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Assessment of groundwater contamination and the role of hydraulic fracturing operation in Weld County, USA

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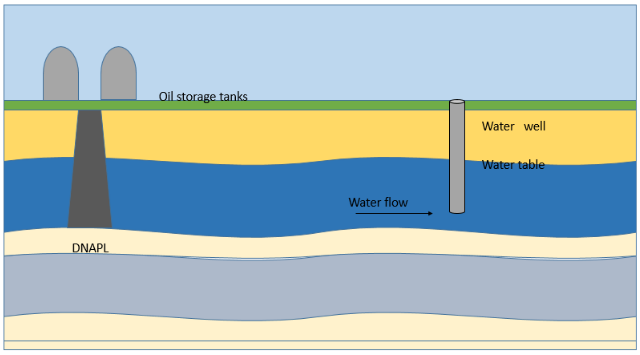
Graphical abstract



Abstract

In shale gas-producing countries, soil, and groundwater contamination due to surface spills associated with hydraulic fracturing operations is one of the most worrying problems that arise, since its elimination is not easy or cheap to carry out, and its effects persist for many years. Thus, this study identifies the environmental and health risks associated with the extraction of unconventional gas. The study was carried out based on the available data obtained from Colorado Oil and Gas Conservation Commission (COGCC) regarding groundwater pollution from spills that have occurred in Weld County where fracking has become a common practice. Data sources related to spills were analyzed. A range of parameters that characterize the quality of the water were investigated to determine the groundwater quality and compared with the international standards to evaluate its suitability for different utilizations. The result showed that the groundwater is not suitable for human consumption nor irrigation purposes. The study shows that there are 33 surface water bodies, 17 wetlands, 23 livestock, and 31 occupied building are threatened with pollution. The study also indicated that about 80 % of cases of spills are due to equipment failures. It can be concluded that the most important cause of surface spills and therefore potential contamination of soil and groundwater is equipment failure. Oil surface spills are the main causes of groundwater contamination, yet the contribution of agricultural activities to the spread of this contamination should not be neglected.

Keywords: groundwater pollution, hydraulic fracking, oil spills, agricultural activities, water aquifers.

1. Introduction

The continuous rise in the population and the rising standard of living of emerging and developing countries with high population numbers have increased the demand for energy in the world, along with the constant fear of depleting oil resources, prompting an expanding search for new sources of energy supply to meet our needs. Natural gas is one of the energies that is being investigated more (Magazzino *et al.*, 2021).

Until now, most exploited natural gas resources came from conventional accumulations of isolated gas and associated gas dissolved in oil. However, natural gas is also found in reservoirs that, due to their low porosity and permeability, have characteristics that until very recently have not been economically profitable and that can only be exploited using unconventional techniques (Zhang *et al.*, 2021). The particularities of these deposits give rise to the so-called unconventional gas. However, concurrent with the increased production of unconventional gas, concerns have arisen about the effects of extraction processes on groundwater quality, human health, and the climate, due in part to the migration of methane and other associated hydrocarbon gases and volatile organic compounds (Hammond *et al.*, 2020).

The exploitation of shale gas through hydraulic fracturing and like any surface industrial activity can affect soil, surface water, and groundwater due to accidental spills and leaks from ponds, etc. Petroleum derivatives deserve special mention. These substances reach the phreatic surface by infiltration from accidental spills or by ruptures of tanks or pipes. Some are less dense than water "light non-aqueous phase liquid" (LNAPL), thus remaining on the surface of the aquifer free superficial, only a part dissolve.

Other hydrocarbons are denser than water "dense non-aqueous phase liquid" (DNAPL) and end up in the lower part of the aquifer, although some of them can dissolve.

Groundwater and surface water pollution, as well as soil contamination, are negative effects that usually occur as a result of such incorrect management of spills. Pollution processes, once started, are not easy to remove and last for many years (Qin *et al.*, 2021). Possible technical solutions for decontamination are also costly, difficult to implement, and relatively successful on many occasions (Talabi & Kayode, 2019). Groundwater is a vital resource not only for domestic use but also for developing industrial and agricultural activities. Without forgetting its importance in sustaining the ecological balance. These possible uses will be conditioned by the quality chemical and biological present in these waters, which must not exceed the values established by the quality regulation. When these values are exceeded, it is said that water is contaminated by human action.

