A Review of Historic and Modern Oil and Natural Gas Well Drilling and Abandonment in Greeley, Colorado, and the Potential Applications of a Historic Geographic Information System

By:

Will Rempel

University of Colorado at Boulder

A thesis submitted to the University of Colorado at Boulder in partial fulfillment of the requirements to receive Honors designation in Geography, May 2016

Thesis Advisors:

Dr. William Travis, Geography, Committee Chair

Dr. Patricia Limerick, Center of the American West

Dr. Holly Barnard, Geography

ABSTRACT

In Colorado, a majority of existing and planned oil and natural gas operations occur along the populous Front Range of the Rocky Mountains, with a particular focus in Weld County. In recent years, unconventional oil and gas operations have lead to a surge of new activity in the region that has affected both rural and suburban areas, bringing environmental impact and social pros and cons. This has been a source of contention for numerous communities, and has brought legal disputes between local and state officials concerning drilling permission jurisdiction. Simultaneously, the region's historic link to oil and gas wells has also resulted in decommissioned and abandoned wells that must be documented and monitored after they cease production. Due to intermittent issues in decommissioning (plugging) and documentation, abandoned wells can have problems involving well integrity and site location. In order to properly understand these issues, I look at how historical geographic information systems can be used to identify patterns of well drilling over several decades, with a focus on Greeley, Colorado, in hopes that this information can be used in future planning scenarios.

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1. INTRODUCTION

This honors thesis stems from the ongoing debates surrounding modern and historic oil and gas development in the United States, as well as my time as a research assistant for the Center of the American West. In this position, I became familiarized with the controversies surrounding the recent boom on both a national and local scale, and have witnessed the Center's role as a mediator between the differing ideologies that intensify this debate. Prior to this position, I had only an rudimentary understanding of the oil and gas industry and the extraction process as a whole, and my personal familiarity was limited to, on one hand, conversations with family in Oklahoma (where oil and gas wells are an everyday part of life and source of income for many in the community), and on the other, growing up in an era where civic discussion can at times gravitate towards the environmental and social predicaments that accompany humanity's relationship with fossil fuels.

As I continued to learn about the topic in-depth, as well as the production lifespan of these wells, and what happens after this lifespan ends, the subject matter suddenly became visible much closer to home (very literally); in the form of a plugged (cemented) yet undocumented natural gas well that stands less than two feet from my family house in Southern Colorado. While I have known about this well my entire life (the exposed well casing has always been an accepted part of the scenery in our backyard), it was only after a recent property inspection to confirm the location of decommissioned wells that we learned it and several other wells were either never logged, nor documented as being in the location where they actually are. While this did not particularly concern

myself or my family, it was nonetheless thought-provoking that something so personally recognizable was in many ways forgotten on a larger scale.

Upon further reading about the lifecycle of wells once they are decommissioned, and both the current and imminent problems that they can cause when not properly sealed, monitored, or mapped, it became apparent that these abandoned wells still have an impact despite being collectively forgotten by many, and that the American West's historical connection to this extractive industry not only highlights a present legacy that must be addressed, but also sheds light on the future legacy from wells that have yet to be decommissioned.

In recent years, technological innovation within the oil and gas industry has caused new and unprecedented activity in the region. In particular, there has been a substantial increase in extraction from low-permeability rock formations[1]. Through conventional and historic drilling means, these formations would return insignificant production and be economically unfeasible. However, through a combination of breakthroughs, particularly that of horizontal drilling and hydraulic fracturing techniques, as well as encouraging economic forces, many communities across the United States have seen an unprecedented rise in what is termed unconventional oil and gas development (Kroepsch, Rempel & Limerick, 2014).

This boom has been an economic revival for oil and gas development in the United States that has interested many individuals and communities with benefits from job creation, mineral leasing, and other related local business opportunities. However,

[1] These formations are generally composed of shales and tight sandstones. Along the Front Range of Colorado, these include the Niobrara shale formation, and parts of the "Muddy J" and Codell sandstone formations (Kroepsch, Rempel & Limerick, 2014).

there is also a strong level of contention about the topic, as the benefits are met with impacts that range from environmental issues (including groundwater contamination, surface spills, methane emissions and other forms of contamination related to the industrial process) to social issues (including leasing dilemmas related to split-estate laws, as well as the other impacts that large scale booms can bring to local communities such as increased traffic on rural roads and noise disturbance). In several studies that observed community response to operations involving fracking, it was found that while nation-wide phone surveys showed many to be unaware and undecided, there was a much stronger polarization of opinions amongst states with high oil and gas activity (Boudet et al. 2014; Rabe and Borick, 2011).

The result of this contention is that many local communities have begun a discussion with both the oil and gas industry and state regulatory agencies on the allowance of oil and gas development near populated areas. Unfortunately, these polarized opinions have also made discourse on these legacies fall short (Limerick, 2013). Many of the leading arguments for and against new operations fail to address the complexity of the issue, which includes the undeniable environmental and social impact that large scale, fast paced extractive booms can create, as well as topics like the historic and modern role of extractive industries in the West and their contribution to our 21st century lifestyles. Undeniably, the history of modern Euro-American settlement in the American West is intrinsically linked to the extractive industries that play a role in the region's social perception and value. This is perhaps best shown and explained in Elliot West's short essay *Golden Dreams: Colorado, California, and the Reimaging of America*, where he describes the shift in America's mental geography of the West from

an image of uninhabitable, unforgiving plains and deserts to one of lands open to opportunity and settlement. The cause for this shift can be traced to the discovery of gold along the Front Range and further beyond on the Coast of California (West, 2012). While West specifically cites only gold mining in his essay, it is quite easy to go further and link this transformation of the region's social value to other extractive industries as well, including the development of regions rich in oil and natural gas. Understanding the role of these industries and the patterns they have created is integral to improving them.

In hopes of moving the conversation, I look at the possibilities of incorporating the use of Geographic Information Systems as a planning tool that would allow for a better understanding of this issue, and hopefully lead to decisions based on evidence and long-term planning to best suit communities. The following literature review provides an overview of the current conflicts around municipal drilling, looks at why the City of Greeley serves as a perfect case study for discussing this, and offers insight into why a historical geographic information system would prove useful as a community tool.

2. LITERATURE REVIEW & RESEARCH QUESTIONS

2.1 Oil and Gas Production and Politics Along the Front Range

The current boom in unconventional oil and gas development has been primarily focused on large shale formations that were previously inaccessible and unfeasible for extraction. These formations include the Marcellus formation in Pennsylvania, the Bakken formation in North Dakota, the Eagle Ford formation in Texas, and the Niobrara formation in Colorado. For the latter, much of this extraction occurs along the northeastern Front Range, in the geologic region known as the Denver-Julesburg Basin. A large majority of these wells are located within Weld County, Colorado. This area and basin has also seen previous conventional oil and gas extraction in the last several decades. In regards to contemporary drilling, this current boom has caused unprecedented activity in the past decade, though for a variety of reasons it is currently seeing a decrease in activity, signifying the beginning of a bust phase (Colorado Geological Survey, 2011). While some communities are newer to experiencing this level of extraction (as exemplified by developments like Vista Ridge), others are seeing this new development as a robust continuation of an industry that has always had a strong presence (Jaffe, 2015a). Greeley is an example of the latter (Healy, 2013).

The rise in drilling operations has come at a time of continued suburban growth along the Front Range[2]. These two areas of growth, and how they relate to one another, are at the core of this issue. One way in which these two expansions have been cohabiting with cities and municipalities (albeit with controversy), is by drilling large multi-well pads and using horizontal drilling to reach formations under dense residential

[2] One news article cites that: "the six Front Range counties where drilling has occurred added nearly 105,000 residents between 2010 and 2013" (Jaffe, 2015a).

areas. Disagreement and debate have particularly begun to focus on whether such extractive companies should be allowed within and around city limits, as well as how much power local communities should have in these decisions in contrast to the powers of the state and its established regulatory agencies (Jaffe, 2014).

For the municipalities that are more strongly opposed to oil and gas development, a common response has been the passing of bans or moratoria that either indefinitely or temporarily restrict new drilling operations, respectively. These are best exemplified by the municipal decisions that occurred in 2012 and 2013 by the cities of Longmont, Lafayette, Boulder, and Fort Collins (Wines, 2013). These decisions have been controversial, as both Longmont's ban and Fort Collins' moratorium were overturned by district courts after lawsuits were filed by the Colorado Oil and Gas Association, on grounds that they supersede the State's regulatory Colorado Oil and Gas Conservation Commission. These cases will soon see a decision by the Colorado Supreme Court (Steffen, 2015).

Another response has been legislative proposals on the state level. Two such initiatives, one supporting increased local control on drilling, the other increasing well setback distances from structures, were to be proposed on the November 2015 ballot but were withdrawn in exchange for a compromise that created the Governor's Task Force. This task force voted on numerous proposals and approved several. One notable recommendation would require operators that wish to drill multi-well pads in municipal areas to work with the local government to find a suitable location before applying for a state permit, while another recommends that operators share 5-year drilling plans so that cities can incorporate oil and gas extraction into their long-term planning practices

(Jaffe, 2015b). The COGCC adopted these recommendations as formal rules in early 2016 (Dunn, 2015).

As a result of these statewide rulings, as well as local initiatives on drilling near communities, local community planners are increasingly involved in the municipal oil and gas development process. As such, it will be important to provide the best information in developing these plans, and to do so will require consideration of not only current drilling operations, but also past and future operations. Going forward, developing tools to accommodate and visualize this will be integral.

2.2 Abandoned and Orphaned Wells

Although the planning of present-day drilling operations is important, so is the study of previously drilled wells that have entered the abandonment phase of their lifecycle. This topic, though not new, has only recently received a higher level of academic and media attention (Joyce, 2016; Kang et al. 2014; Detrow, 2012). And, while all oil and gas wells see an end to production, there are numerous issues related to wells that are not properly sealed, documented, or monitored. By definition, wells are deemed abandoned once they have ceased production and have become inactive. This can occur when it is no longer economically feasible to keep the well running (meaning no return of investment for the amount of oil or gas produced), when mineral leasing terms expire, or when the tapped reservoir has run dry. While the word “abandoned” may give the idea that these wells receive no attention or care, this is not actually the case, as they must be properly sealed to prevent contaminants from exiting the wellbore. This responsibility usually falls to the operator in charge of the well, who must

also work with the state on routine testing and logging of the well conditions overtime. For abandoned wells, potential issues generally involve poor construction (the wellbore not being properly sealed), or poor monitoring and maintenance (Jackson, 2014).

