An Assessment of the Probability of Subsurface Contamination of Aquifers From Oil and Gas Wells in the Wattenberg Field, Modified for Water-Well Location

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Summary

The United States National Science Foundation has funded a sustainability-research network focused on natural-gas development in the Rocky Mountain region of the United States. The objective of this specific study is the assessment of the use of existing water wells to monitor the risk of contamination by the migration of fracturing fluids or hydrocarbons to freshwater aquifers. An additional objective of the study is to modify existing risk estimates using the spatial relationships between the existing water wells and producing oil wells. This will allow estimates of single-barrier failure and multiple-barrier failure, resulting in contamination projections for oil and gas wells in areas without surrounding water wells to detect migration, dependent on well-construction type.

Since 1970, the Wattenberg Field in Colorado has had a large number of oil and gas wells drilled. These wells are interspaced tightly with agricultural and urban development from the nearby Denver metropolitan area. This provides a setting with numerous water wells that have been drilled within this area of active petroleum development. Data from 17,948 wells drilled were collected and analyzed in Wattenberg Field, allowing wells to be classified by construction type and analyzed for barrier failure and source of aquifer contamination. The assessment confirms that although natural-gas migration occurring in poorly constructed wellbores is infrequent, it can happen, and the migration risk is determined by the well-construction standards. The assessment also confirms that there has been no occurrence of hydraulic-fracturing-fluid contamination of freshwater aquifers through wellbores. The assessment determines both the spatial proximity of oil and gas wells and surface-casing depth to water wells to then determine the utility of water wells to monitor migration in oil wells.

Introduction

The Wattenberg Field in the Denver-Julesburg Basin, Colorado, began oil and gas production in 1970. The field is the most-active oil and gas field in Colorado and is bordering the highest-population area of the state in the Denver metropolitan area **(Fig. 1).** There are four main producing formations in the field from deepest deposition to shallowest deposition: Muddy-J, Codell, Niobrara, and the Shannon-Sussex Formations. Vertical and deviated wells were drilled until 2010, when horizontal wells became the principal well design. These horizontal wells primarily target the Niobrara and Codell Formations.

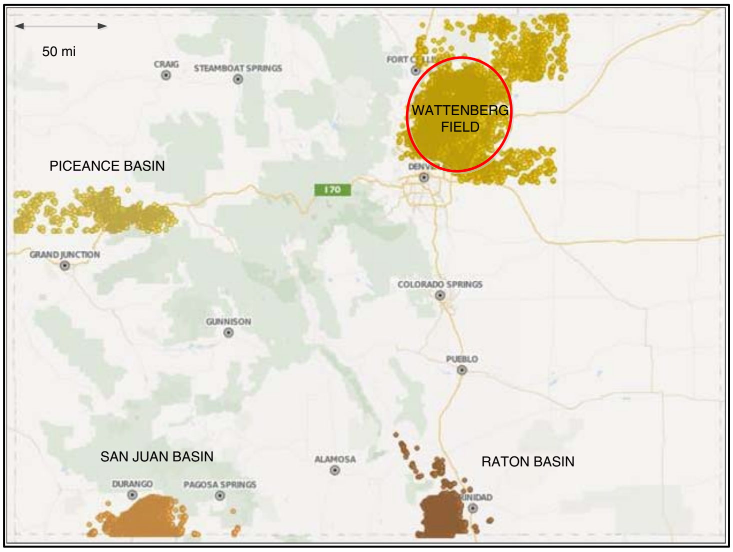

Fig. 1—Location of the Wattenberg Field in Colorado.

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Data from 17,948 oil and gas wells in the Wattenberg Field were analyzed to determine the risk assessment of barrier failure and the overall risk of contaminating freshwater aquifers from hydrocarbon or fracturing-fluid migration. This paper is a continuation of the study first reported by Fleckenstein et al. (2015), adding the water-well data and exploring the depths of the Fox-Hills aquifer system and its effect on the effectiveness of the aquifer protection. In Fleckenstein et al. (2015), the authors assumed a depth of 763 ft to define shallow surface-casing-setting depths. In this study, shallow surface-casing depths are determined in relation to the base of the Fox-Hills aquifer. Approximately 36,000 water wells have been drilled in the midst of these oil and gas wells, providing a unique monitoring system for migration of natural gas and fracturing fluids from the oil and gas wells to the aquifer that overlies the Wattenberg Field.

Barrier Definition

A well barrier "will prevent a formation's liquid or gas from flowing to the surface or another formation" (*API RP 90* 2006). For an oil and gas well, it is imperative that barriers prevent the migration of fluids during stimulation or production operations from a hydrocarbon-bearing zone to the surface or subsurface environment. This is accomplished in the wellbore-construction process, primarily with casing and cement. Other barriers would include the pressure-monitoring equipment, wellhead, tubing, packers, and the completion fluid inside the production-casing/tubing annulus, as well as any fluid in other annuli. During fracture stimulations, there is active monitoring of the pressures both in the fracture-fluid stream and in any annulus between the fracture string and other casing strings. The typical unconventional-resource well slated to be fracture-stimulated includes the following barriers: surface casing cemented to surface, production casing, production cement, wellhead, annular fluids, and pressure-monitoring equipment to assess the barrier effectiveness in real time.

During the production phase of a well, barriers are passive in nature (King and King 2013). Carbon-steel casing is a passive static barrier. Cement, which is also a passive static barrier, is used to create a seal and prevent fluid movement in the annulus around the casing and further re-enforce the strength and durability of the casing. Hydrostatic pressure from drilling mud, formation water, and fresh water in the annulus above the top of the cement is an additional passive dynamic barrier to prevent hydrocarbon migration in the annulus. Not all designs are the same, and there is no one-size-fits-all barrier failure frequency (King and King 2013). Common vertical, deviated, and horizontal subsurface-wellbore-barrier designs were grouped and ranked depending on the risk of multiple-barrier failures **(Fig. 2).**

Well-barrier designs can vary from field to field depending on the geology, trajectory, depths, anticipated pressures, expected hydraulic-treatment rates, and estimated production rates. Whether a well is horizontal, vertical, or deviated has no significance for the ultimate protection of freshwater aquifers because the wells are designed to protect the shallow vertical section of each oil and gas well. Multiple barriers must be in place to prevent breaching of a single barrier and ultimately leading to contamination of an aquifer. All wells in the study have been categorized depending on their original wellbore designs and subsequent current designs after any remediation work.

Further detail on hydrocarbon- or fracturing-fluid-migration flow paths are referenced in Fleckenstein et al. (2015).

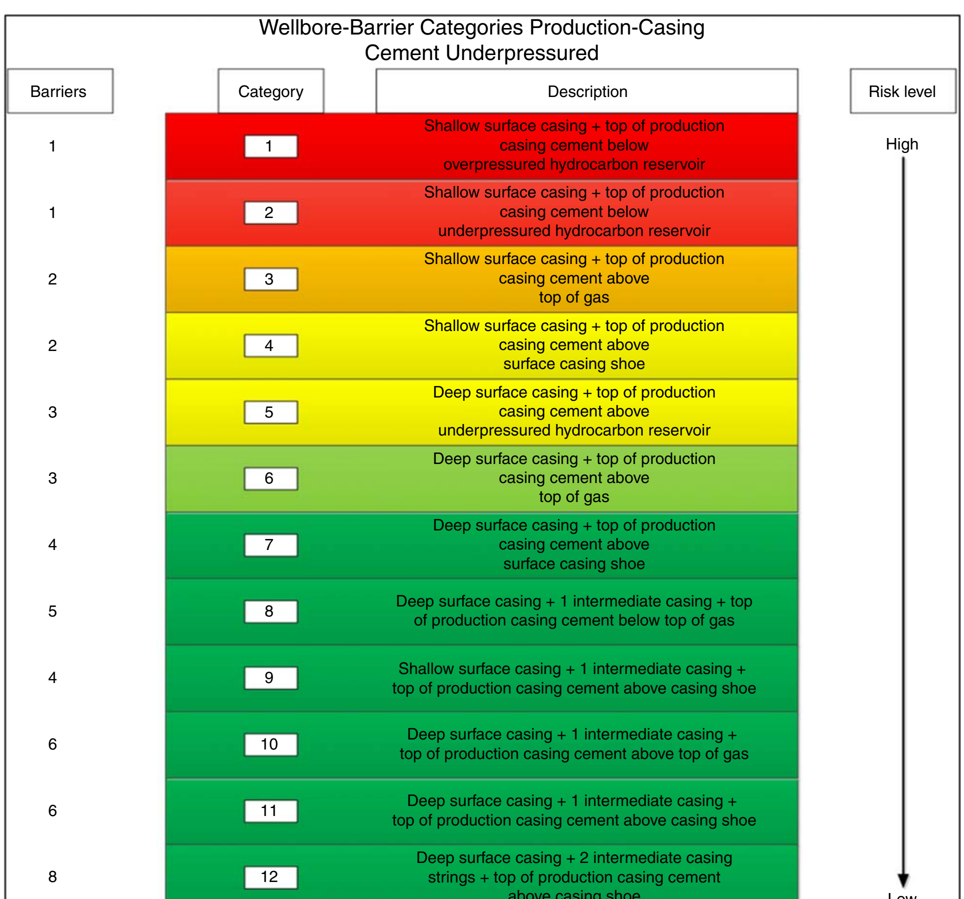

Fig. 2—Wellbore-barrier categories that are ranked from highest risk to lowest risk.

Thermogenic Gas and Biogenic Gas in Freshwater Aquifers

There are two forms of natural gas below ground level: biogenic (microbial methane) and thermogenic gas. The characteristic and composition of both forms of gas differ depending on the components of the natural gas and analytical measurements of the C^{12} and C^{13} stable isotopes. A study of methane in groundwater was performed by the United States Geological Survey (USGS) in a 1,810-sq-mile area of south-central New York state along the Pennsylvania border. The study reported that "results of sampling indicate that occurrence of methane in groundwater of the region is prevalent, occurring in 78% of the groundwater samples" (Kappel and Nystrom 2012).

