**Water acquisition and use during unconventional oil and gas development
and the existing data challenges: Weld and Garfield counties, CO**

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Abstract

Colorado has recently experienced a significant increase in unconventional oil and gas development, with the greatest concentration of activity occurring in Weld and Garfield counties. Water for oil and gas development has received much attention mainly because water resources are limited in these regions and development is taking place closer to populated areas than it did in the past. Publicly available datasets for the period 2011-2014 were used to identify water acquisition strategies and sources of water used for oil and gas. In addition, the annual average water used in these two counties was quantified and compared to their total water withdrawals. The analysis also quantified the water needed for different well types, along with the flowback water that is retrieved. Weld and Garfield counties are dissimilar in respect to development practices for water acquisition, preferred well type and the fate of flowback water. But at the same time, this difference displays how geological characteristics, water availability, and administration localities are the key elements along with economics in the decision making process within the oil and gas sector. This effort also revealed data challenges regarding accessibility and reliability of reported information, and the need for additional data. Improving the understanding of the unconventional oil and gas sector's water use will help identify possible effects and tradeoffs on the local/regional level, which could diminish the conflicting perspectives that shape the water-energy discussions. This would complement the ability to make informed water resources planning and management decisions that are environmentally and socially acceptable.

43 **Keywords:** water use, water acquisition, unconventional oil and gas development, hydraulic
44 fracturing, Colorado, Weld County, Garfield County.

1. Introduction

Several regions in the United States, over the past decade, have experienced a significant rise in unconventional oil and gas development due to technological advancements (Murray, 2013). This has offered new sources of oil and gas supply, and boosted local economies (Considine et al., 2011; Higginbotham et al., 2010). However, the increased development intensity and the proximity to populated areas resulted in increasing public concerns regarding potential environmental effects and associated costs from hydraulic fracturing activities (King, 2012). Several studies have identified potential environmental/human risks related to oil and gas development (Burton et al., 2016; Clark et al., 2012; Colborn et al., 2014; Goodman et al., 2016; McKenzie et al., 2012; McLaughlin et al., 2016; Mehany and Guggemos, 2015, 2015; Osborn et al., 2011; Pacsi et al., 2013; Vengosh et al., 2014; Walton and Woocay, 2013). One of the most debated environmental issue is the possible contamination of fresh water resources. Contamination due to direct hydraulic fracturing fluid migration is highly unlikely to take place (Birdsell et al., 2015). Howarth et al. (2011a) and Vidic et al. (2013) conclude that most common sources of water contamination from hydraulic fracturing activities include: well blowouts, casing leakage, surface spills from storage facilities, and improper disposal of fracking fluids. The oil and gas development boom, apart from the involved concerns about possible environmental implications on water resources (Vengosh et al., 2014), increased water demand for unconventional oil and gas extraction. Water demand for unconventional oil and gas on a local level is competing with traditional water demands on the available water resources. Only recently, some water use estimates for the United States became available (Chen and Carter, 2016; Gallegos et al., 2015; Kondash and Vengosh, 2015). Other studies show that the use of

unconventional sources of energy, especially shale gas, could decrease the overall water consumption if such sources are going to offset coal power plants' water use (Grubert et al., 2012; Laurenzi and Jersey, 2013; Pacsi et al., 2014), but at the same time could increase the greenhouse-gas footprint (Howarth et al., 2011b). There is an intricate connection of energy and water resources formulating the water-energy nexus (Gleick, 1994). A subset of the water-energy nexus is the use and supply of water and unconventional oil and gas resources. Decisions concerning water use related to energy production that are made by oil and gas operators, water managers, and policymakers need to be based on openly available data collected in a reliable and transparent fashion (Goodwin et al., 2013; Malone et al., 2015; Nicot and Scanlon, 2012; Orford, 2013). Although data need to play a critical role in complex decision-making surrounding the water-energy nexus, a lot of data (i.e. water sourcing) are still not available.

In Colorado, the greatest concentration of new drilling has occurred in the formations of the Denver-Julesburg Basin in the northeast portion of the state and the Piceance Basin, is located in western Colorado as seen in Figure 1 (Colorado Oil and Gas Conservation Commission, 2015). The Denver-Julesburg Basin is producing oil and gas. Whereas the Piceance is exploited for the dry gas. In Colorado the 2014 crude oil production increased to 95,192 thousand barrels from the previously recorded amount of 49,435 in 2012 (U.S. Energy Information Administration, 2015a). The gross natural gas production was 1,631,390 million cubic feet (1,709,376 in 2012) (U.S. Energy Information Administration, 2015b). Statewide water use for oil and gas activities is estimated to be approximately 0.1% of overall water use, or 22,202,673 m³ per year (Colorado Division of Water Resources et al., 2012). In reality, this statewide estimate is not useful on a local scale, since different local factors could greatly influence the actual amount water used including competing water demands (Clark et al., 2013; Nicot and Scanlon, 2012; Rahm and

