGS 1984 Web Mercator Sphere coordinate system, commonly used for online mapping purposes, to plot water well and oil and gas well information.

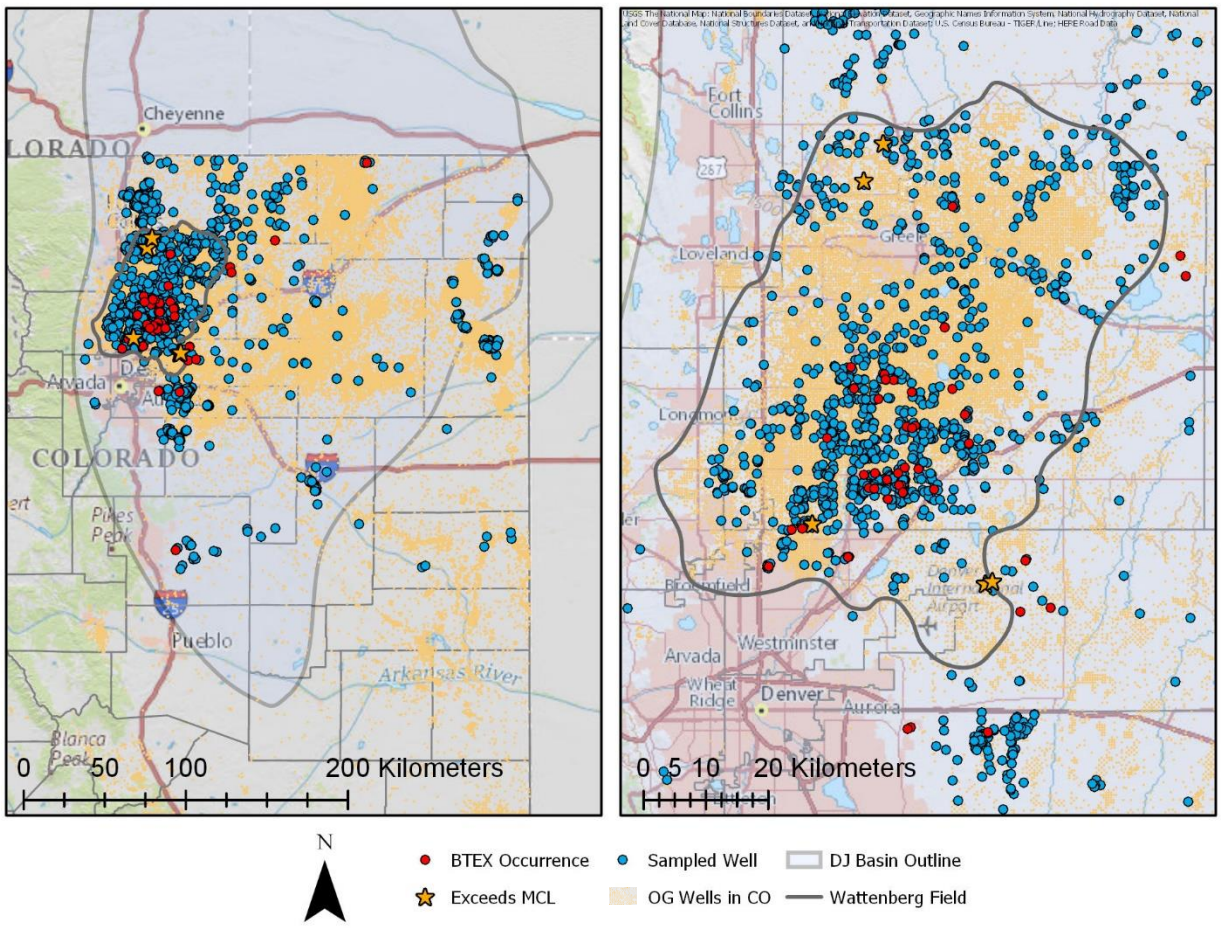

Figure 2 – The Denver-Julesburg Basin (left) and Wattenberg Field (right). Blue dots indicate water wells sampled for BTEX, red dots indicate water wells with a BTEX occurrence above the detection limit, and stars indicate BTEX occurrences above the maximum contaminant level. The yellow dotted texture indicates regions of oil and gas wells.

In addition to well information, we used Python scripts to refine water quality related public complaints and notices of alleged violations (NOAV) between the years 2010 and 2016. The dataset was available for download online (COGIS, 2016). For each BTEX occurrence, we searched oil and gas records within a half-mile radius zone, as a half-mile radius is a specified distance used in baseline groundwater quality monitoring by the COGCC. COGCC Rule 318A states that within a half-mile radius of an oil and gas well, up to four water wells must be

sampled in quarter-sections (a square area of land used for surveying) in contact with the half-mile radius. To simplify application of this rule for our investigation, we searched records for each oil and gas well within a half-mile radius of the water well with a BTEX occurrence using ArcGIS Pro (COGCC, 2016a).

2.4. Case Studies

Each water well with a BTEX occurrence is a unique case study investigated to determine possible contamination sources related to oil and gas activity in a surrounding half-mile (0.8 km) radius. Within this radius of each water well, 862 oil and gas wells were individually examined to identify documents noting issues with surface casings, failed mechanical integrity tests (MITs), high surface casing pressures, NOAVs, or spills and remediation reports. A list of each document searched for is in Table 3.

Table 3 – COGCC forms examined for each oil and gas well within a half-mile radius of BTEX occurrences (COGCC, 2016).

Document	Description
Notice of Alleged Violation (NOAV)	Oil and gas well violations of a regulation
Form 4 Sundry Notice	Miscellaneous information
Form 17 Bradenhead Test	Pressure test on oil and gas well
Form 18 Complaint Report	Complaints opened with COGCC that document issues or request sampling
Form 19 Spill/Release Report	Surface spills or releases
Form 21 Mechanical Integrity Test	Test documents for casing leaks and structural integrity
Form 22 Accident Reports	Accidents reported at an oil and gas facility
Form 27 Remediation Workplan	Soil or water remediation of contamination

We grouped water wells into four categories based on evidence or the lack of evidence of BTEX contamination. Category A water wells have a known source of BTEX from an oil and gas release as identified by the COGCC. Documents identifying contamination were NOAVs or Remediation Forms. The COGCC will often, but not always, issue an NOAV to oil and gas

operators if a specific well or set of wells have a failure known to release oil or gas into the aquifer. For Category B water wells, the COGCC provides documents that state elevated BTEX or gas in water is not from oil and gas drilling and that the COGCC could not identify any other source of contamination. Category C water wells do not have recognition of a contamination source but have nearby oil and gas wells with documents indicative of compromised structural integrity which could result in BTEX or gas releases. We considered structural integrity problems to be high surface casing pressures, casing repairs, or descriptions in remediation reports that state the water well could be a potential receptor of contamination (Table 3). Category D water wells have no documentation of oil and gas well issues that could have caused elevated levels of BTEX in groundwater as well as no recognition that BTEX is in the water.

3. Results

3.1. Overview and Study Boundaries

The following results are divided into three sections following the purposes of study. Foremost, we quantified the occurrences of BTEX in water wells in the Denver-Julesburg Basin of Colorado (Figure 1) examined each occurrence case by case to identify possible sources and spatial trends. Secondly, we calculated the occurrence rate over the study period (2001-2016) and projected that rate onto sampled and unsampled domestic wells in the Wattenberg Field (Figure 1) where BTEX occurrences were most frequent. Lastly, we presented data on possible sources of groundwater contamination, specifically BTEX co-occurrence with methane.

For each case study, we outline the reason for initial sampling, water well information, the BTEX samples above detection limits, and the possible source of contamination. A map of each case shows surrounding oil and gas wells within a half-mile radius which are shown in

Appendix 4 (Case Studies). These case studies form the trends and statistics summarized in the results of this section.

3.2. Number of Benzene, Toluene, Ethylbenzene, and Xylenes Occurrences in Water Wells

The primary goal of the study was to quantify BTEX occurrences in water wells and determine the extent of contamination from oil and gas activity. The extent of contamination from oil and gas wells depends on the reported issues, concentration of BTEX, and proximity to the water well.

BTEX compounds were present above detection limits in 51 water wells in the Denver-Julesburg Basin out of 1,585 sampled. Of these 51 water wells, five had detections of benzene and toluene above the MCL, one for toluene and four for benzene. The occurrence rate of BTEX in groundwater samples is 0.07% to 3.2%. The fraction of 51 of 1,585 water wells that were sampled represents 3.2%. This does not account for factors that may increase the number of BTEX occurrences among samples, such as more densely populated areas that receive higher amounts of complaint submissions regarding poor water quality, or possible sources of BTEX from gasoline from surface spills by landowners. On the other hand, the COGCC must sample the most wells in a feasible manner that is representative of the regional groundwater quality. The fraction of 51 occurrences of 65,379 constructed, unique domestic water wells represents the 0.07% rate. This rate is subject to criticism of whether enough of the constructed water wells are being sampled frequently enough.

The frequency of BTEX by categorization in the Denver-Julesburg Basin are shown in Table 4. Categories indicate how the source of the BTEX or poor water quality was resolved by the Colorado Oil and Gas Conservation Commission (COGCC). In eight cases, the COGCC confidently identified one or more oil and gas wells as the source of the BTEX occurrences. To

identify an oil and gas well, the COGCC provided evidence of similar water chemistries between the oil and gas well (the source) and water well (the receptor). Four water wells had sources

Table 4 – The number of water wells sampled for the BTEX compounds in the Denver-Julesburg Basin. Four categories divide the type of BTEX source based on the COGCC resolution of the contamination. An occurrence is defined as a sample with BTEX above the detection limit. The occurrence rates are presented as a percentage of the sampled wells or total wells.

Category	Description	Count (51)	Fraction of Total Occurrences	Occurrence Rate of all Samples
A	Oil/gas well was source of contamination	8	16%	0.5%
B	Other source of contamination	5	10%	0.3%
C	Documents indicate issues with an oil/gas well	9	18%	0.6%
D	Unresolved - No explanation found	29	57%	1.8%
		51 of 1,585 sampled wells:		3.2%
		51 of 65,379 total water wells:		0.08%

of poor water quality or BTEX attributed to non-oil and gas sources. Nine water wells had nearby oil and gas wells with documents indicating repairs to surface casings, past leaks, or high Bradenhead pressures (“culprit” wells). The remaining 29 water wells had either no oil and gas wells that could be suspect to leaking, or the source of BTEX and poor water quality was identified as a non-oil and gas related source (four water wells).

After quantifying the number of BTEX occurrences by category and compound, we projected the occurrence rates to unsampled water wells to have a better understanding of widespread risks from oil and gas development. The Wattenberg field has a high density of oil and gas wells with 35 of the 43 (90%) case studies. These 35 cases represent 41 water wells among 1,013 sampled water wells amongst a total of 8,653 constructed and unique water wells (Table 5). The fraction of measured occurrences in sampled water wells is 5.0%. The fraction of

occurrences in all wells sampled and unsampled represents 0.59%. This lower rate assumes that samples collected are representative of groundwater in the quarter survey sections that were prescribed baseline samples in COGCC Rule 318A.f (COGCC, 2016a).

Table 5 - The number of water wells sampled for the BTEX compounds in the Wattenberg Field within the Denver-Julesburg Basin. Four categories divide the type of BTEX source based on the COGCC resolution of the contamination. An occurrence is defined as a sample with BTEX above the detection limit. The occurrence rates are presented as a percentage of the sampled wells or total wells.

Category	Description	Count (41)	Fraction of Total Occurrences	Occurrence Rate of all Samples
A	Oil/gas well was source of contamination	8	20%	0.5%
B	Other source of contamination	5	12%	0.3%
C	Documents indicate issues with an oil/gas well	8	20%	0.5%
D	Unresolved - No explanation found	20	49%	1.3%
		41 of 1,013 sampled wells:		5.0%
		41 of 8,653 total water wells:		0.59%

After quantifying the number of water wells with BTEX occurrences, we needed to determine trends of the specific BTEX compounds. The frequency for which each BTEX compound appeared in water wells is shown in Table 6. Median concentrations were calculated because of extreme outliers that represent unusual cases of contamination and would artificially raise the mean to an exaggerated level. For the BTEX compounds, toluene was most frequently measured, being present in 45 of 51 water wells with BTEX occurrences. Ethylbenzene detections were least frequent, appearing in three of 51 water wells. This could be explained by lower aqueous solubility of ethylbenzene and its infrequent presence in water samples.

The COGCC collects baseline samples on quarter-sections intercepting the half-mile radius of the oil and gas well (COGCC, 2016). To simplify this rule, we find that there are 308

water wells meeting the quality control parameters within a half-mile radius of the 71 "culprit" oil and gas wells.

The number of times for which a compound exceeded the MCL is also counted to help interpret the extent of contamination. Colorado has a stricter set of MCLs for BTEX than federal limits by reducing the limits for toluene and total xylenes to 560 μg L^{-1} and 1,400 μg L^{-1} respectively (Water Quality Control Commission, 2016). In five samples, an MCL was exceeded by benzene or toluene. Additionally, the median concentration of benzene was higher than the federal and state MCL. Benzene exceeded its MCL most often because the MCL is closer to the median BTEX concentration.

Table 6 – The frequency of benzene, toluene, ethylbenzene, and xylenes in water wells. Of these occurrences, four detections of benzene, and one detection of toluene exceed the respective maximum contaminant levels in Colorado. The median concentration was used because of extreme outliers of high concentrations. (USEPA, 1992; Water Quality Control Commission, 2016).

	BTEX Occurrences in Water Wells			**Maximum Contaminant Levels**	
Compound	**Count**	**Occurrences Above MCL**	**Median Concentration (μg L^{-1})**	**Federal (μg L^{-1})**	**Colorado (μg L^{-1})**
Benzene	8	4	5.8	5	5
Toluene	45	1	12	1,000	560
Ethylbenzene	3	0	3.5	700	700
Total Xylenes	4	0	2.05	10,000	1,400

3.3. Rate of BTEX Occurrences and Estimated Projection

The rate of occurrences for BTEX from 2001 through 2012 rose relatively steadily at an average of 1.7 cases per year (Figure 3). In 2012, and then 2014 through 2016, the occurrence rate increased to 11 cases per year. There were no BTEX occurrences above detection limit in 2013. The plot also indicates the BTEX occurrences per sample which remains steady after 2012,

because of a larger number of samples collected annually due to voluntary baseline groundwater quality monitoring from the Colorado Oil and Gas Association (COGA) and COGCC.

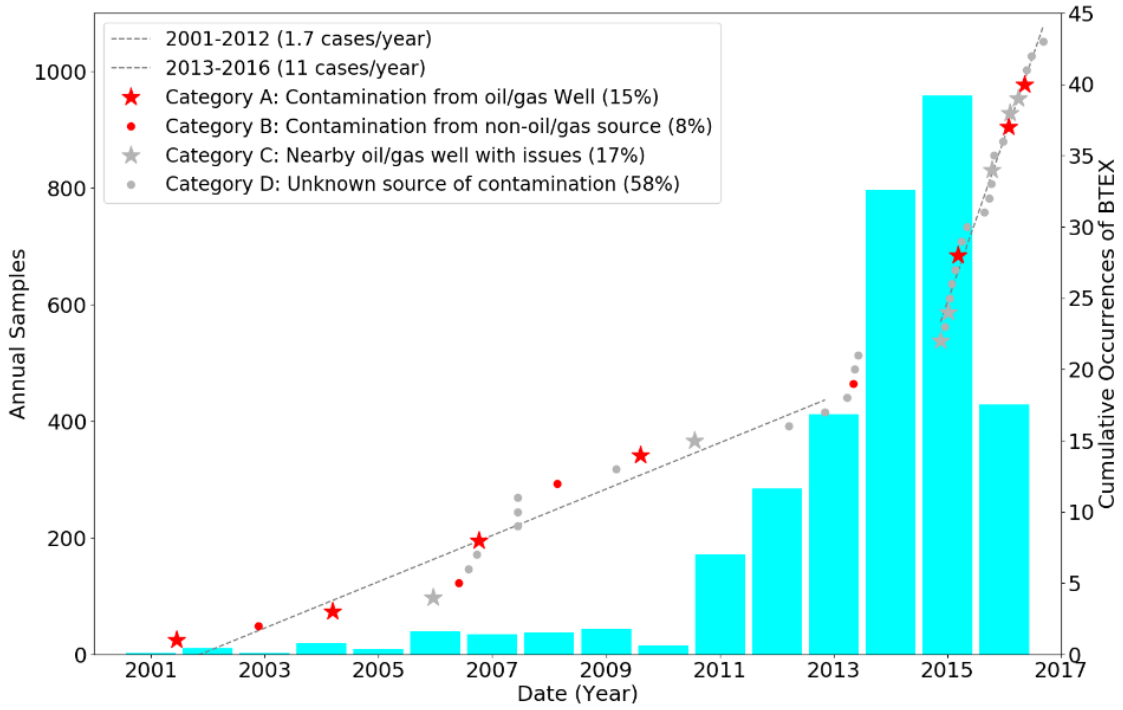

Figure 3 – A plot of cumulative benzene, toluene, ethylbenzene, and xylenes occurrences from the first detection in 2001 through 2016. From 2001 to 2012, the annual rate of occurrences is 1.7 cases per year. After 2012, the rate increases to 11 cases per year, as a result of increased sampling. Cases marked as resolved are shown in red, and cases that are unresolved are grey. Stars indicate whether the case study has an identified or suspected oil and gas well that caused contamination. Samples testing for benzene, toluene, ethylbenzene, and xylenes are show with the light blue bars. Increases in samples begin in 2011 from voluntary baseline groundwater quality monitoring by the Colorado Oil and Gas Association and Colorado Oil and Gas Conservation Commission.

3.4. Sources of Groundwater Contamination

We hypothesized that BTEX compounds would co-occur with thermogenic methane because both are naturally occurring in gases and liquids associated with oil and gas drilling and could be released by the same mechanisms of wellbore failure. BTEX compounds were detected with thermogenic methane in 13 occurrences (25.5%), with biogenic methane in 25 occurrences

(49.0%), and with methane concentrations below 1 mg L^{-1}, and thus no carbon-13 isotope measurement, in 13 occurrences (25.5%). Of the 13 BTEX cases with thermogenic methane, eight cases were in Category A, two were in Category B, and two were in Category D.

In addition to methane, preliminary searches showed a total of 50 organic compounds that could indicate oil and gas contamination of a water well (Appendix 1). The compounds were filtered from the Colorado Oil and Gas Information System (COGIS) archive of environmental samples. The chemicals sampled were from the same 1,585 water wells tested for BTEX. Occurrences are simply any concentration listed above the detection limit. This list does not include the quality controls of matching water wells with occurrences to Colorado Division of Water Resources records, hence the higher number of occurrences for benzene, toluene, ethylbenzene, and xylenes.

Current knowledge of oil and gas wellbore failures predicts that thermogenic methane originates from leaking wells. We applied this knowledge to all oil and gas wells within the half-mile radius of the BTEX occurrences under the assumption that BTEX migration can follow similar pathways as methane. The reports and information examined for each oil and gas wells showed that 71 (8.3%) oil and gas wells within a half-mile radius of the water wells with BTEX had reports of short surface casings, surface casing leaks or repairs, or high surface casing pressures. Eleven of the 71 oil and gas wells were identified as the cause of contamination for all eight Category A cases, meaning that in two of the cases, multiple oil and gas wells were responsible for the contamination (Table 7).

Table 7 – The oil and gas wells with issues associated with a benzene, toluene, ethylbenzene, or xylenes occurrence in the Denver-Julesburg Basin. Each well was manually searched for documents that reported short surface casings, surface casing leaks and repairs, or high Bradenhead pressures.

Oil and Gas Wells Description	Quantity	Fraction of Total Examined
Issue causing contamination	11	1.3%
Records Indicating Issues	60	7.0%
No Issues	791	92%

4. Discussion

4.1. Benzene, Toluene, Ethylbenzene, and Xylenes Occurrence in Water Wells

Benzene, toluene, ethylbenzene, and xylenes (BTEX) are frequently tested in water well samples collected by the Colorado Oil and Gas Conservation Commission (COGCC). The purpose of this section explains the frequency of BTEX detections and the extent to which they contaminate water wells. We will also discuss oil and gas wells as possible sources of BTEX occurrences and how BTEX migration can overlap with stray gas migration.

4.1.1. Benzene, Toluene, Ethylbenzene, and Xylenes Occurrence by Category of Resolution

We divided the occurrences into Categories A, B, C, and D based on the resolution for each case of BTEX occurrence, or by indication of oil and gas well issues as described in the Methods. The categories represent how much information we know about a specific BTEX occurrence which helps describe trends in contamination as a result of oil and gas, or lack thereof.

Eight Category A water wells are resolved by the COGCC to have a determined oil and gas well as the source of contamination. BTEX was usually acknowledged when above the MCL but was not the primary factor in connecting contamination to an oil and gas. The primary evidence of contamination was the signature of thermogenic methane in comparison between water and oil and gas wells.

Four Category B water wells are resolved by the COGCC with the cause of poor water quality from a non-oil and gas related source. In two of these cases, the COGCC identified that the source of gas in water was from coal seams or sandstone stratigraphic gas-trap respectively. In the other two cases, the poor water quality was recorded as unrelated to oil and gas, but no

further context or explanation was provided. As described by Sherwood et al. (2016), coalbeds are present in the Front Range and can be in contact with certain areas of the Laramie-Fox Hills aquifer, which may explain the presence of BTEX. Produced water from coalbed methane wells in the Raton and San Juan Basins contain BTEX compounds at levels between 0.8 µg L^{-1} and 149.7 µg L^{-1} (Dahm et al., 2011). However, the concentrations of BTEX in produced water from the Denver-Julesburg Basin are still being researched (Rosenblum et al., 2017). The COGCC does not track any BTEX occurrences to a specific source, except for one toluene occurrence to new piping in a water well.

In all of these Category B water wells, the source of BTEX compounds is still not known or well described. The COGCC did not demonstrate or prove BTEX detections were from coal. A BTEX occurrence is important because of potentially acute health risks and should not be dismissed but unfortunately there is nothing that can be done if coalbed seams in contact with groundwater are releasing gas. Presently, water quality in the Denver-Julesburg Basin is limited to baseline characterizations of aquifers and have not connected BTEX occurrences to any specific source (Musgrove et al., 2014).

Nine Category C water wells have unresolved BTEX occurrences and nearby oil and gas wells with documented issues. This finding implies that there is more evidence of “culprit” oil and gas wells that should be considered more thoroughly before dismissing cases as not related to oil and gas activity. The COGCC specified in Rules 318 and 609 that the presence of BTEX requires notification of the director (COGCC, 2016a; COGCC, 2016b). The lack of resolutions regarding BTEX occurrences is unexpected because the appearance of BTEX is urgent. Colorado oil and gas development has been ongoing for decades where water pollution could lead to

chronic health problems. By identifying the possible sources of pollution, we show there are oil and gas wells with issues that can be increasing health risks for neighboring landowners.

The remaining 30 Category D cases of BTEX occurrences are unresolved without any explained sources. This category alone represents a majority of the total cases signifying how more studies are needed to determine the sources. When combined, the unresolved Categories C and D water wells are 39 of 51 BTEX occurrences. This is an unjustifiably high fraction of BTEX occurrences when the health effects are well known to be harmful. A more thorough approach to investigating oil and gas wells needs to be implemented. Monitoring for BTEX is standard practice after surface spills because BTEX is common in spilled fluids (Gross et al., 2013; Shores et al., 2017). We also know that oil and gas wells are capable of leaking thermogenic methane (Davies et al., 2014; Ingraffea et al., 2014; Jackson, 2014). This suggests the importance and need to sufficiently test for BTEX if we know oil and gas wells are leaking.

In four Category C and Category D unresolved water wells, an oil and gas well within a one-mile distance was responsible for the contamination of a Category A water well. The fate and transport properties of BTEX compounds show that benzene and toluene are more water soluble and have less soil partitioning than ethylbenzene and total xylenes (Zytner, 1994; Schwarzenbach et al., 2016). This supports why benzene and toluene could be present in the four latter unresolved water wells. When the COGCC collects baseline samples within a half-mile of the oil and gas wells, the tests could be detecting the presence of contamination occurring farther than a half-mile radius. This again highlights the need for more studies on the BTEX transport from oil and gas wells to water wells.

4.1.2. Benzene, Toluene, Ethylbenzene, and Xylenes Exceeding Maximum Contaminant Levels

The Agency for Toxic Substances and Disease Registry (ATSDR) has characterized the health risks of BTEX inhalation and ingestion, and we know that the BTEX compounds are tested for in water samples in the Denver-Julesburg Basin, but we do not know if the occurrences are high enough to be a public health concern (ATSDR, 2004). From our data, 10% of the BTEX occurrences exceeded their MCL (Table 8). However, the median concentration of benzene exceeded the MCL. With the exception of benzene, the median concentrations of toluene, ethylbenzene, and xylenes were significantly lower than their respective MCL (Table 6). Since the era of leaking underground storage tanks, the US EPA has put forth efforts to monitor and remediate spills containing BTEX compounds as early as possible (USEPA, 1993). The source is much harder to find in deep aquifers so there more uncertainty and lag around monitoring and remediation. Specifically, in the Denver-Julesburg Basin, the COGCC only resolved three of five cases that exceeded the MCL. The remaining two wells above the MCL were left unattended because there was not enough connection linking the MCL exceedance to an oil and gas well failure. An additional 38 cases from Categories C and D were below the BTEX MCL and no remedial action was taken.

Table 8 – Five water wells that had benzene or toluene above the maximum contaminant level. The source of contamination describes oil and gas wellbore failures that have released the benzene or toluene into the water *(Water Quality Control Commission, 2016)*.

Well (FacID #)	Contaminant	Category	Concentration ($\mu g\ L^{-1}$)	Colorado MCL ($\mu g\ L^{-1}$)	Source of Contamination
753196	Toluene	A	800	560	Short surface casing, high casing pressure
703884	Benzene	A	150	5	Short surface casing, leaks
704769	Benzene	A	75.6	5	Short surface casing, leaks
753730	Benzene	D	18.6	5	Unknown

704700	Benzene	D	10	5	Unknown, but leaking oil/gas well farther than half-mile

The two Category D water wells with benzene above the MCL raise concern because they present an urgent problem, but the COGCC uses ^{13}C enrichment of $\delta^{13}C_{CH4}$ as the primary indicator of oil and gas well contamination. We assume ^{13}C can be used to describe methane as thermogenic and that it corresponds with oil and gas activity (Vidic et al., 2013; Sherwood et al., 2016). However, we do not know if this always holds true, because in the unconfined Laramie-Fox Hills Aquifer (a region not confined by the Laramie Formation) has higher sulfate content which would not provide suitable conditions for microbial methanogenesis and thermogenic methane may occur naturally (Whiticar, 1999b). Because of this, solely relying upon thermogenic methane is not entirely reliable, and more data is needed to assess the source of contamination.

Produced water and oil spills above surface are known to have BTEX, so in the case of a wellbore failure, these fluids could be leaking into aquifers (Gross et al., 2013; Shores et al., 2017). For the COGCC to make informed decisions on remediation action, there needs to be more study on quantifying and connecting the BTEX occurrences with oil and gas wells.