Another study performed by Li and Carlson (2014) states that biogenic methane gas naturally occurs in freshwater aquifers because of subsurface bacteria and is usually found because of high carbon concentrations and low redox potential. Biogenic gas can be created through two methods: acetate fermentation and carbon dioxide reduction. Biogenic gas has more C^{12} stable isotopes than thermogenic gas. Thermogenic gas is produced through thermal cracking in deeper formations where higher pressure and temperature conditions exist. The thermogenic gas has more C^{13} stable isotopes than biogenic gas (King 2012). This is useful to determine whether gas found in aquifers is naturally occurring in the aquifer, or has migrated from a deeper hydrocarbon source. Natural gas sourced from coals may be either biogenic or thermogenic in nature.

There are two main pathways for thermogenic gas to reach a freshwater aquifer: natural seepage through formations, faults, or natural fractures, or through faulty barrier systems in oil and gas wells. To determine whether oil and gas wells are the source, groundwater sampling must be collected before drilling an oil and gas well to create a baseline analysis, and again after the well is on production to detect changes in the baseline. If a water-well test indicates methane concentrations greater than 1.0 mg/L, then further testing is required to determine the origin of the gas.

Failure Definition

For this study, we define two types of barrier failures: potential barrier failures and catastrophic barrier failures.

Potential barrier failure is the breakdown of a single or multiple barriers in a wellbore that may be detected by sustained annular pressure (SAP) and that did not result in the contamination of freshwater aquifers or surface soil from hydrocarbon or fracturing-fluid migration, but required remediation of the failed barrier(s) to further enhance the effectiveness of the nested-barrier system of the well.

Catastrophic barrier failure is the breakdown of a combination of various wellbore barriers (casing, cement, and hydrostatic pressure of annular fluids) protecting freshwater aquifers during hydraulic-fracturing or production phases of a well cycle, resulting in the contamination of the freshwater aquifers or surface soil. This contamination is detected by the isotopic and compositional analysis of thermogenic hydrocarbons or fracturing fluids in offsetting water wells or in the surrounding surface soil.

Low Risk of Fracturing-Fluid Migration to Freshwater Aquifers

There is a common public misunderstanding of the risk of aquifer contamination caused by hydraulic-fracturing operations. The presence of methane in water wells has been misinterpreted by some as a positive indication of contamination because of hydraulic fracturing. As previously discussed, methane is naturally present in freshwater aquifers and biogenic gas; additional work must be performed to determine if the methane is thermogenic in nature and whether it is the source of the gas. Testing of water wells can indicate the presence of biogenic or thermogenic gas, but we have little to no evidence of barrier failures that led to fracturing fluids migrating to a freshwater aquifer depending on the composition of the fracturing fluids. Wells are hydraulically fractured with thousands of feet of rock between the aquifer and the hydraulically fractured formation, and microseismic monitoring of hydraulic fracturing in a shale development does not indicate that the induced fractures grow in height approaching the aquifers (Fisher and Warpinski 2011).

During hydraulic-fracturing operations, there are several reasons that fracturing fluids have an extremely low risk of contaminating freshwater aquifers:

- Depth of the hydraulically fractured formation
- Pressure monitoring of production casing and annuli
- Potential flow path of the fluid
- Short time duration of hydraulic-fracture operations
- Strength of the passive static barriers

The hydraulically fractured formations are generally more than 4,000 ft below the surface. The fracturing fluid is typically pumped down the casing and out of perforations connecting the wellbore to the formation to be stimulated. The started fractures create a fracture network that is contained within the zone of interest, with higher-compressive-strength rock above that inhibits fracture-height growth. The distance of induced hydraulic fractures from aquifers has been confirmed by microseismic monitoring during hydraulic fracturing, with typical height growth generally limited to 300 ft or less (King 2012).

During hydraulic-fracturing operations, pressure gauges are installed on the wellhead that monitor in real time the pressure of the casing and the annulus. The production casing has a certain burst rating and the treatment pressure is designed to not exceed this burst rating, with an additional safety factor. If any abnormal pressure is detected in the annulus or fracture string, pumping stops immediately, and pressure testing is performed on all casing and equipment.

King (2010) found no documented cases of fracturing fluids migrating to freshwater aquifers or to surface soil for formations hydraulically fractured more than 2,000 ft below ground level. This study also found no evidence of fracturing-fluid migration to freshwater aquifers out of 17,948 wells in the data set from Wattenberg Field. Birdsell et al. (2015) states that "No fracturing fluid reaches the aquifer without a permeable pathway" and "our model corroborates many conclusions derived from previous studies: (i) most notably, without a permeable pathway, HF fluid cannot travel far enough to reach an overlying aquifer in most shale plays." A National Energy Technology Laboratory study (Hammack et al. 2014) found no evidence during a study using tracers of migration for aqueous fluids or natural gas into aquifers during fracturing operations or shortly afterward.

Geologic Overview

The Wattenberg Field in the Denver-Julesburg Basin was deposited in the Late Cambrian and Early Ordovician in shallow marine environments (Kent 1972). The Western Interior Seaway submerged the basin during the Cretaceous, with sea levels transgressing and regressing throughout time. On the western flank of the basin are the Rocky Mountains, which were eroded during the Permian. Dipping beds are present in the western flank and flatten toward the east (Drake et al. 2014).

The Lower Cretaceous Muddy J-Sand and D-Sand, of the Dakota Group, are fine- to medium-grained siliciclastic sandstone. These formations were deposited during the Western Interior Seaway regression. The Skull Creek Shale below the Muddy J-Sand is the source rock for the reservoir. These two formations were the initial targets for oil and gas development beginning in the early 1970s (Drake et al. 2014).

During the Upper Cretaceous, the Niobrara Formation and the Codell Sandstone Member of the Carlile Shale were deposited. The Codell Formation formed during a regression of the Western Interior Seaway. The Niobrara Formation was deposited during transgression of the Western Interior Seaway and is unconformable. It consists of interbedded chalk and marl units and is approximately 290 ft thick in the core of the Wattenberg Field (Drake et al. 2014). The Niobrara and Codell Formations were not exploited until the early 1980s because of their low permeability, even though logs indicated elevated hydrocarbon saturations. Hydraulic fracturing of these formations increases the effective permeability and allows these reservoirs to be commercially economic.

The Pierre Shale overlies the Niobrara Formation and was formed during the Upper Cretaceous in deep-sea environments. The Pierre Shale is a seal for the lower Niobrara and Codell Formations. The Shannon and Sussex Formations were deposited above the lower member of the Pierre Shale, at an average depth of 4,400 to 4,900 ft subsurface, during a regression of the Western Interior Seaway. These formations contain commercial quantities of hydrocarbons but are characteristically underpressured (Sonnenberg and Weimer 2005). The transgression of the Western Interior Seaway allowed the continuation of the Pierre Shale above the top of the Sussex Formation. The Pierre Shale is an important barrier separating the freshwater aquifers of the Wattenberg Field from hydrocarbon-bearing formations below **(Fig. 3).**

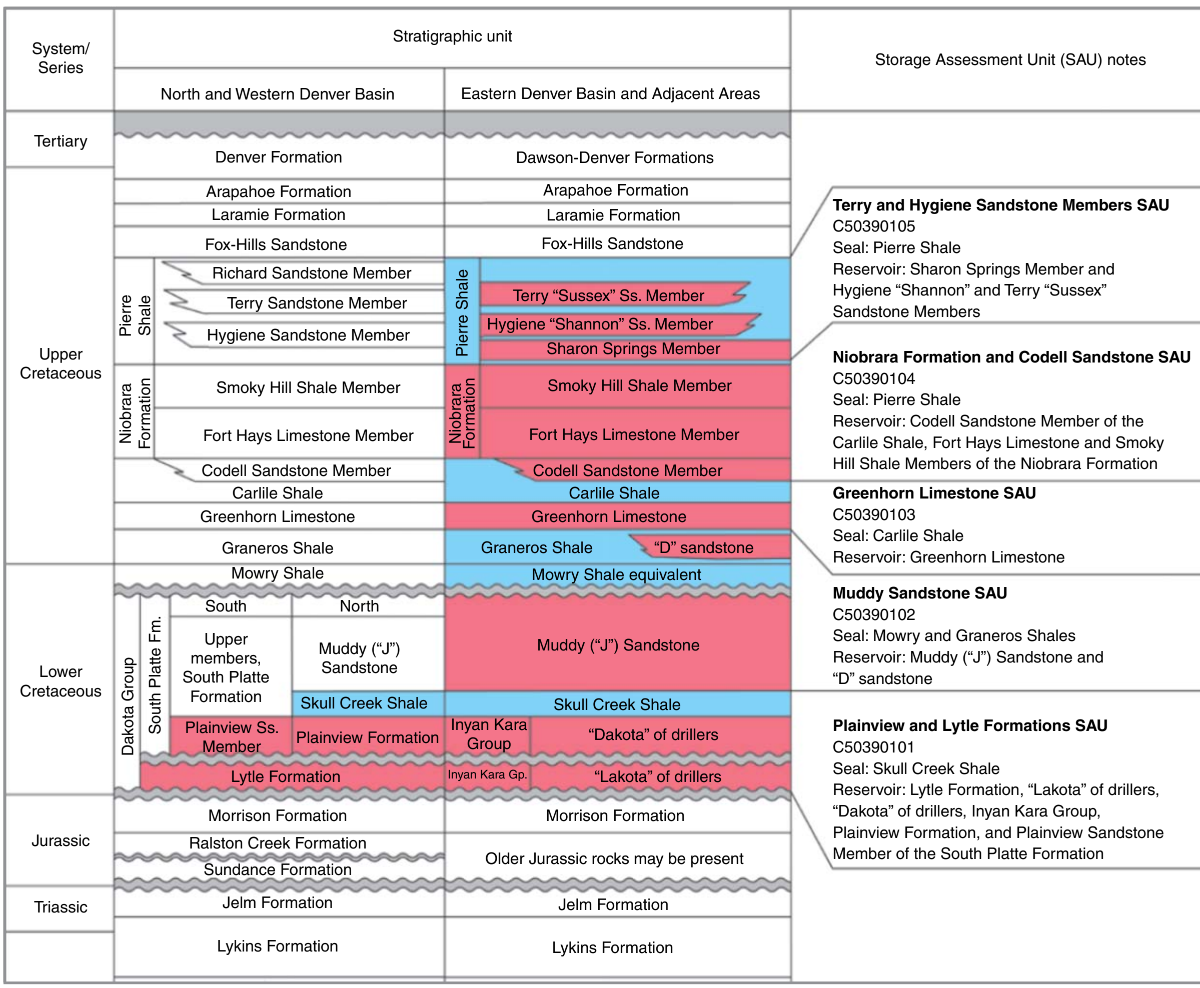

Fig. 3—Geologic stratigraphic units of the Denver-Julesburg Basin, Wattenberg Field, Colorado (Drake et al. 2014).