But an even larger risk comes from orphaned wells. Wells are considered orphaned when, like abandoned wells, they are no longer capable of producing, but have no identifiable operator in charge of reclamation. Orphaned wells are more commonly found in areas where volatile extraction boom and bust patterns have lead many operators to declare bankruptcy. This leaves reclamation efforts in the responsibility of state oil and gas regulatory agencies, adding further strain to manpower and funding (IOGCC, 2008). Orphaned wells are often poorly documented (meaning many wells and their exact locations are unaccounted for), and in cases poorly sealed or never sealed at all, creating a direct passage from the subsurface that can lead to groundwater contamination and air pollution.

The extent of well abandonment issues varies between states. Particularly of note are states that experienced large and early development booms and had yet to establish comprehensive regulation plans for development (King & Valencia, 2014). This is best exemplified by Texas and Pennsylvania[3], two states that notably experienced early and unregulated booms, and have been a focus of research on the topic[4].Today, these states share the largest legacy of abandoned wells compared to

[3] With the high number of unaccounted wells in Pennsylvania, it is estimated that there are roughly 300,000 to 500,000 abandoned or orphaned wells in the state (Kang et al. 2014).

[4] One notable 2014 study published by Kang et Al measured the rate of methane flow from several orphaned wells, and estimated that orphaned well emissions were contributing roughly 4-7% of the state's human-caused methane emissions (Kang et al. 2014).

other states that experienced booms later once developed regulatory frameworks had been put in place. Consequently, it has been determined that nationwide, most abandoned and orphaned wells of particular concern were drilled between 1860 and 1930[5]. Beyond that, it has only been more recently that the extent of this issue is being researched in other states.

While the abandonment problem may not be as large in Colorado as other states, the extent of the state's issues remains unknown because of inadequate data, and documentation and the continued monitoring of well locations leaves something to be desired (Joyce, 2016). One particular issue in Colorado appears to be that many wells have been poorly documented after being sealed, while many of the GPS coordinates documented for each well are inaccurate and their exact locations unknown[6]. In many cases, adequately addressing this would require resources that regulatory agencies currently do not have.

Along the Front Range this is complicated by suburban growth, and new structures (including new buildings and newer oil development) face a risk if built near or on an undetermined abandoned well[7]. Furthermore, most Colorado municipalities do not have laws and ordinances in place that specifically address building near or on

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[5] Interestingly, this date range correlates with the average span between the drilling of exploratory wells and the development of regulatory frameworks (IOGCC, 2008).

[6] It was only in 2005 that more precise GPS locations were required in well documentation (Joyce, 2016).

[7] This is especially so if the well proves to leak methane. While it is a relatively small risk, methane buildup related to improperly sealed wells have been linked to house explosions, including one in Trinidad Colorado in 2007, and one in Bradford, Pennsylvania in 2011 (Joyce, 2016).

abandoned well sites. There are several exceptions to this, including a law passed on November 12, 2002 in the town of Broomfield that requires locating any abandoned wells on the property before development and placing an easement over the site and roadway access in case a leak is detected. While various setback rules have been developed in several counties and municipalities, none of these rules take into account situations where well sites have already been built over or require the exact location of abandoned wells to be logged before development (aside from the previously mentioned law in Broomfield) (Joyce, 2016). Clearly, it will prove just as important to incorporate the historic legacy of oil and gas development into planning as well.

2.3 Greeley as a Case Study

In choosing a city and dataset to base this thesis around, Greeley proved to be the perfect case study. In addition to being in Weld county, Greeley is also located in the middle of the Wattenberg Field, which is arguably the largest zone of drilling and extraction within the Denver-Julesburg Basin. Activity in the Wattenberg first began to reach a commercial scale during the 1970s, and today is seeing new drilling into unconventional reservoirs (American Petroleum Institute, 2013; Ladd, 2005; Scamehorn, 2002). Drilling within city limits first began in 1982, and in the past decade has seen an unprecedented surge. While this has created much fodder for public discussion, Greeley's relationship to drilling has proven much more amicable and welcoming than that of other communities on the Front Range, partly due to the city's long connection to the industry (Romano, 2013).

However, Greeley's history with drilling has seen disputes as well. After an oil and gas related explosion in nearby La Salle, Colorado, the city of Greeley voted to ban drilling within city limits in 1985. This was contested in court by Lundvall Bros. Inc., who had recently obtained drilling permits for several wells within the city (Verlee, 2014). The resulting 1992 decision of *Lundvall V. Voss* overturned the city's ability to ban drilling, and continues to serve as a precedent in past and ongoing lawsuits on city bans and moratoria across the state (*Lundvall v. Voss*). This complicated and unique past further indicates why Greeley makes for an ideal case study. Because of its location in the middle of the Denver-Julesburg Basin and its legal history, Greeley has been, and continues to be, the most intensively drilled city in Colorado.

As of 2013, there are roughly 430 active wells within Greeley city limits, and an additional 1,127 wells are expected be incorporated into Greeley's growth area (Romano, 2013). As previously mentioned, most recent wells are being drilled on large multi-well pads that reduce the overall surface disturbance within the city, yet also concentrates the level of activity and increases disturbance to nearby residents. A community conversation is currently taking place on how to address the issues that come with this. The voices in this conversation vary and include elected officials, city staff, residents, industry members, and opposition groups. In planning the road ahead, it is important to develop tools that help in this conversation.

2.4 Applying Historical Geographic Information Systems

One important aspect of this tool should be the fabrication of a Geographic Information System (GIS) that specifically focuses on oil and gas development. While

this serves as a useful visualization tool and way of conducting modern analyses, it is also recommended because of its ability to display and analyze spatial history through Historical GIS.

As described by Gregory Simon in a 2014 article: “Spatial history holds as foundational that space is much more than an empty container simply filled by history. Rather space is itself historical and continuously produced and reproduced over time through diverse and interrelated social, political and biophysical changes” (Simon, 2014). But as intrinsically linked as history and space are, the latter has until recently been largely ignored. As further explained by Richard White: “Historians still routinely write about political change, social change, class relations, gender relations, cultural change as if the spatial dimensions of these issue matter little if at all” (White, 2010).

In recent decades, numerous advancements have seen historical GIS practices introduce this spatial element into many discourses. And, with the unprecedented recording and creation of digital sets of data, GIS has permitted a form of data visualization that allows us to see historical frameworks that cannot be easily conveyed or understood through other media representation (White, 2010). In other cases, it reveals trends that were overall unnoticed or otherwise invisible, or some that are so seemingly obvious that they have not been properly acknowledged. As further explained by Simon: “Animating spatial data temporally and historical data spatially provides an opportunity to not only represent complex relationships, feedbacks, and thresholds that are difficult to ascertain in static or tabular form; these visualizations also generate opportunities to expose unexpected connections, ask new research questions, and chart new research trajectories” (Simon, 2014).

Another benefit of historical Geographic Information Systems is the many ways in which these data sets can be repurposed and reused depending on the objectives of the user. As explained by White, “These projects are open-ended: everything – both tools and data - becomes part of a scholarly commons to be added to, subtracted from, reworked and recombined” (White, 2010). Additionally, these type of data projects can be both qualitative and quantitative depending on the intentions of the user. This further increases the flexibility and possibilities of these systems (Gregory & Healey, 2007).

One of the greatest challenges in using historical GIS databases is in their creation. These databases can be difficult to produce, as they usually require the integration of data pulled from numerous sources in order to more accurately and completely represent the spatial history they are intended to display. Additionally, the scope and intentions of the database must also be previously considered before its creation. In some cases, historical databases are made to be used for different topics, while others are made with a more specific focus (as would be the case with oil and gas development). Some databases are also created for use on a national level, while others are focused on a specific location (Gregory & Healey, 2007).

One of the intentions of this thesis is to look at how a database might be created to suit the specific topic of oil and gas development, and discuss the future possibilities and requirements to develop this data into a more comprehensive spatial history and database. In order to look at how a tool might be developed for Greeley, I developed a set of research questions aimed at exploring and evaluating some of the relevant data sets related to oil and gas development and visualizing potential patterns that have occurred over the past three decades.

2.5 Research Questions and Objectives

2.5.1 Overarching Research Question: How might historical geospatial analysis improve our understanding of where and how oil and gas extraction occurs inside municipalities, as well as community conversations about how oil and gas extraction might occur inside municipalities in the future?

- **Research Objective 1**: Summarize the geospatial data that is available to city planners contemplating oil and gas development inside their municipalities, with a focus on Greeley, specifically.
    - **RQ1a**: What are the relevant geospatial data sources and where can they be found?
    - **RQ1b**: What are the key attributes of these data sources (metadata, fields, etc.)?
    - **RQ1c**: What are the strengths and weaknesses of these data sources?

- **Research Objective 2:** Understand the spatial history of oil and gas extraction in Greeley over time. Where does drilling occur and are there any spatial patterns to it?
    - **RQ2a:** Where were the first wells drilled in Greeley?
    - **RQ2b:** How many wells were drilled each year from 1980 to 2012? When did drilling rate fluctuate (i.e. which were boom years)?
    - **RQ2c:** How did drilling progress spatially throughout the city?

- **Research Objective 3:** To understand the spatial progression of well abandonment in Greeley, and to investigate whether there is a relationship between the two.
    - **RQ3a:** How many wells have been plugged and abandoned or orphaned each year in Greeley since 1980?
    - **RQ3b:** Does the rate of well abandonment correlate with the rate of well drilling in Greeley?
    - **RQ3c:** Are there any noticeable patterns to well abandonment in Greeley?

3 METHODS & RESULTS

3.1 Research Objective 1: Summarize the geospatial data that is available to city planners contemplating oil and gas development inside their municipalities, with a focus on Greeley, specifically.

- **RQ1a**: What are the relevant geospatial data sources and where can they be found?
- **RQ1b**: What are the key attributes of these data sources (metadata, fields, etc.)?
- **RQ1c**: What are the strengths and weaknesses of these data sources?