4.1.3. Correlation Between Benzene, Toluene, Ethylbenzene, and Xylenes Concentration with Distance to "Culprit" Oil and Gas Wells

As part of quantifying the number of BTEX occurrences in the Denver-Julesburg Basin, we measured the maximum concentration of the BTEX samples, and the distance to the nearest "culprit" oil and gas well. We hypothesized that BTEX concentrations would decrease with distance to the "culprit" oil and gas well. The data was expected to follow this trend because contaminants will have less degradation with closer proximity to water wells. To test the hypothesis, we checked for a correlation between the concentrations and distance and found

there is a decreasing trend (Figure 4). Additionally, to show the importance of benzene and the associated high health risks, all concentrations were normalized to their respective MCL. This resulted in the ratio of the benzene to MCL concentrations being orders of magnitudes greater than for toluene or xylenes data points. The benzene data points on the plot suggest occurrences are much more important to identify, even if it is below the MCL and at similar concentrations to the other BTEX compounds.

However, we cannot use this correlation as a model to predict degradation rates of the BTEX compounds because initial concentrations and times of leaks are unknown, and the "culprit" oil and gas wells are unverified by the COGCC. This correlation suggests that "culprit" oil and gas wells are more likely to be a source of BTEX. The methods used to identify these wells could be applied more broadly to landowner complaints who believe their water has been affected.

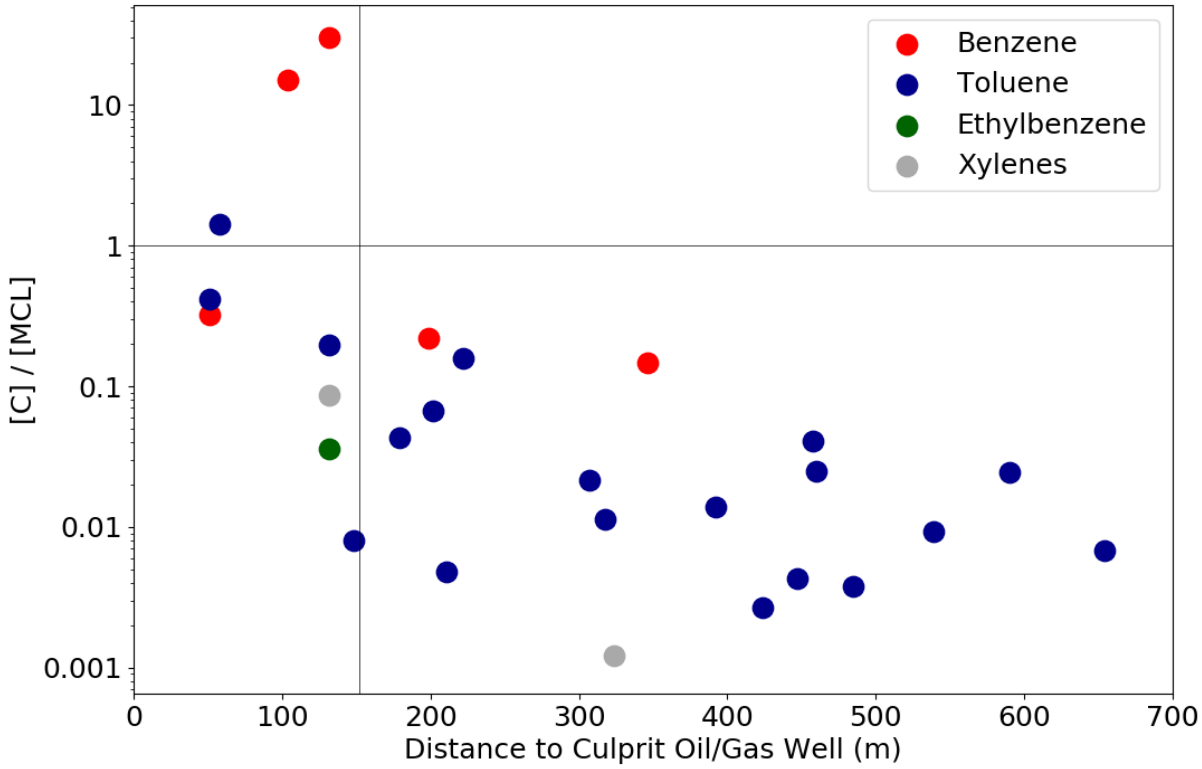

Figure 4 - The ratio of the BTEX concentration to their MCLs as a function of distance to the culprit oil and gas well. The horizontal black line represents concentrations exceeding the maximum contaminant level for the respective compound. The vertical black line represents the 500 ft setback distance for the state of Colorado.

Jackson et al. (2013) correlated methane concentrations with distance to the nearest oil and gas well, regardless of whether it had reported issues. By showing that there was a statistical significance of methane concentration to nearby oil and gas wells, the authors could speculate how the methane could originate and be sourced to oil and gas wells. Similarly, by analyzing the distances to suspect oil and gas wells, we can directly tie the known issues with water well contamination. The exact groundwater flow direction is unknown for specific wells, but since we the bottom elevation of the Laramie-Fox Hills aquifer, we can predict that groundwater flow in that aquifer should follow the contour lines (Figure 5).

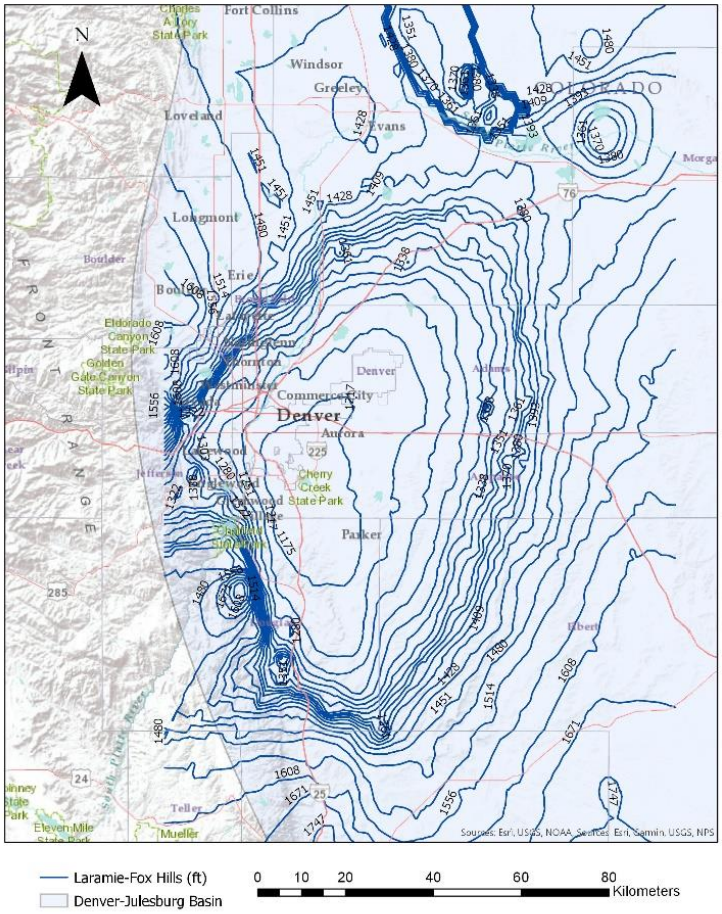

Figure 5 – Contours of the bottom elevation of the Laramie-Fox Hill aquifer. We should expect groundwater flow direction to follow the gradient of the bottom elevation and make general predictions to support whether an oil and gas well could be more or less suspect to a BTEX occurrence. Contour data Sherwood et al. (2016).

Methane has been found at much higher concentrations than BTEX, often by landowners who have bubbling water with methane above saturated concentrations. Leaking stray gas could result in methane moving upwards along the confining formation opposite the groundwater flow direction. BTEX may be dissolved at low concentrations originating from the same source, but then follow the groundwater flow direction. This could reason the discrepancy between BTEX occurrences in water wells where thermogenic methane is not present.

Furthermore, if BTEX is predicted to follow a similar pathway as methane, we expect that it should be detected in wells screening deeper aquifers. Sherwood et al. (2016) suggested that biogenic methane was more common at shallower aquifers because coalbeds interfacing with the Laramie-Fox Hills water are less common. Li et al. (2016) suggest that aqueous phase contamination is unlikely in deep aquifers, but we see in Figure 6 that a majority of the BTEX occurrences exist in the Laramie-Fox Hills aquifer. This can suggest a similar trend and support our hypothesis that BTEX migration pathways may happen in similar conditions.

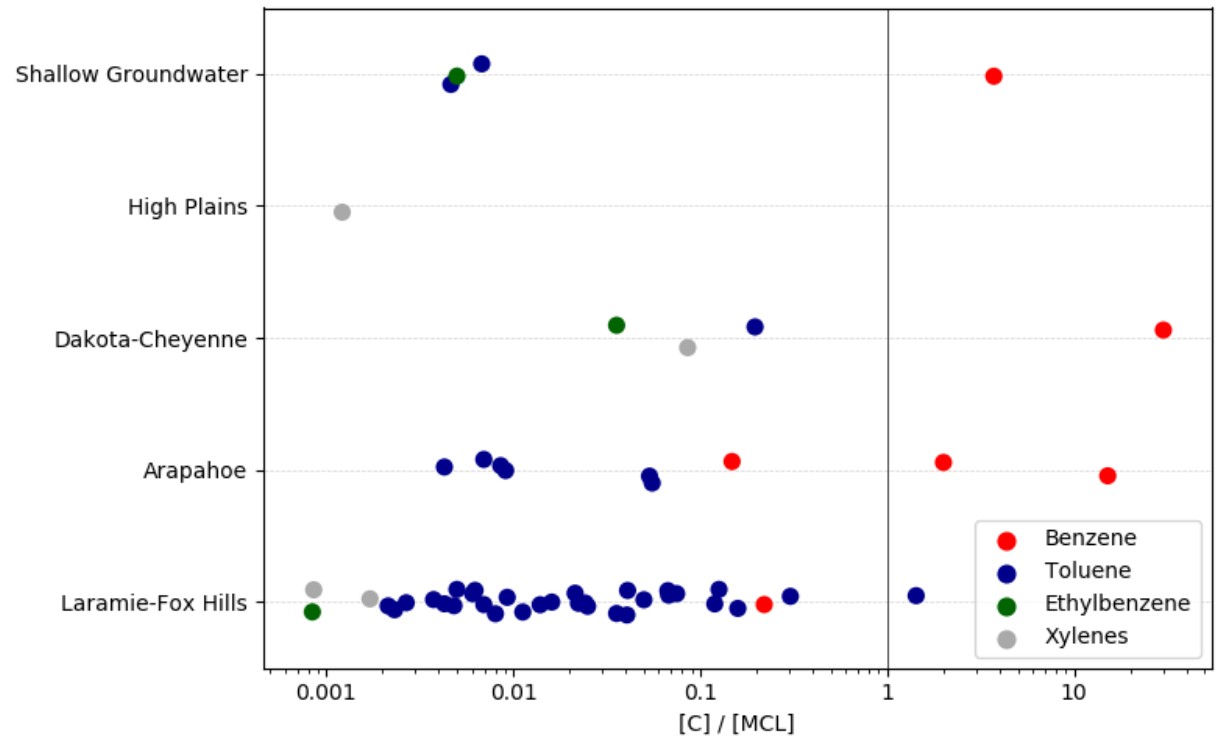

Figure 6 – Concentrations are normalized to the respective maximum contaminant level in the x-axis to emphasize the importance of the health risks associated with benzene. Sampled were collected from wells screened in the aquifers reported by the Colorado Division of Water Resources shown in the y-axis. The vertical black line represents concentrations that exceed the maximum contaminant level.

4.1.4. Wellbore Failures of Oil and Gas Wells

Studies have attributed thermogenic methane contamination to oil and gas wellbore failures. Wellbores can have imperfect cementing that seals gaps between casings and impermeable formations which can result in stray gas release, or fluids like produced water to leak outside of the well (Ingraffea et al., 2014; Jackson, 2014). Inadequate surface casing that do not fully extend to the bottom of an aquifer present the most common source of thermogenic methane in the Denver-Julesburg Basin (Sherwood et al., 2016). Based on the studied migration pathways of methane, we hypothesize that BTEX would follow the same pathways.

Within the half-mile radius of the 43 BTEX case studies, 8.3% of the oil and gas wells had documented integrity issues. Repairs to casing leaks, re-cementing of casings, or high Bradenhead pressures could indicate a source of contamination before the repair. For BTEX occurrences, this rate of potentially faulty oil and gas wells nearby is a concern because most Category A resolutions did not identify more than one oil and gas well as the source of contamination. In the eight Category A case studies, 11 oil and gas wells were responsible for the water well contaminations. In two of these cases, multiple oil and gas wells were responsible for the source of thermogenic methane or BTEX. Four wells with resolved sources of contamination had additional suspect wells within the radius that could also be contributing to the source of BTEX or gas. This could partly be due to a "set" of wells installed that all contain problems, and one oil and gas well reaches a threshold where it leaks into water.

The 8.3% "culprit" rate cannot be applied to all Denver-Julesburg Basin oil and gas wells because they were investigated for their proximity to nearby contaminations. Aside from methane occurrences in the Denver-Julesburg Basin, research has not studied specific chemical identifiers of well issues in public archives (Sherwood et al., 2016). Reporting the "culprit" oil

and gas wells by individual cases shows the need for more transparency. Reports that indicate repairs should be automatic flags to the COGCC that can justify further investigation or not.

4.2. Co-occurrence of BTEX, Methane, and other Organic Chemicals

Methane is understood to be a contaminant that is connected to oil and gas through wellbore failures (Osborn et al., 2011; Jackson et al., 2013; Vengosh et al., 2014; Darrah et al., 2014; Sherwood et al., 2016). Methane that is released from oil and gas wells and accumulates to is an explosion hazard but does not pose health risks like the BTEX compounds. Therefore, it is important to quantify chemicals like BTEX.

Scenarios that can release methane are (1) production casing leaks, (2) improperly isolated hydrocarbon formations, and (3) cement seals (Lackey et al., 2017). These scenarios for methane should be examined for BTEX migration because gases build to high pressures and can be in direct contact with the aquifer. This allows some of the gas to dissolve in water. Therefore, we hypothesized that BTEX compounds should be associated with the thermogenic methane occurrences. To test this hypothesis, we quantified the occurrences of BTEX with biogenic and thermogenic methane to check for correlations which is summarized in Figure 7. We also sought to address whether other contaminants would be present if BTEX compounds are detected. If other contaminants are co-occurrent with BTEX, there is a stronger implication that the water has been affected by oil and gas drilling.

We found 26% of BTEX occurrences had dissolved thermogenic methane. Even though the COGCC commonly uses thermogenic methane as an indicator of oil and gas contamination, four of the 13 thermogenic methane occurrences were not resolved or did not have a determined source. This rate of thermogenic methane occurring with BTEX suggests that the two could be correlated. Sherwood et al. (2016) listed 42 of 924 sampled water wells (7%) as having elevated

thermogenic methane. This suggests that we should see fewer BTEX co-occurrences with thermogenic methane if BTEX occurs naturally. Our higher rate of 26% co-occurrence with thermogenic methane suggests that there is a correlation and that BTEX could be more commonly from anthropogenic sources. This is important because it provides more evidence that oil and gas activity may have a larger affect on groundwater than previously suggested by other research. Li et al. (2016) examined similar data in the Wattenberg Field, but did not include other organic contaminants that are tested before concluding that oil and gas activity has very little effect on aquifers. The BTEX occurrences identified in the Denver-Julesburg Basin in this study contrasts the findings of Li et al. (2016). We believe our data is more representative of the Denver-Julesburg Basin and Wattenberg Field because it includes an order of magnitude greater amount of data and examines each occurrence on a specific case-by-case basis. A widespread occurrence rate of 3.2% shows that some of the occurrences are likely originating from oil and gas activity, considering that eight of the occurrences were resolved by the COGCC.

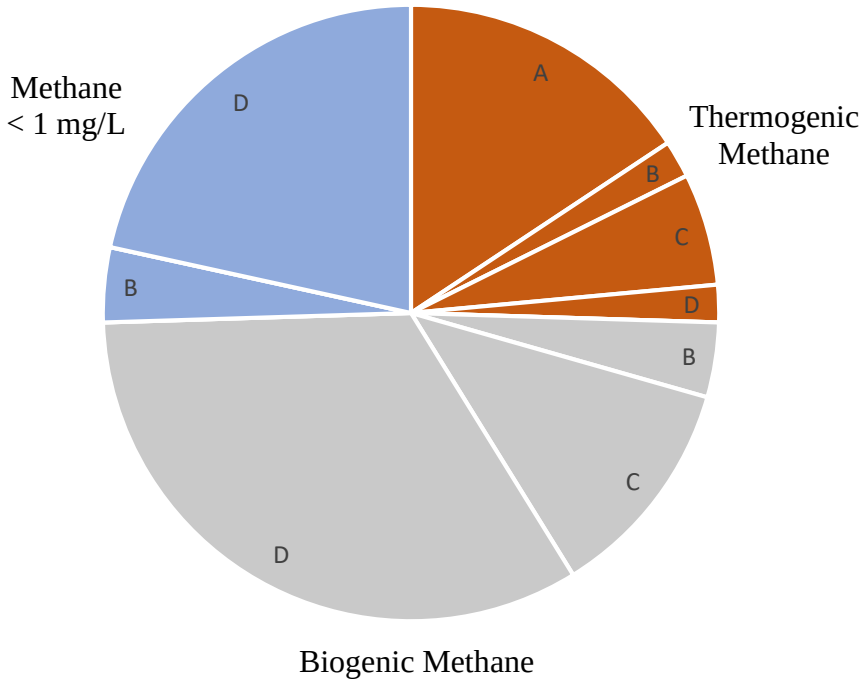

Figure 7 – The methane type that was present with a benzene, toluene, ethylbenzene, or xylenes occurrence. Methane concentrations below 1 mg L^{-1} are not isotopically measured. Letters on each section represent categories A-D.

Almost half (49%) of the BTEX occurrences had biogenic methane, and this could indicate that the BTEX compounds are originating from coal seams. Dahm et al. (2011) showed that BTEX concentrations at low levels are present in produced water from coalbed methane wells. The produced water is in contact with coal seams and would be a source of BTEX that could dissolve in water. Sub-bituminous coal is interbedded with the Laramie-Fox Hills aquifer, where 21 unresolved water wells were screened that also had BTEX compounds with biogenic methane (Musgrove et al., 2007). Five wells also had suspect oil and gas wells nearby so biogenic methane alone does not discount the water wells from oil and gas activity.

The remaining 26% of water wells did not have methane concentrations above 1 mg L^{-1} and did not have isotope tests performed. All of these cases are Category D water wells except

for two that were Category B. The two that were resolved were indicated to have poor water quality from coalbed water contact, or from toluene in new piping. The lack of biogenic methane for this well was explained by high total dissolved solids and sulfate concentrations, which was attributed to coalbed contact. Remaining water wells with no methane occurrences represent a risk that the COGCC is not able to explain or relate to oil and gas activity.

We have shown that roughly half of the BTEX occurrences are co-occurrent with biogenic methane, and the other half are either unexplained or co-occurrent with thermogenic methane. As we have discussed with Category D water wells, the unexplained pollutant source remains important considering the urgency of BTEX health risks. Presently, the COGCC is not responsible for analyzing where every occurrence of BTEX is originating, since they may have no connection to any nearby oil and gas well. Future work should examine whether unexplained BTEX occurrences are indicative of oil and gas well contamination when no other information is available. Our data has not provided enough information to whether the BTEX occurrences in the Denver-Julesburg Basin are found in predictable ratios to each other. Toluene was found to be detected at a median concentration that was higher than benzene, which is unexpected given that benzene has a higher solubility. In characterizations of produced water in coalbed methane wells, BTEX compounds existed together at higher concentrations (Dahm et al., 2011).

We recommend that additional testing be done for better chemical tracers when BTEX is detected. Rosenblum et al. (2017) and Thurman et al. (2014, 2017) characterized “fingerprints” that could specifically be used to test for oil and gas effects on groundwater. Due to the lack of information on tracers that are easily monitored, we suggest that operator specific chemical tracers should be added to hydraulic fracturing fluids. This could allow investigations to more

readily resolve whether water quality is being affected and by which operator. The difficulty lies with a tracer that is persistent enough to be detectable over long time periods.

4.3. Rates of Occurrence from 2001 through 2016

We discovered BTEX occurrences were more frequent with increased sampling rates. From the first BTEX detection in 2001 through 2012, was steady at 1.7 occurrences per year (Figure 2). From 2015 through 2016, the rate of BTEX occurrences rises to 11 per year. This leap in occurrence rate was explained because of rule changes of voluntary groundwater quality monitoring program initiated by the COGA (COGCC, 2017). In 2014, we do not see any occurrence of BTEX despite the rate increasing at the same 11 occurrences per year before and after this gap. We do not have a clear understanding as to why there are no records.

The voluntary baseline sampling program existed from 2011 to 2013, to sample at least two water wells before drilling a new oil and gas well. In 2013, COGCC Rules 318A.e/f and 609 superseded voluntary baseline sampling (COGCC, 2016a; COGCC, 2016b). These new rules required water sampling for all new oil and gas wells outside of the Wattenberg Field (Rule 609), as well as increase the sampling density inside of the Wattenberg Field (Rule 318A.e/f). These rules describe where samples will be collected. Section quarters (quarter-mile squares of land used for surveying) touching a half-mile radius of the proposed new oil and gas wells will be sampled if they have not previously been sampled. In the Wattenberg Field, the density of oil and gas wells is high enough to where all sections have been sampled, thus the rule only increases the sampling density of the section quarters.

As we described in Figure 2, more sampling resulted in an increase in BTEX occurrences. This increase in occurrences was only shown in 2015 and 2016, so more data is needed to see if this trend continues to increase with more sampling. The rate of BTEX

occurrences dropped in 2016 as a result of reduced oil and gas production for that year, and we still see the same trend of 11 BTEX occurrences per year. Only having two years of the high BTEX occurrence rate highlights the importance for further analysis of Colorado's public archive of continuously updated information.

To put the BTEX occurrence per sample rate in context, this study extrapolated the occurrence rate to the unsampled water wells in the Wattenberg Field. Applying the rate to the Wattenberg Field region of the Denver-Julesburg Basin was most relevant because it had 90% of the BTEX case studies. In the Wattenberg Field, an estimated range of 0.59%-5.0% occurrence rate results in 45 to 385 additional unsampled water wells that could have BTEX occurrences (Table 5). The 5.0% rate could be biased by populations that request more water samples to be analyzed and misrepresent less densely populated regions. Additionally, it could account for BTEX occurrences from surface spill activity unrelated to oil and gas development such as private leaking gas tanks used for agriculture.

In a more direct measurement, we listed 308 water wells that are within the half-mile radius of culprit oil and gas wells. These are water wells are even more likely to have BTEX detections. Many of these have been sampled by the COGCC, but at times when BTEX was not present. We suggest that water wells near BTEX occurrences and even more specifically, oil and gas wells with recorded integrity problems, be sampled further.

Despite the decades oil and gas development have existed, relatively little information exists on explaining the direct and indirect health effects that could be a risk to landowners and communities. While there is evidence that stray gas migration is resulting from an older era of oil and gas wells, unconventional methods like horizontal drilling are a newer technology that is seeing concern from the public (Fleckenstein et al., 2015). Modern oil and gas wells are showing

improved integrity, but we are not able to predict their integrity decades into the future, and we are not aware of any life cycle analyses.

5. Conclusions

The primary purpose of this study was to quantify the occurrences of BTEX compounds in water wells in the Denver-Julesburg Basin and determine the extent to which oil and gas is responsible for contamination. We determined 51 water wells had BTEX present out of 1,585 sampled and categorized them into groups based on their source of contamination. Category A contained eight water wells with oil and gas wells as the contamination source. Category B contained five water wells where the COGCC stated that contamination was not from oil and gas development. Category C had nine water wells where nearby oil and gas wells had documents describing well integrity issues, but there was no COGCC resolution. The remaining 28 Category D water wells had no evidence or documented source of BTEX contamination. Between 2001 and 2012, there was an average of 1.7 BTEX occurrences per year. After voluntary regulation by the Colorado Oil and Gas Association in 2012, there were a reported 11 BTEX occurrences per year, except for 2013, with none.

Five of the 51 water wells had BTEX concentrations exceed the MCL. Three were resolved (Category A), but two were not resolved (Category D). This is particularly urgent because BTEX compounds pose known carcinogenic and neurotoxic health risks above the MCL. The lack of action shows that the water quality monitoring did not prevent possible human exposure to these chemicals.

We hypothesized methane would be present with BTEX occurrences because of similar transport pathways. About a half of the water wells had biogenic methane could indicate BTEX is originating from water in contact with coalbeds in the Laramie-Fox Hills aquifer. The other

half, either had thermogenic methane or no methane, which could indicate they are infiltrating aquifers from oil and gas activity.

Nearly all of case studies (90%) exist in the Wattenberg Field. Because this region is representative of the BTEX occurrences, and also has dense oil and gas drilling, applying the occurrence rate of 0.59% to 5.0% resulted in 45 to 485 unsampled water wells having potential BTEX occurrences.

The projected occurrence rate of BTEX in unsampled water wells in the Wattenberg Field results in a high number regardless of the upper or lower estimates. This statistic is concerning because we believe the COGCC process for identifying sources of BTEX contamination is not rigorous enough to thoroughly identify BTEX sources, evident by two unresolved BTEX occurrences above the MCL. Boulder County took the initiative to collect third party baseline groundwater samples by partnering with the University of Colorado Boulder (Boulder County, 2018).

We believe the lack of specific information like pollutant sources including the location, time, the volume released, or even the groundwater flow direction is a result of oil and gas operators not having the incentive or mandate to determine these factors. The burden of the water contamination falls onto the COGCC, and if they are not able to determine the source, the burden then falls to the landowners and consumers. Because of this, communities need to be involved with identifying risks that are most concerning to them.

In late 2017, the COGCC created the Daily Activity Dashboard (DAD), a positive step in improving accessibility of the archive of public records (COGCC, 2017). On a small level, records of oil and gas wells can be viewed in a user-friendly display. From our learnings in data organization and management, we recommend that maps be an essential part of all data

accessibility. If a concerned community sought information, clicking on a map to view relevant information is the most intuitive and understandable. Based on our findings of BTEX occurrences, we also recommend that environmental sampling records be easily viewable by location.

Future work should focus on improving the methodology for connecting contamination with its source. One focus area is further characterization of the compounds in hydraulic fracturing fluids and flowback water that could serve as tracers to possible “culprit” oil and gas wells. Then, when a BTEX compound is detected, we suggest also sampling for additional organic pollutants which could pose additional health risks and serve as tracers. Nearby water wells could also provide more information on affected groundwater regardless of past baseline samples.

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7. Appendix

7.1. Organic Compounds of Potential Concern

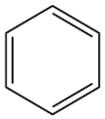
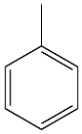
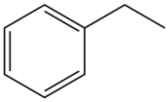
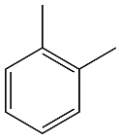
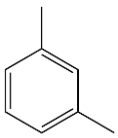
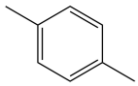
Table 9. Organic chemicals in the Colorado Oil and Gas Information System archive of water well samples. The chemicals sampled were from the same 1,585 water wells tested for benzene, toluene, ethylbenzene, and xylenes. Occurrences are simply any concentration listed above the detection limit. This list does not include the quality controls of matching water wells with occurrences to Colorado Division of Water Resources records, hence the higher number of occurrences for benzene, toluene, ethylbenzene, and xylenes.