Wattenberg Field Water Sourcing

The main freshwater-aquifer system in the Wattenberg Field is the Denver Basin. This aquifer system is composed of the Dawson Arkose, Denver Formation, Arapahoe Formation, Laramie Formation, and the Fox-Hills Sandstone **(Fig. 4).** Below the base of the Fox-Hills Sandstone is the Pierre Shale, which is impermeable Cretaceous shale and acts as a barrier between deeper hydrocarbon deposits. The Denver Basin is recharged from the southerly surface by precipitation near the cross section B marker (Fig. 4) (Robson and Banta 1995). The aquifer system underlying the Wattenberg Field contains localized coal seams, which naturally store methane that has a similar isotopic footprint as biogenic gas.

The Fox-Hills Sandstone is the main freshwater aquifer overlying the Wattenberg Field in Colorado. The depth of this aquifer ranges from 100 ft subsurface in the northeast to greater than 1,100 ft subsurface moving southwest **(Fig. 5).** Early water sourcing in the 1970s was predominantly from local reservoirs, and increased water-well drilling did not occur until the 1980s in the Wattenberg Field after oil and gas development already began.

In 1993, the policy for Fox-Hills aquifer protection was established and stipulated that surface casing must be set 50 ft below the base of the Fox-Hills aquifer or 50 ft below the total depth of the deepest water well within a 0.5-mile radius of the oil and gas well.

Rule 609 for baseline water-well testing was implemented by the Colorado Oil and Gas Conservation Commission (COGCC) in 2009, which required that water wells within a 0.5-mile radius of a permitted oil and gas well be tested for water quality and any presence of hydrocarbons. The aquifer system in the Wattenberg Field has naturally occurring biogenic methane and methane from localized coal deposits within the Laramie Formation.

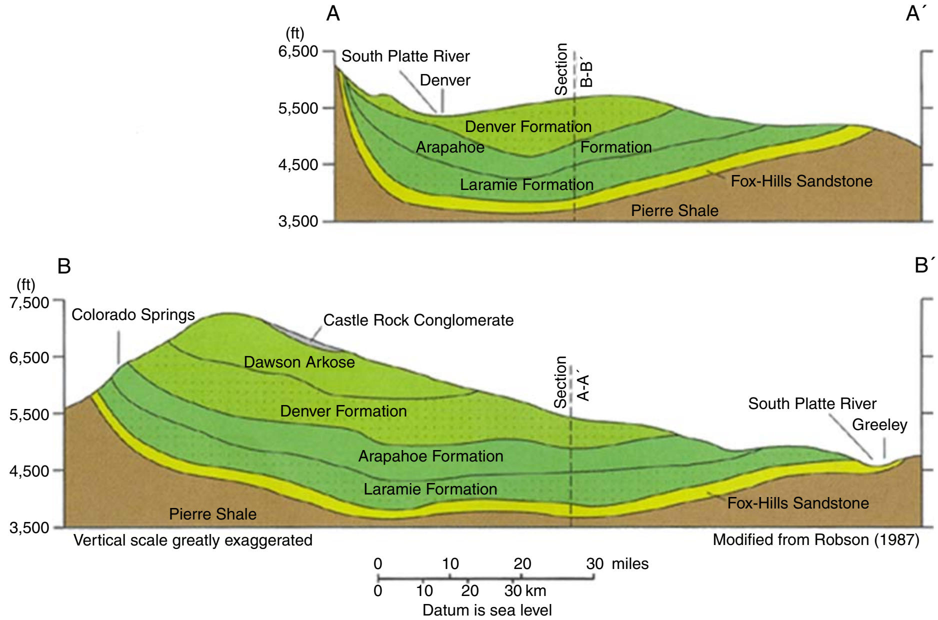

Fig. 4—Cross section of the Denver Basin aquifer system (Robson and Banta 1995).

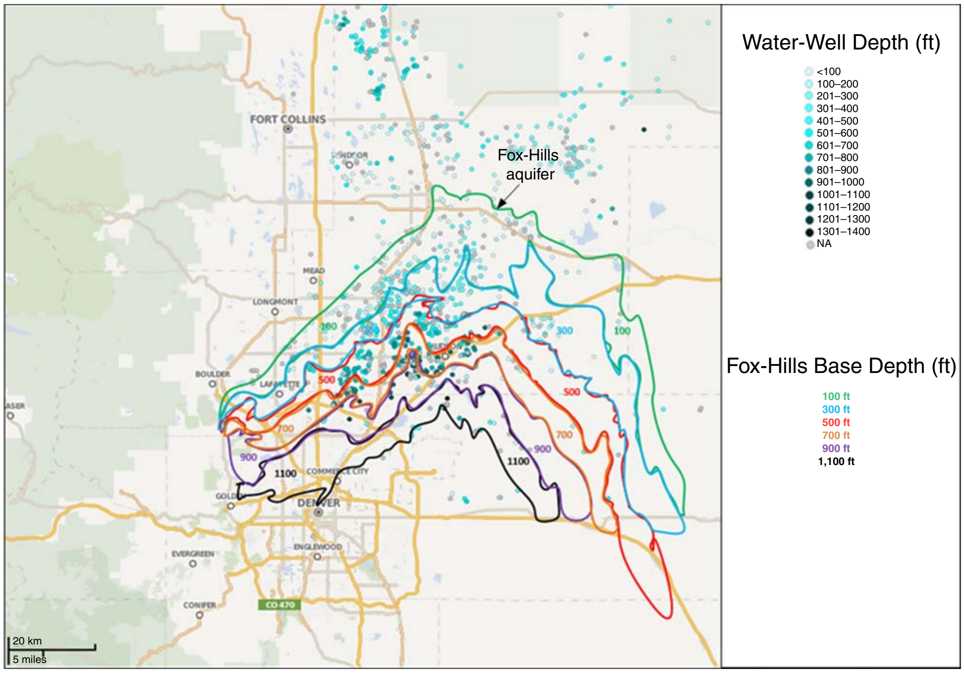

Fig. 5—Fox-Hills aquifer contours in the Wattenberg Field correlated with water-well depths and locations (ArcGIS 2016).

Data Acquisition

The COGCC maintains an online repository of up-to-date well data for Colorado. Documentation is provided for each well from initial permitting to the current status of the well. Information related to remedial cementing, offset monitoring wells, SAP, wellbore-construction methods, and geologic formations can be found in this documentation and were used for this assessment.

Current and original wellbore configurations were taken from the scout cards that are available for each well on the COGCC facility database. This includes completion dates, locations, casing-setting depths, casing specifications, quantity of cement, wellbore diameters, initial cement depths dependent on cement-bond logs, formation tops, and the depths of any remedial cementing that has been performed. Each scout card is for a specific well, and the data are directly supplied from the operator of the oil and gas well to the COGCC. Each well was assigned a wellbore-barrier category dependent on the number of casing strings, casing-setting depths, and cement tops for each casing string related to formation tops. If any cement remediation was performed on a well, a new applicable category was assigned to the well depending on its post-remediation wellbore-barrier design.

The Notice of Alleged Violation (NOAV), referred to as a violation in this study, is a form issued to operators that are suspected of being in violation of the rules enforced by the COGCC. These forms offer descriptions of the alleged violation and can be indicative of hydrocarbon migration directly caused by an individual oil and gas well. The NOAV data were collected from the COGCC database. Text-based search queries were used to identify NOAVs relevant to this assessment. Once identified, corroborating data were located before the well was classified as a catastrophic barrier failure. These data came in the form of isotopic and compositional hydrocarbon analysis, official communications between interested parties, and other published documents.

COGCC orders document the official hearings that follow a NOAV filing. These orders are made available by the COGCC and offer text-based searching. Orders were searched and analyzed in a manner similar to that for the NOAVs. Search queries were used to identify wells that have been the source of subsurface hydrocarbon migration in the field. Because the orders represent a terminus of the rule-enforcement process, no corroborating data were needed to classify these wells.

In addition to the NOAV forms, mechanical-integrity-test (MIT) results and public complaints served as markers for potential instances of hydrocarbon migration to surface soil or freshwater aquifers. These data are made publicly available by the COGCC. A NOAV is not always issued to an operator who has a failed MIT. A rule must be violated for a NOAV to be issued. The same text queries were used to identify wells of interest. Supporting data were located to ensure proper classification of these wells.

Oil- and gas-well data from 17,948 wells that were drilled and completed from 1970 until February 2014 were acquired from the COGCC database. Potential barrier failures were identified by evidence of remedial cement below the surface-casing shoe with the assumption that the oil and gas wells experienced SAP as the reason for the cement remediation. Remedial cement on the production casing string was not identified as potential barrier failures in the Wattenberg Field because of the prevalence of hydraulically refracturing existing older wells. Operators would often perform cement remediation on these wells to further isolate target formations before refracturing operations and not because of a potential barrier failure or observance of SAP.

Catastrophic barrier failures were identified by thermogenic gas detected in offset water wells and evidence of a well-barrier failure(s) in an offset oil and gas well, which contributed to thermogenic-gas migration to a freshwater aquifer. The base depths of the deepest freshwater aquifer (the Fox-Hills) were obtained from ArcGIS online. Shallow surface casing was defined as being set above the base of the Fox-Hills aquifer or any instance of an offset water well that is deeper than the Fox-Hills base depth within a 0.5-mile radius of an oil and gas well.

The top of cement (TOC) of production cement was supplied by the individual well scout cards in the COGCC database. If the depth of the TOC was not supplied, the quantity of cement was used to calculate the estimated TOC using a uniform wellbore geometry and typical yields for 1.18 ft^3/sack of Class H cement. Tubing and packers as an additional barrier are neglected in this study.

In addition, if the Sussex Formation top was not supplied within an individual well scout card, then the average depth of the Sussex Formation was used and adjusted depending on the topographic surface elevation of a well to estimate the top of the Sussex Formation. This formation is assumed to be the top of gas in the Wattenberg Field.