Many studies confirmed that these spills contaminated the groundwater and soils in Weld County (Almaliki *et al.*, 2022). For example, 77 surface spill reports were analyzed, it was noted that the concentration of benzene, toluene, ethylbenzene, and xylene (BTEX) exceeded the World Health Organization (WHO) permissible level(Gross *et al.*, 2013). Oil surface spills in Weld County affect the shallow groundwater aquifer, which contains more than 12,000 domestic groundwater wells (Kanno & McCray, 2021).

Although the extraction of shale gas is the primary suspect in groundwater pollution, we should not neglect other sources of pollutants, especially those related to agricultural activity and animal fecal. Where agricultural activities are one of the most widespread reasons for the deterioration of the groundwater quality(Talabi & Kayode, 2019). The most significant potential pollutants in this field are fertilizers and pesticides (An *et al.*, 2021). Other pollutants of less significance are the dumping of animal waste on the ground, the storage of crop residues, fertilizers, especially nitrogenous compounds (Sun *et al.*, 2021). They are the most important nutrients from the point of view of groundwater contamination due to the mobility of nitrates (Zambito Marsala *et al.*, 2021). Weld County is rich in agricultural activities, the probability of groundwater contamination with these activities must take into consideration, and this is what will be addressed in this study.

Today, there is a lack of information concerning the relation between the groundwater contamination in Weld County and the role of hydraulic fracturing operation related to the extraction of unconventional gas as well as reason of spills.

Thus, the aim of this study is to analyze the groundwater quality in Weld County and compare it with the international standards to demonstrate its suitability for different utilizations. In addition, to determine the cause of those spills, and what actions can be taken to reduce these risks.

2. Methodology

2.1. study area

Weld County is a county located in the U.S. state of Colorado, within the coordinates of (40.5632° or 40° 33' 47.6" north) latitude and (-104.4835° or 104° 29' 0.7" west) longitude. Weld County is the richest agricultural county in the United States with 2.5 million acres of which 75% is devoted to farming and rearing livestock, the county is Colorado's main producer of beef and grain (County, 2021). At the same time, Weld County is one of the most important oil producers in the United States (Robbins *et al.*, 2021). Due to the intensity of unconventional oil and gas extraction using fracturing technology in Weld County, many surface spills occurred (Gross *et al.*, 2013). These spills affected both the soil and groundwater. Agriculture in County Weld is highly dependent on groundwater. Therefore, it is very important to assess the quality of groundwater and its potential to be harmful to human health.

2.2. Spills database considerations

The information related to oil surface spills were obtained from Colorado Oil and Gas Conservation Commission (COGCC) database. The data was analyzed with the aim to clarify the relationship between groundwater pollution and surface spills from fracking operations, which is the focus of our study, to be able to visualize the magnitude of the resulting risks, study their environmental effects, and search for ideal risk management ways.

The obtained data was presented by operators from 2014 to 2021 by Form 19, which is a spill/release report submitted by the party responsible for the oil and gas spill to COGCC database (COGCC, 2019). The data includes three principal parts; spill release report that covers spill details, number of soils and groundwater impacted, and corrective actions completed. The data included details of the operators, fields, and locations of spills, the number, and sizes of spills, the number of impacted soil and groundwater, geology description, as well as details about what surrounds those sites, cities, farms, etc. Finally, the details included active correction and other details. The spill database included 4543 reports submitted by operators between 01/16/2014 to 9/17/2021. Some of the reports, indicated to the oil spill volume, but they did not indicate whether the soil and groundwater were impacted, and accordingly, only the reports that indicated that the soil and groundwater impacted would be considered in assessing whether the neighboring water wells being affected by pollution or not.

2.3. Quality parameters of groundwater

To determine the suitability of groundwater for human consumption, a series of parameters that characterize the quality of the water must be described. The quality parameters are divided into physical-chemical, microbiological, and organoleptic. The total dissolved solids (TDS), which is the mass of salts that obtained and remain unchanged when evaporating a liter of water. The chemical substance that contributes most to the dry residue (TDS) are usually sodium, potassium, calcium and magnesium as cations, and bicarbonate, chloride, and sulfate as anions. Some waters, silicon is also considered, an element of complex chemistry that usually occurs in anionic form, although its concentration is expressed as silica.