3. 1.1 Relevant Geospatial Data and Key Attributes

The largest source of records and data pertaining to oil and gas wells in Colorado is the state's oil and gas regulatory agency, the COGCC. In addition to numerous table-formatted data sets that describe well production in Colorado, the COGCC website has a section specifically centered around spatial data and GIS layers, which includes information on well surface locations, directional well lines, disposal pits, oil and gas fields, wildlife habitats, and floodplains. These layers, formatted as a GIS shapefile, also include a metadata sheet that explains the various data stored within each file, which are separated into individual fields.

For my purposes, the data layer related to well surface locations proved to be the most important. Within this layer, the notable data fields[8] include well coordinates in various options (latitude and longitude, UTM coordinates, and township and range being the most versatile), the well's name, API number[9], operator number and name,

[8] While I used a small number of these data fields, it is easy to see how others could be incorporated into future research, especially when combined with the additional available data layers.

[9] The API number is available both as an entire sequence, or further divided into separate fields to indicate county code, sequence code, and the well's individual API

elevation, wellbore depth, activity status (ranging from producing to abandoned), and the date when drilling first began (referred to as a well's "spud date"). Also available in this data layer are the locations for wells that have yet to be drilled (pending permit), and wells that received permit approval but were subsequently abandoned.

Data was first reduced to include only wells that were drilled and completed (removing permits and uncompleted projects), and limited to wells found within the city limits of present-day Greeley. While my original intentions were to use the drilling "spud date" to visualize the progression of drilling across the city over time, it became apparent after examining the data that many of these date entries were listed as "Null." After consulting with the GIS department at the COGCC, I learned that the absence in data generally relates to the age of the wells, and that, while new wells have this data logged, it would require extensive data entry to update the layer to include older well dates. In order to work around this this issue, I was directed towards another dataset available from the COGCC that summarizes well production and could be joined to the well location layer by linking the two tables through matching API numbers. Within this production data table is a field that describes the well completion date (the date in which the well first starts producing). This date proved to be the most comprehensive recording, and the most accurate in visualizing drilling over the years.

The next step in revising the data was to incorporate the change in Greeley's city boundary over time, as this would help in understanding the impact of city growth and the incorporation of oil and gas wells into city limits (rather than being drilled after city limits were established). Solving this required the incorporation of additional data

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number. This proved useful in separating the wells by county, and also allows for more flexibility when attempting to match the data with other datasets.

sources from the City of Greeley and Weld County GIS departments. What proved especially useful was Weld County's city annexation data[10]. By spatially linking the annexation dataset with the well location layer, and then performing a data query calculation to guarantee well completion dates were newer than the annexation date, I was able to separate wells drilled inside city limits from those incorporated by city growth and land annexation.

3.1.2 Strengths & Weaknesses of the Data

The amount of public data on oil and gas wells, and its accessibility, varies state by state. The COGCC appears to have more publicly available data than other states, and in a highly accessible form (it can be readily downloaded online). The COGCC's data are also updated regularly (either daily or monthly, based on data set). Despite the extensiveness and accessibility of COGCC's GIS data, the data sets that I analyzed also presented drawbacks in terms of completeness and reliability that must be acknowledged.

As noted above in terms of the missing data on drilling "spud date" on older wells, the COGCC's GIS data is not perfect. In my discussions with the COGCC GIS department, agency officials warned that they could not guarantee complete accuracy in the well's "spud date" field and in several other data fields. They explained that much of the agency's GIS data is synthesized from data provided by oil and gas operators, such as well logs. Operator-provided data often contains generalizations and is occasionally

[10] While the data layers provided by the City of Greeley show boundary change each year, they were a consolidation of numerous smaller annexations over the course of a year. I wished to use the individual annexation dates to make sure the wells were drilled within city limits at the time, and not simply incorporated later.

incomplete, especially for older well records. This type of error is to be expected in historical datasets. Furthermore, these sorts of data gaps and inconsistencies are also a key factor in the poor documentation of abandoned wells and their locations.

Production data proved to be particularly important to my analysis. As described above, I joined a well production data set, which included well completion dates, to the original well location data set in order to narrow the well locations down to only wells that had been completed (removing wells that were permitted, but never drilled). As I joined and formatted these data sets, I discovered that numerous wells did not have production data associated with them. At the scale of Greeley, the number of wells missing this data was minimal, so they were removed from the data set. On a larger county scale, the number of missing records was much higher. As a result, mapping the entirety of Weld County would require further investigation on the gaps in well production data and the reason behind them. Overall, it would take extensive work to ensure accuracy in well numbers and data if a larger-scale planning tool were to be developed from these large and complex data sets.

Ultimately, the data sets described here – well locations and production/completion data from COGCC and Greeley city limits data from Weld County – proved to be the sufficient for visualizing oil and gas development over time in the city of Greeley. As previously mentioned in section 3.1.1, other data sources from the GIS resources of Greeley, Weld County and the COGCC are also available, and could be incorporated into future research depending on specific research goals, or for creating a broader spatial history of drilling in the Denver-Julesburg Basin, which is beyond the scope of this project.

3.2 Research Objective 2: Understand the spatial history of oil and gas extraction in Greeley over time. Where does drilling occur and are there any spatial patterns to it?

- **RQ2a:** Where were the first wells drilled in Greeley?
- **RQ2b:** How many wells were drilled each year from 1980 to 2012? When did drilling rate fluctuate (i.e. which were boom years)?
- **RQ2c:** how did drilling progress spatially throughout the city?

3.2.1 The Early Days of Drilling in Greeley

Drilling activity in Greeley began in 1982, after the Greeley City Council approved the first permit to drill in a residentially zoned area (Bangert, 1987). As shown in Fig. 1a, the first wells drilled inside the city are mostly located in West Greeley, in an area that would have been the edge of town in the 1980s[11]. Because Greeley's city limits have shifted significantly further west over the years and West Greeley has been further developed, these old wells are now located much more centrally in the city. Past-and present-day West Greeley are characterized by intermixed farmland and housing, and making this part of the city more spacious and rural than other areas of town. Another noted area of early drilling that technically occurred within city limits is found in the central north part of town, within 1,589-acres that were annexed to provide land for a proposed Anheuser-Busch Brewery. After disputes between the landowner and the company, the proposed brewery moved to Fort Collins. The annexed land, referred to as the North Poudre Annexation, remains largely vacant and as a result has seen

[11]Many of the wells drilled within city are found in areas that saw sporadic city boundary growth through small land annexations. Much of this annexation moved westward.