Riha, 2012). The quantity of water used per well is dependent on several different factors including: the geologic formation, type of well (vertical, directional, horizontal), number of hydraulic fracturing stages, distance of the total reach within the production zone, and the type of hydraulic fracturing fluid (e.g. cross-linked gel or slickwater). Prior work estimating water use in the Denver-Julesburg Basin, Goodwin *et al.* (2013) found that horizontal reaches in productive shale formations are increasing from 1.6 km to 3.2 km or longer. The length of the reach increases the number of stages and the total quantity of water used during completion. , Goodwin *et al.* (2013), also reported that the median water requirement in the Denver-Julesburg Basin was 1,363 m³ per vertical well and 10,868 m³ per horizontal well, whereas the extended horizontal wells (greater than 25 hydraulically-fractured stages) require more water (median 21,274 m³). Studies examining water use in Piceance Basin and more specifically within Garfield County report a wide range of water use estimates. A study conducted by the U.S. Environmental Protection Agency (2012), estimated a range of 3,785 to 34,069 m³ per well (median 4,921 m³). Another study conducted by the EPA suggests a median of 6,462 m³ per well (U.S. Environmental Protection Agency, 2013). The aforementioned studies illustrate data inconsistencies that can create barriers to predicting future water use and associated tradeoffs for making policy decisions and developing regulations. At the same time, there are water quality studies within the literature (Gross et al., 2013; Kassotis et al., 2013), investigating surface and groundwater contamination that could be associated with hydraulic fracturing activities in Weld and Garfield counties.

Figure 1: Map of oil and gas wells in Colorado (wells shown as green dots, the polygon in yellow is the Denver-Julesburg Basin and Piceance Basin in pink). The number of producing wells in Weld County and Garfield counties as of 14/7/2015 is 20,918 and 10,499 respectively. (Colorado Oil and Gas Conservation Commission, 2015)

Developing and implementing water resources planning and management focused on water use for unconventional oil and gas, is imperative. It is also important to identify the local or administrative characteristics that influence water sourcing decisions along with the development patterns that impact water use intensity. In response, this study explores water acquisition strategies for oil and gas and their sources in Garfield and Weld counties in Colorado. It also identifies how much water is used for oil and gas well starts in these two counties and compares it to the total water withdrawals. The present effort analyzed, and compared publicly available water use datasets and identified well development patterns, normalized water use per well, and flowback water (see glossary of terms) and its disposal practices that are taking place in Garfield

and Weld counties. The two Colorado counties were also chosen because they are located on two distinctly different basins in terms of producing products, which makes this study more representative. Additionally, this work discusses the existing data limitations and the relevance for other regions. The need for accessible and reliable data is underlined as the basis of better water use predictions which would support complex decisions that involve local communities and other competing and conflicting water uses, such as agriculture.

2. Datasets & Methods

This study used a comparative case study approach on the county level and was conducted by using a variety of sources and datasets from publicly available sources described below.

2.1. Water Acquisition

Gathering information about water sourcing for oil and gas development in Colorado is challenging since there is no state or federal regulation in place to require its reporting. Water right decrees and substitute water supply plans (SWSPs) were collected from Colorado's Division of Water Resources electronic document archive called Laserfiche Weblink (<http://dwrweblink.state.co.us/>) and the Hydrobase (<http://water.state.co.us/DataMaps/Pages/default.aspx>) datasets. Those datasets were searched with Boolean search logic that included searching for various combinations of county name, oil and gas company name, water organization name, and keywords such as natural gas, oil, produced water, and nontributary groundwater (Supporting Information: Glossary of Terms). Records returned from searches were coded for specific information, such as applicant and water right holder name, diversion location, case number, appropriation date, water source(s), decreed

use(s), volume, and proposed new use(s). In addition, records obtained from the Colorado Division of Water Resources website offered general insight into the municipalities working with oil and gas companies and water service companies. Searches included: prominent oil and gas and municipality names, and keywords such as energy, oil, and gas. Analysis of these documents was the first step in determining the water buyers and sellers in the study areas.

Nontributary groundwater wells are a reliable source of water for the oil and gas operators. This water is not subject to administration within the prior appropriation law, meaning that there is no obligation to senior water right owners. The identification of the nontributary groundwater wells used for oil and gas development, were used the Colorado Division of Water Resources open data sets (<https://data.colorado.gov/browse?category=Water>) and Hydrobase. Although, they are produced by the same organization, the different formatting and attributes made it necessary to use both. Despite the availability of information, the state does not categorize the water decrees used for oil and gas separately from other industrial uses. This hinders the process of acquiring data on water use by oil and gas operators and increases the chances of not capturing all of them. Data were collected and analyzed in a three-step process. First, all of the recorded active water well structures located within Weld County were identified and the nontributary wells were queried from the Department of Water Resources structures dataset. There are not any nontributary wells within Garfield County. Then, a code was developed (Visual Basic for Applications in Microsoft Excel) to automatically retrieve the permit attributes (such as permitted use) from the website version of Hydrobase, for the water well structures that had an associated permit number. Thus, it was possible to narrow down the nontributary water wells to those that included an industrial permitted use. The Department of Water Resources permits database was also used to identify industrial water well permits without an associated active well

structure and to record the issued nontributary groundwater permits with unknown well construction status. The latter is important because it depicts the current status and gives an accurate picture of the future water extraction capacity from those wells. The final step involved evaluating the documentation of each candidate well permit, in order to identify the nontributary groundwater wells used in oil and gas operations.