The ground water can contain a long list of metallic elements of different origins. For example, iron and manganese are common in groundwater. Arsenic is usually of natural origin and linked to the geological characteristics (Shaji *et al.*, 2021). Other metals, such as mercury, cadmium, chromium, and selenium are linked to the industrial activities. Natural water (sea, rivers, lakes, and groundwater) is the natural habitat of many species of microorganisms. Most of these microscopic forms do not pose a danger to humans, yet some can affect people and cause disease.

Analytical sample database obtained from 971 domestic water wells near the spill locations were analyzed. About 16107 samples taken from 971 domestic water wells were selected for hydro chemical modeling. The samples were collected between t 1st/January /2014 to 12th /May 2021.

A wide variety of organic and inorganic parameters has been identified as potential groundwater contaminants. These include inorganic compounds such as (Arsenic, Barium, Boron, Cadmium, Calcium, Fluoride, Manganese, Nickel, Nitrate, and Zinc). Organic compounds such as (benzene, toluene, ethylbenzene, and xylene (BTEX). In addition, some parameters that indicate the quality of groundwater have been identified, such as (pH and conductivity) which are closely linked.

3. Result and dissection

3.1. Spills analysis by year

The report indicates that more than 4,539 oil spills have affected 16 cities. The vast majority were from Weld City, due to the extraction intensity in that city. About 80 % of those spills were the result of equipment failures. The report reveals that approximately 15,271 barrels were spilled between 2014 and 2021. Table 1 presents the spill analysis and causes from 2014 - 3rd Quarter 2021.

Table 2 shows the type of facility associated with groundwater impact in Weld County, there were 304 spills during 2021 due to equipment failure, and the major cause of spills was tanks battery by 56%. Out of the 4543 reports, only 2650 reports referred to soil and groundwater were impacted. The reports indicated that 2145 cases of soil were impacted and only 505 cases of groundwater were impacted. It was noticed that only 23% of soil pollution cases led to groundwater pollution. This is due to the speedy corrective actions on the site. Figure 1 shows the number of soils cases impacted compared to the number of groundwater impacted in the spill location.

The data included information about what around spill location such as surface water near, Wetlands, Livestock near and occupied buildings. If these sites are less than one mile from the spill location, they considered at risk of contamination as shown in the Table 3 (based on 2021 database).

3.2. Groundwater contamination

Table 4 shows the number of samples in which the concentration of BTEX compounds exceeded the permissible limit.

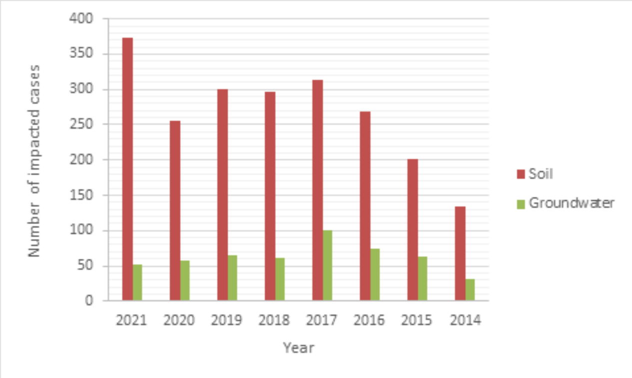


Figure 1. Number of soil cases impacted vs number of groundwater impacted.

Unusual concentrations of BTEX were detected in the analyzed water samples. One of the most common forms of BTEX contamination detected over the years is the oil spills from storage tanks, mainly located at fracturing location. These compounds are found in hydraulic fracturing fluid, forming a large part of its soluble fraction. All of them are considered toxic and dangerous compounds and are included as such in the list of elements susceptible of analysis according to WHO. Table 5 shows the number of samples in which the concentration of inorganic compounds exceeded the permissible limit.