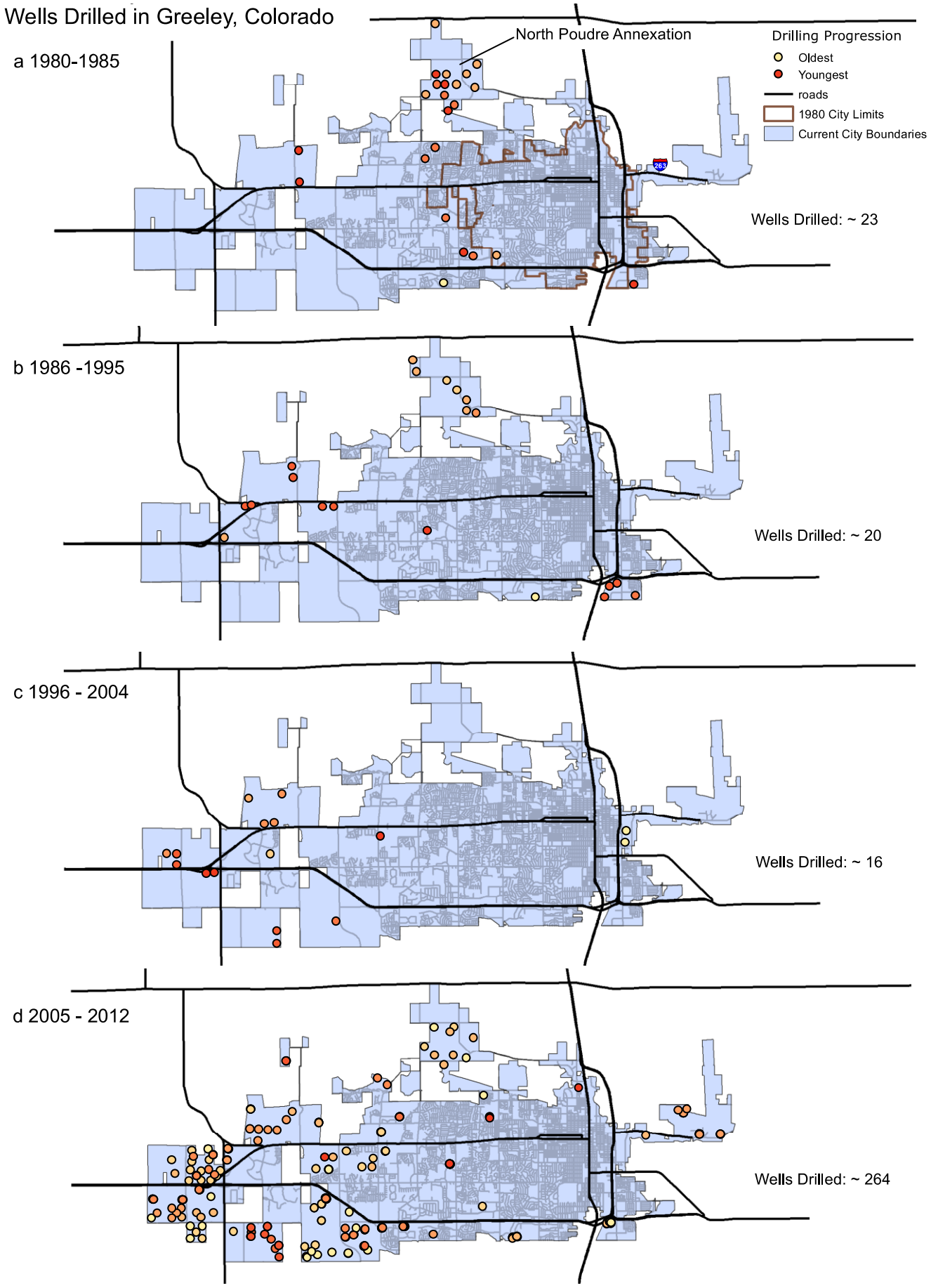


Fig. 1 Wells in Greeley, based on the year they were drilled

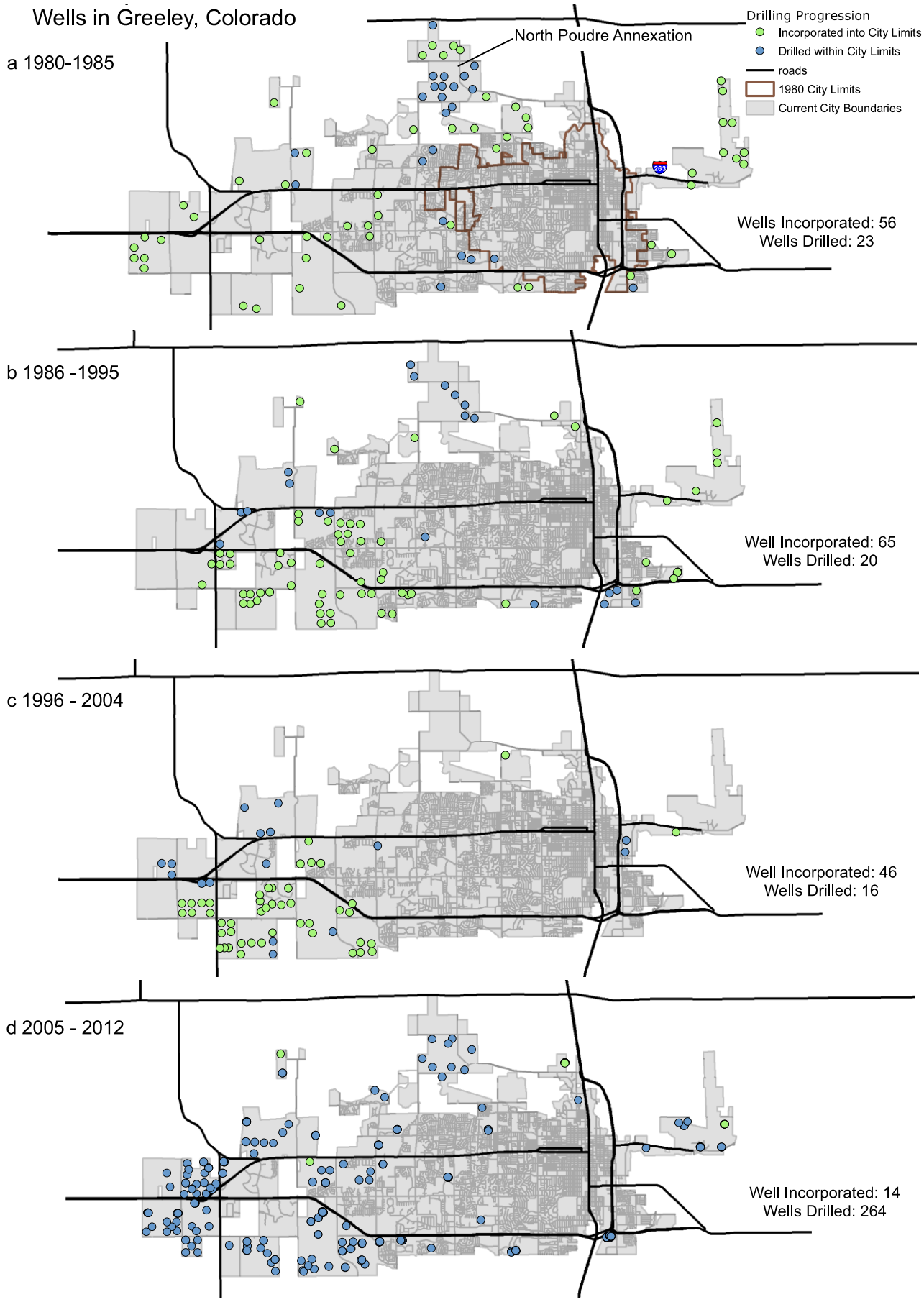


Fig. 2 Wells in Greeley, divided into those drilled with city permits, and those incorporated by city growth.

frequent drilling over the years (Seeman, 1985a). A third zone worth noting is located south of the North Poudre Annexation, in a residential area near West 4th Street and 47th Avenue. This area saw two of Greeley's earliest wells, as well as other proposed wells. These wells drew complaints from area residents and sparked neighborhood organizing that lead to a Greeley drilling ban in 1985 (Seeman, 1985b).

It is important to note that Fig. 1 only shows wells that were drilled within city limits, which is only half of the drilling story in Greeley. As shown in Fig. 2, many other wells that now exist in city limits were originally drilled outside of the city and were later incorporated through city growth and land annexation. These incorporated wells are typically found on the outlying areas of town, particularly in the western parts of Greeley.

3.2.2 Drilling Rates in Greeley Over Time

The number of wells drilled per year and per decade, in both Greeley and Weld County as a whole, can be seen on Fig. 3, Fig. 4, and Fig. 5. The first notable period of increased drilling for the city begins between 1982 and 1985. As previously mentioned in 3.1.1, this is when in-city drilling was first permitted; that timeframe also coincides with a rise in oil and natural gas prices (Fig.4 & Fig.5).

Between the years of 1986 and 1990, a lull in drilling activity occurred after the unanimous passing of a 1985 city-wide ban on drilling by Greeley City Council (Seeman, 1985c). The city council ban was later upheld by a city vote (Crona, 1985).

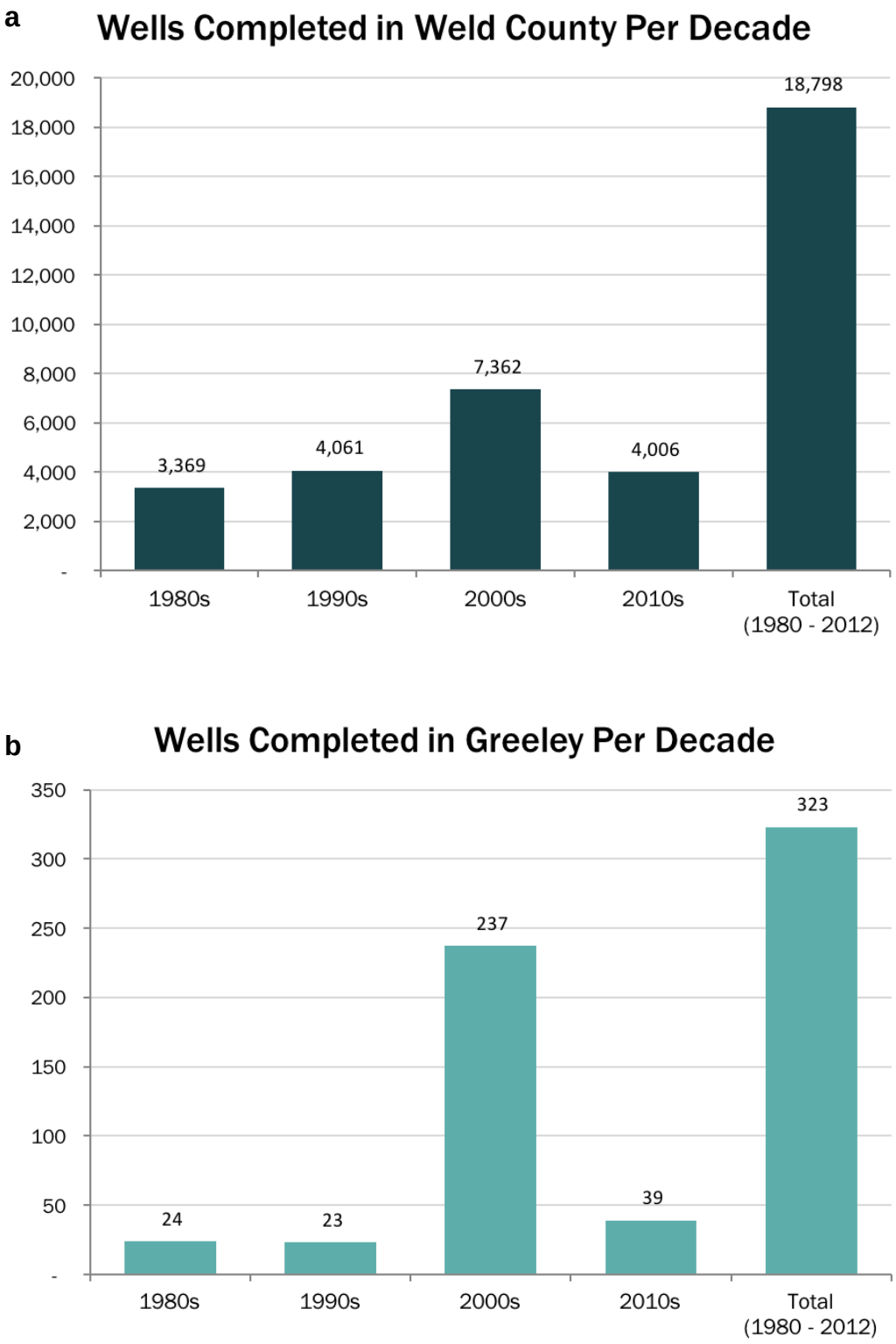
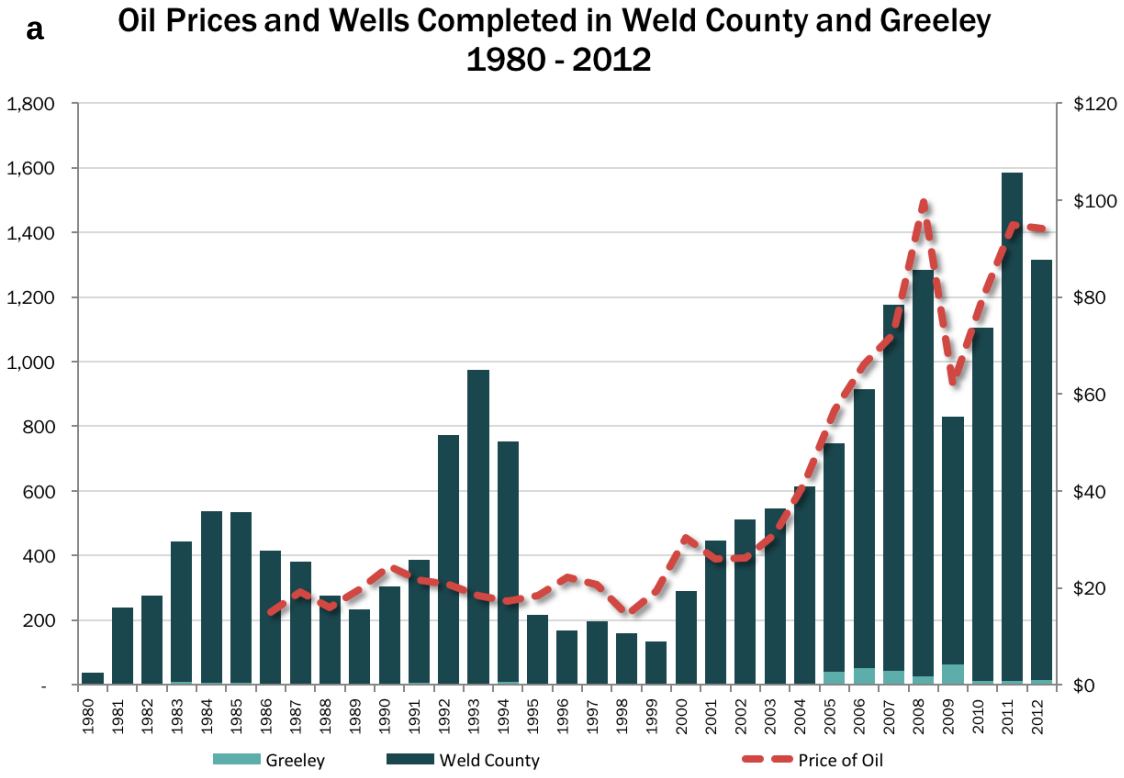