Considering the lack of readily-available data in this topic, especially about water acquisition, it was necessary to incorporate a series of personal communications. This was conducted through snowball sampling, with irrigation company staff, municipal water suppliers, the Colorado State Engineer's Office, the Colorado Oil and Gas Conservation Commission, and oil and gas industry representatives. Those personal contacts made it possible to gather information, which otherwise would not be captured by the aforementioned databases. Thus, it provided a better understanding about water acquisition strategies.

2.2. Oil & Gas Well Development and Water Use

Well characteristics and water consumption data were extracted from publicly available databases from state organizations and the FracFocus database (FracFocus Chemical Disclosure Registry, 2015). Per existing administrative protocols, within 30 days of completing a well, the Colorado Oil and Gas Conservation Commission (<http://cogcc.state.co.us/>) requires operators to report their water use through the Completed Interval Report form (Form 5A). Completed Interval Reports for both counties were extracted for the period of time from 2011-2014. The available data in 2014 for Garfield County were till July while for Weld County were until April. Data collected on active oil and gas wells contained total volume of fluids used in treatment because the amount of water was not reported frequently in the completion forms. Also, the data collected included, not always, whether fresh or recycled water was used, the amount of

flowback water recovered within the period of well completion and reporting, disposal methods for flowback water and the number of staged intervals. In order to categorize the wells into different types (vertical, directional, and horizontal), the directional well database by Colorado Oil and Gas Conservation Commission was utilized for identifying the directional and horizontal wells, along with their length. Any well that was not included in the the directional well database was assumed to be a vertical well. A thorough quality assurance and quality control (QA/QC) procedure was performed for the Completed Interval Report dataset that included: consolidation of duplicate well entries with fracture jobs in several geologic formations, correction of entries reporting values in incorrect units, and exclusion of entries with missing values. Furthermore, several QA/QC tests were performed on each record (e.g., amount of total fluids used should have been greater than flowback water) to make sure that discrepancies were not present. The consolidation of duplicate well entries yielded 1077 records in Garfield County and 2076 records in Weld County. The QA/QC procedure resulted in 712 and 2022 records, respectively for the two counties. The main reason for discarding a record was the lack of reporting total fluids used. Lastly, outliers and spurious data were detected and excluded from further analysis by using an adjusting boxplot method, (Hubert and Vandervieren, 2008) that accounted for distributional asymmetry. This approach was chosen instead of other methods (extreme Studentized deviation, percentiles) because the data were not normally distributed and contained outliers.

Information from FracFocus was extracted for the period of 2011-2014. Prior to April 1, 2012, disclosure of certain well completion information by Colorado oil and gas companies was reported to FracFocus (<http://fracfocus.org>) on a volunteer basis. Since then, operators have been required to report data to FracFocus within 60 days following the conclusion of a hydraulic fracturing treatment. FracFocus data for the two counties included the combined water volume

on a per well basis, without specifying the source of that water (freshwater or recycled). Data were evaluated following the QA/QC procedure resulting in 1,843 producing gas well records in Garfield County from 1852, due to outliers, and 4,046 producing oil and gas well records in Weld County from 4093. Although through FracFocus more records were available, the information was less detailed. Thus, it was used mainly for cross-checking the information about total water volume used with the dataset from Colorado Oil and Gas Conservation Commission.

3. Results & Discussion

3.1. Water Acquisition Strategies

Understanding how water is acquired gives us insight into the changing nature of water use. In this case, the South Platte and Colorado River Basins, provide critical insight into the assessment of possible impacts on these water systems. All water rights in Colorado have a legal designated use and water used for oil and gas development must be adjudicated as industrial or multi-use water (Supporting Information: Glossary of Terms). In Garfield County, the Colorado River and its tributaries are the major sources of water sought after for gas development. In Weld County, the South Platte River and groundwater aquifers serve the water needs of oil and gas companies. Additionally, some water originating from the Colorado River is diverted across the continental divide and becomes part of the water portfolio of the South Platte River Basin. This water, known as the Colorado Big Thompson Project, is of interest to oil and gas operators due to its multi-use designation. Because available surface and groundwater supplies in both basins are for the most part fully appropriated, water for oil and gas development is typically acquired from existing users and sources including: municipalities, agricultural organizations and producers, tributary and nontributary groundwater, native produced water, and acquisitions through new

appropriations during times of excess water (Colorado Division of Water Resources, 2014; Colorado Division of Water Resources et al., 2012).

3.1.1. Weld County

In Weld County, there are few oil and gas companies who actually own water rights. Due to the short-term nature of exploration and drilling, most companies prefer to lease needed water from municipalities, private entities such as water service companies, as well as irrigation and reservoir companies.

There are documented cases of municipalities and quasi-municipal water suppliers leasing their excess supplies, including treated water and wastewater effluent, to oil and gas companies.