Parameter	Occurrences Above Detection Limit
METHANE	2784
ETHANE	2023
PROPANE	802
BUTANE	234
C6+ (hexanes +)	224
PENTANE	198
TVPH - Gasoline Range Organics	104
TOLUENE	91
TEPH DIESEL RANGE ORGANICS	50
BENZENE	44
PROPENE	23
m-+p-XYLENE	22
TOTAL XYLENES	19
ETHYLBENZENE	17
CHLOROFORM	12
METHYL CYCLOHEXANE	11
CYCLOHEXANE	11
2-BUTANONE	9
MBAS (mol.wt 320)	7
N-HEXANE	7
ETHENE	5
o-XYLENE	4
CHLOROMETHANE	5
BROMODICHLOROMETHANE	5
CHLOROETHANE	4
BROMOMETHANE	4
IODOMETHANE	4
bis(2-ETHYLHEXYL)PHTHALATE	4
DI-n-BUTYL PHTHALATE	3
NAPHTHALENE	3
1,2,4-TRIMETHYLBENZENE	2

1,3,5-TRIMETHYLBENZENE	2
DIBROMOCHLOROMETHANE	2
PYRENE	2
TEPH MOTOR OIL RANGE ORGANICS	2
CYCLOHEXANONE	1
4-BROMOFLUOROBENZENE	1
METHYL-tert-BUTYL-ETHER (MTBE)	1
ACENAPHTHYLENE	1
OIL AND GREASE	1
PHENANTHRENE	1
DIETHYL PHTHALATE	1
DICHLOROMETHANE (methylene chloride)	1
n-PROPYLBENZENE	1
2-PROPANOL	1
1-METHYLNAPHTHALENE	1
FLUORANTHENE	1
STYRENE	1
2-METHYLNAPHTHALENE	1
ISOPROPYLBENZENE	1

7.2. Chemical Properties of Benzene, Toluene, Ethylbenzene, and Xylenes

Table 10. Fate and transport parameters for benzene, toluene, ethylbenzene, and xylene isomers.

	Benzene	**Toluene**	**Ethylbenzene**	**o-Xylene**	**m-Xylene**	**p-Xylene**
						
Molecular formula	C_6H_6	C_7H_8	C_8H_{10}	C_8H_{10}	C_8H_{10}	C_8H_{10}
Molecular weight (g/mol)	78	92	106	106	106	106
Aqueous solubility at 25°C (mol L_w^{-1})	0.0224	0.0060	0.0016	0.0018	0.0015	0.0017
Vapor pressure at 25°C (kPa)	12.59	3.72	1.23	0.89	1.10	1.17
Air–Water partition at 25°C (L_w L_a^{-1})	0.22	0.25	0.32	0.20	0.30	0.28
Octanol-water partition at 25°C Log(K_{ow})	2.17	2.69	3.20	3.16	3.30	3.27

7.3. Maximum Contaminant Levels (MCL)

Table 11. The state and federal maximum contaminant levels for each of the compounds in this study. Colorado maximum contaminant levels are stricter for ethylbenzene and total xylenes.

Maximum Contaminant Levels		
Compound	**National (µg L^{-1})**	**Colorado (µg L^{-1})**
Benzene	5	5
Toluene	1,000	560
Ethylbenzene	700	700
Total Xylenes	10,000	1,400

7.4. Case Studies

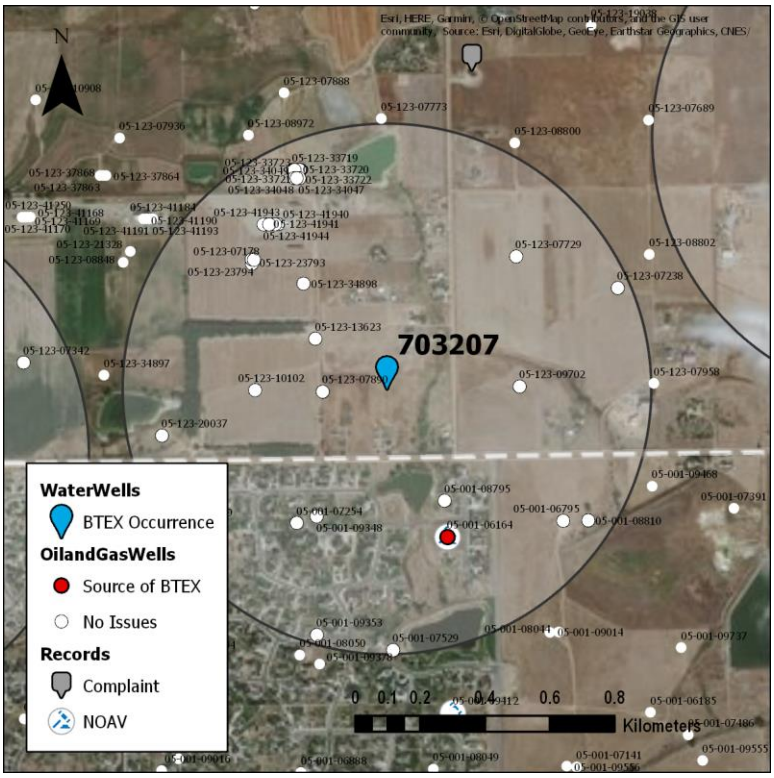
Each of the following case studies provides details about why the groundwater well was sampled, information about the groundwater well, sampling results, and a summary of whether the COGCC concluded a definitive source of the water contamination. Groundwater well information indicates whether an oil and gas well issue is reasonable as a source of contamination. For example, a water well screened in the Laramie-Fox Hills aquifer could be more susceptible to contamination from a leaking oil and gas surface casing than a surface spill.

A map of each case study is provided which shows a half-mile (0.80 km) radius around the water well with a BTEX occurrence. Yellow circle icons represent oil and gas wells with a documented issue of wellbore structural integrity where gas or fluid could leak. Red circle icons represent oil and gas wells where the COGCC formally issued an NOAV or documented the well as a source of contamination to the water well. All other oil and gas wells are indicated by a white circle icon. Oil and gas wells are labeled with a unique identifier (API number) that is used for searching public records.

For each case with supporting documentation and information, a “suspected pathway” assesses how an oil and gas well issue could be the source of the BTEX occurrence. The suspected pathway is based on integrity issues such as high surface casing pressures, short surface casings, and leaks within the surface casing as identified by failed mechanical integrity tests.

Case #1

Groundwater well: FacID #703207



Initial Sampling Reason
Mountain View Water Users Association (MVWUA) opened Complaint # 200016437 with the COGCC on 5/2/2001 and reported gas in water after a pumphouse explosion.

Groundwater Well Information

- Depth: 258 meters
- Aquifer: Laramie-Fox Hills
- Number of users: 128 homes
- Usage type: Municipal Well

Groundwater Well Sampling Information

- Water: Six samples collected from 2001 to 2016.
  - Toluene detected in one sample on (6/14/2001).
  - Most recent sample in 2016 showed no detection of BTEX.
  - Thermogenic methane found at 6.3 mg/L on 5/13/2016.
- Gas: Four samples collected from 2001 to 2016. Isotope analysis showed thermogenic origin.

Contamination Source Analysis

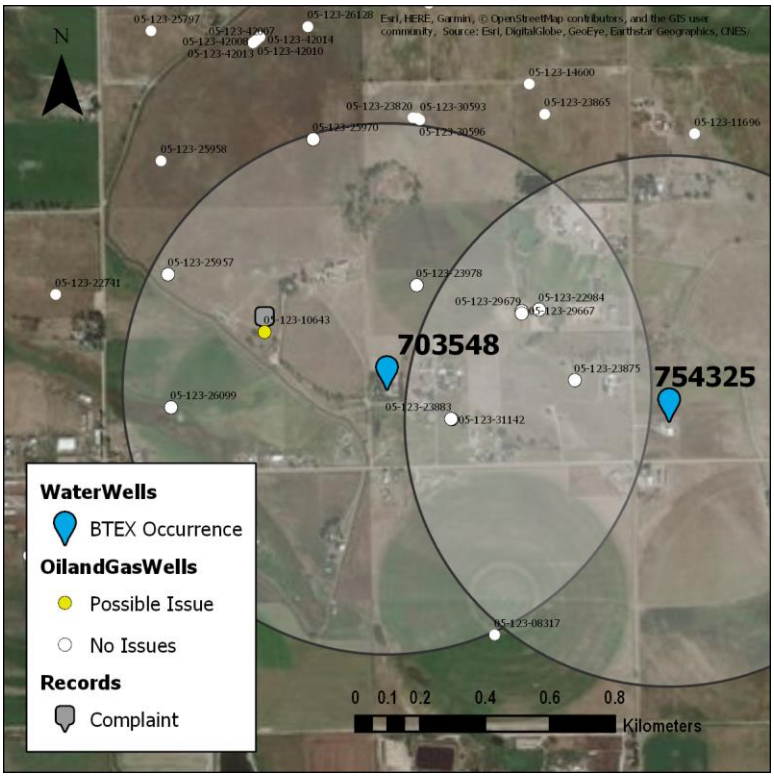
- **Category A**: The COGCC identified an oil/gas well as the source of the gas and BTEX occurrence.
- Source of BTEX:
  - Oil/Gas Well name: Degenhart 1 (API #05-001-06164)
  - Operator: Merit Gas
  - Issue: The COGCC identified leaking from a surface casing hole in August 2001. Pressure tests and MITs were performed Degenhart 1 and surrounding oil and gas wells. The Degenhart 1 well had high surface casing pressure and one previous repair to the casing. Further testing found another leak. The holes were found at depths between 371 m and 380 m.
  - Resolution: Holes were repaired and the well subsequently passed a mechanical integrity test. The well passed inspection in 4/1/16 and is still producing.
- Suspected pathway: High pressure from the leaking oil/gas well casing likely released gas into the Laramie-Fox Hills Aquifer which migrated towards the groundwater well pumphouse.

Summary

COGCC identified the Degenhart 1 well (API# 05-001-06164) with evidence that leaking occurred from surface casing holes after a pumphouse explosion, and gas was reported in water by the RVWUA.

Case #2

Groundwater well: FacID #703548



Initial Sampling Reason
The landowner opened Complaint #200031991 with the COGCC on 11/18/2002 reporting gas in the water three months after installing a new groundwater pump. The landowner commented that oil/gas wells directly to the west were refractured.

Groundwater Well Information

- Depth: 91 meters
- Aquifer: Laramie-Fox Hills
- Usage type: Domestic Well

Groundwater Well Sampling Information

- Water: Two water samples both collected on 11/22/2002. Toluene detected at 9 µg/L. Biogenic methane detected in one sample at 7.1 mg/L on 11/22/2002.
- Gas: Isotope analysis showed biogenic origin.

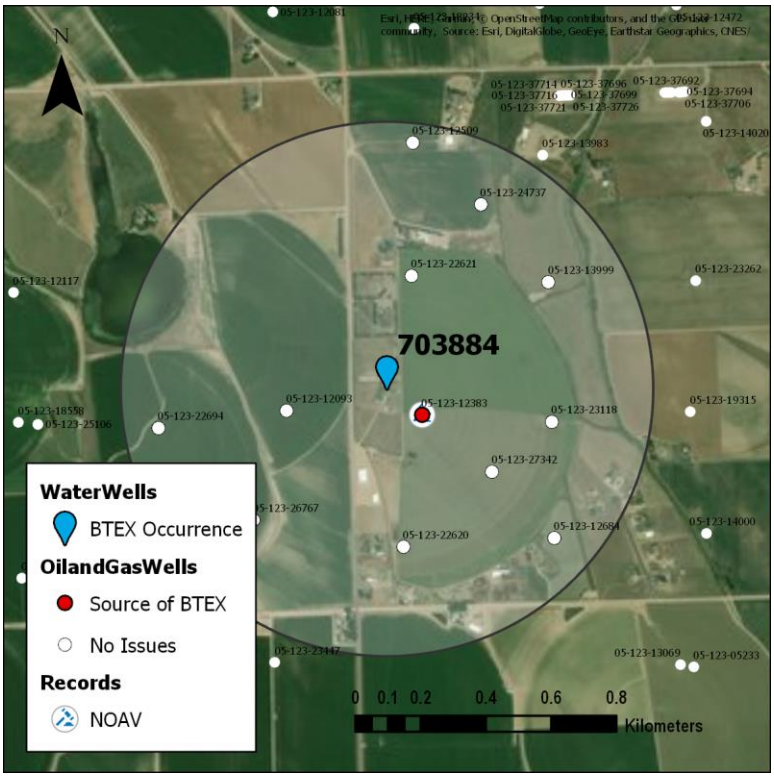
Contamination Source Analysis

- **Category B:** The COGCC determines the source of gas is unrelated to oil and gas activity.
- Source of BTEX:
  - Issue: The methane measured was biogenic in origin and matched nearby coal seams. Coalbed methane can sometimes migrate into nearby aquifers but does not pose health risks. The toluene detection was not
  - Resolution: N/A
- Other: A sundry notice for the Leonard Avey et al oil/gas well (API# 05-123-10643) reported remedial cement procedures for repairing potential hole in casing on 1/5/2017. No high surface casing pressures were reported in 2002, but a high critical surface casing pressure was reported in 2016 at 3172 kPa.

Summary
In 2002 when the toluene and biogenic methane were detected, the COGCC concluded the gas was from shallow coal seams and unrelated to oil and gas activity. However, records of surface casing pressures in 2016 show that pressure has built to critical levels, and a hole has been identified in a nearby oil and gas well. The hole was identified 15 years after the poor water quality and unknown if it is connected.

Case #3

Groundwater well: FacID #703884



Initial Sampling Reason
The well owner opened Complaint #200051005 on 3/9/2004 with the COGCC after their drinking water turned black, was sticky and slimy, and smelled like oil. Gas bubbles were also observed.

Groundwater Well Information

- Depth: 205 meters
- Aquifer: Dakota-Cheyenne
- Usage type: Domestic well

Groundwater Well Sampling Information

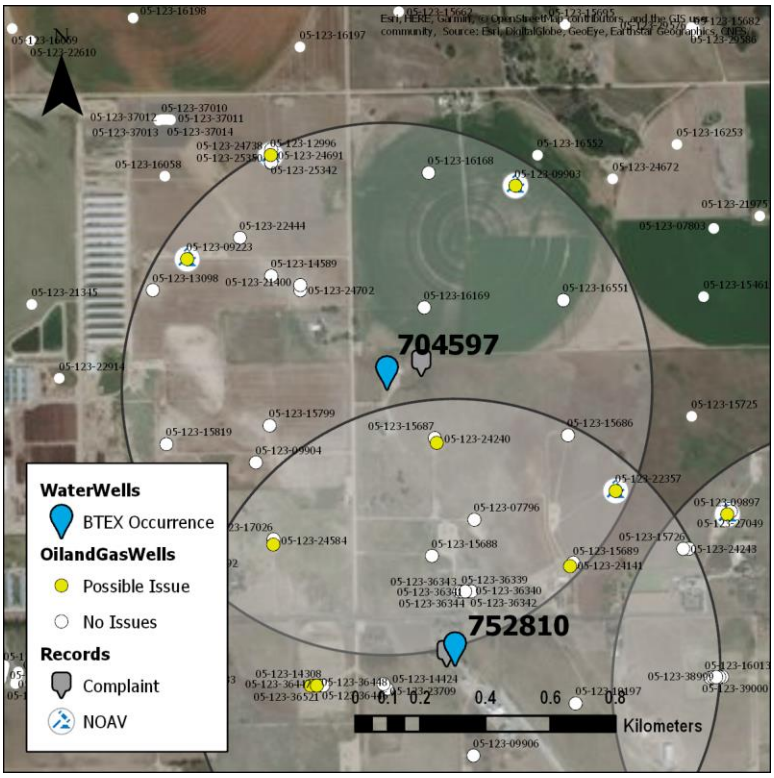
- Water: Six samples collected from 3/10/2004 to 9/28/2004.
  - Benzene, toluene, ethylbenzene, and xylene isomers all detected among one of the six samples. Benzene appeared above the Colorado Basic Ground Water Standard (5 µg/L) twice at 150 µg/L in 3/10/2004, and at 5.1 µg/L in 6/23/2004.
  - Thermogenic methane present at 1.3 mg/L on 6/23/2004.
- Gas: Four samples collected from 3/11/2004 to 9/28/2004. Methane isotope analysis showed thermogenic origin.

Contamination Source Analysis

- **Category A**: The COGCC identified an oil/gas well as the source of the gas and BTEX occurrence.
- Source of BTEX:
  - Oil/Gas Well name: CEI-Gutterson #1
  - Operator: Bonanza Creek Oil Company
  - Issue: Holes were discovered in the casing between 232 m and 242 m and at 381 m depths.
  - Resolution: Gas composition and isotope analyses from CEI-Gutterson #1 well match the characteristics of gas in the ground water well. The remediation project was closed on 12/19/2005 after water quality improved over the sampling period.

Summary
Holes in the casing of CEI-Gutterson #1 oil/gas well resulted in elevated BTEX concentrations in groundwater with benzene exceeding the Basic Colorado Ground Water Standards twice. Casing holes were repaired on 3/25/2004 and the well passed an MIT on 3/26/2004.

Case #4



Groundwater well: FacID #704597

Initial Sampling Reason
Owner filed a complaint (#200080649) to the COGCC detailing gas in a new groundwater well.

Groundwater Well Information

- Depth: 142 meters
- Aquifer: Laramie-Fox Hills
- Usage type: Domestic Well

Groundwater Well Sampling Information

- Water: Thirteen samples collected between 2005 to 2016.
  - Toluene first detected at 89 µg/L on 12/15/2005. No further samples found BTEX above detection limits.
  - Mixed biogenic and thermogenic methane present up to 39 mg/L on 4/16/2015.
- Gas: Eight samples collected from 2005 to 2016. Methane isotope analysis indicated mixed thermogenic and biogenic origins.

Contamination Source Analysis

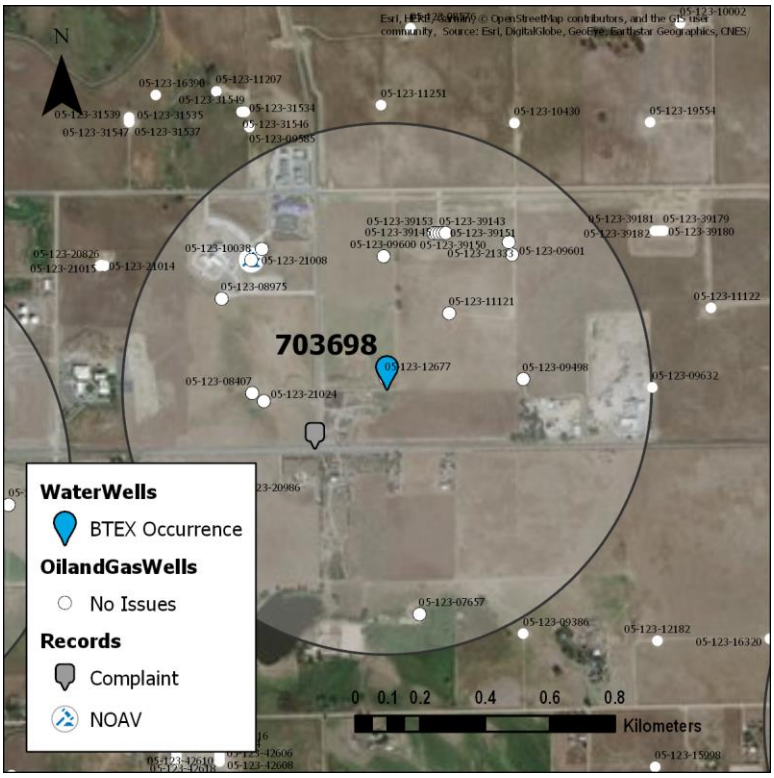
- **Category C:** Documents indicate the source of BTEX could have originated from an oil/gas well. The COGCC has not concluded any oil/gas well is responsible for the BTEX occurrence.
- Four oil/gas wells with high surface casing pressure were issued NOAVs to Kerr McGee Oil & Gas Onshore LP. None were confidently identified as the source of the toluene or thermogenic methane.
  - Well name: 2 BRETHAUER*JAKE B UNIT (API# 05-123-09903)
  - Well name: 1 UPRR 22 PAN AM 'R' (API# 05-123-09223)
  - Well name: 41-15 KEENAN-UPRR (API# 05-123-12996)
  - Well name: 23-14 BARNEY (API# 05-123-22357)
- Suspected pathway: High surface casing pressures can cause gas to escape through any holes and migrate into the aquifer. No holes in surface casings were found in the oil/gas wells issued an NOAV.

Summary

Toluene was detected in a newly drilled groundwater well concurrently with thermogenic methane. The COGCC was not able to discover a definite source of the toluene but issued NOAVs to four oil/gas wells within a half-mile of the groundwater well for high surface casing pressures. The well is nearby two other water wells (Case #30).

Case #5

Groundwater well: FacID #703698



Initial Sampling Reason
Complaint #200032354 was opened on 12/9/2002 with the COGCC after the owner drilled a new water well and noticed gas effervescing in the water. The methane gas in the water was determined thermogenic, prompting monitoring of the new water well and older well.

Groundwater Well Information

- Depth: 228 meters
- Aquifer: Laramie-Fox Hills
- Usage type: Domestic Well

Groundwater Well Sampling Information

- Water: Two samples between 2006 to 2008.
  - Toluene detected on 5/30/2006 at 1.2 µg/L. No other BTEX compounds detected.
  - Thermogenic methane present at 6.3 mg/L on 5/20/2006.
- Gas: Five samples collected from 2003 to 2008. Methane isotope analysis showed thermogenic origin.

Contamination Source Analysis

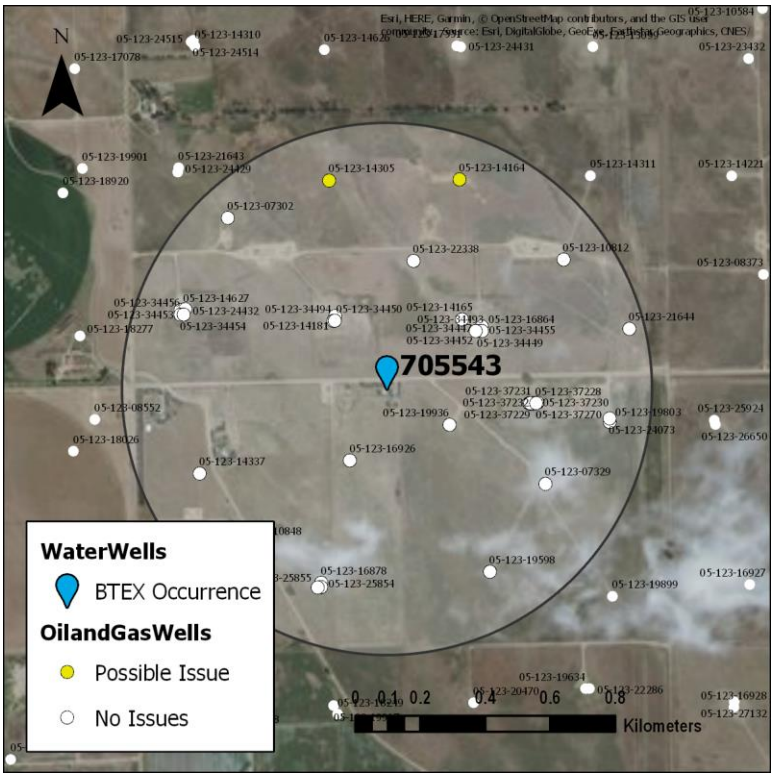
- **Category B:** The COGCC determines the source of gas is unrelated to oil and gas activity.
- Source of BTEX:
  - Issue: The COGCC concludes that the source of methane is from coal seams. Analysis reports claim the well has tapped into a sandstone stratigraphic gas-trap. Since the toluene detection is 1.2 µg/L, sampling issues or measurement error could be a concern, though the Weld County Water Well Sampling Project says the samples appeared to meet quality control criteria. No other samples showed BTEX, so the water quality analysis did not consider it problematic.
  - Resolution: The COGCC recommends gas separation or ventilation to prevent accumulation.
- Other: No oil/gas wells reported any issues within a half-mile radius of the groundwater well.

Summary

A newly drilled groundwater well was sampled to determine the source of gas effervescing in the water. Thermogenic methane was found in the new well, but biogenic methane was found in the older well on the same property. The pressure heads of the wells differed significantly, leading the analysis to believe the new groundwater well tapped a sandstone gas trap near a gas-water interface which could explain thermogenic methane. No explanation for a toluene detection was described because it was at a low concentration.

Case #6

Groundwater well: FacID #705543



Initial Sampling Reason
Baseline sampling. No complaints opened with the COGCC within a half-mile.

Groundwater Well Information

- Depth: 27 meters
- Aquifer: Shallow groundwater
- Usage type: Ground Water

Groundwater Well Sampling Information

- Water: Five samples from 2006 to 2014.
  - Toluene detected in one sample at 3.8 µg/L on 8/2/2006.
- Gas: N/A

Contamination Source Analysis

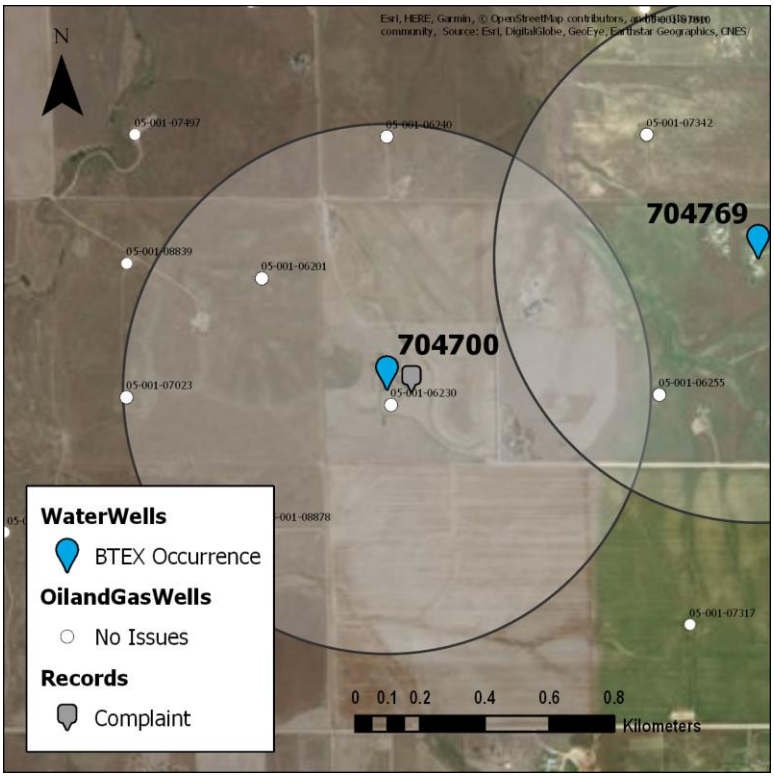
- **Category D:** No explanation found for source of BTEX.
- Suspected pathway: Shallow ground waters are more susceptible to surface spills of oil or gasoline. Approximately one year after the detection of toluene in FacID #705543, three surface spills occurred and are reported to have BTEX concentrations exceeding Colorado Ground Water Quality Standards in monitoring wells. Shallow groundwater flow from the spills is reported to move towards the N/NW, in the opposite direction of the groundwater well.