Fig. 3 Indicates wells completed for Weld County (a) and Greeley (b).



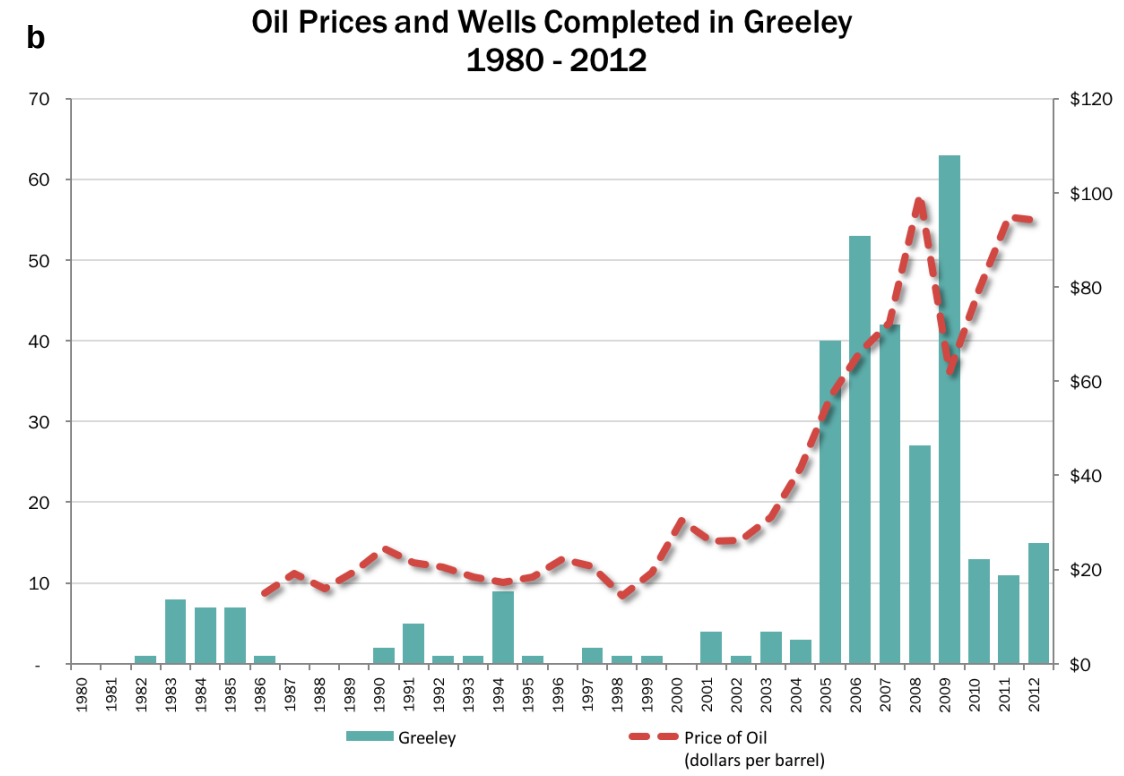


Fig. 4 Compares wells completed per year with equivalent price of oil Weld County (a) and Greeley (b).

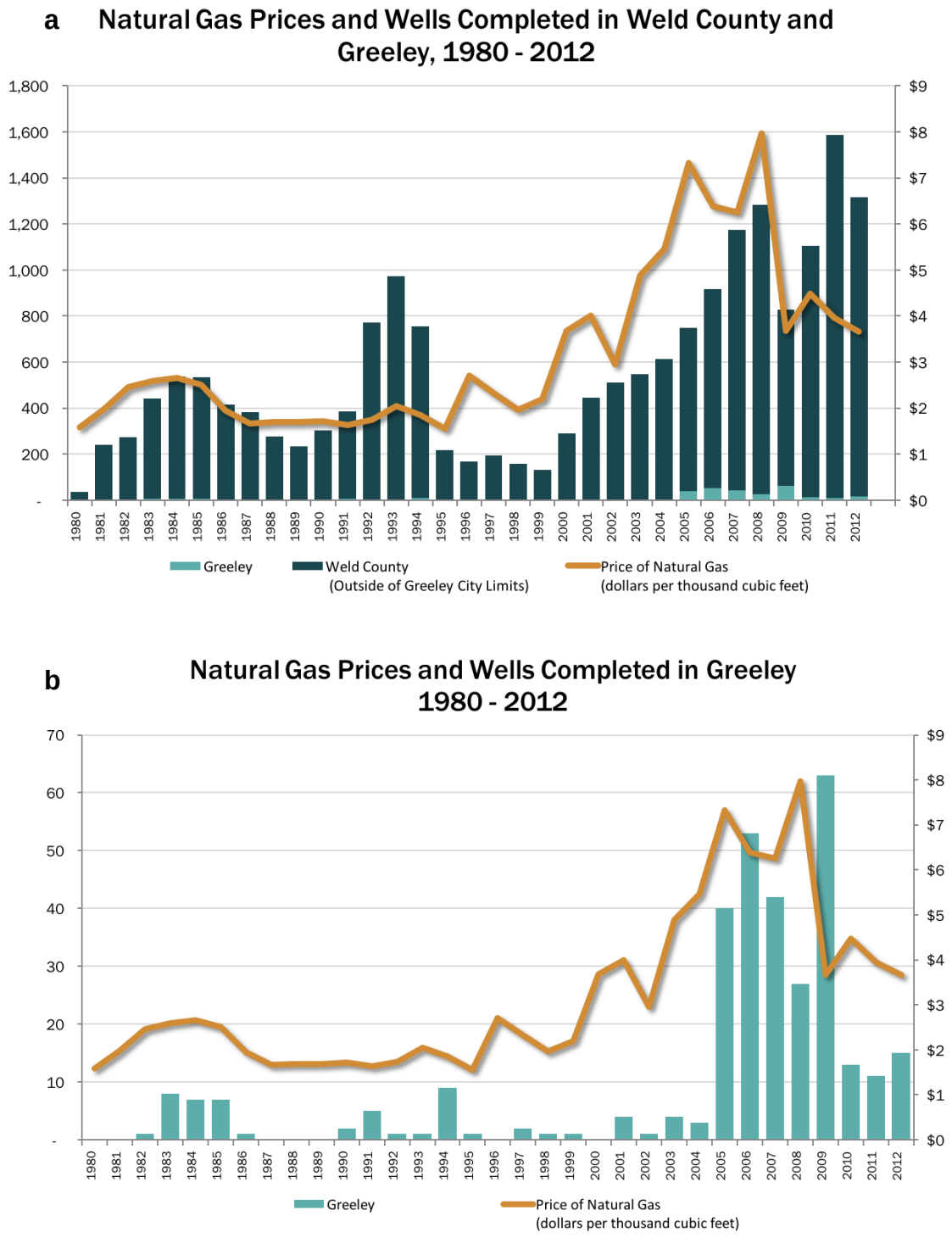


Fig. 5 Compares wells completed per year with equivalent price of natural gas in Weld County (a) and Greeley (b).

Local oil and gas companies that wished to drill inside Greeley sued the city shortly thereafter, launching a protracted legal battle that went all the way to the Colorado Supreme Court (Wade, 1985). As the lawsuit circulated through the courts, the Greeley City Council eased the drilling ban by allowing drilling in industrial zones in 1987 (Lock, 1987). However, even with this exception in place, Greeley saw no drilling for several more years. One can only speculate drilling remained stagnant after the ban was lifted in industrial zones. Three possible factors include operator hesitancy related to the recent ban and court case, a plateau and decrease in oil and gas prices at the time (Fig.4 & Fig. 5), or perhaps because of an increased focus on drilling in other parts of Weld County (Fig. 4a).

The next notable period of drilling within the city came shortly after Greeley's loss of the legal challenge to its municipal drilling ban. That loss came in the form of a Colorado Supreme Court Decision upholding state pre-emption of oil and gas regulation in 1992 (*Lundvall v. Voss*, 1992). In response, the City of Greeley drafted and established new in-city drilling ordinances in 1994 (Taugher, 1994). Interestingly, the data show a rise in wells drilled that very year, which are likely related to Greeley's adoption of drilling ordinances and allowance of drilling in all zones following a Use By Special Review process.