Because accounting of water deliveries by municipalities is tracked by the municipal agency itself, this information is not available from a single source and is usually commingled with their other water data available to the public. To legally be used for oil and gas, the water must be adjudicated as industrial or multi-use water, or a substitute water supply plan (SWSP) must be obtained from the state. An example of multi-use water that is an important source for oil and gas companies is the Colorado Big Thompson trans-mountain diversion of water. As long as a provider's water right allows for industrial use and the water is delivered within their service area, it is considered a legal use of the water. However, the final destination of the water is difficult, if not impossible, to track in many cases.

The agricultural sector has become a significant source of water for oil and gas companies.

Irrigation and ditch companies lease their water, and in some cases, lease income makes up a significant portion of their annual operating budget. One particular irrigation company in Weld County has filed several applications in water court to increase infrastructure, storage, and recharge water rights with lease income totaling \$2,180,000 out of a total projected income of

\$3,189,959 in 2014, representing 68% of their total water lease sales. As cited in their 2013 Annual Stakeholder Meeting documents, it was indicated that one particular lease would allow them to pay off loans for water projects. Coding of water decree records from Weld County identified 22,189,105 m³ of water, which changed use from irrigation to industrial or multi-use for oil and gas activities.

For-profit water service companies in Weld County play a significant role in the water acquisition and delivery processes. There are several examples of water service companies who have actively pursued new water rights, in order to provide water to oil and gas operations. One specific case involves a water service company which, prior to 2010, supplied water for multiple uses, but which is now applying for joint decrees with other water service companies. This type of collaboration helps the chances of approval of their water right applications because both parties have strengths to contribute. This same company has several augmentation plans which allow for the ability to pump a well and replace their senior surface water at a different place and time. They can replace water in the system through their augmentation plans, effectively always having a reliable source instead of building a pipeline.

Oil and gas companies in Weld County are further implementing flexible strategies to ensure reliable water supplies for their operations. This includes tapping into nontributary freshwater aquifers to help reduce competition for fully-appropriated surface and tributary groundwater sources. Nontributary groundwater has a limited hydrological connection to surface water and it is considered a viable source for oil and gas companies, because it is not administered within the priority system. Data from the Colorado Division of Water Resources includes 103 records (77 permitted and constructed; 26 permitted with unknown status of completion) of nontributary groundwater wells related to oil and gas development in Weld County (Figure 2). The annual

maximum average withdrawal for all 103 nontributary well permits could yield about $15 \times 10^6 \text{ m}^3$. If those wells were to be used exclusively for oil and gas development could meet 2.5 times the current estimated water demand in the county. New well permits are issued for properties which have already secured a nontributary groundwater right, allowing the water rights holder to utilize the full permitted amount. In addition to industrial use, all of the wells have additional uses (e.g., irrigation, commercial, municipal).

Figure 2: Nontributary groundwater wells used for oil and gas in Weld County (red diamonds; includes permitted with unknown status of completion, and permitted with constructed status) (Colorado Division of Water Resources, 2015).

In order to better understand present practices in Weld County related to water transfers, the potential pathways of water acquisition, is necessary to represent the findings relevant to a county level. Figure 3 is a graphical representation of Weld County water withdrawal estimates based on Maupin et al. (2014), expressed in percentages of total withdrawals. The last level of

connection was added to provide representation of the pathways of water acquisition for oil and gas development, identified by this study. It also helps link water use for oil and gas with other uses. The annual average water used for oil and gas according to the FracFocus records for Weld County for the period of 2011-2013 was 16,240 m³/day, which, according to the total estimated water use in Weld County (Maupin et al., 2014), is approximately equal to 1.0% of total annual withdrawals taking place in Weld County. This small percentage of water is not necessarily all from sources within the county. The reason that the links are of equal width at the last section of Figure 3 is due to the lack of source reporting in Colorado.

Figure 3: Estimated water withdrawals and their sources in Weld County, along with the sources of water acquisition for oil and gas. The annual average water used for oil and gas development during 2011-2013 is expressed as percentage of total withdrawals (FracFocus Chemical Disclosure Registry, 2015; Maupin et al., 2014).

3.1.2. Garfield County

In general, Garfield County oil and gas companies tend to hold historic water rights that they obtained during the 1950s-1970s, with the expectation of a federally-supported oil shale boom. Since then, some companies sold their water rights and others continue to speculate on gas shale extraction. With improved hydraulic fracturing technologies, unconventional natural gas has become the dominant form of gas extraction and now maintains a steady presence in Garfield County and throughout the Piceance Basin.

The relatively senior date of Garfield County oil and gas companies' water rights gives them some certainty of available water. They are currently active in firming their conditional water rights. Once a conditional right is awarded, the holder has reserved a place in the priority system. The applicant must demonstrate that they are making progress toward beneficial use of the water and that the appropriation can and will be completed. During the summer of 2014, there were three change cases for conditional water rights, where oil and gas companies applied to change multi-use, conditional water rights adjudicated for oil shale development into a single-use decree for unconventional natural gas development. In these cases, oil and gas companies would need to show that they are working toward the level of extraction that would make use of the beneficial use quantities, defined in the conditional water right.