Errors

Under the data assumptions provided, there exist potential errors that can lead to inaccurate categorization of the oil and gas wells. Any missing data point on an individual oil and gas well scout card within the COGCC database requires certain assumptions that can be inaccurate for proper wellbore-barrier categorization. If the TOC is not listed, or appears inaccurate depending on the quantity of cement pumped, then an estimated top of cement was calculated using the quantity of cement, a yield of 1.18 ft^3/sack of cement, and a uniform wellbore geometry. The yield for the cement was not provided in the scout card, and wells use a variety of cement types that all have different yields. In addition, a uniform-diameter wellbore was assumed with no washouts. Because of these assumptions, the estimated TOC can be in error. Under the calculated cement-top assumption laid out in this study, the TOC could be lower or higher than in reality.

Error can also be caused by missing depths of formation tops for certain older wells, supplied on an individual-well scout card, for the top-of-gas designation for a specific well. The assumption in this study is to take the average depth of the top of gas using formation tops supplied on the scout cards for all wells in the basin and projecting an individual-well formation top depending on topographic elevation. This assumption can be inaccurate because of erosion or structural alterations subsurface. By assuming the top of gas for wells that were lacking these data, improper wellbore-barrier categorization can result.

Wellheads, production-pressure monitoring, tubing, and packers, which can add additional barriers to the wellbore-barrier system, are also ignored because of simplification or lack of data. Certain higher-risk wellbore-barrier categories can contain all or some of these additional barriers, which explains differences in potential barrier-failure rates and catastrophic barrier-failure rates for high-risk wellbore-barrier categories.

Historical Wellbore Construction

The Wattenberg Field is near Denver. Increased oil and gas development began in 1970, initially targeting the J-Sand Formation, which underlies the Niobrara and Codell Formations. The well designs in the 1970s set shallow 8⅝-in. surface casing that was cemented to surface and 4½-in. production casing set to total depth and cemented above any "known" hydrocarbon-bearing formations. State regulations during that era required surface casing to be set at a minimum depth of 200 ft or 5% of the total measured depth of the well. Many older wells had surface casing set above the base of the Fox-Hills aquifer. As populations have increased in the Wattenberg Field, the Fox-Hills aquifer became an important freshwater source for agriculture, commercial, municipal, and federal purposes. Current COGCC regulations for surface-casing-setting depths are designed for setting 50 ft below the base of the Fox-Hills aquifer or 50 ft deeper than the deepest water well within a 0.5-mile radius. Many current cement-remediation jobs below the surface-casing shoe are caused by this new regulation.

Beginning in 1993, the COGCC-strengthened regulations and designs were revised to further protect aquifers from hydrocarbon migration. Surface casing was set below the base of the Fox-Hills aquifer and production casing TOC was regulated to 200 ft above any known hydrocarbon zone **(Fig. 6).** Many current well designs have production-casing cement overlap into the surface casing to add additional barriers and create a nested-barrier system. In 2010, horizontal wells, targeting the Niobrara or Codell Formations, were introduced in the Wattenberg Field. These newer horizontal-wellbore-barrier designs, as well as recent vertical-wellbore designs, have a lower risk of hydrocarbon or fracturing-fluid migration to freshwater aquifers because of their redundant barrier designs.

The production-casing TOC was designed to cover "known" hydrocarbon-bearing formations in the 1970s. The Niobrara and Codell Formations, at an average depth of 6,950- to 7,400-ft true vertical depth, were thought to be unproductive until their discovery in the early 1980s. Because these overpressured formations had low permeability, often the design of the production-cement top was below the top of the Niobrara Formation.

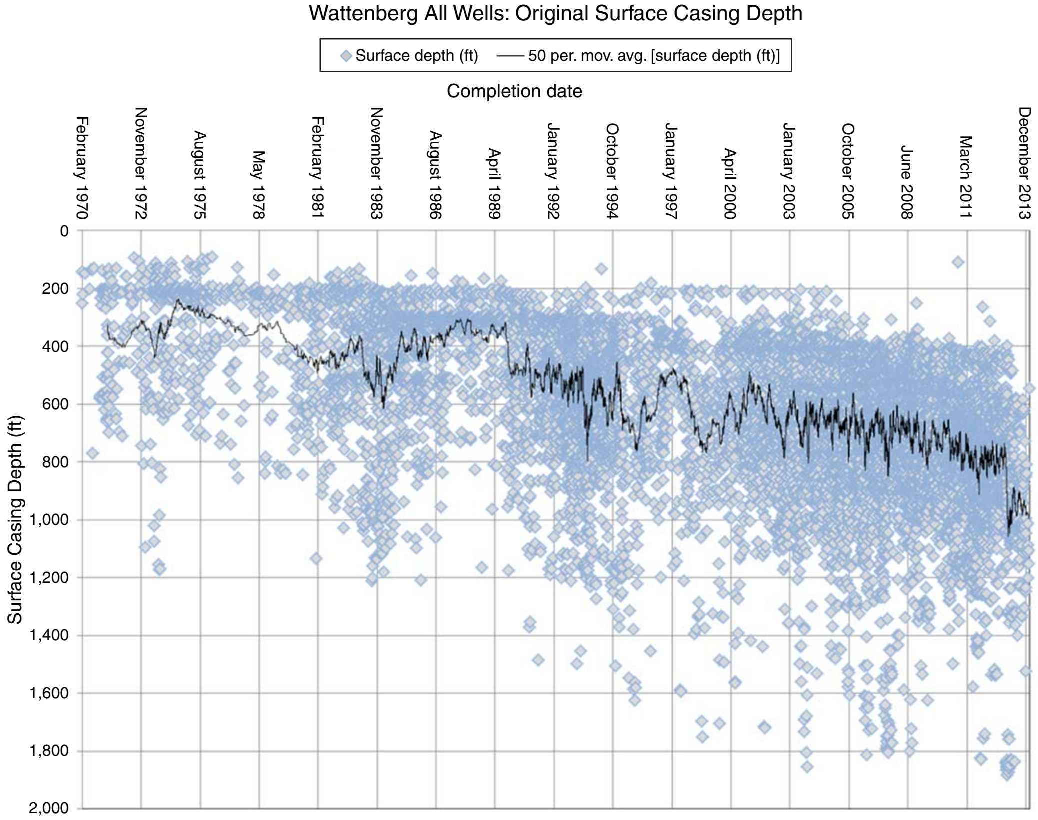

Fig. 6—Chronologic original surface-casing-setting depths in the Wattenberg Field.

The common design in the 1980s until the mid-1990s had the TOC of the production cement below the top of the Sussex Formation. The Sussex Formation is characteristically underpressured, defined as pressure less than the hydrostatic pressure of fresh water (Weimer et al. 1986; Sonnenberg and Weimer 2005) **(Fig. 7).** The annular-fluid hydrostatic pressure from the original drilling mud and formation salt water often prevents hydrocarbon migration if zonal isolation is not achieved from production cement. However, the pressure of the Sussex Formation is not uniform across the field and could exhibit normal to overpressured environments in localized areas.

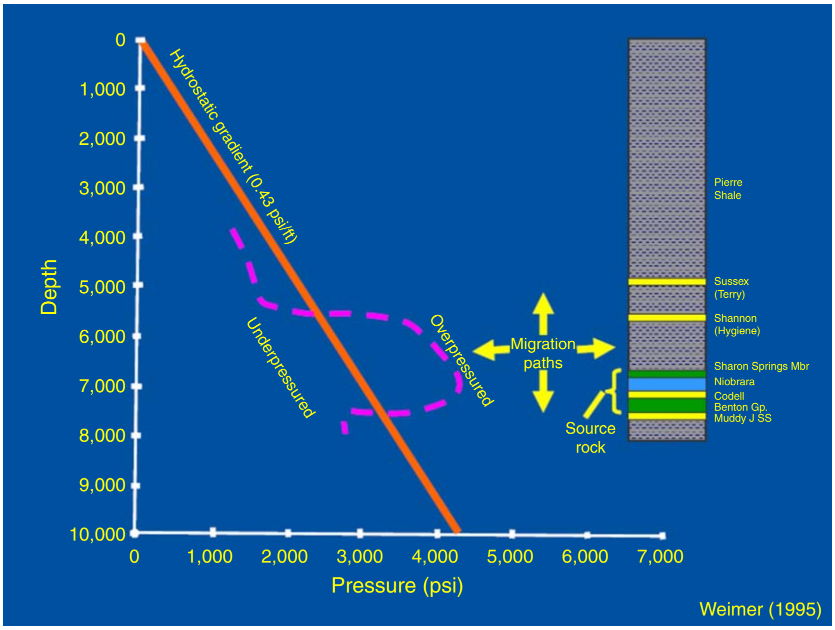

Fig. 7—Pressure profile of formations in the Wattenberg Field, which displays the underpressured nature of the Sussex Formation (Sonnenberg and Weimer 2005).

Since the late 1990s, production-cement tops were designed to cover shallow hydrocarbon-bearing zones from the Sussex and Shannon Formations at depths of 4,400 to 4,900 ft **(Fig. 8).** Since then, many wells have had remedial cementing operations to address these older designs and to further ensure zonal isolation of all hydrocarbon-bearing formations **(Fig. 9).** In addition, many wells in the

Wattenberg Field are hydraulically refractured to further stimulate existing producing formations or target new formations. Many wells must comply with current cement regulations before any refracturing treatment. Many wells had cement remediation performed on the production casing because of subsequent hydraulic-refracturing work and not necessarily because of a potential barrier failure.