The next and largest boom occurred in Weld County around the year 2000 and continued for over a decade, until oil prices began dropping in 2014. For Greeley, the recent boom appears to manifest inside city limits starting in 2005. As shown in Fig.4 and Fig.5, this increased drilling activity clearly coincides with rising in oil and gas

prices, which climbed from about $30 per barrel in 2000 to $100 per barrel in 2008.[12] One potential explanation for delayed activity within the city is that horizontal drilling became more widespread in the second half of the decade, making it possible for operators to reach under densely populated areas of town.

Drilling activity has remained high for Weld County as a whole since 2000 (Fig. 4 & Fig. 5), however there has been a sharp decrease in drilling activity inside Greeley since 2010. Several factors might explain this decrease. First, it is possible that the easiest and most obvious well sites were already drilled by 2010. Second, 2011 is a notable year for a rise in conflicts with city residents and for national attention on the topic of hydraulic fracturing (Casey, 2011). It has become more difficult and more time consuming to permit wells in the city of Greeley in the years since. Also, as oil and gas prices softened, in-city drilling may have been less economically attractive.

3.2.3 The Spatial Progression of Drilling Throughout the City

Between 1980 and 1985, as drilling began inside city limits, there was a notable concentration of wells on the western edge of town and in the North Poudre Annexation (Fig. 1a). Drilling activity dropped between 1986 and 1995, and well distribution retained similar spatial patterns to previous years (Fig. 1b). Numerous wells were drilled in the North Poudre Annexation in the earlier half of the 1980s (Fig.1a), while the later half of

[12] After a dip in oil prices during the 2008-2009 financial crisis, they rose again to $100 per barrel until 2014, when they began their continued slide.

the decade saw drilling activity further westward in the main part of city limits and in industrially zoned lands slightly to the southeast (Fig. 1b).[13]

Throughout the next era of study (1996 to 2004), general patterns were retained, with a majority of new wells appearing in the west Greeley and a smaller number in the city's eastern industrial zone (Fig. 1c). Interestingly, this is also the one decade of study that saw no activity in the North Poudre Annexation[14].

The decade between 2005 and 2012 proved to be the busiest for in-city drilling activity (Fig. 1d). This is also the first time that in-city activity was greater than the number of wells being incorporated into Greeley by city growth. While much of this drilling occurred in the far western portion of Greeley (by this time, city boundaries are more similar to current boundaries), new well technologies and practices have also allowed for increased productivity in areas that have already seen extensive drilling. Of particular note is the rise of large-multi well pads near the center of town (closer to the areas of drilling conflict in the early 1980s), as well several sites that are more central and further east. These well-pads include Kelly Farms (next to Northridge High School), Bestway, and the pad near Aims Community College. These large, multi-well pads being drilled in busy parts of the city are at the center of the social debate on municipal drilling, whereas the wells located in more spacious West Greeley have received less attention. In relation to the increased spatial concentration of wells into multi-well pads,

[13] This southeastern area is part of an industrial zone, and sees continued well drilling and production to this day.

[14] It is hard to say why this might be. However, it is possible that the area had been maxed out in terms of well spacing. After 2005, drilling activity would return, possibly because of a combination of technological advancement and the changing of policies that reduce well spacing restrictions.

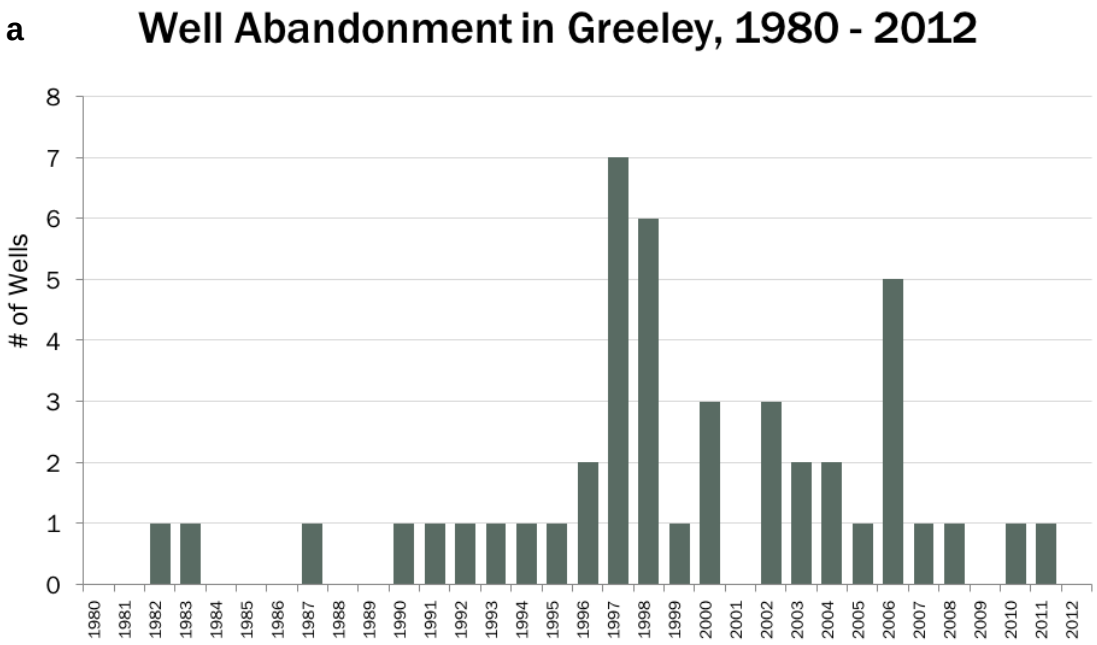
the number of wellbores drilled saw a sharp increase in proportion to the number of well sites.

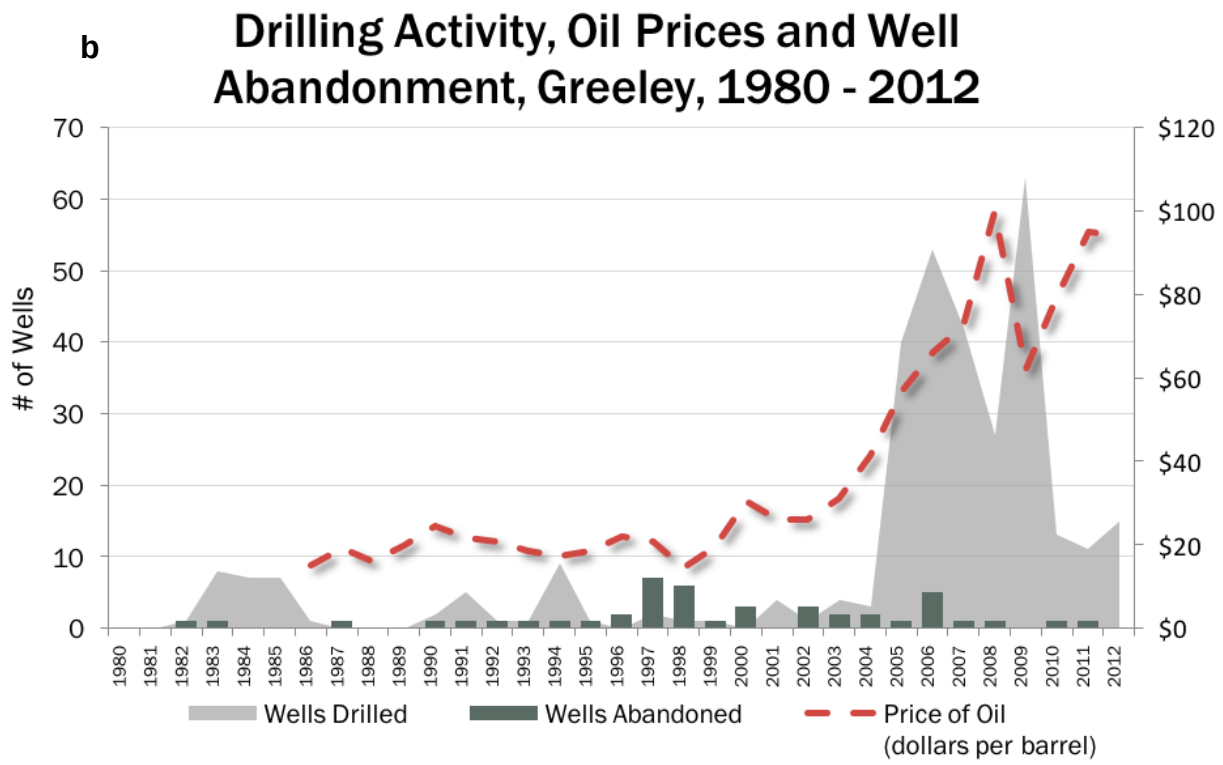
3.3 Research Objective 3: To understand the spatial progression of well abandonment in Greeley, and to investigate whether there is a relationship between the two.

- **RQ3a:** How many wells have been plugged and abandoned or orphaned each year in Greeley since 1980?
- **RQ3b:** Does the rate of well abandonment correlate with the rate of well drilling in Greeley?
- **RQ3c:** Are there any noticeable patterns to well abandonment in Greeley?