When oil and gas companies do not hold enough decreed water or consider it uneconomical to transport water to the well location, and may lease reservoir units from local water entities. Between 2000-2013, one entity reported leasing a total of 5,481,593 m³ to natural gas uses in Garfield County, at a rate of \$125 to \$170 per 1,223.48 m³ (1 acre-foot). This entity also charged \$400 application fee per lease and reported selling 13,014,467 m³ in supplemental contracts which is the total quantity available for lease. Another entity reported charging \$185 per

334 1,223.48 m³ plus a \$250 application fee. These data illustrate the range of costs associated with
335 acquiring water for natural gas development. While reservoir units provide a significant source
336 of leased water for operations, some companies have contracts directly with the U.S. Bureau of
337 Reclamation, although these quantities are relatively small compared to other leased reservoir
338 units. Leasing is also occurring under a new type of augmentation plan called an umbrella case.
339 In contrast to water right decrees that tend to have very specific parameters, umbrella cases are
340 considered more flexible by allowing individuals to lease water without going through the
341 process of changing a water right. These portfolios have multi-use specifications and have
342 largely replaced SWSPs in Garfield County. The umbrella portfolios are less expensive, more
343 conducive to development, available on a contract basis, and each individual who needs water
344 will not be required to obtain their own decree. While the number of SWSPs have decreased with
345 diminished production and normalized use of umbrella cases, they are still a source of short-term
346 water supplies and can result in a more simplified path to temporary approval.

347 The Colorado Division of Water Resources is currently undergoing litigation with oil and gas
348 companies in Garfield County who have applied for 100% of the multi-use decrees (irrigation,
349 municipal, gas shale, etc.) to be changed into 100% gas use, or a change of use from multi-to
350 single-use. The agency aims to allocate only the amount of water that can realistically be put to
351 beneficial use in order to combat speculation, which is not allowed under Colorado water law.
352 Within these cases, companies are changing type and place of use to accommodate new
353 technologies and access gas resources. A personal communication from Colorado Division of
354 Water Resources confirmed that the firming of water rights into gas use will prove to be a
355 significant water source for operations in Garfield County, with the caveat that speculation and
356 awarding more water is of great concern. In addition to the most recent firming activities, many

oil and gas companies hold conditional water rights secured from water right change cases out of irrigation use in the 1970s and 1980s. Due to the dynamic nature of the water right system is important to track all changes in order to understand regional level trends and their implications.

Figure 4: Estimated water withdrawals and their sources in Garfield County, along with the sources of water acquisition for natural gas. The annual average water used for natural gas development during 2011-2013 is expressed as percentage of total withdrawals (FracFocus Chemical Disclosure Registry, 2015; Maupin et al., 2014)

Scaling water transfers to local level and identifying the possible pathways of water acquisition, for Garfield County are also necessary to have a relevant picture. Garfield's County water withdrawal estimates are based on Maupin et al. (2014), and expressed as percentages of total withdrawals (Figure 4). The last level of connection was added to provide a representation of the pathways of water acquisition for gas development, identified by this study, and to link water use for oil and gas with other uses. The annual average water used for oil and gas, according to the FracFocus records for Garfield County for the period of 2011-2013 was 19,319 m³/day.

According to the total estimated water use in the county (Maupin et al., 2014), this is approximately equal to 2.0 % of total annual withdrawals taking place in Garfield County. This small percentage of water is not necessarily all from sources within the county. The reason that the links are of equal width at the last section of Figure 4 is due to the lack of source reporting in Colorado.

3.2. Oil & Gas Well Development Trends

Garfield and Weld counties dominate oil and gas extraction in Colorado (Figure 5) and different oil and gas development practices are taking place in the two counties. The noticeable difference between the well types (vertical, directional and horizontal) drilled in the two counties is attributed to operational decisions and the geological characteristics of the shale formations, namely the exploitable thickness of the formations in Piceance Basin are greater than in the Denver-Julesburg Basin. Over the last six years, Garfield County experienced a declining rate of new well starts (Figure 5) and directional wells are drilled more often than other well types (Figure 6). In Weld County, about 1,500 new well starts were recorded every year since 2011 and the preferred well type shifted during the last years from vertical to horizontal wells (Figure 6). A reported increase of horizontal reach length was found. The 2011 median length was 1.5 km whereas in 2014 was more than 1.8 km(Figure 7), with many cases extending beyond 3.0 km, which is in agreement with the findings of Goodwin *et al.* (2013). The well type and lateral length factors can explain the rise of median staged intervals per well in Weld County (Figure 8). The different shape of the stage interval kernel density estimation for 2014 in Weld County (Figure 8) is the product of very few vertical and directional well completions reported until April, 2014. As for Garfield County, there is not a significant change in the median number of

395 staged intervals (Figure 8). The outliers in Figure 8 are related to the high number of staged
396 intervals of horizontal wells.