Summary
One sample detected toluene at 3.8 µg/L in in groundwater well FacID #705543. The groundwater well is 27 m deep and could be more susceptible to surface spills. However, no surface spills were reported before the detection of toluene. Three large surface spills a year later did result in shallow groundwater contamination of BTEX.

Case #7

Groundwater well: FacID #704700

Initial Sampling Reason
Complaint #200095139 was filed on 8/22/2006 describing oily water and sampling ensued. Complaint #200412560 was filed on 9/22/2014, requesting water sampling and investigation because of land subsidence near an oil/gas well.



Groundwater Well Information

- Depth: 158 meters
- Aquifer: Upper Arapahoe
- Usage type: Ground Water

Groundwater Well Sampling Information

- Water: Eleven samples collected from 2006 to 2015.
  - Toluene first detected at 31 µg/L on 9/25/2006, and again at 1.6 µg/L on 3/18/2008.
  - Benzene detected after second filed complaint at 9.1 µg/L on 9/5/2014 and remained elevated above the MCL (5 µg/L) through 9/9/2015.
- Gas: N/A

Contamination Source Analysis

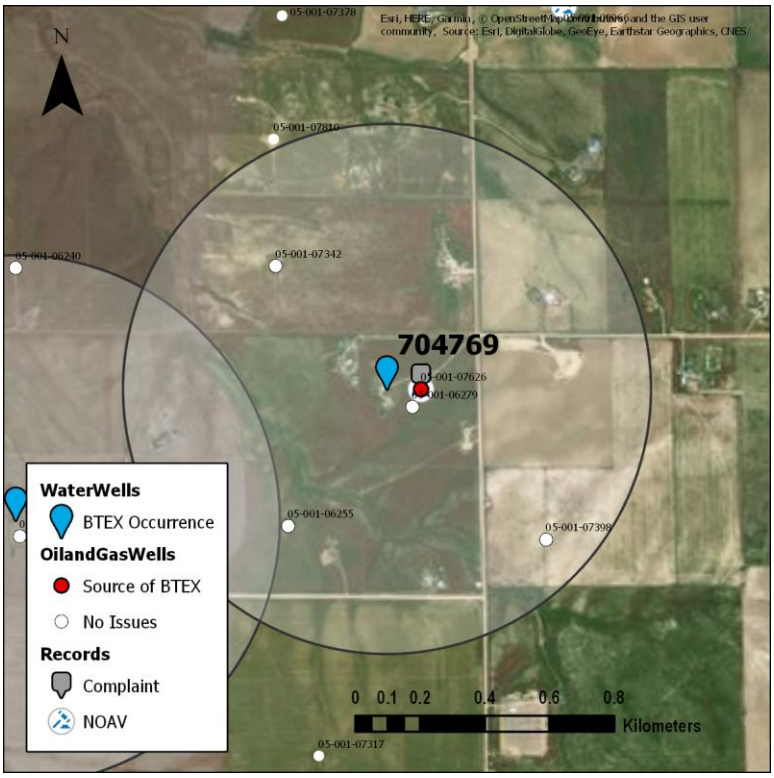
- **Category D:** No explanation found for source of BTEX within a half-mile.
- Oil and Gas Well of Concern: The water well is 1200 m from FacID #704769 (Category A) which was determined to be contaminated from 1-X WAILES 41-33 (API# 05-001-07626) because of a short surface casing and leaked thermogenic methane.
- 2006 investigation
  - The COGCC compared oily water with three nearby producing oil/gas wells. Signatures of each oil/gas well was compared to the oil in the water sample. The ratio of diesel range organics (DRO) to gasoline range organics (GRO) was significantly different between oil/gas wells and the water sample. The COGCC concludes that the benzene in the groundwater is not related to oil and gas activity.
- 2015 investigation
  - The second complaint described poor water quality because of land subsidence in the immediate vicinity of the plugged and abandoned oil/gas well 1 UPRR 23 PAN AM B (API# 05-001-06230). The COGCC contracted a Ground-Penetrating Radar (GPR) survey and found no direct cause for the subsidence or benzene in the water.
- Suspected pathway: A letter in 2015 described that the groundwater well with benzene contamination is not isolated from surface water infiltration and surface spills could introduce BTEX compounds to the well.

Summary

In 2006, toluene was detected after complaints of oily water in a newly drilled water well. An investigation to compare nearby oil/gas wells to the oil in the water showed that the ratios of DRO/GRO were significantly different, so oil in the water could not be from oil and gas activity. A second investigation began after land subsidence occurred in a horse corral immediately near an oil/gas well. Benzene and toluene were present, with benzene above the Colorado Ground Water Quality Standards. A GPR survey was conducted and did not find evidence that the oil/gas well caused the subsidence.

The water well is 1200 m from Case #8 that had BTEX contamination resulting from 1-X WAILES 41-33 (API# 05-001-07626) because of a short surface casing. This oil and gas well is farther than a half-mile from the water well, so it did not meet our criteria for a nearby well. However, the oil and gas well could be an exception to where BTEX migrated farther than the expected half-mile (0.80 km) baseline sampling radius.

Case #8



Groundwater well: FacID #704769

Initial Sampling Reason
The owner found gas effervescing in the water well and filed Complaint #200097544 with the COGCC.

Groundwater Well Information

- Depth: 122 meters
- Aquifer: Upper Arapahoe
- Usage type: Groundwater

Groundwater Well Sampling Information

- Water: Seven samples collected from 2006 to 2007.
  - Benzene was detected at 75.6 µg/L on 10/6/2006.
  - A second sample on 10/20/2006 did not detect benzene, and the first sample was reduced to a false positive.
  - Thermogenic methane present at 6.46 mg/L on 10/6/2006.
- Gas: One sample collected in 2006. Isotope analysis showed thermogenic origin.
  - Isotope composition of the gas in the water well was characteristic of the J-Sand formation.

Contamination Source Analysis

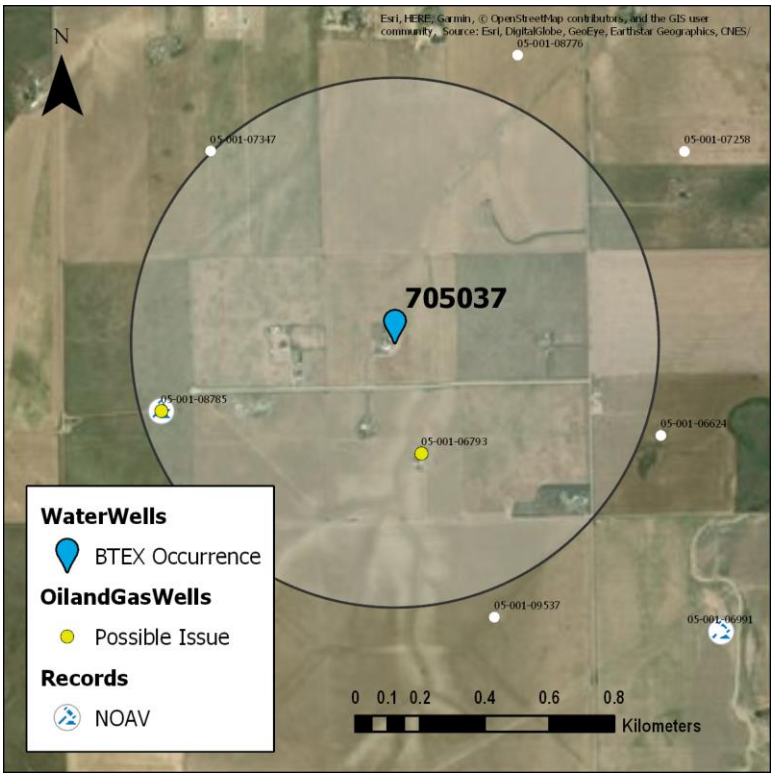
- **Category A**: The COGCC identified an oil/gas well as the source of the gas and BTEX occurrence.
- Nearby oil/gas well with issue:
  - Oil/Gas Well name: 1-X WAILES 41-33 (API# 05-001-07626)
  - Operator: HRM Resources II LLC
  - Issue: High surface casing pressure and short surface casing cause thermogenic methane to escape and contaminate the groundwater well 100 m to the west.
  - Resolution: The oil/gas well 1-X WAILES 41-33 was repaired by plugging holes between 61 m and 70 m. The complaint investigation was closed on 2/28/2009, but the well owner still reported skin rashes from the water. A new groundwater well was drilled for the well owner on 6/30/2009 and water quality met Colorado Ground Water Quality Standards.

Summary

While benzene was originally detected at 75.6 µg/L, a second sample 14 days later found no benzene, and the COGCC annulled the first sample to be a false positive. Sampling originally took place because of the 1-X WAILES 41-33 oil/gas well contaminating the Britton water well with thermogenic methane due to a short surface casing and high surface casing pressure.

Case #9

Groundwater well: FacID #705037



Initial Sampling Reason
Baseline sampling. No complaints opened with the COGCC within a half-mile.

Groundwater Well Information

- Depth: 122 meters
- Aquifer: Upper Arapahoe
- Usage type: Ground Water

Groundwater Well Sampling Information

- Water: Two samples collected on 6/12/2007 and on 8/27/2007.
  - Benzene detected in two samples at 0.74 µg/L on 6/12/2007.
  - Thermogenic methane present at 1.5 mg/L on 6/12/2007.
- Gas: One gas sample on 8/27/2007. Isotope analysis indicated thermogenic origin.

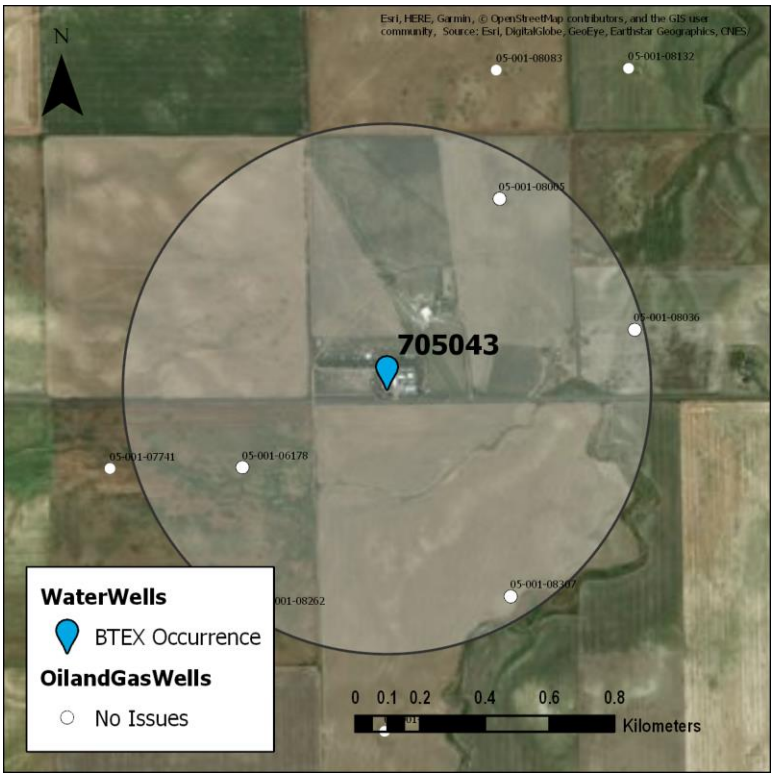
Contamination Source Analysis

- **Category D:** No explanation found for source of BTEX.

Summary
A slightly elevated concentration of benzene was detected in the water alongside thermogenic methane. The concentration of benzene was below Colorado Ground Water Quality Standards. No complaint was filed with the COGCC and no documents described an investigation. Two reports were provided for oil and gas wells that had surface spills. No groundwater impacts were recorded. Both yellow icons are surface spills with unknown effects on groundwater.

Case #10

Groundwater well: FacID #705043



Initial Sampling Reason
Baseline sampling. No complaints opened with the COGCC within a half-mile.

Groundwater Well Information

- Depth: 61 meters
- Aquifer: Upper Arapahoe
- Usage type: Ground Water

Groundwater Well Sampling Information

- Water: One sample collected on 6/12/2007.
  - Toluene detected at 4.8 µg/L.
- Gas: N/A

Contamination Source Analysis

- **Category D:** No explanation found for the source of BTEX.

Summary
A slightly elevated concentration of toluene was detected in the water. The toluene detection was below the Colorado Ground Water Quality Standards. No complaint was filed with the COGCC and no documents described an investigation.

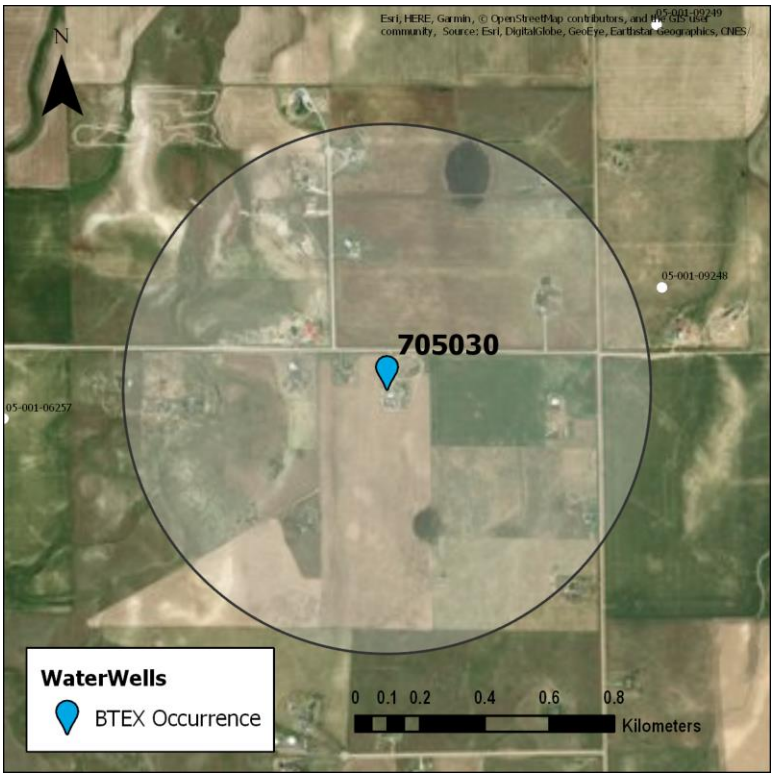
Case #11

Groundwater well: FacID #705030

Initial Sampling Reason
Baseline sampling. No complaints opened with the COGCC within a half-mile.

Groundwater Well Information
- Depth: 137 meters
- Aquifer: Upper Arapahoe
- Usage type: Ground Water

Groundwater Well Sampling Information
- Water: One sample collected on 6/13/2007.
  - Toluene was present at 2.4 µg/L.
- Gas: N/A

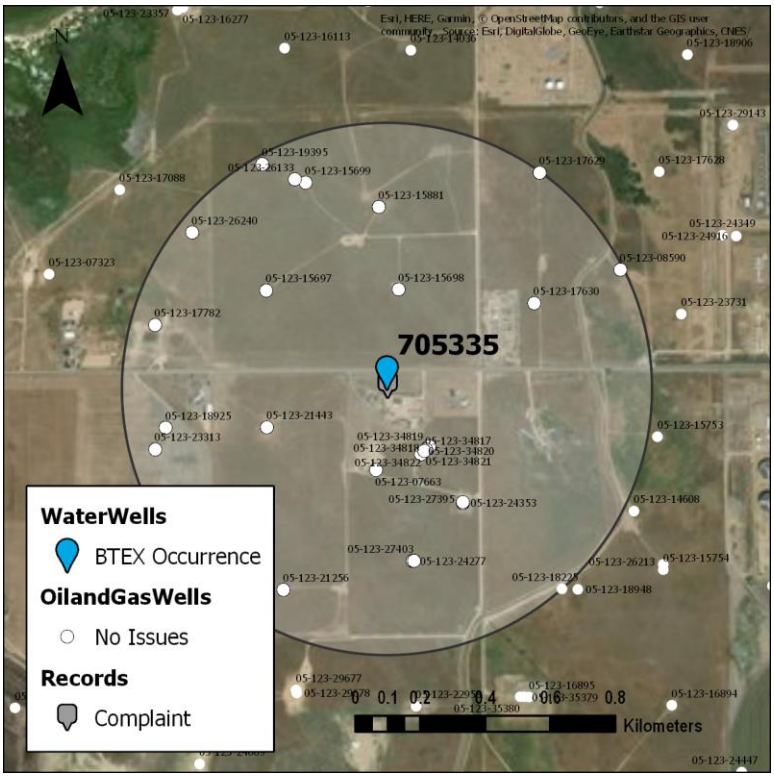


Contamination Source Analysis
- **Category D:** No explanation found for the source of BTEX.

Summary
Toluene was present at 2.4 µg/L in the groundwater sample. No documents indicate an investigation to the source and no complaint was filed with the COGCC. No oil/gas wells are within a half-mile of the property.

Case #12

Groundwater well: FacID #705335



Initial Sampling Reason
Complaint #200126789 was filed on 2/13/2008 alleging impact to domestic water well after a nearby oil and gas well was worked on. The water was described as yellow with a gaseous odor.

Groundwater Well Information

- Depth: 146 meters
- Aquifer: Laramie-Fox Hills
- Usage type: Domestic Well

Groundwater Well Sampling Information

- Water: Two samples collected on 12/13/2006 and 2/22/2008.
  - Meta/para-xylenes were detected at 2.4 µg/L on 2/22/2008.
- Gas: N/A

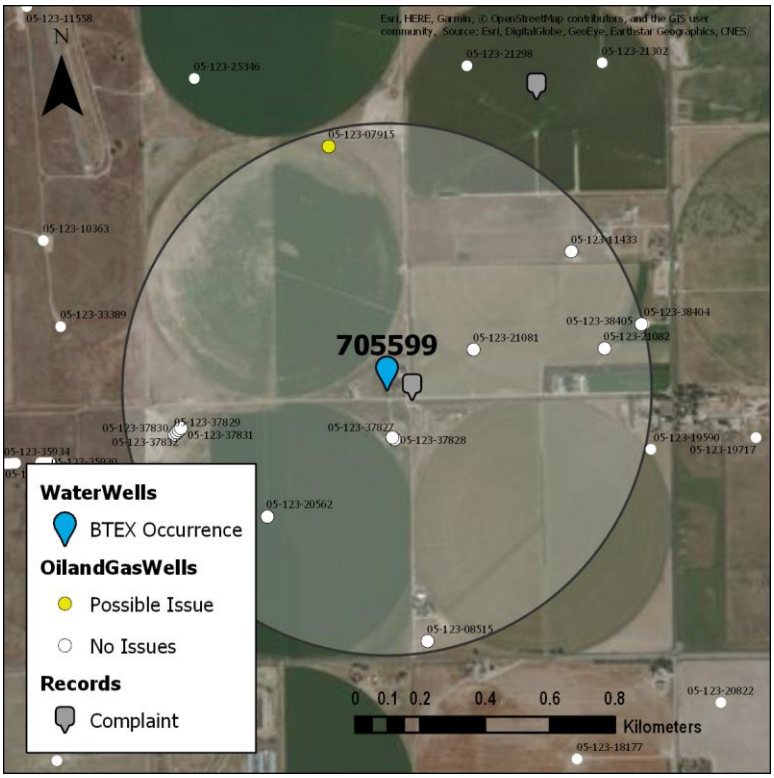
Contamination Source Analysis

- **Category B:** The COGCC determined the source of gas was unrelated to oil and gas activity.
- Source of BTEX:
  - Issue: Meta/para-xylenes were detected at 2.4 µg/L, which is below the Colorado Basic Standards for Ground Water at 1,400 µg/L and this poses no health risk.
  - Resolution: In addition to the meta/para-xylenes, the high TDS and high sulfate concentrations were deemed likely to be from coal zones within the lower Laramie Formation. From the laboratory data, the COGCC judged there was no impact from oil and gas activity and closed the investigation.

Summary
The well owner filed a complaint to the COGCC that detailed poor water quality and odor after nearby oil/gas wells were worked on. The investigation found the occurrence of meta/para-xylenes at low concentrations alongside high TDS and sulfate concentrations. The COGCC judged the water quality to be from coal zones in the aquifer and the investigation was closed.

Case #13

Groundwater well: FacID #705599



Initial Sampling Reason
The well owner filed complaint #200207674 requesting a water sample from his water well.

Groundwater Well Information

- Depth: 217 meters
- Aquifer: Laramie-Fox Hills
- Usage type: Domestic Well

Groundwater Well Sampling Information

- Water: One sample was collected on 3/5/2009.
  - Toluene was present at 170 µg/L.
  - Biogenic methane present at 23 mg/L.
- Gas: One gas sample was collected on 3/5/2009. Methane isotope analysis indicated biogenic origin.

Contamination Source Analysis

- Category B: Source of toluene is unknown.
- Source of BTEX:
  - Issue: Toluene was present at 170 µg/L which is below the Colorado Basic Ground Water Standards. The COGCC states that recent work on the groundwater well could be a cause of toluene as it is commonly found in glues.
  - Resolution: The COGCC determined the methane was biogenic in origin and that precautions should be made to avoid buildup. The investigation was closed on April 21, 2009.
- Other: The oil/gas well 1 BRACHTENBACH (API# 05-123-07915) had a sundry notice describing remedial cement work but no further details were provided.

Summary
A complaint was filed requesting water sampling. The complaint did not describe poor water quality. Sampling showed high concentrations of biogenic methane and toluene at 170 µg/L. While the toluene is below water quality standards, it is higher than cases where oil and gas was known to have contaminated a water well. Glue containing toluene would likely not be a long-term source of toluene dissolving into water, but no further samples were collected so more information is needed.

Case #14

Groundwater well: FacID #705746

Initial Sampling Reason
Complaint #200217527 was filed on 9/1/2009 when the well owner expressed concern of possible contamination to the water well that may have resulted from a tubing leak at a nearby oil/gas well. The owner noted that the 0-6-23 BRANCH (API# 05-123-24148) had bubbles emerging from standing surface water at the oil/gas wellhead. That oil/gas well has been repaired but the owner is now experiencing bubbles effervescing from his groundwater well.

Groundwater Well Information

- Depth: 137 meters
- Aquifer: Laramie-Fox Hills
- Usage type: Domestic Well

Groundwater Well Sampling Information

- Water: Two samples collected on 8/11/2009 and 6/2/2010.
  - Toluene was present at 12 µg/L and 0.72 µg/L for each sample respectively.
  - Thermogenic methane present at 25 mg/L on 6/2/2010.
- Gas: One sample was collected on 8/11/2010. Methane isotope analysis indicated thermogenic origin.

Contamination Source Analysis

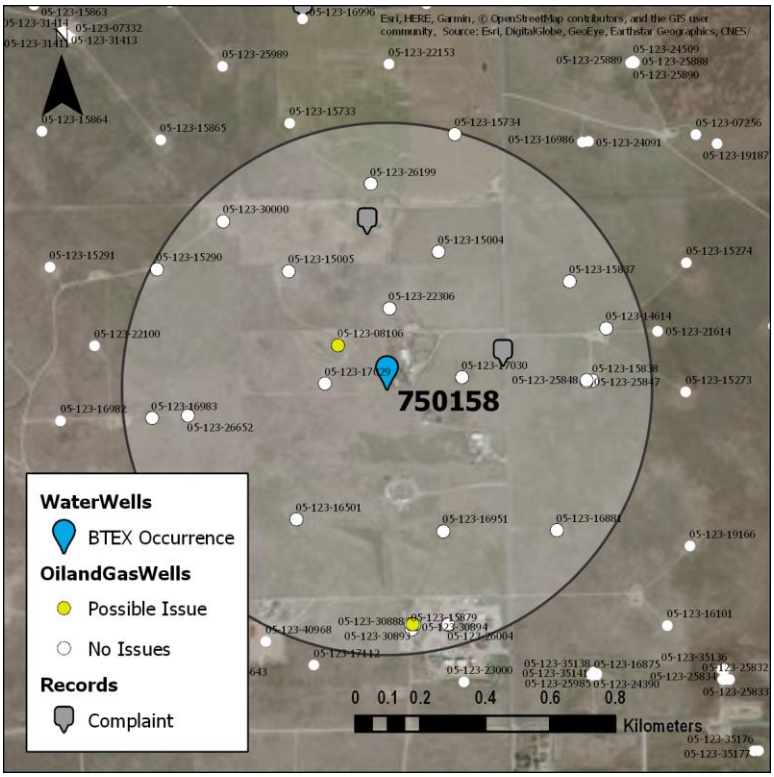
- **Category A**: The COGCC identified an oil/gas well as the source of the gas and BTEX occurrence.
- Source of BTEX:
  - Oil/Gas Well name: 2 DUPPER (API# 05-123-11848)
  - Operator: Eddy Oil Company
  - Issue: The 2 Dupper oil/gas well had a high surface casing pressure at 1655 kPa and failed a MIT. Holes in the casing were found upon further inspection. In addition, the surface casing was set above the bottom of the Laramie-Fox Hills aquifer.
  - Resolution: Eddy Oil was issued an NOAV for failing the surface casing test and MIT and issued another NOAV for contamination of the landowner's water well. Eddy Oil was fined $46,200 for rule violations relating to the release. A new groundwater well was paid for by Eddy Oil.

- Suspected pathway: High surface casing pressures could cause gas to escape the casing through holes or the bottom of the short surface casing. BTEX can dissolve into the water which could have migrated to the groundwater well.
- Other potential sources of BTEX:
  - 26-5 DUPPER R G (API# 05-123-13075) oil/gas well reported high surface casing pressures in 2012, three years after the contamination incident. This well has a short surface casing, so it could be another source of gas. It is twice as far from the well as the 2 DUPPER oil/gas well (732 m).

Summary

A year earlier before an oil and gas well was repaired, the landowner filed a complaint describing gas bubbling in the water and noted that gas bubbled from surface water around the wellhead. Sampling indicated that thermogenic methane and toluene were present. surface casing pressure tests and a MIT were completed and the oil/gas well failed both and was issued an NOAV. Surface casing holes were also found, and Eddy Oil was issued another NOAV for water contamination. The oil/gas well additionally had a short surface casing which could have released more gas into the aquifer if under high pressures.

Case #15



Groundwater well: FacID #750158

Initial Sampling Reason
Unknown sampling reason but two neighboring groundwater wells also filed complaints requesting baseline sampling on the same week.

Groundwater Well Information

- Depth: 168 meters
- Aquifer: Laramie-Fox Hills
- Usage type: Ground Water

Groundwater Well Sampling Information

- Water: Five samples were collected in 2010 and in 2017.
  - Benzene present at 1.1 µg/L on 7/20/2010.
  - Biogenic methane present at 27 mg/L.
- Gas: One sample of methane collected in 2017. Methane isotope analysis indicated biogenic origin.