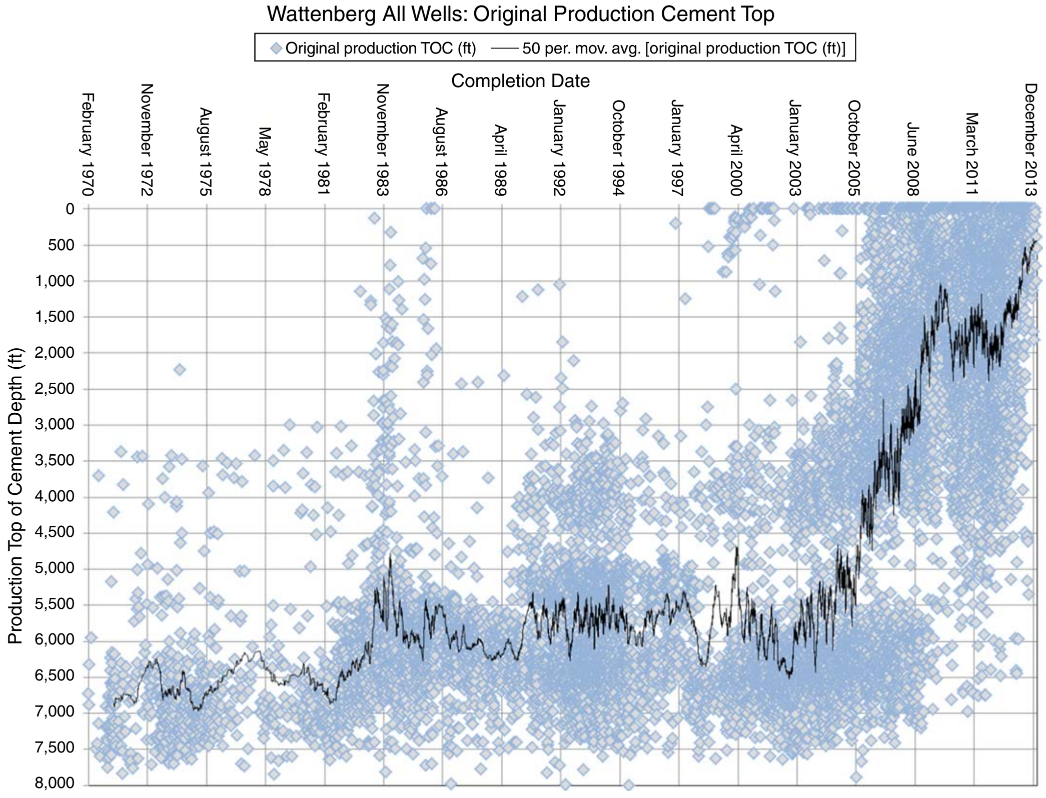

Fig. 8—Chronologic original top of production-cement depths in the Wattenberg Field.

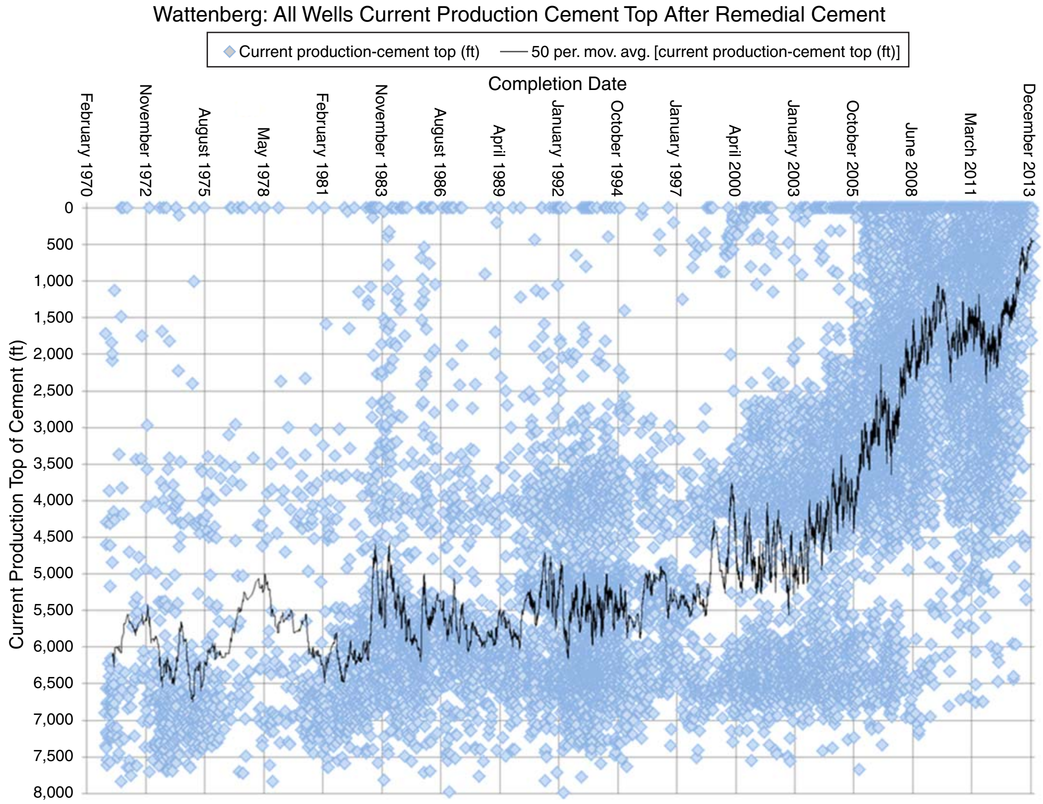

Fig. 9—Chronologic current top of production-cement depths after cement remediation in the Wattenberg Field.

Wattenberg Field Wellbore-Barrier Categories

The oil and gas wells in the Wattenberg Field have varying designs depending on the age, target formations, and bottomhole trajectory. Wells are designed from the total anticipated depth to surface, using various sizes of casing and different volumes of cement to isolate fluid transport between different formations. Seven common barrier designs exist in the field (**Table 1**). Each has different risk levels depending on the number and type of barriers preventing hydrocarbon or fracturing-fluid migration to freshwater aquifers from hydrocarbon-bearing formations below the upper Pierre Shale. Appendix A contains detailed wellbore diagrams for each wellbore-barrier category.

	Vertical or Deviated Original Well Count	Horizontal Original Well Count
Category 1	166	0
Category 2	621	0
Category 3	46	0
Category 4	7	0
Category 5	8,789	0
Category 6	5,433	269
Category 7	1,766	704
Total	16,828	973
Drilled and abandoned well count	147	0
Total well count	17,948	–

Table 1—Original well counts by wellbore-barrier category in the Wattenberg Field.

Of the 17,948 wells analyzed, 15,723 vertical or deviated wells are currently producing or shut-in in the Wattenberg Field and 1,105 vertical or deviated wells have been plugged and abandoned. Another 147 vertical or deviated wells in the sample were drilled and abandoned without installing production casing. Of the 973 horizontal wells analyzed, three were plugged and abandoned, while the remainder are currently producing or shut-in. All drilled wells that were eventually completed were categorized depending on their wellbore construction and number and types of barriers that protect groundwater from hydrocarbon or fracturing-fluid migration.

Higher-risk well-barrier designs were prevalent from 1970 to 1994 **(Fig. 10).** After strengthening the regulations of surface-casing-setting depths by the COGCC, lower-risk barrier designs replaced the higher-risk designs that had shallow surface casing in relation to the base depths of the Fox-Hills aquifer.

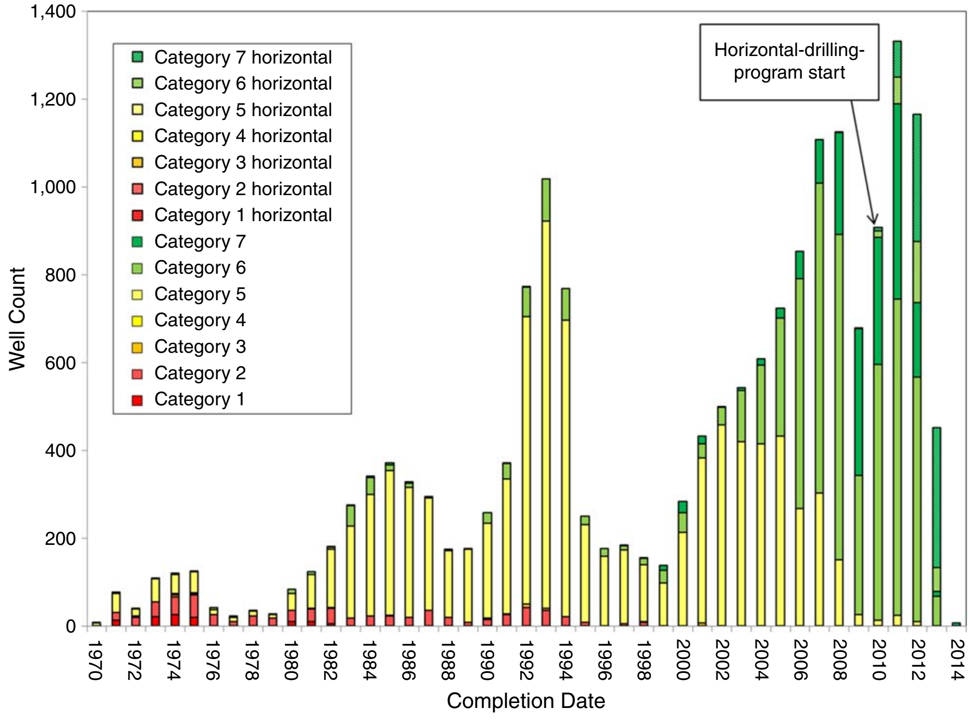

Fig. 10—Histogram of originally completed wells that are color coded by their original wellbore-barrier design in the Wattenberg Field.

Higher-risk Category 1 and 2 wells are primarily in the southern area of the field, where the base of the Fox-Hills aquifer is structurally deeper **(Fig. 11).** In the Wattenberg Field, 721 wells (4% of the data sample set) were originally drilled and completed as Category 1 and 2 designations. Although these wells met the state regulations at the time of their completion, they all had surface casing set above the base of the Fox-Hills aquifer and inadequate production-casing-cement tops over hydrocarbon-bearing zones.