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398 **Figure 5: Annual (bars) and cumulative (lines) hydraulic fracturing well starts (COGCC**
399 **2015)**

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402 **Figure 6: Well type trends in Garfield and Weld counties, 2011-2014 (COGCC dataset)**
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Figure 7: Length of horizontal wells in Weld County and their rotated kernel densities on each side (COGCC dataset)

Figure 8: Stage intervals for Garfield and Weld counties and their rotated kernel densities on each side (COGCC dataset)

3.3. Water Use

Water needed in oil and gas well completions is dependent on several different factors including: the geologic formation, type of well, number of hydraulic fracturing stages, length of the reach within the production zone, and the type of hydraulic fracturing fluid (cross-linked gel or slickwater). Given these differences, it is more appropriate the reporting of a normalized water volume on a per well basis rather than lumping records with dissimilar attributes that could skew

the results. Horizontal wells are becoming more common in Weld County. The calculation of the water amount used per stage results in more precise determination of total water use per well as suggested by Goodwin et al. (2013). In addition, it is essential to disaggregate this information into single-stage wells vs. multi-stage wells, because they represent different forms of development. The normalized total fluid amount used per staged interval in multi-staged wells in Weld County is less than those for single-staged wells. The annual normalized total fluids used per staged interval for Weld County are 783.01 m³ per stage for single-staged wells and 542.62 m³/stage for multi-staged wells (Figure 9). In Garfield County, the median normalized total fluid amount used per staged interval at multi-staged wells is 682.02 m³ per stage. Due to very few records available for single-staged wells in Garfield County for the period 2011-2014, it was not possible to estimate the statistical characteristics of the normalized total fluids per stage.

In order to understand the effects of different development practices on water requirements, it is essential to investigate total volume of fluid per length for directional and horizontal wells.

Figure 10 illustrates the difference in the normalized total volume of fluid per length for horizontal and directional wells in both counties for the study period. Horizontal wells tend to require more water than directional wells. In Garfield County, the median normalized total volume of fluid per length for horizontal wells is 19.66 m³ per m and for directional is 11.02 m³ per m. There are cases where directional wells exceeded 50 m³/m. In Weld County, the median normalized total volume of fluid per well length for horizontals is 7.25 (m³ per m) and for directionals is 3.43 (m³ per m). The upward trend in horizontal well length (Figure 7) increases the number of stages, and subsequently, the total quantity of water used during completion.

Figure 9: Normalized total volume of fluid used per staged interval in Weld County and their rotated kernel densities on each side (NA: not enough data) (COGCC dataset)

Figure 10: Normalized total volume of fluid used per length of well and their rotated kernel densities on each side (COGCC dataset)

The comparison of the two publicly available datasets (COGCC and FracFocus) for Weld and Garfield counties provides a quality check for discrepancies between the two. Water consumed for oil and gas development reported to COGCC includes all liquids used (treatment fluid, acid and water). In FracFocus, the total amount of water used in hydraulic fracturing is reported. In

Garfield County, the median volume of water per well reported in the COGCC database is 5,441.02 m³ and in FracFocus is 7,138.39 m³. For Weld County, the median volume of water per well is 2,740.62 m³ for the COGCC dataset and 1,706.94 m³ for FracFocus. The annual distributions and the quantiles in both counties are presented for both datasets in Figure 11. It was anticipated that some inconsistency would be present between the two datasets, since the reported amounts were not equal. However, the present differences between the datasets raise questions about the quality of the reported data.

Figure 11: Total volume of fluid consumed for hydraulic fracturing on a per well basis and their rotated kernel densities on each side (COGCC and FracFocus dataset)

3.4. Flowback Water and Disposition Strategies

For the purpose of this study, flowback water was defined as the water volume that returns to the surface between completion and reporting to COGCC (max of 30 days). For Garfield County,

COGCC data indicate that the flowback water is 48% of the total volume of fluid injected. In Weld County, flowback water is 11% of the total volume of fluid injected. In Garfield County, companies that recycle nearly all of their water are also acquiring new water rights, which could be explained by the need for more water to be allocated per hydraulic fracturing job, than the readily available recovered flowback water. The annual flowback water as a percentage of total fluids used is presented for both counties in Figure 12.

At the same time, the significant amount of the fluids recovered in Garfield County within the flowback period has created incentives for the industry to adopt a pro-reuse strategy. The reported amount of flowback water recycled in Garfield County is 96% compared to only 28% in Weld County. Informal personal communications with Weld County oil and gas operators indicated that they recycle about 25% of flowback water. Figure 13 presents the annual percentage of flowback water reused. The 2014 shift towards recycling in Weld County (Figure 13) could be an artifact of incomplete data. However, the movement toward reusing flowback water and recycling produced water appears to be of interest to oil and gas companies as these practices can reduce diversions of freshwater. This has the potential to be beneficial especially during periods of drought, but also reduces the amount of flowback water going to deep well injection disposal and thus minimizing the risk of seismic activity. Although there are no publicly available relevant data to support the argument of why the industry is not utilizing more flowback water in Weld County, the literature (Scanlon et al., 2014) suggests that if the water recovery is too small the first 30 days of production, compared to water demand for new well starts, then flowback recycle is not the preferred practice. This may be the case in Weld County until 2014, when there was an influx in the number of well starts (Figure 5). At the same time Weld County had a low water recovery rate during the first 30 days after well completion. The

489 COGCC well completion records indicate that fresh water is the primary water source for new
490 wells in Weld County, where recycled water is mainly used in Garfield County.