Contamination Source Analysis

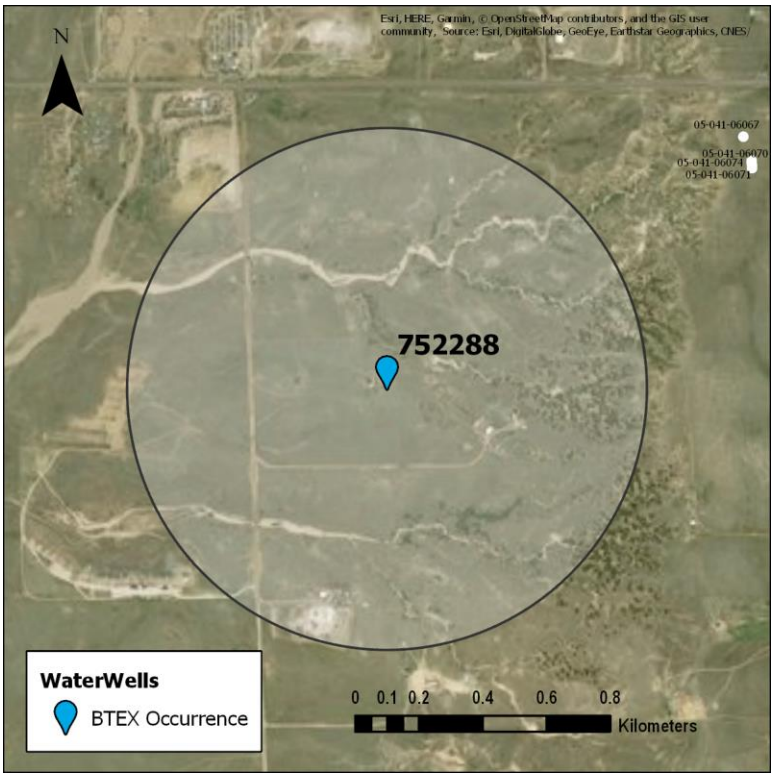
- **Category C:** Documents indicate the source of BTEX could have originated from an oil/gas well.
- 1988 Casing Repair
  - Oil/Gas Well Name: 1 BOOKER, HAROLD E (API# 05-123-08106)
  - Operator: Amoco Production Company
  - Issue: In 1988, sundry notices documented a repair to a casing leak at 293 m. The surface casing is at 62 m, which is above the bottom of the Laramie-Fox Hills aquifer. The well is currently abandoned.
- Other
  - Oil/Gas Well name: 24-30 CONQUEST (API# 05-123-30888)
  - Operator: Kerr McGee Oil and Gas Onshore
  - Issue: Surface casing pressure above calculated critical pressure in 2012 which should be noted, however the well passed a MIT, and 2010 inspection was satisfactory.
  - Resolution: N/A
- Suspected pathway: High surface casing pressures could cause gas to escape the casing through holes or the bottom of the short surface casing. BTEX can dissolve into the water which could have migrated to the groundwater well.

Summary

Groundwater sampling showed the occurrence of benzene at 1.1 µg/L. This is below the Colorado Basic Ground Water Standards of 5 µg/L. One oil/gas well was noted to have repairs to the casing due to holes at 62 m depth in 1988. This particular oil/gas well has a short surface casing which could be a point of gas release to the Laramie-Fox Hills aquifer.

Case #16

Groundwater wells: FacID #752288



Initial Sampling Reason
Baseline sampling for oil and gas wells to the northeast that are farther than a half-mile radius.

Groundwater Well Information

- Depth: 335 meters
- Aquifer: Upper Arapahoe
- Usage type: Domestic

Groundwater Well Sampling Information

- Water: Two samples collected on 3/19/2012, and on 3/12/2013.
  - Toluene present in the 2012 sample.
- Gas: N/A

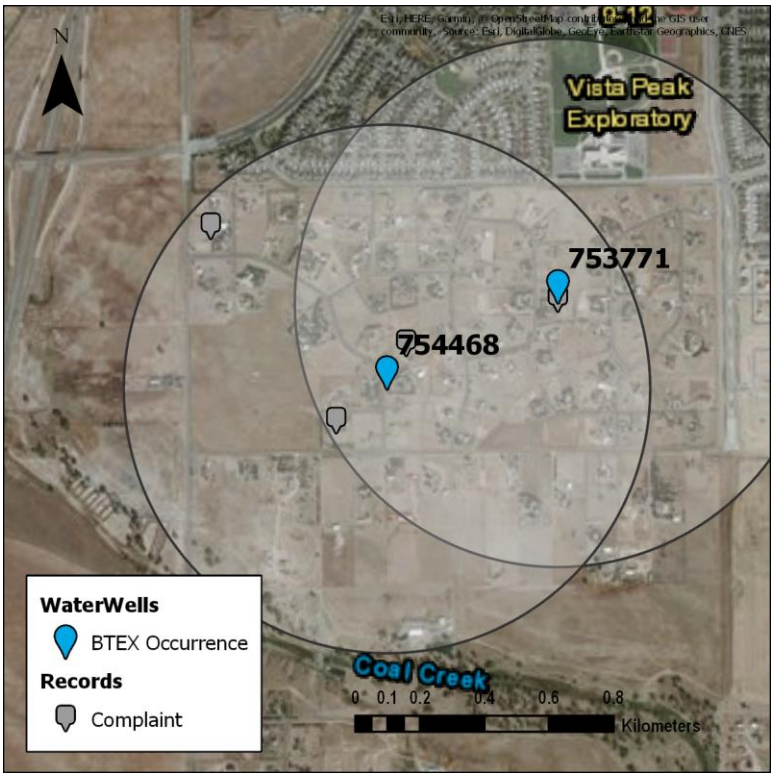
Contamination Source Analysis

- **Category D:** No explanation found for source of BTEX.

Summary
No oil and gas wells are present within a half-mile. However, the water well was sampled as a baseline for oil and gas wells to the northeast. None of the oil and gas wells had documented issues, and the source of BTEX remains unknown. Toluene was present in the 2012 sample but did not appear in the sample the following year.

Case #17

Groundwater wells: FacID #753771, FacID #754468



Initial Sampling Reason
FacID #753771 was sampled after the well owner filed Complaint #200350987 requesting a baseline water sample. FacID #754468 was sampled after the well owner filed Complaint #200350947 requesting a baseline water sample. The two water wells are 620 m apart.

Groundwater Well Information

- FacID #753771
  - Depth: 335 meters
  - Aquifer: Upper Arapahoe
  - Usage type: Domestic
- FacID #754468
  - Depth: 335 meters
  - Aquifer: Upper Arapaho
  - Usage type: Domestic, Stock

Groundwater Well Sampling Information

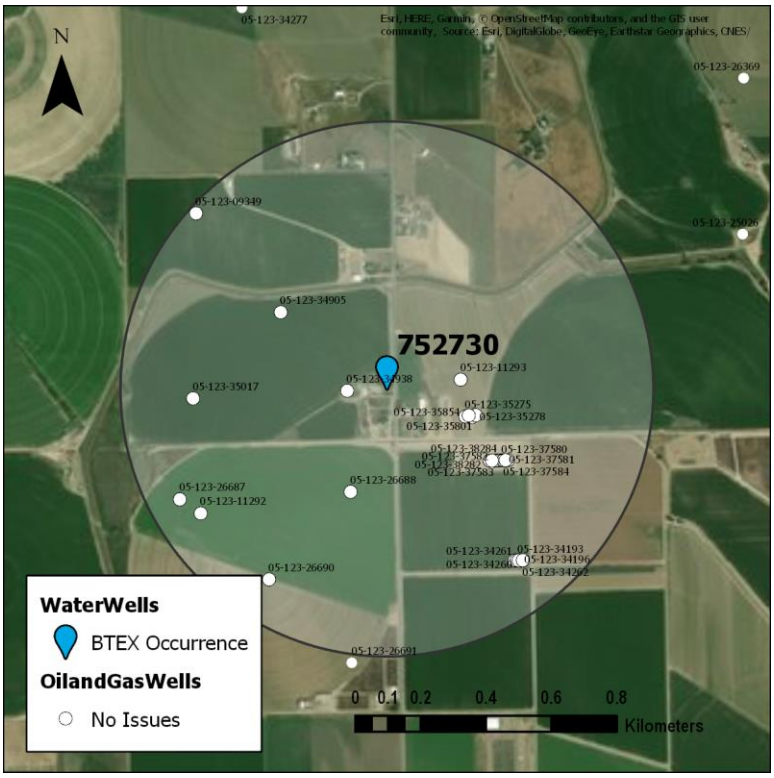
- Water:
  - FacID #753771: One sample collected on 11/7/2012. Toluene was detected at 30 µg/L.
  - FacID #754468: One sample collected on 4/3/2012. Toluene was detected at 3.9 µg/L.
- Gas: N/A

Contamination Source Analysis

- **Category D:** No explanation found for source of BTEX.

Summary
Two water wells, 620 m apart, showed occurrences of toluene. The occurrences are both in the same neighborhood and occurred seven months apart. No source of toluene is known, but the occurrences are below Colorado Basic Ground Water Standards (560 µg/L). No oil/gas wells are within a half-mile radius of either groundwater well.

Case #18



Groundwater well: FacID #752730

Initial Sampling Reason
Baseline sampling.

Groundwater Well Information

- FacID #753771
  - Depth: 17 meters
  - Aquifer: Shallow Groundwater
  - Usage type: Ground Water

Groundwater Well Sampling Information

- Water: One sample collected on 3/29/2018.
  - Benzene (18.6 µg/L), toluene (2.6 µg/L), and ethylbenzene (3.5 µg/L) were present.
- Gas: N/A

Contamination Source Analysis

- **Category D:** No explanation found for source of BTEX.
- No nearby oil/gas wells within a half-mile radius of the groundwater well indicated any problems.

Summary
The groundwater well was sampled for baseline water quality and benzene, toluene, ethylbenzene compounds were detected. Benzene exceeded groundwater standards of 5 µg/L, but no further investigations were done to determine the source. Methane was not detected alongside the BTEX occurrences. Since the groundwater well is in a shallow unconfined aquifer at 17 m depth, surface spills could be a source of contamination.

Case #19

Groundwater well: FacID #752587

Initial Sampling Reason
Complaint #200379695 was filed with the COGCC describing yellow-orange colored water after a nearby oil/gas well was recently drilled. The well owner described a "rotten eggs" sulfide smell to their water.

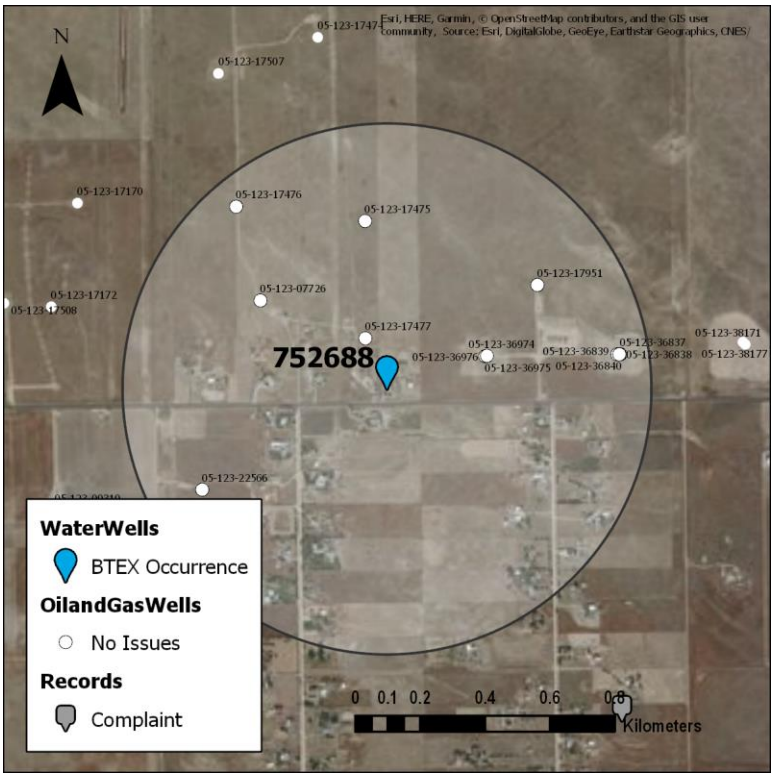
Groundwater Well Information
- Depth: 102 meters
- Aquifer: Lower Arapaho
- Usage type: Domestic Well

Groundwater Well Sampling Information
- Water: One water sample was collected on 5/7/2013.
  - Toluene was present at 5.1 µg/L.
- Gas: N/A

Contamination Source Analysis
- **Category B:** The COGCC determines the source of toluene is unrelated to oil and gas activity.
- Source of BTEX:
  - Issue: Change in water color and smell. The toluene present was presumed to be from new glue in pipes following new piping installation. Complainant noted that the North Washington #8-23 (API #05-001-09666) was the oil/gas well recently drilled, but had not been hydraulically fractured at the time of complaint and was performing tests on producing zones.
  - Resolution: The COGCC determined the poor water quality is not from oil/gas activity and closed the investigation. They attributed the toluene occurrence to replacement of the groundwater well casing and glue connecting new piping.

Summary
A complaint of poor water quality was filed with the COGCC and sampling detected toluene at a level below Colorado Basic Ground Water Standards. The toluene was associated with glue connecting new piping to the groundwater well. No surface spills or issues with other oil/gas wells were listed.

Case #20



Groundwater well: FacID #752688

Initial Sampling Reason
Baseline sampling. No complaints opened with the COGCC within a half-mile.

Groundwater Well Information

- Depth: 329 meters
- Aquifer: Laramie-Fox Hills
- Usage type: Ground Water

Groundwater Well Sampling Information

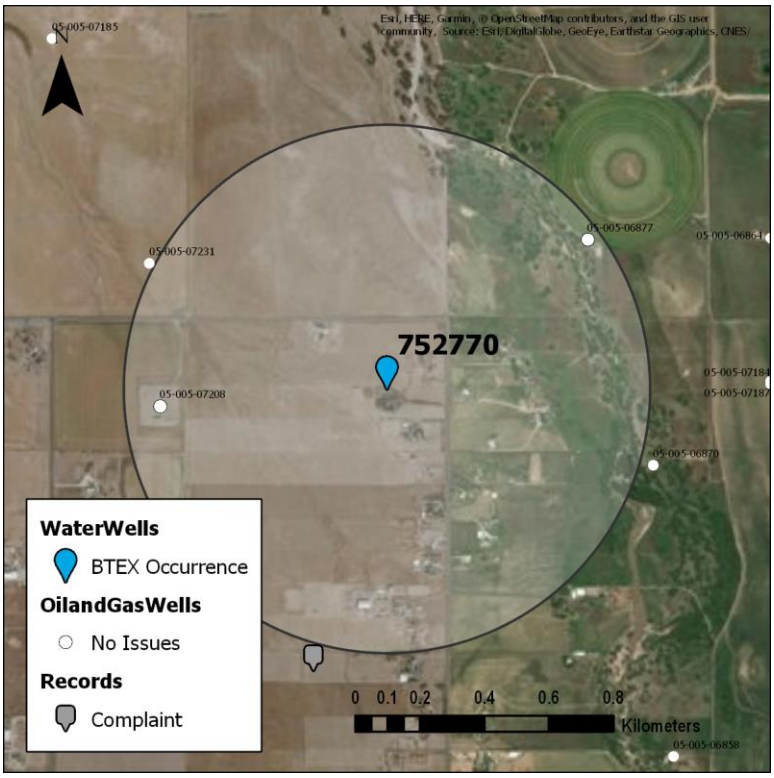
- Water: Three samples were collected between 2013 and 2015.
  - Toluene was detected at 3.4 µg/L on 5/14/2013. No BTEX compounds were detected in subsequent sampling.
  - Biogenic methane present at 10.6 mg/L on 9/10/2014.
- Gas: Three samples collected between 2013 and 2015. Methane isotope analysis showed biogenic origin for each sampling.

Contamination Source Analysis

- **Category D:** No explanation found for source of BTEX.
- No issues were reported among any of the oil/gas wells within a half-mile radius of the groundwater well.

Summary
Toluene was present in one sample, but no complaints were opened with the COGCC for investigation of the source. The toluene present was at low concentrations below the Colorado Basic Ground Water Standards. Biogenic methane was present in all samples.

Case #21



Groundwater well: FacID #752770

Initial Sampling Reason
The samples were collected as a voluntary baseline sample and post drilling sample.

Groundwater Well Information

- Depth: 183 meters
- Aquifer: Laramie-Fox Hills
- Usage type: Ground Water

Groundwater Well Sampling Information

- Water: Two samples were collected on 6/6/2013 and 7/23/2014.
  - Both samples had toluene present at 2.8 µg/L and 1.1 µg/L respectively.
- Gas: N/A

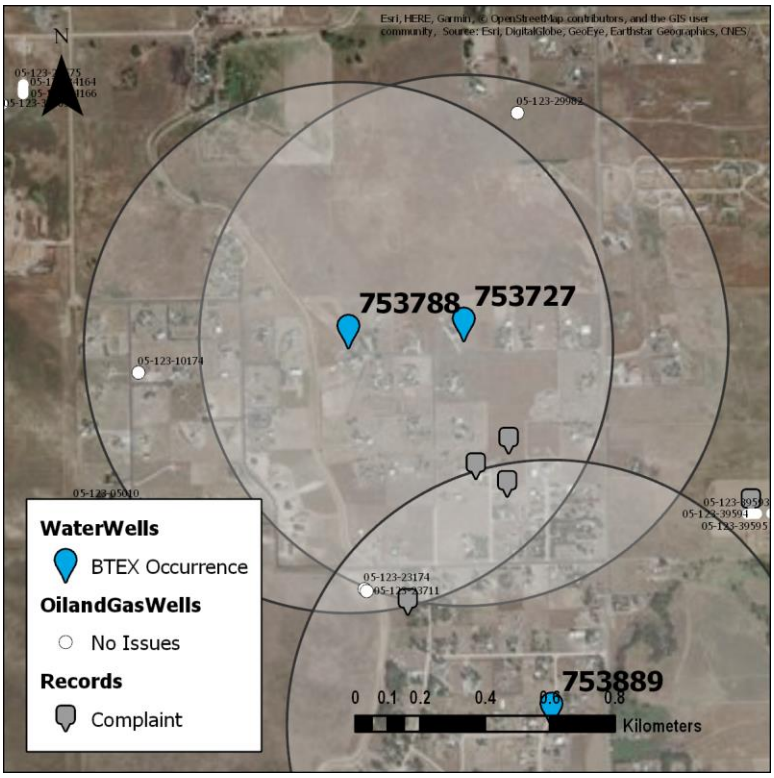
Contamination Source Analysis

- **Category D:** No explanation found for source of BTEX.
- The baseline sample had a higher presence of toluene than the post-drill sample. This indicates that toluene was present in the groundwater before drilling.
- Two oil/gas wells are within a half-mile of the groundwater well, both at the outer radius of the half-mile threshold and neither had any reported problems associated with them.

Summary
Toluene was detected in two subsequent samples of the groundwater well. Only two oil/gas wells are present at the half-mile threshold and neither have issues. The source of the toluene is unknown.

Case #22

Groundwater wells: FacID #753788, FacID #753727



Initial Sampling Reason
Landowner filed Complaint #200422259 with the COGCC describing poor water quality and the water well depth shortening by 76 m as privately tested by Kerr McGee on 11/20/2014. The water was noted to have gas bubbling.

Groundwater Well Information

- FacID #753788
  - Depth: 291 meters
  - Aquifer: Laramie-Fox Hills
  - Usage type: Domestic Well
- FacID #753727
  - Depth: 265 meters
  - Aquifer: Laramie-Fox Hills
  - Usage type: Domestic Well

Groundwater Well Sampling Information

- FacID #753788
  - Water: Four samples were collected on two dates, 11/20/2014 and 2/19/2015. Toluene was present in the second sample at 67 µg/L. Biogenic methane present at 12 mg/L on 2/19/2015.
  - Gas: One sample collected on 11/20/2014. Methane isotope analysis showed biogenic origin.
- FacID #753727
  - Water: Four samples collected on two dates, 10/29/2014 and 12/4/2014. Toluene was present in both samples at 22.7 µg/L and 7.2 µg/L respectively.
  - Gas: N/A

Contamination Source Analysis

- **Category D:** No explanation found for source of BTEX.
- No issues were recorded with any wells within a half-mile radius of either of the groundwater wells. Additionally, oil/gas wells being drilled near the time of complaint are greater than a half-mile to the south/southeast of the groundwater well.
- The neighboring community has filed four complaints requesting water sampling.
- The depth of the wells indicates that surface spills probably did not infiltrate deep groundwater.

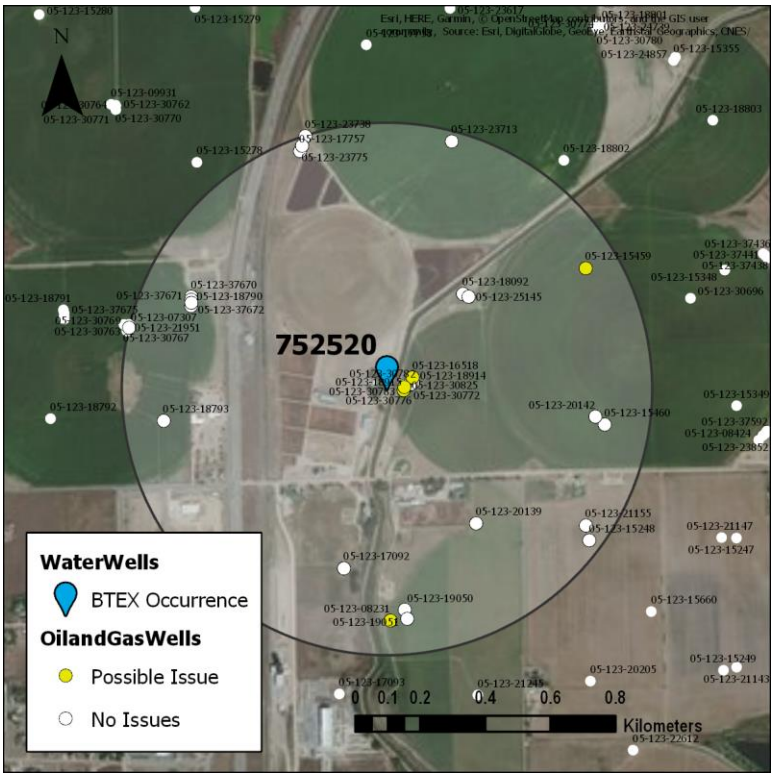
Summary

Toluene was detected in two subsequent samples of the groundwater well FacID #753727 and in a second sampling of groundwater well FacID #753788. The BTEX compounds at low concentrations might be associated with the concurrent biogenic methane. The oil/gas wells within the half-mile threshold have no issues. The source of the toluene is unknown.

Case #23

Groundwater well: FacID #752520

Initial Sampling Reason
Complaint #200378738 was opened with the COGCC on 4/23/2013 alleging impacts to water well from oil and gas activity. Complaint #200311007 was also opened on 5/25/2011 requesting a baseline water sample but has not been resolved.



Groundwater Well Information

- Depth: 96 meters
- Aquifer: Laramie-Fox Hills
- Number of users: One household
- Usage type: Ground Water

Groundwater Well Sampling Information

- Water: Forty-five samples collected on 16 dates between 2013 and 2016.
  - Benzene was present in 11 of the dates sampled between 0.8 µg/L and 1.6 µg/L.
  - Toluene was present in three of the dates sampled between 1.9 µg/L and 233 µg/L.
  - Mixed thermogenic and biogenic methane present at 61 mg/L on 7/14/2015.
- Gas: Sixteen samples collected on 26 dates between 2013 and 2016. Methane isotope analysis showed thermogenic and biogenic mixed origins.

Contamination Source Analysis

- **Category C:** Documents indicate the source of BTEX could have originated from an oil/gas well.
- Oil/Gas Well of Concern 1
  - Oil/Gas Well name: 16-7 HSR-BATES (API #05-123-16518)
  - Operator: Kerr McGee Oil and Gas Onshore LP
  - Issue: High surface casing Pressure of 1469 kPa.
  - Resolution: Well was remediated on 5/17/2014. No surface casing leaks discovered.
  - Suspected pathway: High surface casing pressures are suspected to force gas through holes or under short surface casings which can result in groundwater migration of gas to water wells.
- Oil/Gas Well of Concern 2
  - Oil/Gas Well name: 36-7 BELLA FEDERAL (API #05-123-30776)
  - Operator: Kerr McGee Oil and Gas Onshore LP
  - Issue: High critical surface casing pressures in 2013 where the gas pressure could displace water from a well. This was one year before the first benzene occurrence.
  - Resolution: Pressure was relieved by early 2015.

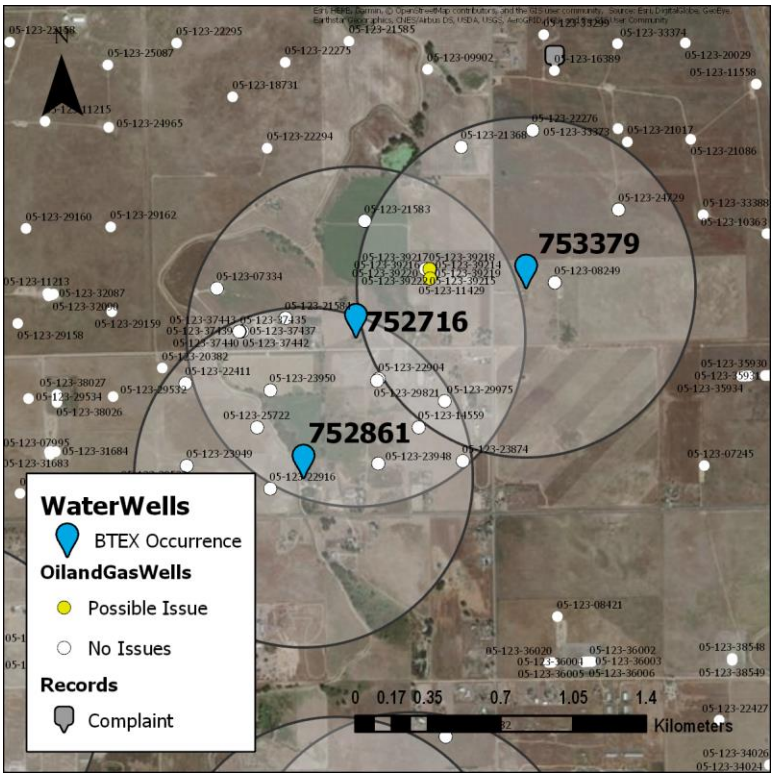
  - Suspected pathway: High surface casing pressures are suspected to force gas through holes or under short surface casings which can result in groundwater migration of gas to water wells.
- Oil/Gas Well of Concern 3
  - Oil/Gas Well name: 37-7 BELLA FEDERAL (API #05-123-30783)
  - Operator: Kerr McGee Oil and Gas Onshore LP
  - Issue: High critical surface casing pressures where the gas pressure could displace water from a well. The pressure was 2799 kPa on 11/21/2012, 2813 kPa on 4/11/2013, and reduced to 469 kPa on 1/23/2015. These high pressures are during the period where benzene and toluene were present in the groundwater.
  - Resolution: N/A
  - Suspected pathway: High surface casing pressures are suspected to force gas through holes or under short surface casings which can result in groundwater migration of gas to water wells.
- Oil/Gas Well of Concern 4
  - Oil/Gas Well name: 16-7 BELLA (API #05-123-30825)
  - Operator: Kerr McGee Oil and Gas Onshore LP
  - Issue: High critical surface casing pressures where the gas pressure could displace water from a well. The pressure on 11/21/2012 was 1462 kPa, increased to 1558 kPa on 1/23/2015, decreased to 986 kPa on 8/29/2016, and then increased to 2179 kPa on 10/4/2016. The increasing pressures during the period of benzene and toluene occurrences could be a concern.
  - Resolution: N/A
  - Suspected pathway: High surface casing pressures are suspected to force gas through holes or under short surface casings which can result in groundwater migration of gas to water wells.
- Oil/Gas Well of Concern 5
  - Oil/Gas Well name: 1 MAUDE ANDERSON GAS UNIT (API #05-123-08231)
  - Operator: Kerr McGee Oil and Gas Onshore LP
  - Issue: A sundry notice from 11/14/1996 documents a repair to surface casing with holes and leakage between 152 m and 162 m.
  - Resolution: Holes were repaired and the well held pressure in the test after repairs.
  - Suspected pathway: Since this is an old well with known leakages, more leaks could have opened since this well is still producing.