3.3.1 Abandoned Wells in Greeley

a





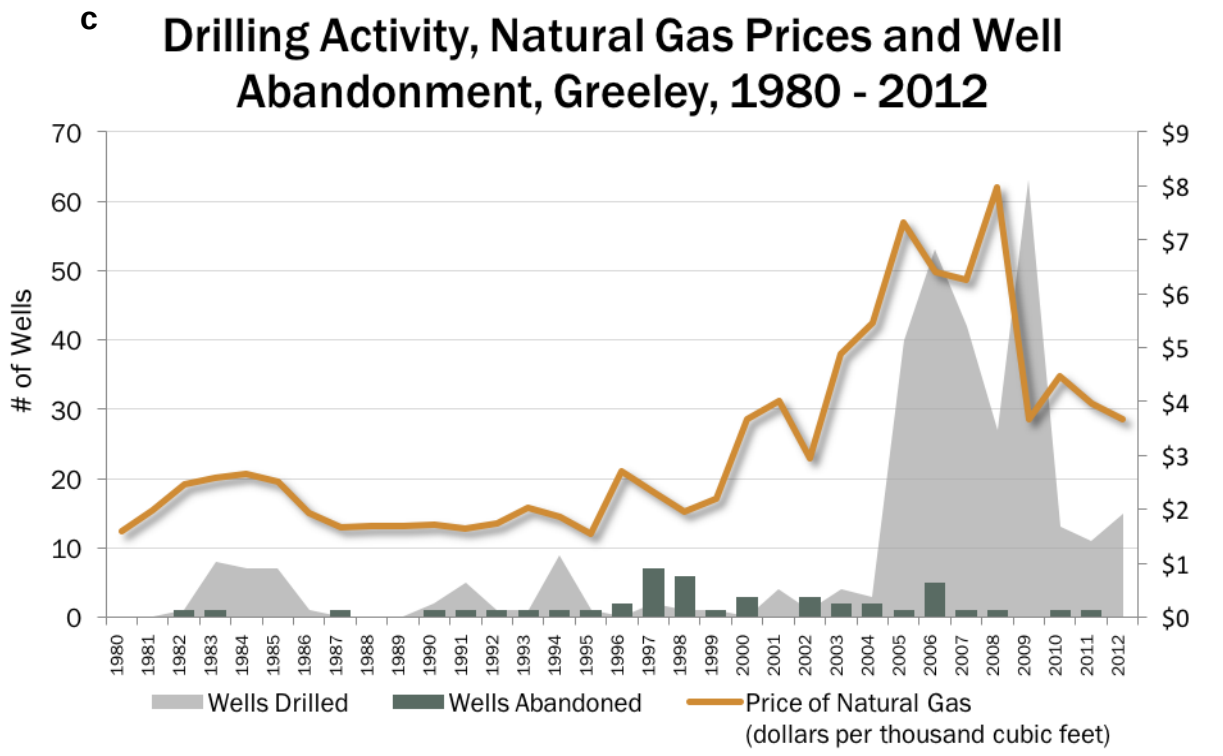


Fig. 6 Indicates well abandonment per year (a) and compares it to drilling activity, oil (b) and natural gas (c) prices.

Abandoned Wells Drilled in Greeley, Colorado

Number of Abandoned Wells: ~ 60

Fig. 7a

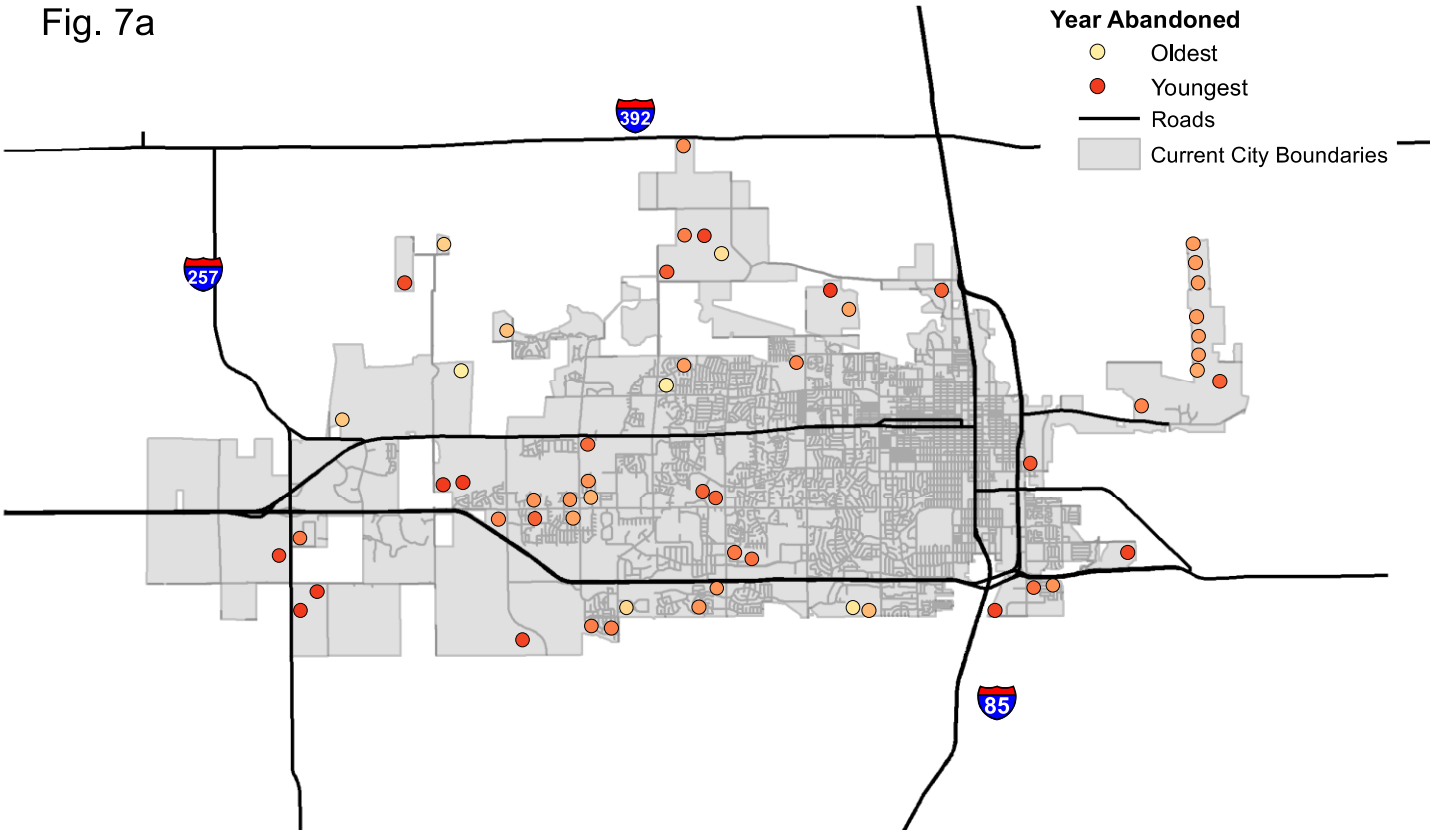


Fig. 7b

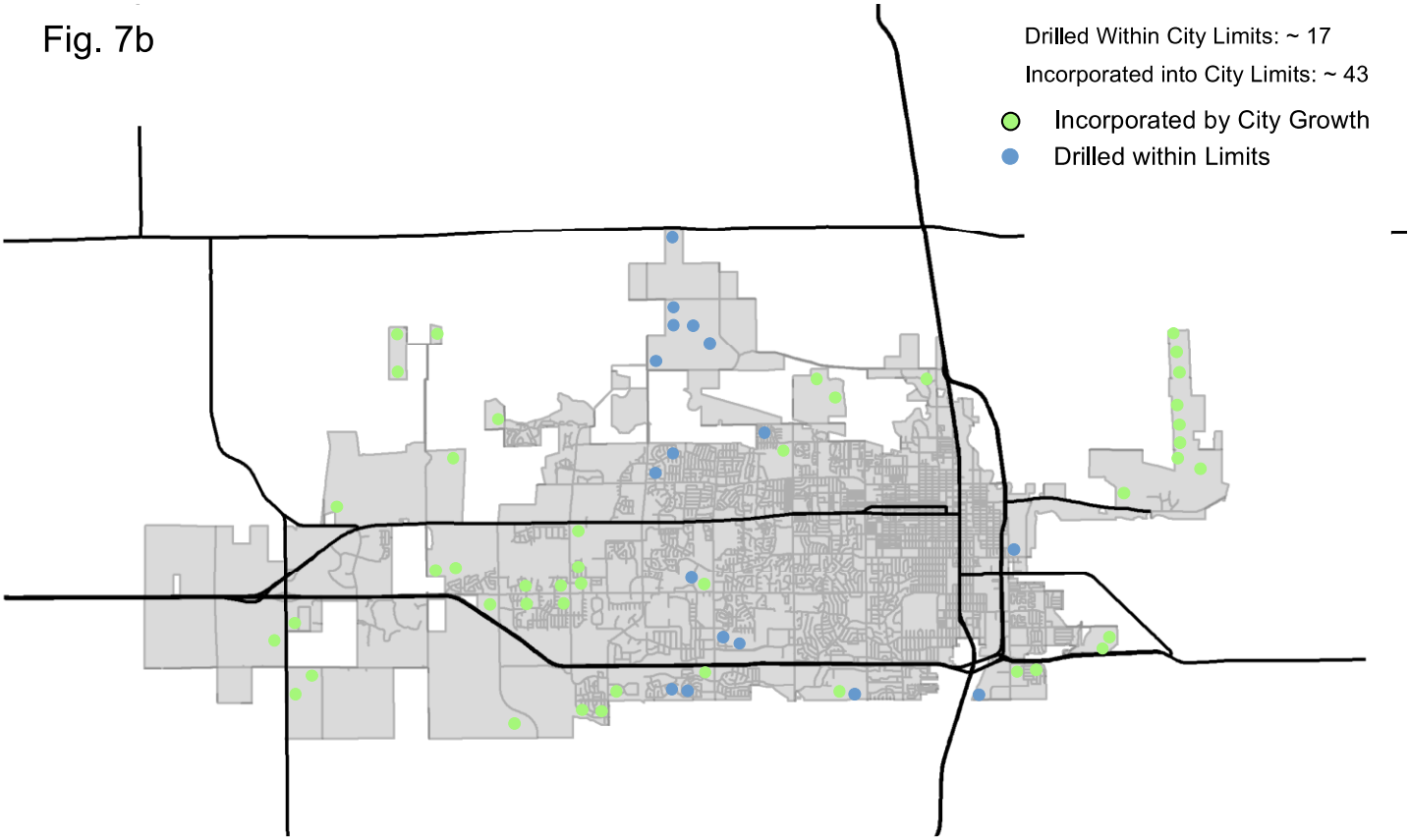


Fig. 7 Abandoned wells in Greeley. Fig. 7a indicates when wells were abandoned, while 7b divides them into wells drilled with city permits and wells annexed into city limits

The number and location of wells abandoned each year, as well as its relation to drilling activity at the time and to gas and oil prices is shown in Fig. 6 and Gif. 7. Between 1982 and 1995, well abandonment remains low, ranging from no wells being abandoned to one well being abandoned (Fig. 6a). Abandonment then spikes in 1997 and 1998 to 7 and 6 wells abandoned, respectively. For 1997, this increase can be explained by 6 wells being abandoned at the location of Greeley's city airport (Fig. 7a) on the east side of town. In 1998, the abandoned wells are more spread out, but three of these wells are located near 20th Street and 71st Avenue, and were all found within the same annexation area, which was annexed the year before. This might highlight a connection between annexation and well abandonment (or city growth vs oil and gas growth), or could relate to suburban development causing these wells to be decommissioned. As shown in Fig. 7b, this western portion of Greeley has experienced the most number of abandoned wells that have been incorporated into the city through annexation[15]. The next spike in abandonment occurs in 2006, and does not have any obvious location pattern, but it is possible that a rise in drilling growth could influence the abandonment of nearby wells, or that a dip in gas prices or some other economic factor could be an influence (Fig. 6)[16].