491
492 **Figure 12: Flowback water as percentage of total fluids used and their rotated kernel**
493 **densities on each side (NA: not enough data) (COGCC dataset)**

494

Figure 13: Percentage of annual flowback water recycled in Garfield and Weld counties (COGCC dataset)

3.5. Data Limitations and Recommendations

Colorado is a water-limited region, with strict water administration. Much attention is paid to the volume of water required for drilling and hydraulic fracturing of oil and gas wells, since this water is considered fully consumed as it is rarely returned to the system. This effort revealed the need for additional data and metadata in Colorado. The availability of additional data parameters would greatly improve the understanding of water use for oil and gas development in Colorado. Research suggests transparent, accessible, and reliable data can provide multiple benefits including: improved trust in scientific research, better information for regulations and policy which protect human and environmental health, better data-sharing arrangements among agencies, and expansion of stakeholder involvement (Laituri and Sternlieb, 2014; Malone et al., 2015).

COGCC data have changed over time in order to be relevant to the rising concerns regarding unconventional oil and gas development. The State of Colorado's regulatory institutions are still developing their data reporting systems and requirements. Challenges for data comparability and questions about their reliability were created as data requirements increased during the booming oil and gas development in Colorado. Because water use data for oil and gas development are self-reported by the operators, different reporting approaches cause inconsistencies and errors that might not always be addressed by the regulating agency unless brought to their attention. There were cases where some data records were reported multiple times, or in differing units than required, which made QA/QC process an integral part of this effort in order to correct or discard unreliable records before further analysis. Most of the well completion reports used for this study were missing data fields and as a result valuable information is lost. An automated reporting system should be in place to ensure compulsory information is filled and this would help reduce the loss of information and data errors. An integral part for the success of such an automated process is the mandatory and comprehensive training for the end users, the operators. Another issue identified in the well completion reports is that flowback water volumes reported are not tied with the number of days flowback water is recovered. Since operators have a 30-day window to submit the well completion report to COGCC, it creates variation on the amount of the water reported. In addition, it is unknown how many days of production were taken into account to calculate the reported flowback water volume. Instead, the reported flowback water should be the amount recovered in a fixed time period in order to have a meaningful unified metric of flowback recovery. Currently, in Colorado, water use data and acquisition methods are not reported by a single entity, and this overlap hinders the existence of seamless datasets. Most of this information, if available, is fragmented in multiple datasets. Thus, there is not a

comprehensive dataset that can answer relative water management questions without cumbersome analysis. In cases where datasets can be joined, the probability of introducing errors increases. The COGCC should enforce the reporting of each water source used in every hydraulic fracturing operation, because a crucial part of the water life cycle used in oil and gas development is missing. This makes it difficult to track the water, identify possible local effects, and quantify potential tradeoffs. Analysis of the decrees and lease agreements from the Colorado Division of Water Resources was very time-intensive and could be avoided with a different classification, which separates oil and gas activities from other industrial uses. Some documents presented an additional challenge because they were hard copies scanned into databases and were not electronically searchable by keyword. Moreover, data downloads provided no direct method to distinguish nontributary groundwater sources used for oil and gas operations from other industrial uses. Therefore, additional review of each permit and its supporting documents was required to determine if it was related to oil and gas activities. Furthermore, data reported to FracFocus combines total water volume per well (freshwater, produced water, or recycled water), which makes it impossible to determine separate volumes for each element. Finally, volumes of water used in secondary activities such as dust suppression, drilling mud, and site restoration, although insignificant to the amount used for hydraulic fracturing, should be also reported.

4. Conclusions

The comparison of the two Colorado counties showed that the challenges are local and thus solutions should be tailored to the specific area of interest, in order to achieve sustainable water

555 management. Oil and gas development practices and water acquisition approaches followed in
556 Weld and Garfield counties in Colorado, as well as the effects of those on water use intensity are
557 different. Oil and gas companies operating in the Denver-Julesburg Basin within Weld County
558 borders have a highly decentralized approach towards acquiring water for operational use. There
559 are several players involved in this system including: water service companies, private party
560 transactions, and leasing from municipalities. Natural gas companies in the Piceance Basin,
561 within Garfield County, also apply multiple methods to acquire water. However, the nature of
562 the acquisition process is more centralized and easier to document. This is simply because the oil
563 and gas companies are less reliant on other entities (water service companies, municipalities, and
564 irrigation companies) for sourcing their water. In general, data related to water leases and sales
565 are limited in Colorado and this creates challenges when drawing conclusions and comparing
566 findings between the two counties.