Summary

Several complaints opened with the COGCC have expressed concern over oil and gas impacted to groundwater. Complaint #200311007 is still unresolved and has not concluded whether oil/gas well Noble 05-123-29622 is a concern to the water quality. Despite no conclusion to the source of the BTEX presence or methane, four nearby oil/gas wells within a half-mile radius of the groundwater well have documented high critical surface casing pressures at the time of BTEX occurrence, and a fifth oil/gas well had repaired surface casing leaks in 1996.

Case #24

Groundwater wells: FacID #753379, FacID #752716, FacID #752861



Initial Sampling Reason
All three water wells were part of baseline sampling. Sampling was further conducted to determine if oil and gas development has impacted the water wells.

Groundwater Well Information

- FacID #753379
  - Depth: 219 meters
  - Aquifer: Laramie-Fox Hills
  - Usage type: Domestic Well
- FacID #752716
  - Depth: 244 meters
  - Aquifer: Laramie-Fox Hills
  - Usage type: Ground Water
- FacID #752861
  - Depth: 260 meters
  - Aquifer: Laramie-Fox Hills
  - Usage type: Domestic Well

Groundwater Well Sampling Information

- FacID #753379
  - Water: Two samples collected on 4/10/2014 and 10/9/2015 respectively. Toluene present in the second sample at 22.9 µg/L. Biogenic methane present at 15 mg/L on 10/9/2015.
  - Gas: Two samples collected on 4/10/2014 and 5/15/2015 respectively. Methane isotope analysis showed biogenic origin.
- FacID #752716
  - Water: Two samples collected on 7/1/2013 and 11/18/2014. Toluene present at 2.4 µg/L. Biogenic methane present at 8.81 mg/L on 11/18/2014.
  - Gas: Two samples collected on 7/1/2013 and 11/18/2014. Methane isotope analysis showed biogenic origin.
- FacID #752861
  - Water: Five samples collected on two dates, 9/26/2013 and 4/2/2015. Xylenes present at 1.2 µg/L. Biogenic methane present at 25 mg/L on 4/2/2015.
  - Gas: Two samples collected on 9/26/2013 and 4/2/2015. Methane isotope analysis showed biogenic origin.

Contamination Source Analysis

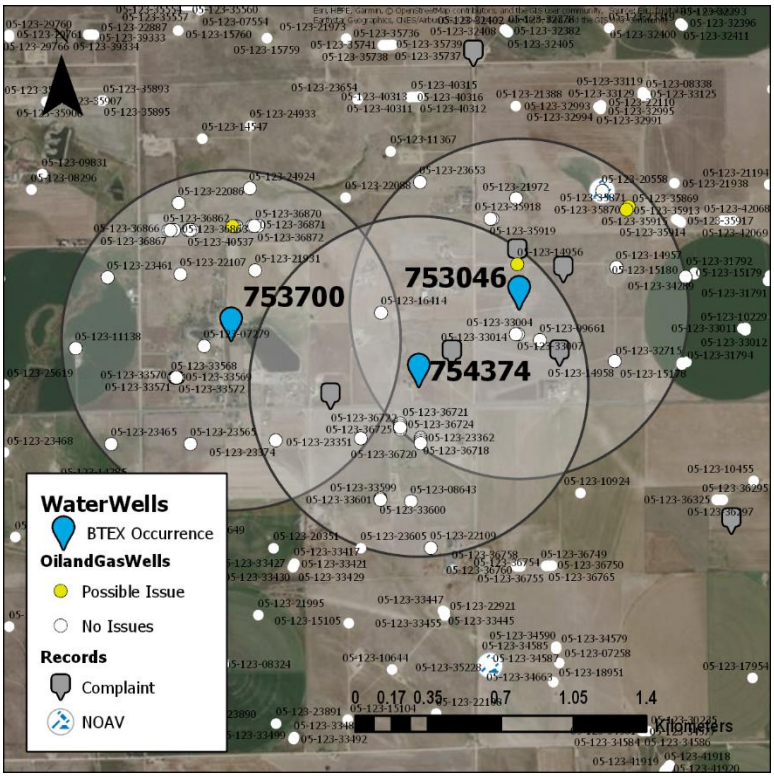
- Category D. No explanation found for source of BTEX.
- Oil/Gas Well of Possible Concern
  - Oil/Gas Well name: 4G-36H P266 Mumby State (API #05-123-39218)
  - Operator: Crestone Peak Resources Operating LLC
  - Issue: Spill or release form that is blank.
  - Resolution: Unresolved
  - Suspected pathway: No details to the size of the spill or receptors, so this remains a concern to the occurrence of BTEX compounds.

Summary

Three groundwater wells within a half-mile proximity of each other showed occurrences of toluene and xylenes at low concentrations below Colorado Basic Ground Water Standards. The BTEX compounds at low concentrations might be associated with the concurrent biogenic methane. No oil/gas wells had documents describing issues to surface casings or high surface casing pressures. Several spills were reported in the area but are unlikely to have reached the Laramie-Fox Hills aquifer.

Case #25

Groundwater wells: FacID #753046, FacID #754374, FacID #753700



Initial Sampling Reason

Complaints #200192755 and #200296411 were opened with the COGCC by the land owner of FacID #753046 requesting investigation of changing water color and odor. Groundwater well was sampled in 2008 with no signs of oil and gas development impacting groundwater. The groundwater wells FacID #754374 and FacID #753700 were baseline samples.

Groundwater Well Information

- FacID #753046
  - Depth: 200 meters
  - Aquifer: Laramie-Fox Hills
  - Usage type: Domestic Well
- FacID #754374
  - Depth: 177 meters
  - Aquifer: Laramie-Fox Hills
  - Usage type: Domestic Well
- FacID #753700
  - Depth: 207 meters
  - Aquifer: Laramie-Fox Hills
  - Usage type: Domestic Well

Groundwater Well Sampling Information

- FacID #753046
  - Water: Ten samples collected between 2008 and 2015. Two sampling dates 12/1/2014 and 3/25/2015 had elevated occurrences of toluene at 1.8 µg/L and 2.7 µg/L respectively. Biogenic methane was present at 61 mg/L on 3/25/2015.
  - Gas: Three samples collected between 2014 and 2015. Methane isotope analysis showed biogenic origin.
- FacID #754374
  - Water: Six samples in total were collected on the two dates 9/24/2015 and 3/30/2016. The first sample showed the occurrence of toluene at 12.5 µg/L. Toluene was not present in the second sample. Biogenic methane was present at 63 mg/L on 9/24/2015.

  - Gas: Two samples were collected on 9/24/2015 and 3/30/2016. Methane isotope analysis showed biogenic origin.
- FacID #753700
  - Water: Nine samples collected on three occasions between 2014 and 2015. Toluene was present at 5.2 µg/L on 12/21/2015. Biogenic methane was present at 39 mg/L on 3/25/2015.
  - Gas: Three samples collected on each of the three sample dates between 2014 and 2015. Methane isotope analysis showed biogenic origin.

Contamination Source Analysis

- **FacID #753046: Category C:** Documents indicate the source of BTEX could have originated from an oil/gas well
- Oil/Gas Well of Possible Concern 1
  - Oil/Gas Well name: 3N-5HZ NICHOLS (API #05-123-35870)
  - Operator: Kerr McGee Oil and Gas Onshore LP
  - Issue: High critical surface casing pressure of 3061 kPa on 7/19/2013, with no subsequent readings. The critical pressure is defined by the pressure being able to displace water in the anulus of the oil/gas well which could release to an aquifer.
  - Resolution: N/A
  - Suspected pathway: This well is 700 m from the groundwater well with elevated toluene. If the pressure was still high a year after the measurement this oil/gas well could be of concern.
- Oil/Gas Well of Possible Concern 2
  - Oil/Gas Well name: 29N-5HZ NICHOLS (API #05-123-35871)
  - Operator: Kerr McGee Oil and Gas Onshore LP
  - Issue: High critical surface casing pressure of 1986 kPa on 7/19/2013, with no subsequent readings. The critical pressure is defined by the pressure being able to displace water in the anulus of the oil/gas well which could release to an aquifer.
  - Resolution: N/A
  - Suspected pathway: This well is 700 m from the groundwater well with elevated toluene. If the pressure was still high a year after the measurement this oil/gas well could be of concern.

- **FacID #754374, FacID #753700: Category D.** No explanation found for source of BTEX. One unresolved spill form is tagged to an oil and gas well near FacID #753700.

Summary

Three groundwater wells had toluene present in their water wells detected in late 2014 and 2015. The toluene present was at low concentrations below Colorado Basic Ground Water Standards. All wells had biogenic methane present as well, between 14.8 mg/L and 20.1 mg/L. The BTEX compounds at low concentrations might be associated with the concurrent biogenic methane. No definitive oil/gas wells were the cause of the toluene presence, but two had high critical surface casing pressures where the gas pressure is high enough to displace water in the well anulus near FacID #753046. If there were leaks, gas could escape to the Laramie-Fox Hills aquifer.

For FacID #753374 and FacID #753700, the wells of concern were farther than a half-mile from the water well and labeled as unresolved. While these issues could have related to the toluene occurrences, it does not meet our criteria for a nearby well. Sampling also indicated that the methane present in the water well did not match the oil/gas wells of concern.

Case #26

Groundwater wells: FacID #753889

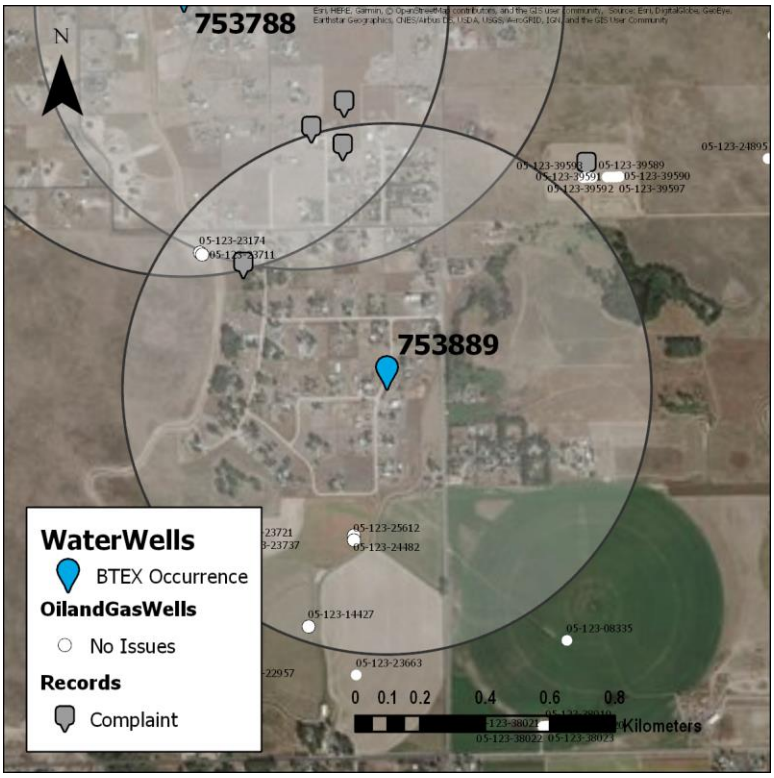
Initial Sampling Reason
Water was sampled as part of the voluntary baseline sampling.

Groundwater Well Information

- Depth: 38 meters
- Aquifer: Lower Arapaho
- Usage type: Domestic Well

Groundwater Well Sampling Information

- Water: Two samples collected on 12/16/2014.
  - Toluene present at 1.3 µg/L.
- Gas: N/A



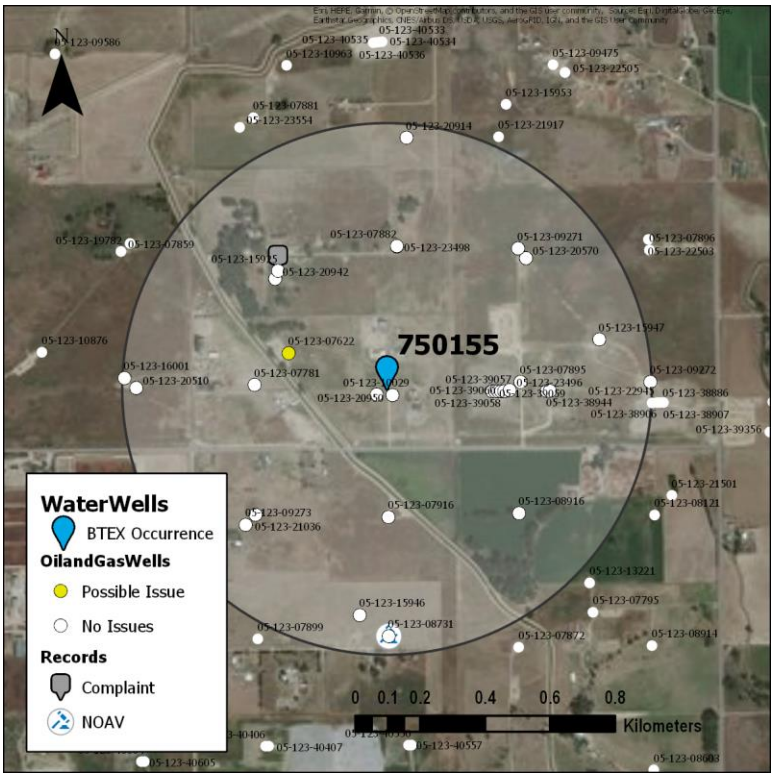
Contamination Source Analysis

- **Category D:** No explanation found for source of BTEX.

Summary
Toluene present at 1.3 µg/L, far below the Colorado Basic Ground Water Standards. No source of toluene is known. The groundwater well is shallower and may have had a surface spill or incident that reached the aquifer.

Case #27

Groundwater well: FacID #750155



Initial Sampling Reason
The groundwater was first sampled in 2011 for baseline sampling. It was again sampled for voluntary baseline sampling in 2015.

Groundwater Well Information

- Depth: 158 meters
- Aquifer: Laramie-Fox Hills
- Usage type: Ground Water

Groundwater Well Sampling Information

- Water: Five samples collected between 2011 and 2015.
  - Toluene present at 6.3 µg/L on 1/8/2015.
  - Biogenic methane present at 14 mg/L on 1/8/2015.
- Gas: Two samples collected between 2011 and 2015.
  - Methane isotope analysis showed biogenic origin.

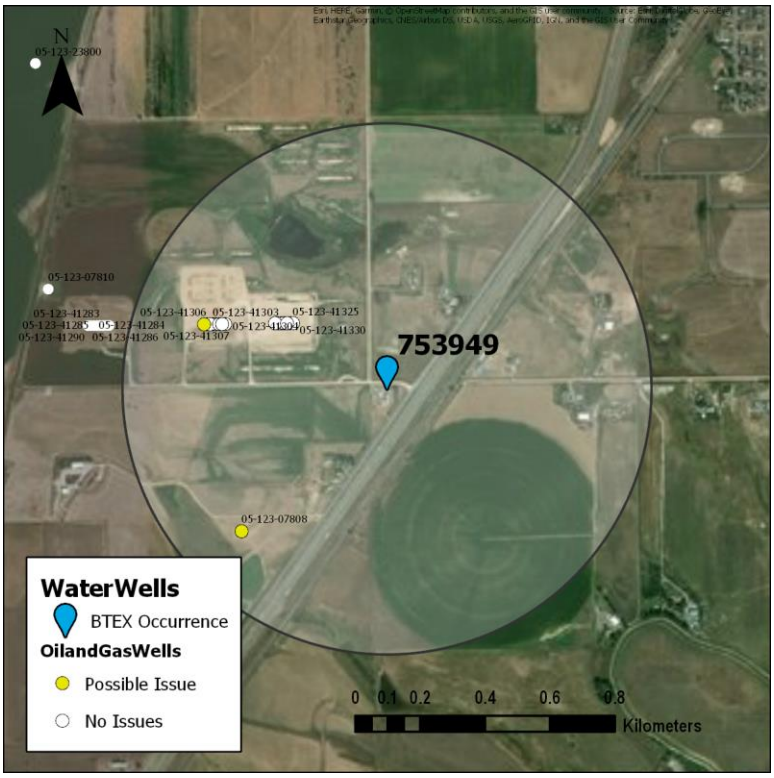
Contamination Source Analysis

- **Category C:** Documents indicate the source of BTEX could have originated from an oil/gas well
- Other Issues Nearby
  - Oil/Gas Well name: 1 1415 CORP GAS UNIT (API #05-123-07622)
  - Operator: Kerr McGee Oil and Gas Onshore LP
  - Issue: Surface spill at a tank battery that caused significant soil contamination and possible groundwater impact. Two monitoring wells were installed which found BTEX compounds above Colorado Basic Ground Water Standards.
  - Resolution: Soil was removed. Groundwater impact unknown. The investigation and remediation were closed on 9/24/2015.
  - Suspected pathway: The remediation report lists the groundwater well as a potential receptor to the BTEX contamination of shallow groundwater. The report notes that the shallow groundwater flow direction is in the direction of the water well.

Summary

Toluene was detected at a low concentration (6.3 µg/L) on 1/8/2015 which is below Colorado Basic Ground Water Standards. The BTEX compounds at low concentrations might be associated with the concurrent biogenic methane. The only issue recorded with any oil/gas wells was a large surface spill 300 m to the west of the groundwater well. The spill did have BTEX contamination of shallow groundwater, with the flow direction moving towards the water well. The impact of the groundwater contamination is unknown, and the case is now closed.

Case #28



Groundwater well: FacID #753949

Initial Sampling Reason
Baseline sampling. No complaints opened with the COGCC.

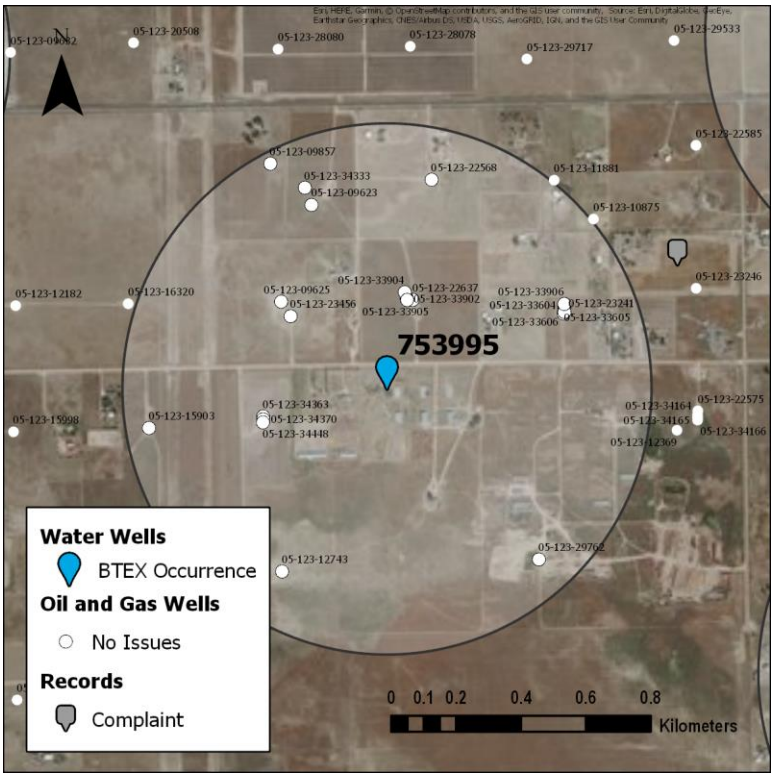
Groundwater Well Information
- Depth: 248 meters
- Aquifer: Laramie-Fox Hills
- Usage type: Domestic Well

Groundwater Well Sampling Information
- Water: Three samples collected on 1/14/2015
  - Toluene detected at 13.6 µg/L.
  - Biogenic methane present at 17 mg/L on 1/14/2015.
- Gas: One sample collected on 1/14/2015. Methane isotope analysis determined biogenic origin.

Contamination Source Analysis
- Category D. No explanation found for source of BTEX.
- Other
  - Oil/Gas Well name: 39 ACCO-TERRA-STATE (API #05-123-07808)
  - Operator: Kerr McGee Oil and Gas Onshore LP
  - Issue: Sundry notice for repairing well. Described procedure for annular fill for aquifer coverage. The well had a short surface casing before 11/5/2015.
  - Resolution: Well was repaired.
  - Suspected pathway: A short surface casing could lead to possible release of gas if pressure builds. No surface casing pressure was recorded in measurements from 2010 through 2016.

Summary
Baseline sampling detected the presence of toluene at 13.6 µg/L. This is below Colorado Basic Ground Water Standards. No source of the toluene is identified, and no complaints were opened with the COGCC. The BTEX compounds at low concentrations might be associated with the concurrent biogenic methane. One well had a repair to the surface casing pressure increasing the coverage because the original surface casing did not extend to the bottom of the Laramie-Fox Hills aquifer. This oil/gas well had no reported pressure buildup.

Case #29



Groundwater well: FacID #753995

Initial Sampling Reason
Baseline sampling. No complaints opened with the COGCC within a half-mile.

Groundwater Well Information

- Depth: 280 meters
- Aquifer: Laramie-Fox Hills
- Usage type: Domestic Well

Groundwater Well Sampling Information

- Water: Nine samples collected on three dates between 2015 and 2016.
  - Toluene present at 38 µg/L on 1/29/2015.
  - Biogenic methane present at 18 mg/L on 7/28/2015.
- Gas: Three samples collected on the same dates between 2015 and 2016. Methane isotope analysis showed biogenic origin.

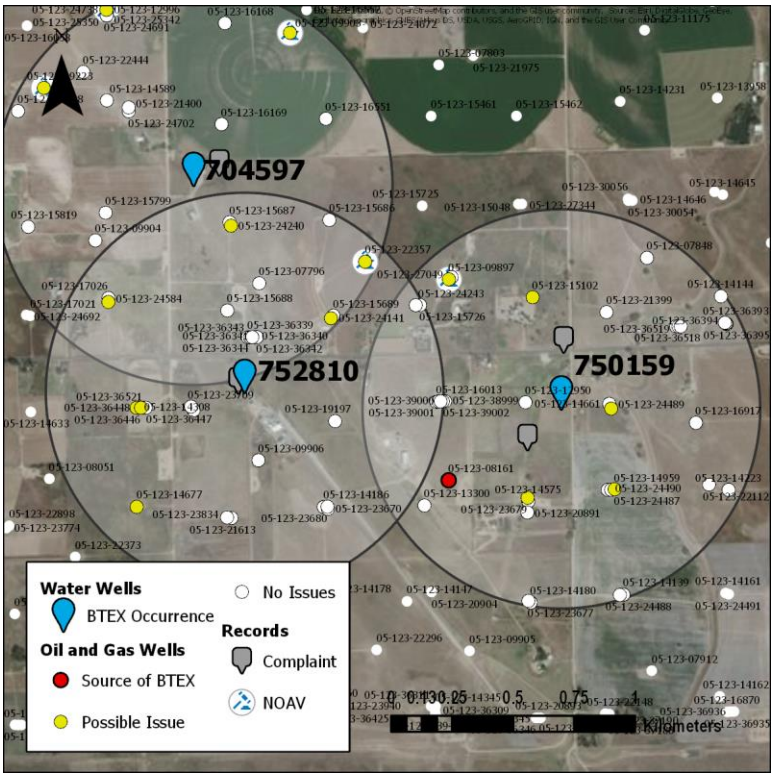
Contamination Source Analysis

- Category D. No explanation found for source of BTEX.

Summary
Toluene was detected at 38 µg/L which is below Colorado Basic Ground Water Standards, but no source was formally identified. The BTEX compounds at low concentrations might be associated with the concurrent biogenic methane.

Case #30

Groundwater wells: FacID #750159, #752810



Initial Sampling Reason
Sampling of FacID #750159 took place after complaint #200276485 was filed to report methane in a neighboring water well to the south. Sampling of FacID #752810 took place because of complaint #200388222 regarding a wellhouse fire the prior year due to thermogenic methane. Both thermogenic methane occurrences were concluded as not related to oil and gas activity.

Groundwater Well Information

- FacID #750159
  - Depth: 121 meters
  - Aquifer: Laramie-Fox Hills
  - Usage type: Groundwater
- FacID #752810
  - Depth: 70 meters
  - Aquifer: Laramie-Fox Hills
  - Usage type: Domestic Well

Groundwater Well Sampling Information

- FacID #750159:
  - Water: Twenty-three samples collected from 2010 to 2017. Toluene was detected in two separate samples in 2015, at 4 µg/L, and 37 µg/ respectively. Thermogenic methane present at 35 mg/L on 4/21/2016.
  - Gas: Nine samples collected from 2010 to 2017. Methane isotope analysis showed thermogenic origin.
- FacID #752810:
  - Water: Twelve samples collected from 2005 to 2016. Toluene was detected in one sample at 1.5 µg/L. Thermogenic methane present at 10 mg/L on 1/17/2014.
  - Gas: Four samples collected from 2005-2016. Methane isotope analysis showed thermogenic origin.