Similar spikes occur in more recent years, and may be influenced by similar factors. Spatially, most of these more recent well abandonments occur in west Greeley or other

[15] Whether these wells are spatially connected to annexation over time, as the three wells previously mentioned might suggest, or abandonment is more widely distributed across the incorporated area, would be an interesting future study to further explore the relationship between city growth and oil and gas growth.

[16] Perhaps slight market volatility caused an operator company to go out of business. Relating the number of wells abandoned each year to the operators of those wells would be worthwhile in future research.

areas of more recent annexation, which makes sense as most wells are drilled in this area and are being incorporated into city limits (Fig. 7b).

4 DISCUSSION

The main goal of this thesis was to explore the related GIS data in order to see how extraction and drilling patterns in Greeley changed over time. This can then serve as an example of how historical spatial analysis might be applied, while simultaneously evaluating the data and indicating factors that helped shape the drilling history of Greeley. In order to do so, I divided this goal into three separate objectives: to summarize the available data, analyze the drilling patterns, and address well abandonment within the city, respectively.

First, I will discuss the spatio-temporal drilling patterns in Greeley, and the possible factors that can explain them. After that, I will discuss the quality of data, and how historical GIS can be incorporated into city planning and community discussion. I will then conclude by offering my thoughts on the use of historical inquiry and data in present-day conflicts and debate, and how modern tools like GIS might improve this conversation.

4.1 Patterns Seen

One main goal of this research project was to provide an example of how geospatial oil and gas development data could be mapped or graphed to visualize drilling trends, as well as to connect spatial patterns in drilling to Greeley history. Here, I wish to highlight several observed well drilling and abandonment patterns and explore potential historical explanations for them.

There are several major factors that could explain drilling and well abandonment patterns within Greeley, the first being the economic forces that drive the oil and gas

industry. Potential examples of market impact as an encouraging force can include the rise of gas prices during the period of 1980 and 1985 (the first notable spike in drilling) as well as the large rise in prices that occurred between 2005 and 2012, while as an example of negative impact can include a lull in prices between 1987 and 1994, and the slight dip in gas prices around 2011. Changes in standards and practices, including technological advances such as horizontal drilling and high-volume hydraulic fracturing, are also examples of industry change influencing drilling rates. It is also possible that more ideal drilling conditions elsewhere in the county and state might also discourage municipal drilling.

A second factor explaining drilling patterns is the influence of policy and legislation change. Examples include the initial allowance of city drilling permits in 1982 (a rise in drilling), the ban in 1985 (a drop in drilling), the passing of ordinances in 1994 (another rise), and the slight gap in drilling activity between 1995 and 2004 in the North Poudre Annexation (perhaps influenced by well spacing regulations).

A third factor worth mentioning is that of social reaction and community response to drilling activity in city limits[17]. The social conflict related to drilling along the Front Range, most commonly reflected through petitions, bans and moratoria, and initiatives in state legislation, quite possibly affect the rate of activity within city limits, especially in recent years. This is closely related to the second factor, as exemplified by the 1985 ban being created through petitions and later community voting. It is also quite possible that, although drilling in industrial zones was once again permitted by 1987, activity remained low because of public resistance to drilling in the city. Similarly, in addition to

[17] This brings to mind the concept that operators must also have a social license to operate, and not only a legislative one.

falling natural gas prices in 2011, the rise in conflict over hydraulic fracturing and multi-well pads in Greeley starting in 2011 may be pushing some operators to drill in less contentious areas in rural Weld County (or even right outside the city of Greeley on unincorporated land).

A fourth factor that explains well drilling and abandonment patterns in Greeley is the relationship between city growth and oil and gas development growth. Spatially, areas of more recent well drilling are seen in the same areas as recent city annexations. While this relationship may seem obvious when city growth occurs in an area known for widespread oil and gas activity, it deserves closer attention because it will be key to future trends in Greeley. Before 2005, a majority of wells within Greeley became so through annexation and city growth, and it is only after this year that new drilling operations with city permits would be greater than the number of wells annexed in (Fig. 2). As such, the composition of wells within Greeley has been clearly affected by city growth. Similarly, most abandoned wells found within city limits were also incorporated through annexation (Fig. 7b). As a result, any continued city expansion means more abandoned wells within city limits (and the potential for future issues). Aside from this, the sample size of abandoned wells in Greeley makes it difficult to directly correlate abandonment to drilling activity and/or prices.

And, while city annexation growth into areas of older oil and gas activity is causing this relationship in the western part of town, multi-pad drilling growth in the center and eastern areas of town is creating some of the larger current social conflicts. Here, we see that various parts of town might be experiencing different patterns based on the level and type of extraction, and this has resulted in different community

reactions and issues for each area in the city. It is quite possible that the relationship between city growth and oil and gas growth is one of the factors that cause this.

4.2 Data Evaluated

The other goal of this paper was to evaluate the practicality of a historical Geographic Information System for conducting community planning and community conversations about oil and gas development along the Front Range, particularly in regards to accessibility and quality of data. The following section discusses the availability and variety of data available for Colorado, and reflects on the benefits and drawbacks of these sources.

Developing a specifically GIS tool requires synthesizing data from multiple sources, some of them centrally focused around the topic (oil and gas data, in this case form the COGCC), and others being related to general information pertaining to the study area (city and municipality boundaries, annexation data, road data, elevation data, property data, etc.). While the latter type of data very commonly exists in many countries, states, counties, and cities, the former varies significantly by state and region. For Colorado, this specialized data is very easily accessible thanks to the Colorado Oil and Gas Conservation Commission, and goes beyond just simple well locations by providing a wide range of data layers, with each layer containing even more specific data fields, overall providing a large range of information that could result in much research being conducted with even one layer. As such, this GIS tool could have a wide range of data, bringing to mind Richard White's description of these systems as a

"scholarly commons" that can have unlimited combinations based on the focus of the individual user (White, 2010).

While the potential for a topic-focused GIS system is promising, there are some drawbacks that must be noted, particularly in regards to data quality. As documented in this paper, particularly in the methods section, there were many steps that required for cleaning and customizing data. In order to do so, metadata and consultation with the COGCC was required to have an understanding of how to work with it, and based on the density and detail of the data, it is quite possible that this customization process can introduce user error. And documentation error is present, with some entries either being empty, or having inaccurate information logged by well operators[18]. This documentation error is especially of note with abandoned well data, considering the issues that have arose from attempting to locate these wells. Complications can also arise from attempting to combine the various data sets[19], especially as some of the non-spatial data sets (i.e. production data) provide information for multiple wellbores for each well, while GIS layers only reflect individual well locations. Because of this, quantitative research should be carefully conducted, as the accuracy of numerical data may not be guaranteed.

However, this issue in uncertainty is common in Geographic Information Systems, as discussed by Gregory Simon who explains that many historical GIS databases can have error related to "The mathematical, the representational, and the documentary" (Gregory & Healey, 2007). These types of error are to be expected when

[18] For example, there were several wells that had their drilling date listed as 2099.
[19] Making sure data formats were compatible and that data tables were properly joined proved to be the largest challenge of this project while using Arc GIS.

developing these databases, especially as these systems are in early development. Simon goes on to recommend that the best way to build these system (a lengthy process) and to understand the level of error present, is through their continued and varied use by different researchers and planners (Gregory & Healey, 2007).

Disseminating this data to the public by qualitative means is also important[20]. This is possible in a variety of ways, ranging from static and animated cartographic design, to the development of an online historical GIS program that allows users to customize an interactive map with various available layers. This program would ideally involve data sets from multiple sources, as well as making layers and data information more accessible to those unfamiliar with GIS (Gregory & Healey, 2007). Distributing these tools for city planners would not only allow to them to understand existing patterns from several decades of drilling, but also predict future trends either through qualitative cartographic methods or through quantitative prediction models.

[20] For the goals of my research, a more qualitative method proved sufficient.

5 CONCLUSION

In the past decade, unprecedented rise in oil and gas operations nationwide has made the role of extractive industries in the 21st century a focus of public attention. As exemplified by the debates occurring along the Front Range and elsewhere in the nation, the industry is experiencing a time of conflict with communities and suburban growth, and as a result its benefits and impacts are being carefully weighed. Arguably, the current relationship between the industry and these communities it affects is unlike its relationship in the past. With recent developments in this conversation, city planning may see a much larger role in navigating this modern relationship, and it will be important to introduce the proper tools to do. With the help of historic data, this navigation may be enlightened by identifying existing patterns and applying these insights from the past into our future decisions.

As I was investigating my findings, I noticed that the two wells located near West 4th Street and 47th Avenue in Greeley, originally the source of the neighborhood conflict that led to the 1985 ban on drilling, are now designated as abandoned. Just like the forgotten well located in my backyard in Chromo, it is likely that these two locations now blend into the scenery as a historical afterthought. The fact that something less than several decades old, once enough the source of controversy to provoke a community response and ban, is now predominantly forgotten in our collective consciousness despite still being present and worth acknowledging, should be considered. It is my hope that, as the conversation about oil and gas extraction continues, it creates opportunity to combine this historic knowledge with modern ways of analyzing and

displaying information, and allows us to remember and understand this relationship in all of its complexity and importance.

ACKNOWLEDGEMENTS

Guidance for this project was provided by Patricia Limerick and the Center of the American West. A very special thanks to Adrianne Kroepsch, who is is currently pursuing her PhD in Environmental Sciences, and provided guidance and advice to many aspects of this paper. Further guidance on the process was provided by my thesis advisor in geography, Bill Travis. This project was also made possible with funding from the Undergraduate Research Opportunity Program (UROP).

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