567 The oil and gas well development pattern in Garfield County shows a decline of new well starts.
568 The new well starts are primarily multi-stage directional wells with the median number of staged
569 intervals per well remaining at the same level for the entire study period. The water used for the
570 hydraulic fracturing is mainly recycled water, since the industry has adopted a pro-recycle
571 strategy. In Weld County, data show a shift of preference towards horizontal wells. The length of
572 horizontal wells has increased since 2011 and with it the median number of staged intervals
573 reported. The comparison of single-stage wells and multi-stage wells showed that the normalized
574 per stage consumption is lower for multi-stage wells. The water needed for new well starts is
575 mainly coming from fresh water sources because a small percentage of the flowback water is
576 recycled. Further research is required to investigate if the low re-use practice in Weld County is
577 driven by the cost of treating the chemical profile of flowback water or it is due to low flowback

recovery in comparison with the water demand for new well starts. The study also revealed data gaps, inconsistencies and pointed needed enhancements to data parameters, reporting protocols, and dissemination practices. Availability of reliable data for the entire water life cycle (source, drilling, fracturing, flowback/produced water recovery, and disposal/reuse) is critical for water resources planning and quantifying tradeoffs associated with oil and gas development. The use of an integrated, standard reporting system would allow for consistency across different scales and geographic regions improving our understanding about water use the sourcing strategies and their effects.

In water-stressed regions, the water-energy nexus is a topic of heated discussion within the water community, decision-makers, as well as the lay public. The already complicated discussion due to uncertainties, such as market fluctuation, advancements in extraction and water recycling technologies, changes in industry regulations, local bans or moratoria, and the availability and the price of water, is further complicated since there is not a consensus of the effects associated with unconventional oil and gas activities. Ultimately, a common ground will help reduce conflicting perspectives which shape the water-energy discussion and will allow for water resources planning and management that is environmentally and socially acceptable.

5. Supporting Information

Glossary of Terms

The following glossary provides the necessary information to familiarize the reader to specific notions in Colorado's water law, as well as defining terms used in the text.

Municipal Use	Water from a municipal or quasi-municipal entity that is treated or considered wastewater effluent. Leased water must be used inside existing service area.
Industrial Use	Water that is leased or purchased from an existing industrial water use.
Agricultural Use	Agricultural water rights often undergo a change in type of use from irrigation to municipal and industrial through the water court process. Water can be leased or purchased, but changed use must include industrial.
Free River Diversion	Water that is diverted during times of excess water. The diversion needs to be in priority and is likely not a consistently reliable source of water for oil and gas development. Some reservoir owners have stored water during times of free river for oil and gas companies. Because this type of water is diverted and stored at a time during which there is no call on the river, the water can be used for any beneficial use, including oil and gas activities.
Tributary Groundwater	Groundwater that has a hydrological connection to the surface stream system. Each well permit requires an augmentation plan or substitute water supply plan for replacement of water.
Nontributary Groundwater	As defined by Colorado Senate Bill 213, effective July 6, 1973 is the "groundwater, located outside the boundaries of any designated ground water basin in existence on January 1, 1985, the withdrawal of which will not, within 100 years, deplete the flow of a natural stream, ...at a rate greater than one tenth of one percent of the annual rate of withdrawal." [C.R.S. 37-90-137(4) and 37-90-107(7)]
Nontributary Groundwater located in the Denver Basin and Designated Basins	New sources of nontributary groundwater which have a limited hydrological connection to surface water. Nontributary groundwater is not administered within the legal priority system and does not require replacement of water.
New Determinations of Nontributary	Nontributary groundwater located outside of the Groundwater located in designated groundwater basins which has a limited hydrological connection to surface water. This water is not administered within the legal

Groundwater	priority system and does not require replacement of water. This is a relatively new source of water for oil and gas operations in the Denver-Julesburg Basin.
Multi-use water	Return flows from the first use of water are claimed by the Northern Water District for successive uses by other downstream water users
Produced	Water that is native to the surrounding formation and is produced throughout the oil and gas recovery process. Produced groundwater is a diversion that is subject to administration and well permitting by the Colorado Division of Water Resources. The State Engineer has authority to conduct rulemaking to determine whether groundwater in specific oil and gas formations underlying certain geographic areas is nontributary. Pursuant to section 37-90-137(7), C.R.S., an oil and gas company who withdraws nontributary groundwater during the mining of minerals is not required to obtain a water well permit, unless the produced groundwater being removed will be beneficially used ^{ab} .
Flowback	Flowback is the water and excess proppant returned to the surface after hydraulic fracturing for about the first 30 days of production and may be recycled and reused for subsequent needs, depending on its quality. Recycled flowback water is not a new source of water because it was previously acquired for oil and gas well development. Note: Form 5A classifies “Flowback Volume Recovered” to include treatment fluids and produced water.

599 ^a This statement is not applicable to coalbed methane wells because the Colorado Supreme
600 Court found that the withdrawal of water in the coalbed methane extraction process is, in and
601 of itself, a beneficial use (Colorado Supreme Court, 2009). Therefore, each coalbed methane
602 well that produces water must be permitted as a water well by the Colorado Division of
603 Water Resources.

604 ^b While a water well permit is required if the nontributary ground water is put to a beneficial
605 use, a provision, in section 37-90-137(7) C.R.S., states that no water well permit is required
606 if the nontributary ground water is used for the mining of minerals in the same geological
607 basin.

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