Contamination Source Analysis

- **Category A**: The COGCC identified an oil/gas well as the source of the gas and BTEX occurrence.
- Source of BTEX:

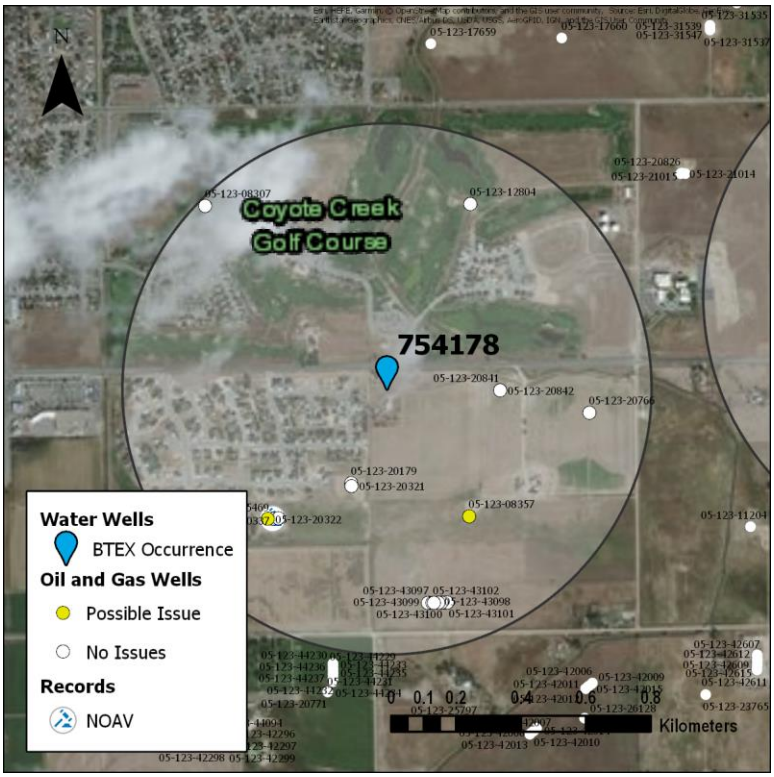
  - Oil/Gas Well name: 1 UPRR 22 PAN AM GAS UNIT J (API# 05-123-08161)
  - Operator: Kerr McGee Oil & Gas Onshore LP
  - Issue: The well had a casing leak gas and repairing it eliminated the source of thermogenic methane.
  - Resolution: The 1 UPRR 22 PAN AM GAS UNIT J well was plugged and abandoned on 4/19/2012. Kerr McGee provided an alternate source of water for both owners of the wells.
- Other oil/gas wells with issues operated by Kerr McGee Oil & Gas Onshore LP:
  - The following wells had high critical surface casing pressures that were calculated to be able to displace fluid from their surface casing into the aquifer but were not issued an NOAV.
    - 2 BOHLENDER JACOB T. UNIT A (API# 05-123-09897) was issued an NOAV for high surface casing pressure. Pressure relieved afterwards.
    - 22-24 MILLER (API# 05-123-24487) had a high surface casing pressure on 10/28/2010 of 2172 kPa, decreasing to 1634 kPa on 6/10/2013.
    - 29-24 MILLER (API# 05-123-24489) had a high surface casing pressure on 10/29/2010 of 1606 kPa, reduced to negligible pressures on 6/10/2013.
    - 1-22A HSR-THE CHAIRMAN (API #05-123-14308) had a high surface casing pressure in 7/1/2014 of 1606 kPa.
    - 8-22A HSR-GIBSON (API #05-123-14677) had a high surface casing pressure in 1/2/2014 of 965 kPa, which increased to 1924 kPa on 5/11/2016.
    - 35-14 BARNEY (API #05-123-24141) had a high surface casing pressure on 4/26/2012 of 2144 kPa, reduced to negligible pressure on 6/17/2015.
    - 37-15 BAILEY (API #05-123-24584) had a high surface casing pressure on 4/18/2012 of 2661 kPa through 2014, reduced to 110 kPa on 6/2/2015.
    - 37N-22HZ HEDGE (API #05-123-36446) had a high surface casing pressure on 4/3/2014 of 6060 kPa, reduced to 2551 kPa on 2/2/2015.
- Suspected pathway: High pressure from the leaking oil/gas well casing likely released gas into the Laramie-Fox Hills Aquifer which migrated towards the groundwater well pumphouse.

Summary

Two water wells within a half-mile radius of each other had detected toluene in 2015. The oil/gas well 1 UPRR 22 PAN AM GAS UNIT J (API# 05-123-08161) was reported to have a hole in the casing leaking gas and repairing it resulted in no further BTEX measurements or thermogenic methane occurrences. However, eight other nearby oil/gas wells had surface casing pressures calculated to be able to displace liquid from the surface casing if there was a hole or short surface casing. The eight wells with high surface casing pressures were not listed as a concern by the COGCC.

Case #31

Groundwater well: FacID #754178



Initial Sampling Reason
Baseline sampling. No complaints opened with the COGCC within a half-mile.

Groundwater Well Information

- Depth: 219 meters
- Aquifer: Laramie-Fox Hills
- Number of users: One household
- Usage type: Domestic Well

Groundwater Well Sampling Information

- Water: Four samples collected on 4/2/2015.
  - Toluene detected at 14 µg/L.
  - Biogenic methane present at 24 mg/L on 4/2/2015.
- Gas: One sample collected. Methane isotope analysis shows biogenic origin.

Contamination Source Analysis

- **Category C:** No explanation found for source of BTEX.
- Oil/Gas Well of Concern 1
  - Oil/Gas Well name: 15-5A HSR HOLTON FEDERAL (API #05-123-20322)
  - Operator: Kerr McGee Oil and Gas Onshore LP
  - Issue: Sundry Notice #401124520 to repair well with annular fill procedure from 472 m to 262 m depth. This is the bottom of the Laramie-Fox Hills aquifer. Prior to 10/13/2016 procedural start date, this well may have had a short surface casing where stray gas could potentially escape.
  - Resolution: Well repaired, passes surface casing pressure test.
- Oil/Gas Well of Concern 2
  - Oil/Gas Well name: 1 ADDIE M. KINGS GAS UNIT (API #05-123-08357)
  - Operator: Kerr McGee Oil and Gas Onshore LP
  - Issue: Sundry Notice #401204160 describes repair to well with remedial cement procedure. The well needs “Niobrara/Fox Hills remedial cement.” This is an issue if the cement was not protecting the Laramie-Fox Hills aquifer prior to the repair.
  - Resolution: Well repaired, passed surface casing pressure test.
  - Other: This well also had a surface spill in 2002 where a dump line leaked, impacting groundwater. Spill Report #1120647 describes 300 barrels of groundwater being pumped for removal. BTEX compounds not documented.

Summary

A voluntary baseline sample showed an occurrence of toluene at 14 µg/L. This is below Colorado Basic Ground Water Quality Standards. The BTEX compounds at low concentrations might be associated the concurrent biogenic methane. Two oil/gas wells had sundry notices documenting well repairs to the interface of the Niobrara/Laramie-Fox Hills aquifer interface. If the bottom of the aquifer was not adequately protected, stray gas could be introduced to the water. No other oil/gas wells had documented issues or repairs.

Case #32

Groundwater well: FacID #754329

Initial Sampling Reason
Baseline sampling. No complaints opened with the COGCC within a half-mile.

Groundwater Well Information

- Depth: 302 meters
- Aquifer: Laramie-Fox Hills
- Usage type: Domestic Well

Groundwater Well Sampling Information

- Water: Two samples were collected from 2015 to 2016.
  - Toluene detected at 20 µg/L on 5/6/2015.
  - Ethylbenzene detected at 0.59 µg/L on 5/6/2015.
  - Biogenic methane present at 40.6 mg/L.
- Gas: One sample collected on 7/8/2016, methane isotope analysis showed biogenic origin.

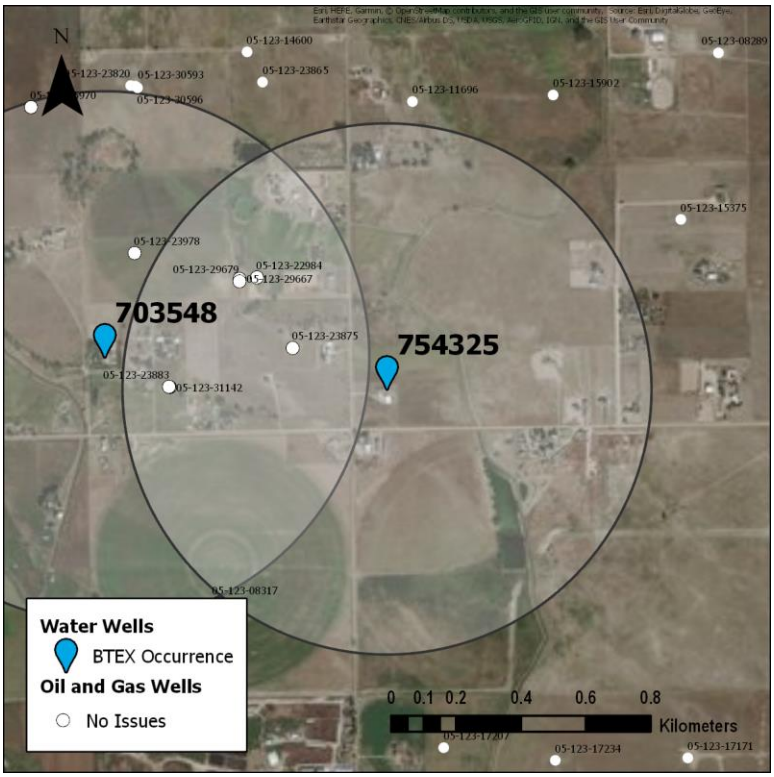
Contamination Source Analysis

- **Category D:** No explanation found for source of BTEX.

Summary
A voluntary baseline sampling showed the occurrence of toluene and ethylbenzene. The BTEX compounds at low concentrations might be associated the concurrent biogenic methane. No source has been definitively identified.

Case #33

Groundwater well: FacID #754325



Initial Sampling Reason
Baseline sampling. No complaints opened with the COGCC within a half-mile.

Groundwater Well Information

- Depth: 258 meters
- Aquifer: Laramie-Fox Hills
- Usage type: Domestic Well

Groundwater Well Sampling Information

- Water: Three water samples all collected on 8/27/2015. Toluene detected at 3.5 µg/L. Biogenic methane detected in one sample at 17 mg/L on 8/27/2015.
- Gas: Isotope analysis showed biogenic origin.

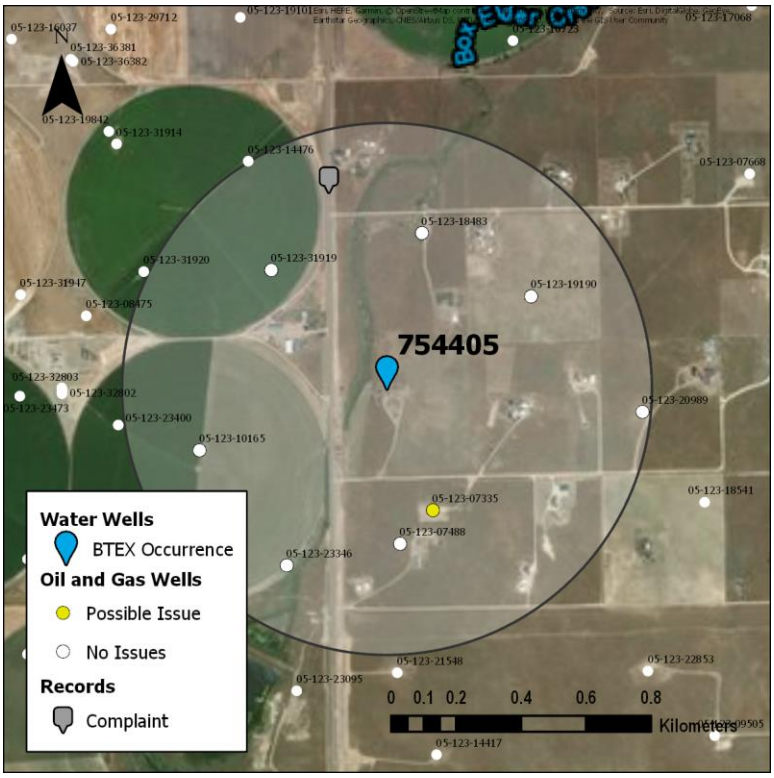
Contamination Source Analysis

- **Category D:** No explanation found for source of BTEX.
- This water well is near (0.8 km) FacID #703548 which had toluene present in 2002.
- Potential oil and gas well of concern *greater than half-mile radius*: A sundry notice for the Leonard Avey et al (API# 05-123-10643) oil/gas well reported remedial cement procedures for repairing potential hole in casing on 1/5/2017. A high critical surface casing pressure was reported in 2016 at 3172 kPa.

Summary
No oil and gas wells within a half-mile radius of the water well show documentation of issues that could cause potential groundwater contamination. However, outside of the radius, Leonard Avey et al (API# 05-123-10643) had high critical surface casing pressure in 2016 and surface casing hole identified in early 2017, however this oil and gas well is greater than a half-mile away from the water well. It may be suspect to the occurrence of toluene but does not meet the criteria of a nearby oil and gas well for this study.

Case #34

Groundwater well: FacID #754405



Initial Sampling Reason
Baseline sampling. One complaint opened to the northwest but requested sampling for a different water well.

Groundwater Well Information

- Depth: 141 meters
- Aquifer: Laramie-Fox Hills
- Usage type: Groundwater

Groundwater Well Sampling Information

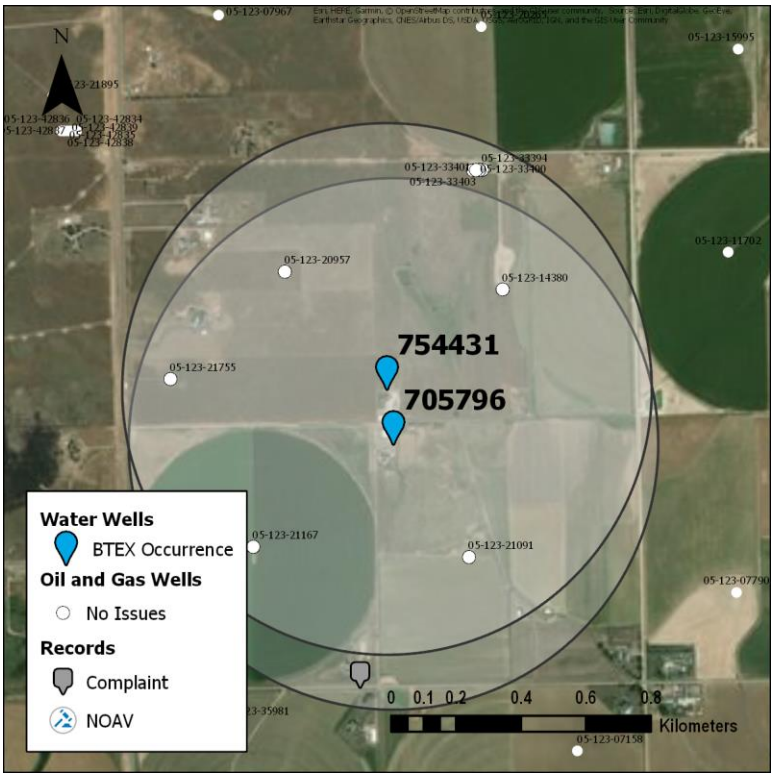
- Water: Three samples collected on 10/15/2015.
  - Toluene detected at 7.8 µg/L.
  - Biogenic methane detected at 26 mg/L on 10/15/2015.
- Gas: One sample collected. Methane isotope analysis showed biogenic origin.

Contamination Source Analysis

- **Category C:** Documents indicate the source of BTEX could have originated from an oil/gas well.
- Oil/Gas Well of Concern 1
  - Oil/Gas Well name: 14-6 NORRIS (API #05-123-07335)
  - Operator: Kerr McGee Oil and Gas Onshore LP
  - Issue: Historic impacts encountered under the water sump while tank battery was being abandoned. Remediation Report #2146088 states that surface water 343 m to the west could be affected, and a water well in the immediate vicinity.
  - Resolution: Chemical oxidation and soil excavation were the main components of remediation.
  - Suspected pathway: Contaminated surface water could migrate to the groundwater well to the north. While this is not a direct pathway, this spill is the only oil/gas event that occurred near the groundwater well.

Summary
Toluene was found in groundwater well after baseline monitoring. Two years prior to the baseline sampling, a historic sized surface spill contaminated surface waters and shallow groundwaters 300 m to the south of the water well. The BTEX compounds also occurred at low concentrations and might be associated the concurrent biogenic methane. The source is unknown.

Case #35



Groundwater well: FacID #754431, FacID #705796

Initial Sampling Reason
Baseline sampling. The landowners of these water wells did not open complaints with the COGCC within a half-mile.

Groundwater Well Information

- FacID #754431
  - Depth: 245 meters
  - Aquifer: Laramie-Fox Hills
  - Number of users: One household
  - Usage type: Domestic Well
- FacID #705796
  - Depth: 244 meters
  - Aquifer: Laramie-Fox Hills
  - Number of users: One household
  - Usage type: Groundwater

Groundwater Well Sampling Information

- FacID #754431
  - Water: Three samples collected on 10/29/2015. Toluene present at 70.6 µg/L. Biogenic methane present at 50 mg/L on 10/29/2015.
  - Gas: One sample collected, methane isotope analysis showed biogenic origin.
- FacID #705796
  - Water: Four samples collected from 2009 to 2015. Toluene present at 3.9 µg/L. Biogenic methane present at 56 mg/L on 12/2/2015.
  - Gas: One sample collected, methane isotope analysis showed biogenic origin.

Contamination Source Analysis

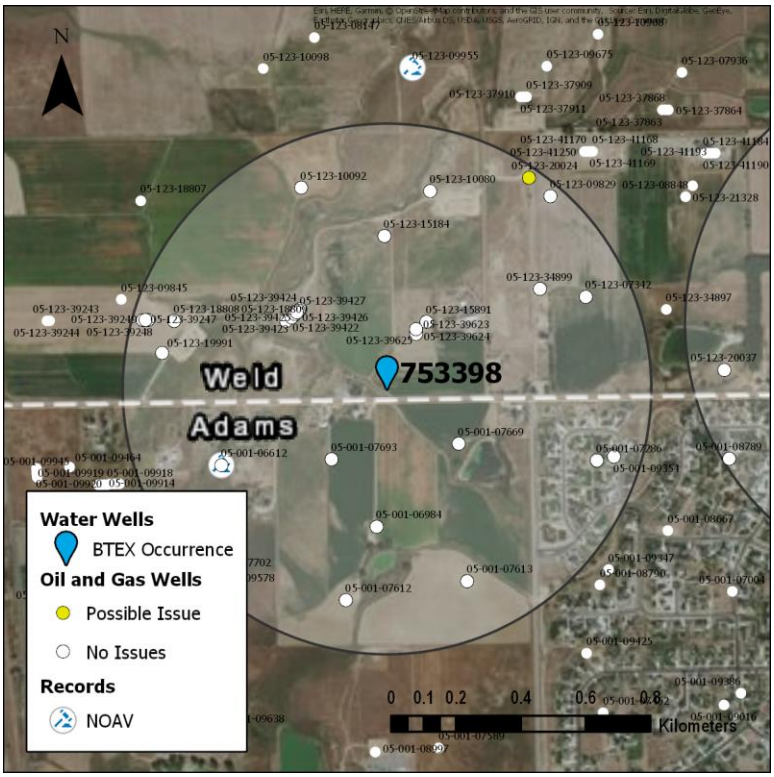
- **Category D:** No explanation found for source of BTEX.

Summary
Toluene was present in two wells 166 m from each other. No source of the toluene was identified, and no oil/gas wells had any documentation of issues.

Case #36

Groundwater well: FacID #753398

Initial Sampling Reason
Baseline sampling. The NOAVs in the map are unrelated to this water well.



Groundwater Well Information

- Depth: 248 meters
- Aquifer: Laramie-Fox Hills
- Number of users: One household
- Usage type: Domestic Well

Groundwater Well Sampling Information

- Water: Six samples collected from 2014 to 2015.
  - Toluene present at 41.9 µg/L on 12/22/2015.
  - Biogenic methane present at 18 mg/L on 6/11/2014.
- Gas: Two samples collected with the water samples from 2014 to 2015. Methane isotope analysis showed biogenic origin.

Contamination Source Analysis

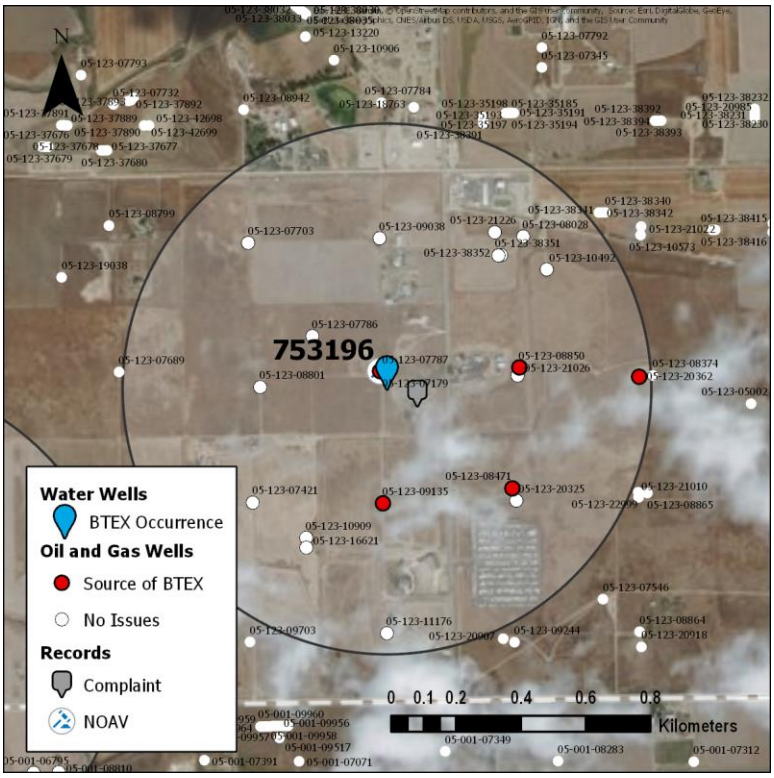
- Category D: No explanation found for source of BTEX.
- Surface spill of concern
  - Oil/Gas Well name: 13-32 JACOBUCCI (API #05-123-20024)
  - Operator: PDC Energy Inc
  - Issue: Historical soil and groundwater impacts discovered when a dump line was being replaced on 3/25/2013.
  - Resolution: Eight monitoring wells in place, vacuum enhanced fluid recovery, air sparging. Groundwater has been monitored through 2015. A 2016 report showed that benzene (40 µg/L), ethylbenzene (2.7 µg/L), and xylenes (8.5 µg/L) were present in a monitoring well on 4/21/2015, and benzene was found again in the same monitoring well at 1.3 µg/L on 10/15/2015. Since the BTEX compounds were still present in shallow groundwater over two years later than the initial discovery, there is a possibility that they could have migrated to the groundwater well where toluene was present.

Summary

Toluene was present in a groundwater well on 12/22/2015 below Colorado Basic Ground Water Standards. The only event that has documents describing BTEX groundwater contamination is from a historical surface spill on 3/25/2013. Even though this spill took place over two years prior to the toluene occurrence, BTEX compounds were still present in monitoring wells near the spill as late as 10/15/2015. The definitive source of toluene in the groundwater is unknown, but a possible pathway could have been from shallow groundwater migrating to the water well 1375 m away over the years.

Case #37

Groundwater well: FacID #753196



Initial Sampling Reason
Complaint #200402859 was opened with the COGCC on 4/22/ 2014 who described discoloration in their water well.

Groundwater Well Information

- Depth: 256 meters
- Aquifer: Laramie-Fox Hills
- Number of users: One household
- Usage type: Domestic Well

Groundwater Well Sampling Information

- Water: Twenty-five samples collected between 2013 and 2016.
  - Toluene present at 800 µg/L on 12/22/2015. This is above Colorado Basic Ground Water Standards.
  - Thermogenic methane present at 29 mg/L on 3/27/2015.
- Gas: Fourteen samples collected between 2013 and 2016.
  - Gas characterization was similar to thermogenic gas of the Sussex formation.
  - The COGCC sampled four other water wells within a 1.21 km (0.75 mile) radius and found thermogenic methane in water well FacID #753680 and found mixed biogenic and thermogenic methane.

Contamination Source Analysis

- **Category A**: The COGCC identified an oil/gas well as the source of the gas and BTEX occurrence.
- Oil/Gas Well of Concern 1:
  - Oil/Gas Well name: 6 AMOCO-CHRTR-SCHNEIDER U B (API#05-123-07787)
  - Operator: K P KAUFFMAN COMPANY INC
  - Issue: The COGCC ruled this specific well as the most like source as it is closest to the water well. The methane isotope analysis matches the methane in the water. The well has a short surface casing, above the groundwater well screen, and above the bottom of the Laramie-Fox Hills aquifer. No surface casing pressures observed.
  - Resolution: The well must be repaired with cement bond logging and pass a Mechanical Integrity Test. An NOAV was issued for a short surface casing.
  - Suspected pathway: Gas likely escaped from the short surface casing and migrated into the aquifer near water well FacID #753196.
- Oil/Gas Well of Concern 2:

  - Oil/Gas Well name: 1-A SELTZER (API#05-123-08471)
  - Operator: K P KAUFFMAN COMPANY INC
  - Issue: Short surface casing producing thermogenic methane with same signature as found in the water well.
  - Resolution: Must be repaired with cement bond logging and pass a Mechanical Integrity Test. An NOAV was issued for a short surface casing.
  - Suspected pathway: Gas likely escaped from the short surface casing and migrated into the aquifer near water well FacID #753196.
- Oil/Gas Well of Concern 3:
  - Oil/Gas Well name: A-2 WAGNER (API#05-123-08850)
  - Operator: K P KAUFFMAN COMPANY INC
  - Issue: Short surface casing producing thermogenic methane with same signature as found in the water well.
  - Resolution: The well must be repaired with cement bond logging and pass a Mechanical Integrity Test. An NOAV was issued for a short surface casing.
  - Suspected pathway: Gas likely escaped from the short surface casing and migrated into the aquifer near water well FacID #753196.
- Oil/Gas Well of Concern 4:
  - Oil/Gas Well name: 12 AMOCO-CHARTER SCHNEIDER (API#05-123-09135)
  - Operator: K P KAUFFMAN COMPANY INC
  - Issue: Short surface casing producing thermogenic methane with same signature as found in the water well.
  - Resolution: The well must be repaired with cement bond logging and pass a Mechanical Integrity Test. An NOAV was issued for a short surface casing.
  - Suspected pathway: Gas likely escaped from the short surface casing and migrated into the aquifer near water well FacID #753196.
- Oil/Gas Well of Concern 5:
  - Oil/Gas Well name: 22-34 GRENEMYER-WAGNER (API#05-123-20362)
  - Operator: Encana Oil and Gas (USA) Inc
  - Issue: The COGCC also determined that four Encana oil/gas wells matched the thermogenic methane signature found in the water well.
  - Resolution: Encana must provide an alternate source of potable water and conduct Mechanical Integrity Tests on the oil/gas wells. An NOAV was issued to Encana for the four oil/gas wells.
  - Suspected pathway: Gas likely escaped and migrated into the aquifer near water well FacID #753196.
- Oil/Gas Well of Concern 6:
  - Oil/Gas Well name: 14-34 SELTZER (API#05-123-20907)
  - Operator: Encana Oil and Gas (USA) Inc Issue:
  - Issue: The COGCC also determined that four Encana oil/gas wells matched the thermogenic methane signature found in the water well.
  - Resolution: Encana must provide an alternate source of potable water and conduct Mechanical Integrity Tests on the oil/gas wells. An NOAV was issued to Encana for the four oil/gas wells.
  - Suspected pathway: Gas likely escaped and migrated into the aquifer near water well FacID #753196. This well was outside of the half-mile radius but will be listed as a

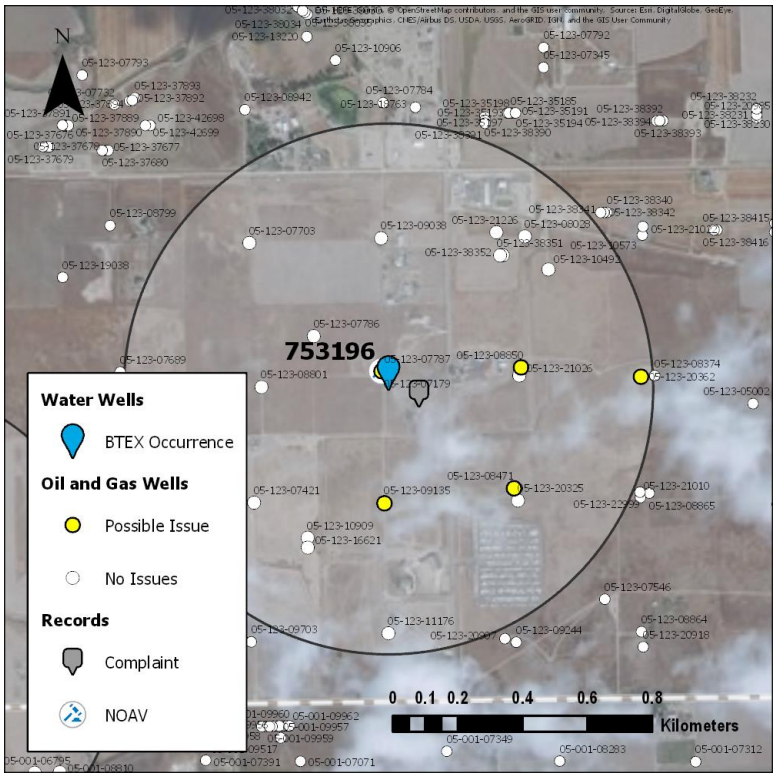
suspect oil/gas well since the COGCC identified it as a possible source of contamination.