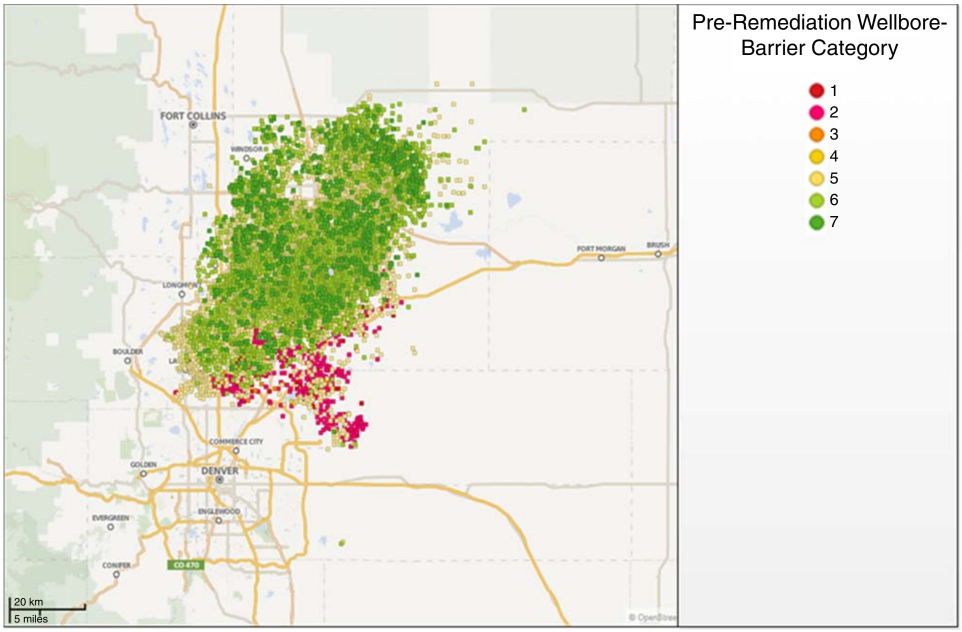

Fig. 11—Map of originally completed wells in the Wattenberg Field, color coded by their wellbore-barrier category.

Wattenberg Field Potential and Catastrophic Barrier Failures

Potential barrier failures were identified by remedial cement operations performed below the shoe of the surface casing to further protect the freshwater aquifer in the Wattenberg Field. Of the original wells, 418 (2.48%) vertical or deviated wells were identified as having potential barrier failures that required cement remediation below the surface-casing shoe **(Table 2).** Higher-risk Category 1, 2, and 3 well-barrier designs had the highest potential barrier failure rates of 60.24, 35.27, and 34.78%, respectively. The shallow surface casing, coupled with the age of the wells, all led to SAP and subsequent cement remediation. However, no potential barrier failures were associated with evidence of thermogenic-gas migration to the Fox-Hills aquifer depending on baseline-water testing on adjacent water wells within a 0.5-mile radius of the existing oil and gas well. Lower-risk wellbore-barrier Categories 5 and 6 had very low potential barrier-failure rates because of the increased number and strength of passive static barriers present in the wells. No Category 7 vertical well nor any horizontal wells were identified as having potential barrier failures because of their more-robust wellbore-barrier designs and recent average completion dates **(Tables 2 and 3).**

	Original Well Count	Potential Barrier Failures	Potential Barrier Failure (%)	Catas-trophic Barrier Failures	Catas-trophic Barrier Failure (%)	Average Completion Date	P&A Well Count	Current Well Count	Original Average Surface-Casing Depth (ft)	Original Average Top of Production Cement (ft)
Category 1	166	100	60.24	3	1.81	1979	57	15	253	7,334
Category 2	621	219	35.27	5	0.81	1983	138	301	306	6,566
Category 3	46	16	34.78	1	2.17	1987	14	31	321	4,008
Category 4	7	0	0.00	0	0.00	1982	1	15	222	125
Category 5	8,789	77	0.88	1	0.01	1995	782	6,140	559	6,111
Category 6	5,433	6	0.11	0	0.00	2007	105	7,181	712	2,816
Category 7	1,766	0	0.00	0	0.00	2009	8	2,040	719	534
Total	16,828	418	2.48	10	0.06	–	1,105	15,723	–	–
D&A	147	–	–	–	–	–	–	–	–	–

Table 2—Potential and catastrophic barrier failures of vertical and deviated wells in the Wattenberg Field. D&A = drilled and abandoned; P&A = plugged and abandoned.

Higher-risk wellbore-barrier designs exhibited the highest potential failure rates. A total of 319 original Category 1 and 2 wells received cement remediation below the surface casing shoe. Corrosion is not a common cause for production-casing failure in the field because of the quality of the produced water, which has lower total dissolved solids and lower salinity compositions than many unconventional gas fields in the US (Li 2013). However, corrosive gas in the production stream from the Niobrara and Codell Formations has 1.0 to 3.4 mol% of carbon dioxide (Weimer et al. 1986; Higley 2007). Corrosion can contribute to production-casing failure, but the lower salinity of the produced water, which has fewer cations and anions than high-salinity water, generally offsets the potential for high corrosion rates of the carbon-steel pipe. However, leaks can occur at casing connections because of thread galling during installation of the production casing or increased loading conditions experienced because of thermal and stress alterations throughout the life cycle of the well.

	Original Well Count	Potential Barrier Failures	Potential Barrier Failure (%)	Catas-trophic Barrier Failures	Catas-trophic Barrier Failure (%)	Average Completion Date	P&A Well Count	Current Well Count	Original Average Surface-Casing Depth (ft)	Original Average Top of Production Cement (ft)
Category 1	0	0	0.00	0	0.00	–	0	0	–	–
Category 2	0	0	0.00	0	0.00	–	0	0	–	–
Category 3	0	0	0.00	0	0.00	–	0	0	–	–
Category 4	0	0	0.00	0	0.00	–	0	0	–	–
Category 5	0	0	0.00	0	0.00	–	0	0	–	–
Category 6	269	0	0.00	0	0.00	2012	1	268	789	2,153
Category 7	704	0	0.00	0	0.00	2012	2	702	929	442
Total	973	0	0.00	0	0.00		3	970	–	–
D&A	0	–	–	–	–	–	–	–	–	–

Table 3—Potential and catastrophic barrier failures of horizontal wells in the Wattenberg Field. D&A = drilled and abandoned; P&A = plugged and abandoned.

Eighty percent of the potential barrier failures occurred on wells with shallow surface casing set above the base of the Fox-Hills aquifer. The age of the wells is also an important consideration, with the majority of the potential barrier failures occurring on legacy vertical and deviated wells from the 1970s and 1980s **(Fig. 12).** Potential barrier failures were common where the base depth of the aquifer was greater than 300 ft subsurface on the southern area of the field **(Fig. 13).**

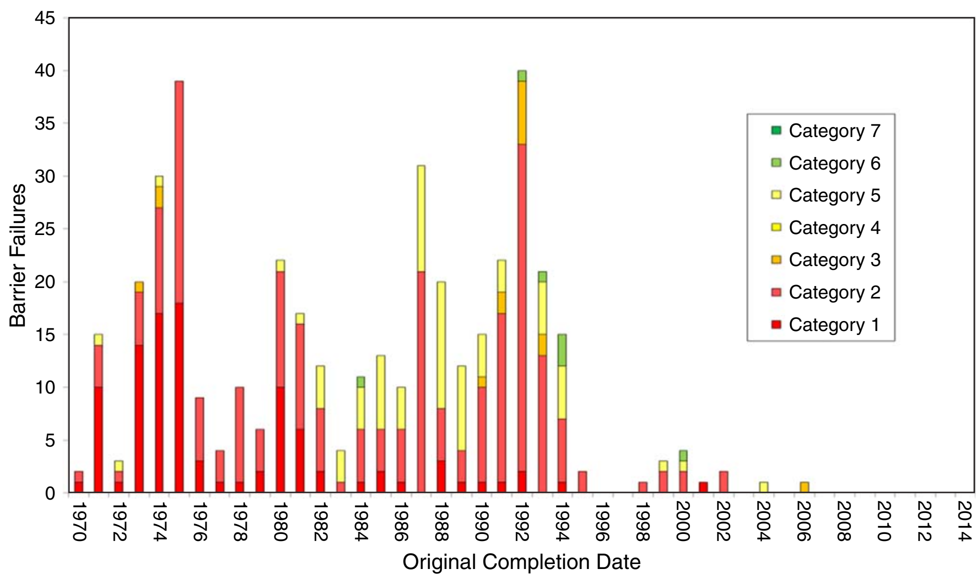

Fig. 12—Histogram of potential barrier failures for vertical and deviated wells in the Wattenberg Field, color coded by the original wellbore-barrier design of the well.

No evidence was found in this study that hydraulic-fracturing operations directly contaminated freshwater aquifers in the Wattenberg Field. All catastrophic barrier failures were related to hydrocarbon migration through the wellbore to the freshwater aquifer or surface. Ten of 16,828 originally producing vertical and deviated wells were identified that had a catastrophic barrier failure, representing a catastrophic barrier-failure rate of 0.06% (Table 2). The most-common failure characteristic is shallow surface casing and inadequate production-cement design on older wells in the Wattenberg Field. No lower-risk Category 6 or 7 wells experienced a catastrophic barrier failure because of their redundant nested-barrier designs. In addition, no horizontal wells were identified as having a catastrophic barrier failure.

Catastrophic barrier failures, plotted in **Fig. 14,** were identified in three Category 1 wells, five Category 2 wells, one Category 3 well, and one Category 5 well. Nine wells had a commonality of shallow surface casing set above the base of the Fox-Hills aquifer. One Category 5 catastrophic barrier failure had deep surface casing, but had no evidence of freshwater-aquifer contamination. This well had elevated benzene levels at surface near the well, which could be because of surface leaks in the flowlines or production tanks. Unfortunately, there was no evidence one way or another. Therefore, this well was determined to be a catastrophic barrier failure in the analysis. The remaining catastrophic barrier failures either have improper cement isolation in the production-casing annulus, leaks in the production casing at shallow depths that were potentially caused by corrosion, or leaks at the casing collars that resulted in a direct migration pathway to the freshwater aquifer in the annulus. Violations were issued by the COGCC to current operators that affected the water quality of a water well.