- Oil/Gas Well of Concern 7:
  - Oil/Gas Well name: 24-34 SELTZER (API#05-123-20918)
  - Operator: Encana Oil and Gas (USA) Inc
  - Issue: The COGCC also determined that four Encana oil/gas wells matched the thermogenic methane signature found in the water well.
  - Resolution: Encana must provide an alternate source of potable water and conduct Mechanical Integrity Tests on the oil/gas wells. An NOAV was issued to Encana for the four oil/gas wells.
  - Suspected pathway: Gas likely escaped and migrated into the aquifer near water well FacID #753196. This well was outside of the half-mile radius but will be listed as a suspect oil/gas well since the COGCC identified it as a possible source of contamination.
- Oil/Gas Well of Concern 8:
  - Oil/Gas Well name: 21-34 GRENEMYER-WAGNER (API#05-123-21022)
  - Operator: Encana Oil and Gas (USA) Inc
  - Issue: The COGCC also determined that four Encana oil/gas wells matched the thermogenic methane signature found in the water well.
  - Resolution: Encana must provide an alternate source of potable water and conduct Mechanical Integrity Tests on the oil/gas wells. An NOAV was issued to Encana for the four oil/gas wells.
  - Suspected pathway: Gas likely escaped and migrated into the aquifer near water well FacID #753196. This well was outside of the half-mile radius but will be listed as a suspect oil/gas well since the COGCC identified it as a possible source of contamination.

Summary

A complaint alleged impacts to a water well and water sampling confirmed the presence of thermogenic methane that matched the signatures of eight nearby oil/gas wells. Three of the oil/gas wells fall outside of the half-mile radius of the groundwater well but were listed as suspects to contamination by the COGCC. Since toluene was above the Colorado Basic Ground Water Standards limit, and numerous nearby oil/gas wells, it is likely that toluene originated from these oil/gas wells.

Case #38



Groundwater well: FacID #707193

Initial Sampling Reason
Complaint #200113299 was opened with the COGCC on 6/20/2007 alleging impact to landowner's water well from a nearby injection well.

Groundwater Well Information

- Depth: 311 meters
- Aquifer: High Plains Aquifer
- Usage type: Domestic Well

Groundwater Well Sampling Information

- Water: Eighteen samples collected from 2010 to 2016.
  - Xylenes present at 1.7 µg/L on 3/30/2016.
- Gas: N/A

Contamination Source Analysis

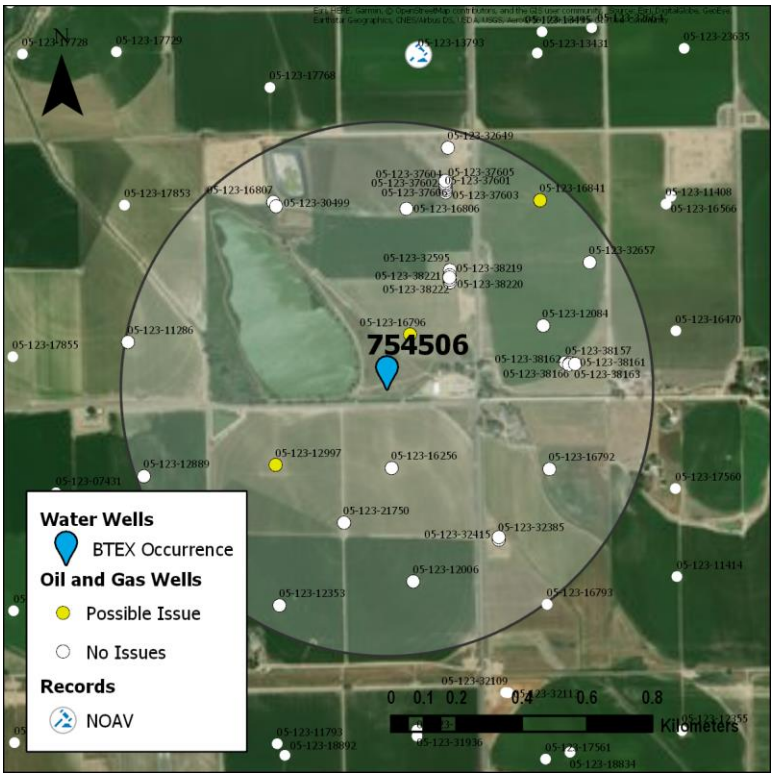
- **Category C:** Documents indicate the source of BTEX could have originated from an oil/gas well.
- Oil/Gas well of concern
  - Well name: 6-13 WPD007-2 ECGS (API #05-075-09411)
  - Operator: East Cheyenne Gas Storage LLC
  - Issue: High critical surface casing pressure recorded on 2/23/2016 at 5447 kPa. The well also has a short surface casing above the bottom of the aquifer.
  - Resolution: N/A
  - Suspected pathway: High pressures can displace gas through the bottom of the protective surface casing.
- Oil/Gas well of concern
  - Well name: A-2 Schwake (API #05-075-07181)
  - Operator: East Cheyenne Gas Storage LLC
  - Issue: The tank battery produced water pits were found to have leaked and contaminated the landowner's water well in 2007.
  - Resolution: This well (FacID #707193) was installed as a replacement and the landowner was satisfied on 10/9/2009.
  - Suspected pathway: Surface water contaminated and infiltrated the shallow water well (76m).

- Oil/Gas well of concern
  - Well name: 2 Gillham (API #05-075-07180)
  - Operator: East Cheyenne Gas Storage LLC
  - Issue: Sundry notice #401020802 documents expedited need to repair well to prevent further vertical migration of gas in the production casing anulus on 4/7/2016.
  - Resolution: N/A
  - Suspected pathway: The high surface casing pressure and need for repair was documented one week after xylenes were detected in the water well. Gas under pressure could have escaped and migrated to the High Plains aquifer.
- Oil/Gas well of concern
  - Well name: 6-18 WPD011-2 ECGS (API #05-075-09406)
  - Operator: East Cheyenne Gas Storage LLC
  - Issue: Observation of high surface casing pressures documented in Sundry Notice #401050058. Casing hole logs were run, and operators found two zones where cementing would prevent vertical migration of gas up the surface casing anulus.
  - Resolution: The oil/gas well was repaired, and subsequent monitoring indicated the repair was successful.
  - Suspected pathway: If gas was migrating vertically and there was a leak, the high pressure could force gas into the aquifer. The repair was after the xylenes detection, so it could be a possible suspect of gas release.
- Oil/Gas well of concern
  - Well name: 1 DORTHY STRANGE (API #05-075-07146)
  - Operator: East Cheyenne Gas Storage LLC
  - Issue: Sundry Notice #401049608 documented high surface casing pressures on 5/16/2016. Casing hole logs were run, and operators found two zones where cementing would prevent vertical migration of gas up the surface casing anulus.
  - Resolution: A surface casing test on 6/14/2016 indicated no pressure was found in the surface casing.
  - Suspected pathway: If gas was migrating vertically and there was a leak, the high pressure could force gas into the aquifer. The repair was after the xylenes detection, so it could be a possible suspect of gas release.

Summary

A replacement groundwater well showed the occurrence of xylenes at 1.7 µg/L which is below Colorado Basic Ground Water Standards. Several nearby oil/gas wells had high surface casing pressures and sundry notices to repair wells to reduce vertical gas migration. The oil/gas well 6-13 WPD007-2 ECGS (API #05-075-09411) had a high critical surface casing pressure and a short surface casing. This combination can result in gas pressure buildup displacing water and gas inside the surface casing anulus into the aquifer. The COGCC has not identified a source of the xylenes.

Case #39



Groundwater well: FacID #754506

Initial Sampling Reason
The well was initially sampled as a voluntary post drill sample a year after installation of an oil/gas well. Additional sampling is still in progress due to high concentrations of thermogenic methane present in the groundwater.

Groundwater Well Information

- Depth: 104 meters
- Aquifer: Laramie-Fox Hills
- Usage type: Groundwater

Groundwater Well Sampling Information

- Water: Eleven samples collected between 2015 and 2016.
  - Toluene was present at 24 µg/L on 2/5/2016.
  - Thermogenic methane present at 51 mg/L on 11/24/2015.
- Gas: Seventeen samples collected. Isotope analysis showed thermogenic origin.

Contamination Source Analysis

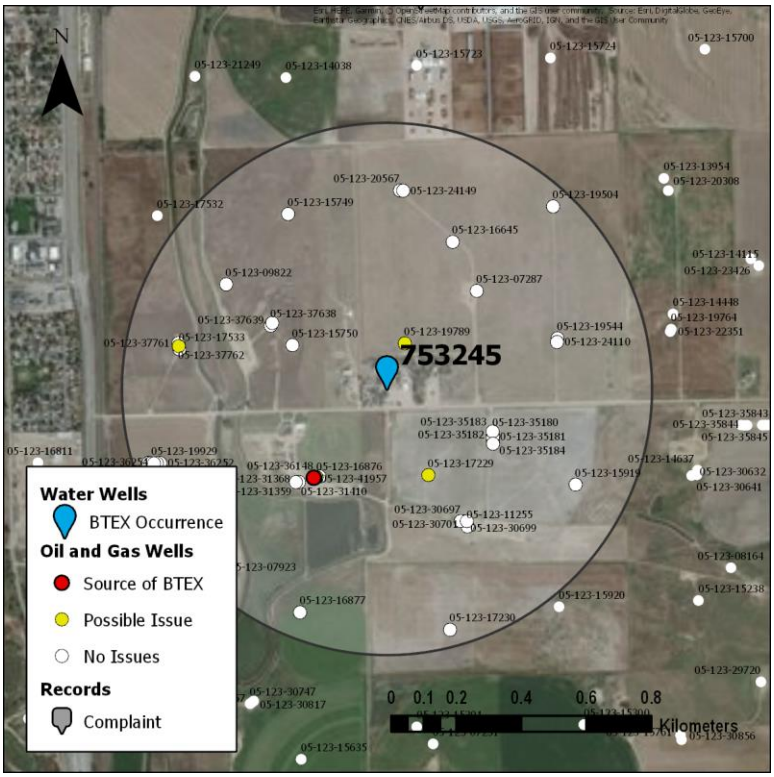
- **Category C:** Documents indicate the source of BTEX could have originated from an oil/gas well.
- Oil/Gas well of concern
  - Well name: LI'L DARLIN' 8-23 (API #05-123-13793)
  - Operator: Conquest Oil Company.
  - Issue: In 2008, the operator failed to provide a MIT by the dead line. A mechanical integrity test was performed and the well failed on 11/24/2008. The well has a surface casing depth of 67 m, while the groundwater well has a depth of 104 m.
  - Resolution: Well was repaired and eventually abandoned on 9/13/2014.
  - Suspected pathway: The combination of a short surface casing and MIT failure can indicate that gas escaped from the bottom of the short surface casing or another point of failure, into the aquifer.
- Oil/Gas well of concern
  - Well name: E 23-16 FEIT (API #05-123-16796)
  - Operator: Noble Energy Inc.
  - Issue: Holes in casing between 782 m and 1250 m depth found in 2003. Casing test was good above 780 m depth.
  - Resolution: Well was repaired and eventually abandoned on 9/13/2014.
  - Suspected pathway:

- Oil/Gas well of concern
  - Well name: 14-26EG HOWARD (API #05-123-12997)
  - Operator: Noble Energy Inc.
  - Issue: A sundry notice documented a casing leak repair in 2006. The oil/gas well failed a pressure test and the leak was located between 615 m and 678 m in depth, with corrosion of the casing from 343 m to 809 m.
  - Resolution: A casing repair and cement squeeze was performed. The well was abandoned on 10/28/2016.
  - Suspected pathway: A leak could allow the vertical migration of gas into the aquifer. Failing a pressure test means that pressure in the casing of the well escaped outside of it.
- Oil/Gas well of concern
  - Well name: E 24-12 ANDERSON (API #05-123-17841)
  - Operator: Noble Energy Inc.
  - Issue: A casing leak was discovered while testing prior to a hydraulic refracturing in 2003.
  - Resolution: Repaired well with cement job. Well abandoned on 3/19/2014.
  - Suspected pathway:

Summary

Toluene was detected in a groundwater well after a voluntary post drill water sampling. The LI'L DARLIN' 8-23 (API #05-123-13793) oil/gas well is a suspect of gas migration because of a short surface casing and MIT failure. The oil/gas well lies just outside of the half-mile radius at 1007 m north of the water well. Additionally, three other oil/gas wells near the water well have reported deeper casing holes and gas leakages reported in 2003 and 2006. While BTEX compounds were not detected in the first sample, thermogenic methane was at 51 mg/L. This indicates that methane and other volatiles could have been present before the sampling closer to the times the oil/gas wells were producing.

Case #40



Groundwater well: FacID #753245

Initial Sampling Reason
An anonymous landowner filed Complaint #200409931 on 8/8/2014 reporting methane in their water well.

Groundwater Well Information
- Depth: 117 meters
- Aquifer: Laramie-Fox Hills
- Usage type: Domestic Well

Groundwater Well Sampling Information
- Water: Thirty-six samples collected on 12 dates from 2014 to 2016.
  - Toluene present at 4.5 µg/L on 5/10/2016.
  - Thermogenic methane reached 21 mg/L on 5/6/2015.
- Gas: Twelve samples collected on the same dates as the water samples from 2014 to 2016. Mixed thermogenic and biogenic methane present according to methane isotope analysis.
  - Three other water wells were found containing thermogenic methane: FacID #752764, FacID #753242, and FacID #700018.

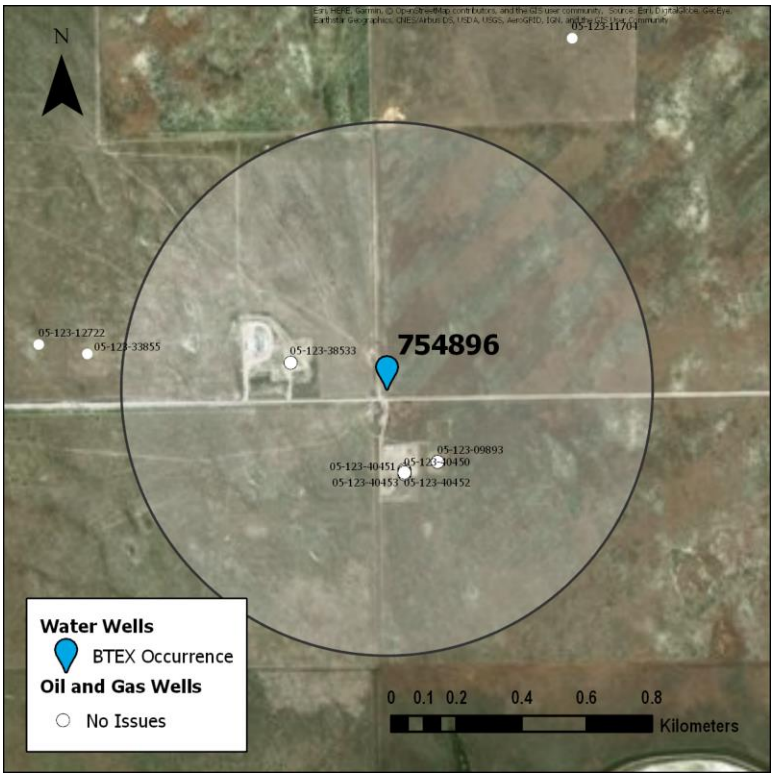
Contamination Source Analysis
- **Category A**: The COGCC identified an oil/gas well as the source of the gas and BTEX occurrence.
- Oil/Gas well source of contamination
  - Well name: 1-30A HSR-WEGNER (API #05-123-16876)
  - Operator: Kerr McGee Oil and Gas Onshore LP
  - Issue: High critical surface casing pressures recorded and increasing from 1724 kPa on 9/27/2013 and increasing to 2551 kPa on 2/2/2015.
  - Resolution: Kerr McGee provided temporary sources of potable water to the affected landowners in 2014. Water wells were disconnected. This oil/gas well was plugged and abandoned, and assuming the source is eliminated, natural attenuation is the expected remediation procedure.
  - Suspected pathway: High critical surface casing pressure in the casing of the oil/gas well can displace gas and water in the anulus to migrate into the aquifer and then groundwater well.
- Oil/Gas well of concern
  - Well name: 4-29 HSR-SABS (API #05-123-17229)

  - Operator: Kerr McGee Oil and Gas Onshore LP
  - Issue: High critical surface casing pressures recorded at 1296 kPa on 9/26/2013, lowered to 7 kPa on 5/10/2016.
  - Resolution: N/A, not recognized as a problem.
  - Suspected pathway: High critical surface casing pressure in the casing of the oil/gas well can displace gas and water in the anulus if there is a leak to migrate into the aquifer and then groundwater well. The decrease in pressure is after the toluene and methane detection events.
- Oil/Gas well of concern
  - Well name: 16C-30HZ RAYMOND FEDERAL (API #05-123-36148)
  - Operator: Kerr McGee Oil and Gas Onshore LP
  - Issue: High critical surface casing pressures recorded and decreasing from 2151 kPa on 6/17/2013, to 421 kPa on 5/18/2016.
  - Resolution: N/A, not recognized as a problem.
  - Suspected pathway: High critical surface casing pressure in the casing of the oil/gas well can displace gas and water in the anulus to migrate into the aquifer and then groundwater well. A release of gas from the casing anulus could be a reason for the three-year decrease in pressure if the excess pressure was not regularly released at the surface.
- Oil/Gas well of concern
  - Well name: 14-20 BARCLAY CRISMAN (API #05-123-19789)
  - Operator: Crestone Peak Resources Operating LLC
  - Issue: Failed a MIT on 11/13/2015. Pressures never stabilized. This indicates a leak in the well in either the packer, casing, or tubing.
  - Resolution: N/A
  - Suspected pathway: A casing leak could result in a gas release and migration to the aquifer.
- Oil/Gas well of concern
  - Well name: 14-20 BARCLAY CRISMAN (API #05-123-19789)
  - Operator: Kerr McGee Oil and Gas Onshore LP
  - Issue: High critical surface casing pressure on 3/24/2014 of 2041 kPa, reduced to 228 kPa on 4/7/2014.
  - Resolution: N/A, not recognized as a problem.
  - Suspected pathway: High critical surface casing pressure in the casing of the oil/gas well can displace gas and water in the anulus to migrate into the aquifer and then groundwater well. Pressure decreased over the period of two weeks, but pressure remained.
- An additional 11 oil/gas wells not within the immediate half-mile radius of FacID #753245, but around the other nearby impacted water wells had high Surface casing pressures greater than 689.5 kPa (100 psi).

Summary

Toluene was present in one water well and thermogenic methane was present in an additional three water wells. The COGCC ruled that the source of the thermogenic methane was from oil/gas well 1-30A HSR-WEGNER (API #05-123-16876), due to high surface casing pressure and similar isotopic characteristics. The well was plugged and abandoned, and natural attenuation is expected to reduce methane and BTEX contamination assuming the source was removed.

Case #41



Groundwater well: FacID #754896

Initial Sampling Reason
Baseline sampling. No complaints opened with the COGCC within a half-mile.

Groundwater Well Information

- Depth: 277 meters
- Aquifer: Unknown
- Usage type: Commercial

Groundwater Well Sampling Information

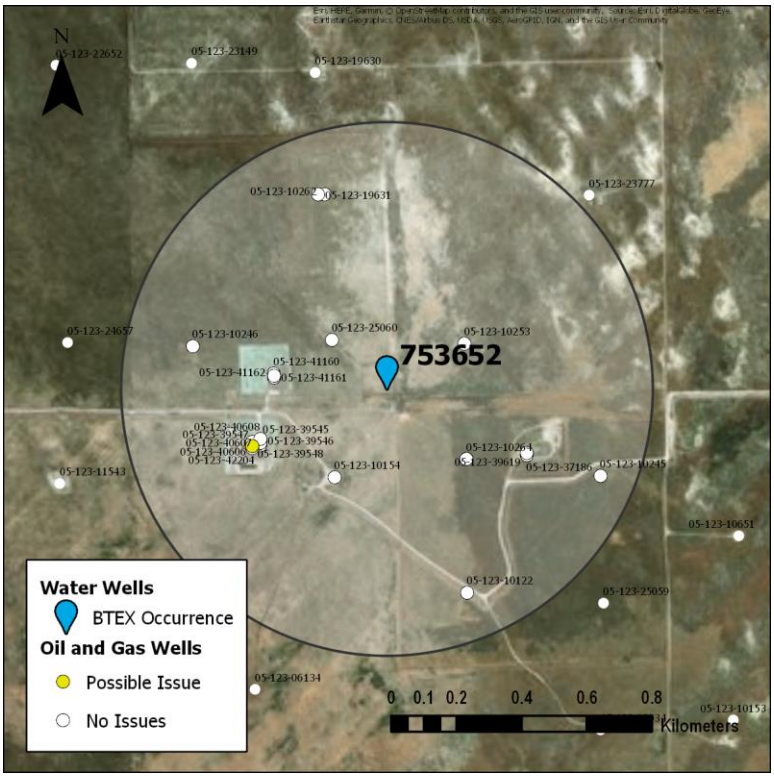
- Water: Three samples collected on 5/25/2016.
  - Toluene present at 16 µg/L.
  - Biogenic methane present at 11 mg/L.
- Gas: One sample collected on 5/25/2016. Methane isotope analysis shows biogenic origin.

Contamination Source Analysis

- **Category D:** No explanation found for sou037f BTEX.

Summary
Toluene found in groundwater well at 16 µg/L. Only one oil/gas injection well is nearby and has no issues. Source of toluene is unknown.

Case #42



Groundwater well: FacID #753652

Initial Sampling Reason
Baseline sampling. No complaints opened with the COGCC within a half-mile.

Groundwater Well Information

- Depth: 226 meters
- Aquifer: Shale
- Usage type: Stock or Irrigation

Groundwater Well Sampling Information

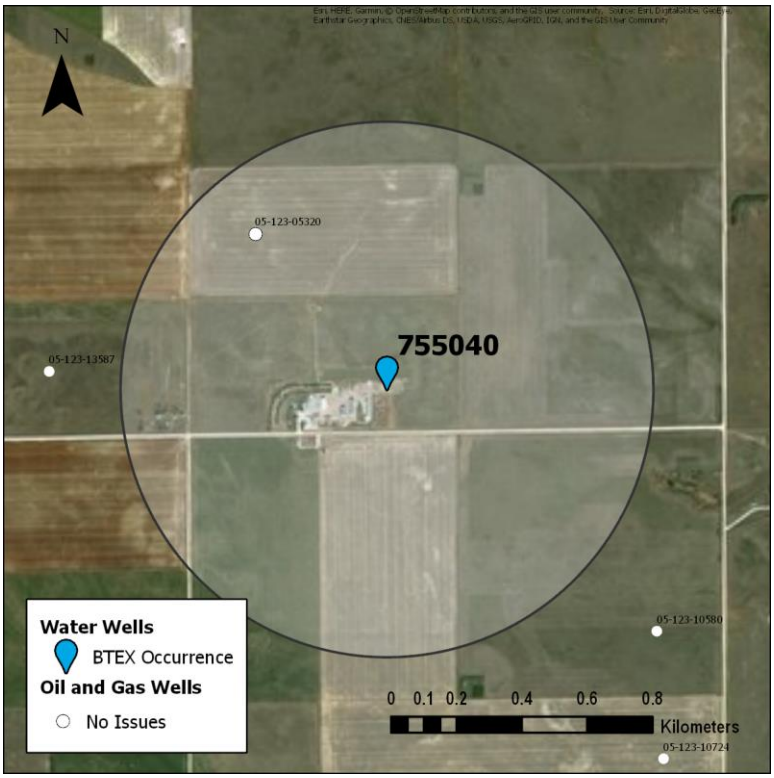
- Water: Eleven samples collected from 2014 through 2016.
  - Benzene present at 1.3 µg/L on 6/22/2016.
  - Toluene present at 33 µg/L on 6/22/2016, and at 2.3 µg/L on 7/27/2016.
  - Biogenic methane present at 4.1 mg/L on 10/20/2016.
- Gas: Three samples collected from 2014 through 2016. Methane isotope analysis showed biogenic origin.

Contamination Source Analysis

- **Category D:** No explanation found for source of BTEX. The yellow dot indicates an unresolved surface spill with no further details, however it is unlikely that it reached the water well.

Summary
Benzene and toluene were found below Colorado Basic Ground Water Standards. Toluene was found in a subsequent sample one month later. There is no definitive source to the benzene and toluene, but they also occur concurrently with biogenic methane. Coal seams that release biogenic methane may release low amounts of BTEX compounds.

Case #43



Groundwater well: FacID #755040

Initial Sampling Reason
Baseline sampling. No complaints opened with the COGCC within a half-mile.

Groundwater Well Information

- Depth: 471 meters
- Aquifer: Upper Pierre
- Usage type: Stock or Irrigation

Groundwater Well Sampling Information

- Water: Three samples collected on 9/7/2016.
  - Toluene present at 3.6 µg/L.
  - Biogenic methane present at 33 mg/L.
- Gas: One sample collected on 9/7/2016. Methane isotope analysis showed biogenic origin.

Contamination Source Analysis

- **Category D:** No explanation found for source of BTEX.

Summary
Toluene was found below Colorado Basic Ground Water Standards. There is no definitive source to the toluene but is occurs concurrently with a significant amount of biogenic methane. Coal seams that release biogenic methane may release low amounts of BTEX compounds.