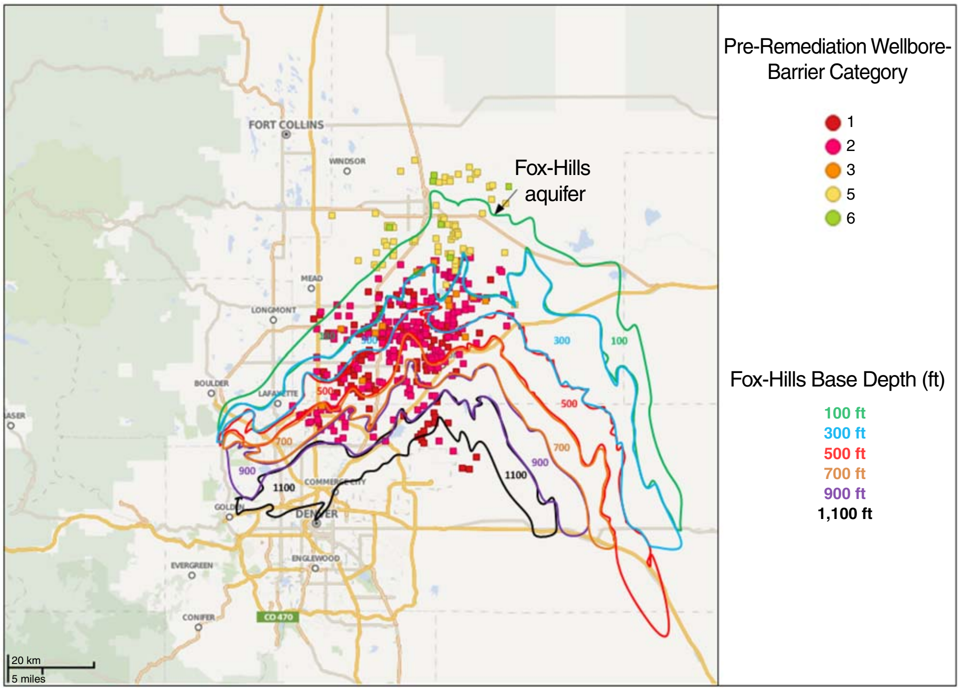

Fig. 13—Map of potential barrier failures in vertical and deviated wells with locations and base depths of Fox-Hills aquifer in the Wattenberg Field (ArcGIS 2016).

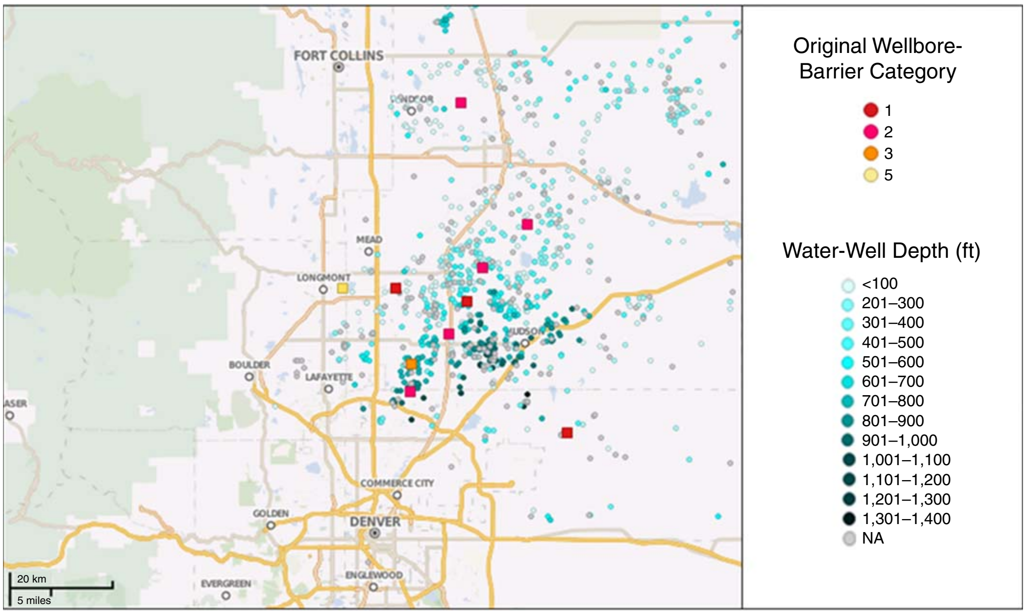

Fig. 14—Map of catastrophic barrier failures in vertical and deviated wells with locations and depths of water wells in the Wattenberg Field.

Catastrophic barrier failures were more common in high-risk well-barrier categories. Categories 1 and 2 had only a single hydrostatic pressure barrier in the annulus preventing hydrocarbon migration. Category 1 wells have the highest risk of barrier failure because of shallow surface casing and noncement isolation of the overpressured Niobrara Formation. This barrier design had a 60.24% potential-barrier-failure rate and a 1.81% catastrophic-barrier-failure rate. Category 2 barrier designs have a 35.27% potential-barrier-failure rate and a 0.64% catastrophic-barrier-failure rate. Category 3 barrier designs have a 34.78% potential-barrier-failure rate and a 2.17% catastrophic-barrier-failure rate. Category 5 wellbore-barrier designs, the most-common original vertical or deviated well design in the Wattenberg Field, have a 0.88% potential-barrier-failure rate and a 0.02% catastrophic-barrier-failure rate. The remaining vertical- or deviated-wellbore-barrier categories had no evidence of catastrophic barrier failures.

Horizontal wells began in 2010 and represent more-recent nested-barrier designs with a lower risk of catastrophic barrier failure. No horizontal wells have shallow surface casing in the data set. Of the wells originally completed in the field, 269 were Category 6 horizontal wells and 704 were Category 7 horizontal wells. Because of the infancy of these wells and the redundant nested-barrier designs, no failures have been identified from the horizontal wells in the data set.

Li and Carlson (2014) attempted to identify the presence and origin of biogenic and thermogenic gas in the Fox-Hills aquifer. They sampled 176 water wells across the Wattenberg Field. The study found that 70.5% of water wells sampled had methane concentrations of <5 mg/L and 1.2% of water wells sampled had methane concentrations of >25 mg/L. However, only two samples detected thermogenic gas in the study, which correlated with two catastrophic barrier failures of this study **(Fig. 15).** All remaining methane samples from the water wells were biogenic, originating naturally in the aquifer or coal seams. This result is consistent with the prevalence of naturally occurring biogenic methane in the Denver Basin aquifer system.

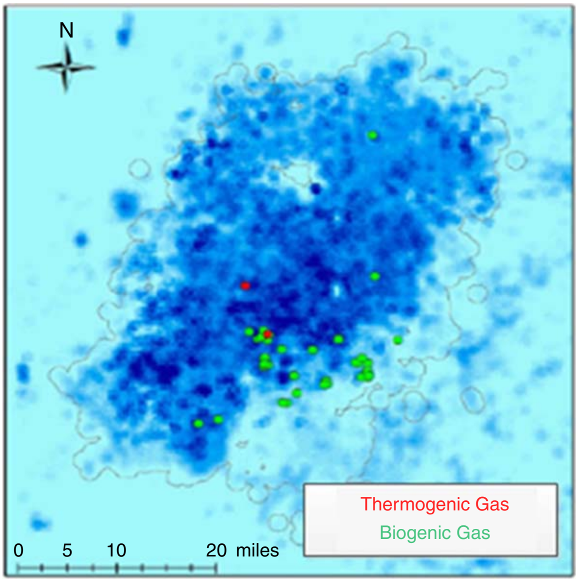

Fig. 15—Study performed by Li and Carlson (2014) that displays locations of water wells that tested positive for the presence of biogenic or thermogenic gas in the Wattenberg Field.

A similar study was performed by Strauss et al. (2014); they detected 12 of 93 water wells that tested positive for methane concentrations greater than 1 mg/L that were thermogenic in origin from the J-Sand, Codell, Niobrara, or Sussex Formations **(Fig. 16).** Eighty-one of the remaining water wells that tested positive for methane were bacterial (biogenic) in nature and originated from methanogens within the aquifer system. The locations of the thermogenic-gas presence in the aquifers match this study's findings for the oil- and gas-well catastrophic barrier failures. Both studies demonstrate the common presence of biogenic methane in the aquifer system.

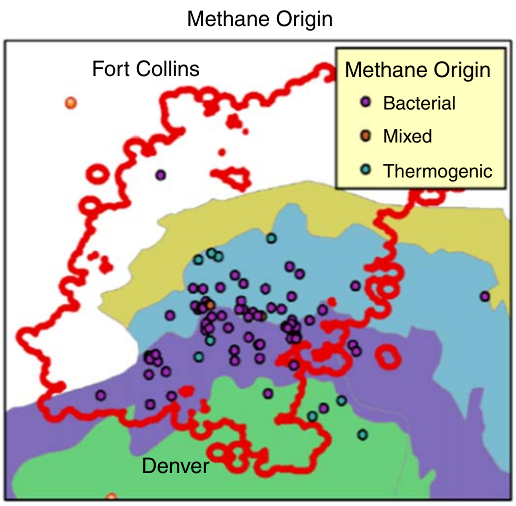

Fig. 16—Study performed by Strauss et al. (2014) that displays locations of water wells that tested positive for bacterial or thermogenic gas in the Wattenberg Field.

Wattenberg Field Catastrophic Barrier Failures

Ten of the 17,801 originally producing oil and gas wells experienced a catastrophic barrier failure related to hydrocarbon migration to freshwater aquifers or surface soil in the Wattenberg Field **(Table 4).** This small percentage of catastrophic barrier failures (0.06%) proves the low risk of aquifer contamination, but also confirms that there is a risk of contamination related to hydrocarbon migration in the Wattenberg Field if wellbores are designed poorly. Nine of the 10 catastrophic failures were attributed to 833 poorly constructed Category 1, 2, and 3 wells. Only one of 15,995 Category 4, 5, 6, and 7 vertical wells had catastrophic failures.

Well	API	Spud Date	Date of Incident	Surface/Aquifer Breach	Old Category	Nearest Water-Well Radial Distance	Current Category	P&A Date	Surface Depth (ft)	Production TOC (ft)
1	0500107626	6/17/1980	10/4/2006	Yes	1	323	5	–	212	7,036
2	0512307854	9/24/1974	1/29/2004	Yes	1	161	5	–	222	7,000
3	0512308926	10/5/1976	4/10/2012	Yes	1	968	5	–	212	7,090
4	0512312383	3/21/1985	3/9/2004	Yes	2	320	P&A	4/29/2014	302	6,100
5	0512311848	11/21/1984	8/1/2009	Yes	2	960	P&A	10/30/2009	337	6,185
6	0512308385	8/7/1975	1/1/2002	Yes	2	5,160	6	–	690	6,440
7	0500106164	6/22/1970	8/6/2001	Yes	2	1,610	P&A	9/15/2012	136	7,420
8	0512308161	12/2/1974	1/1/2010	Yes	2	1,600	P&A	4/19/2012	640	7,000
9	0512316027	10/14/1992	6/7/2006	Yes	3	320	3	–	761	4,010
10	0501306096	2/11/1982	7/17/2006	No	5	–	5	–	200	6,190

Table 4—Catastrophic barrier failures of vertical and deviated wells in the Wattenberg Field. API = American Petroleum Institute well identification number. P&A = plugged and abandoned.

There were 973 Category 6 and 7 horizontal wells that had neither potential nor catastrophic barrier failures. Common catastrophic failure characteristics were shallow surface casing, inadaquate cement isolation from the production cement, holes or leaks developing in the production casing, and the age of the oil and gas wells **(Table 5).**

Well	API	Cause of Catastrophic Failure
1	0500107626	Production TOC below top of Niobrara, water well drilled in 2003 to depth of 400 ft, shallow hole in production casing
2	0512307854	Production TOC below top of Niobrara; well Passed MIT; SAP of 130 psi, flow path in annulus
3	0512308926	Production TOC below top of Niobrara; well Passed MIT; SAP of 130 psi, flow path in annulus
4	0512312383	Shallow holes in production casing at 1,250 ft and 761 to 795 ft; SAP observed
5	0512311848	Shallow holes in production casing; water well drilled to 450 ft in 2009; SAP observed
6	0512308385	Seal leak in wellhead; gas-migration path to aquifer behind production casing
7	0500106164	Shallow holes in production casing; well failed MIT
8	0512308161	Shallow holes in production casing; well failed MIT
9	0512316027	Shallow holes in production casing; well failed MIT
10	0501306096	Benzene in soil samples; complaint filed; most likely from fiberglass production tank on location

Table 5—Description of catastrophic barrier failures of vertical and deviated wells in the Wattenberg Field. API = American Petroleum Institute well identification number.

The radial distance that a water well detected thermogenic gas related to a catastrophic barrier failure in an oil and gas well ranged from 161 to 5,160 ft. However, the catastrophic barrier failure of the oil and gas well that affected a water well 5,160 ft radial distance away was related to a leak in the wellhead and is an outlier in the data set because of the high rate of the leak. **Table 6** displays the average, standard deviation, and median of the radial water-well distances from the catastrophic barrier failures observed in the oil and gas wells. No evidence of fracturing-fluid migration was detected in the data set, even in wells that had higher-risk wellbore-barrier designs. This also establishes that adding pressure-monitoring equipment to the fracturing-fluid string and casing annulus during hydraulic-fracturing operations reduces the overall risk of aquifer contamination. In addition, the geologic barrier of the Pierre Shale validates that fracture-height growth is limited to within the targeted formations and does not extend thousands of feet to surface aquifers.

Wattenberg Field average water-well distance	1,449 ft
Standard deviation	1,744 ft
Median	968 ft

Table 6—Average distance of thermogenic-gas detection from catastrophic barrier failures of oil and gas wells in the Wattenberg Field.

Conclusions

For the Denver-Julesberg Wattenberg Field, the following conclusions are made:

1. No evidence of aquifer contamination by stimulation operations through wellbores was discovered in the Wattenberg Field.
2. Ten undisputed cases of methane migration to aquifers out of 17,948 wells, or 0.06%, in the study area were discovered in the Wattenberg Field. All but one of these cases occurred in legacy wells with poor well-construction methods; nine of the 10 catastrophic barrier failures were attributed to 833 poorly constructed wells. Only one of 15,995 lower-risk vertical wells had catastrophic barrier failures.

3. Eighty percent of the wells with potential barrier failures in the Wattenberg Field had surface casing not through the entire aquifer and 95% of the wells with potential failure had the cement top outside of the production casing below the top of hydrocarbons. The low percentage of potential barrier failures for wells with deep surface casing and the TOC of production casing above the top of hydrocarbons validates the effectiveness of more-robust nested-barrier designs in the field and demonstrates the use of the geologic shale barrier (Pierre Shale) separating the aquifer system from hydrocarbon deposits below.
4. The probability of hydrocarbon migration correlated to the age of the well. All catastrophic barrier failures in the Wattenberg Field occurred on wells drilled before 1992. Older wells had less-robust construction standards, and the barriers preventing migration were not as redundant.
5. Potential barrier failure of one or more barriers in all vertical or deviated wells without hydrocarbon migration was determined to be 2.4%, but this rate was heavily dependent on the rigor of the completion standards. Compared with 0.5% of well-constructed wells, 40.2% of poorly constructed wells had potential barrier failures.
6. Of the 973 horizontal wells analyzed in this study, none have had either potential or catastrophic barrier failures.

The procedures outlined in this paper are applicable to many other geographic regions and basins that have the inclusive type of governmental database that the state of Colorado has created through the COGCC. Collecting, organizing, and analyzing the data is somewhat tedious, but the potential of software, artificial intelligence, and machine learning may help with this process. Regardless of the effort, the conclusions demonstrate that whole-scale freshwater-aquifer contamination in the Denver-Julesberg Basin of Colorado will not occur if wellbores are constructed correctly.

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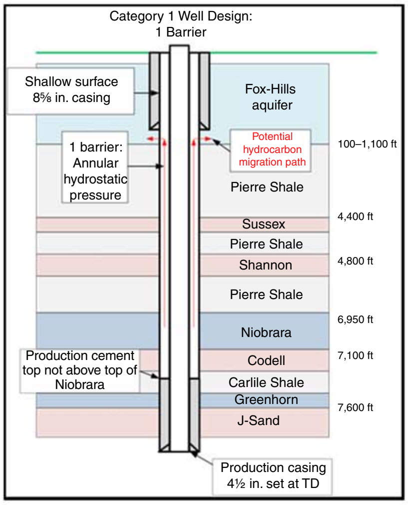
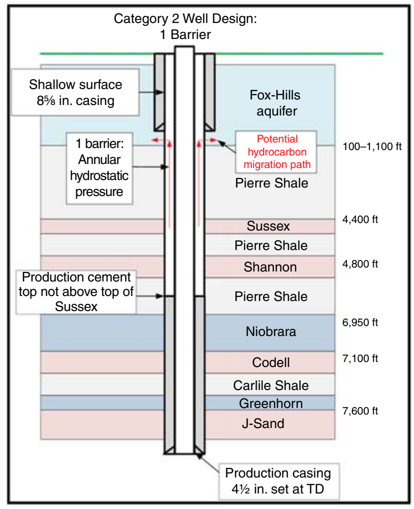
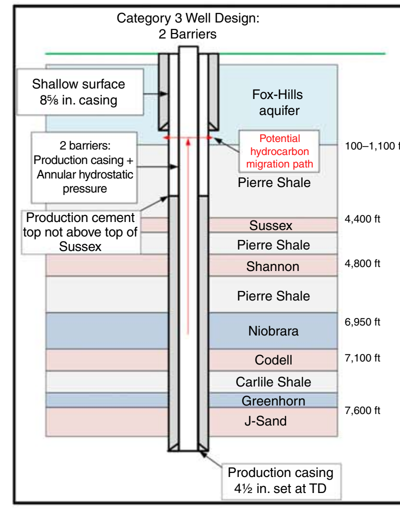
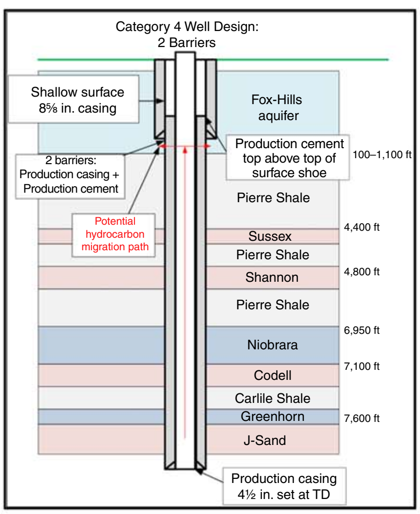
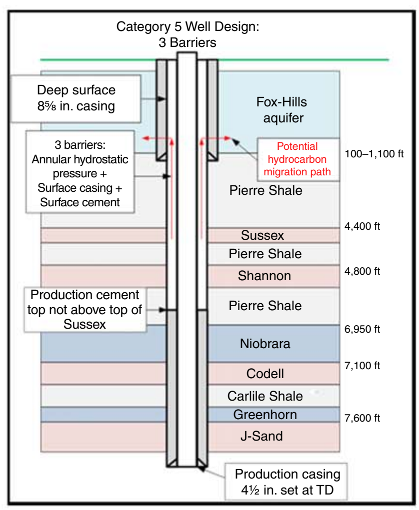
Appendix A—Detailed Wellbore Diagrams for Each Wellbore-Barrier Category

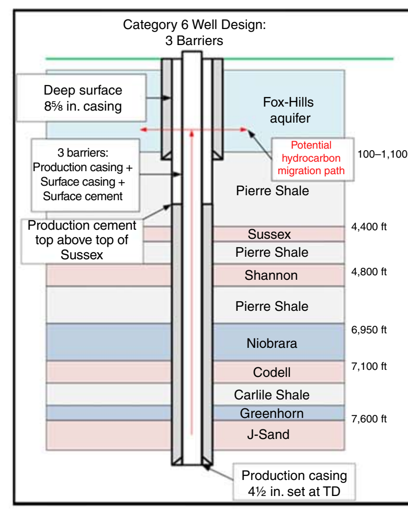


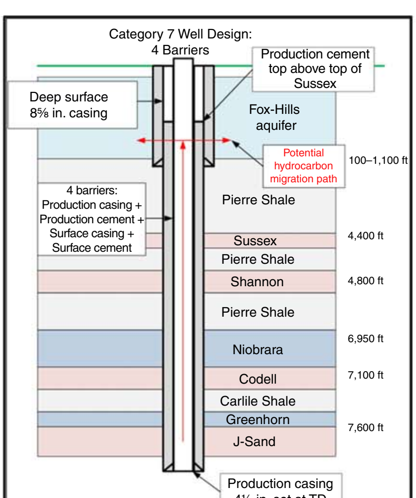












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