Table 1. Spill analysis and causes

Year	Spill	Oil Spilled bbl	Cause of the spill		
			Human error	Equipment Failure	Historical Unknown
2014	361	1940	31	87	243
2105	460	1351	41	85	334
2016	582	3155	16	172	394
2017	708	3171	30	134	544
2018	709	1024	31	111	567
2019	608	2378	30	126	452
2020	531	759	3	16	512
2021	579	3433	Not available	Not available	Not available

Table 2. Spill caused by equipment

City	Facility Type	N° of Spills	N° Soil impacted	N° Groundwater impacted	N° Data not available
Weld	Flow line system	6	5		1
Weld	Off-location flow line	51	20	1	30
Weld	Oil and Gas location	23	8	3	12
Weld	Other	22	10		12
Weld	Partially buried vessel	3	2	1	0
Weld	Pipeline	8	4	2	2
Weld	Production line	1			1
Weld	Tank battery	171	121	14	36
Weld	Well	15	12	12	3
Weld	Well site	4	4	4	0
	Total	304			

Table 3. Number of sites near the spill location are at risk of contamination

City	Surface Water Near	Wetlands	Livestock Near	Occupied Buildings
Weld	33	17	23	31

Table 4. Number of samples in which the concentration of BTEX exceeded the MCL

Organic compound	N° Samples exceed MCL	Maximum concentration μg/l	
		Median	Range
Benzene	603	4186	10.5 - 6.4E+4
Toluene	133	10861	310 - 1.2E+5
Ethylbenzene	190	5241	710 - 1.1E+5
Xylene	228	9067	510 - 1.2E+5

Table 5. Number of samples in which the concentration of inorganic compounds exceeded the MCL

Inorganic compounds	N° Samples exceed MCL	Maximum concentration mg/l	
		Median	Range
Arsenic	1698	4.5	0.0105 - 290
Barium	4810	0.13	0.011- 85.2
Boron	1708	185.8	0.502 - 2500
Cadmium	1225	1.7	0.0035 - 307
Calcium	4906	186	75.5 - 90000
Fluoride	5460	4.4	1.6 - 929
Manganese	1025	4.7	0.5 - 1000
Nickel	921	0.09	0.00728 - 20
Zinc	6	54	19 - 92

Unusual concentrations of inorganic compounds were detected in the analyzed water samples. These elements can have different origins. In the case of groundwater, they can pass through lithographic substrates rich in some of these metals and contaminate them. In regard, to the suitability of groundwater for drinking, for example, when arsenic encounters groundwater, it can end up in drinking water if not properly treated. Due to this natural geological contamination, high levels of arsenic can be found in some drinking waters that come from deep wells. Consumption of arsenic-rich water for prolonged periods has been shown to be detrimental to health, causing skin problems and certain cancers, such as skin and lung.

In certain aquifers, variable amounts of boron appear because of the filtration of certain fertilizers used for some crops or due to the existence of hot springs of volcanic origin. In general, the detected concentrations are related to the geochemical background of the aquifer. Table 6 shows the number of samples in which the concentration of nitrate and phosphorus exceeded the permissible limit.

The existence nitrate and phosphorus may be due to pollution caused by agricultural activity, where nitrogen is used as chemical fertilizer and that from nitrogen present in livestock wastewater.

Table 7 shows the results of measurements of physicochemical parameters, which consider a very useful methodology to evaluate the quality of water and establish plans for its management.

The obtained results shows that the pH indicates that in general it is water with a tendency to neutrality, oscillating between 7.28 and 8.18. The conductivity of groundwater presents values between 558 and 5120 (μS/cm), considered within the range of freshwater (<2,000 μS/cm).

Regarding dissolved oxygen, values between 0.4 and 1.24 mg/L are measured, indicative of moderate to low oxygenation. The Oxidation Reduction Potential (ORP), which is indicative of anaerobic environments, which consistent with the low concentrations of oxygen that have been consumed by aerobic bacteria during degradation of the hydrocarbons present in the subsoil.

Table 6. Number of samples in which the concentration of nitrate and phosphorus exceeded the MCL

Organic compound	N° Samples exceed MCL	Maximum concentration µg/l	
		Median	Range
Nitrate (as NO_3^-)	120	102	51.5 – 9999.9
Phosphorus	802	0.51	0.11 – 71.6

Table 7. The results of measurements of physicochemical parameters

Parameter	Unit	Range
pH	-	7.28 – 8.18
Conductivity	µS/cm	558 - 5120
TDS	mg/l	122 - 5500
Dissolved Oxygen	mg/l	0.2 – 1.24
Redox	mV	71-258

The total dissolved solids (TDS) classification is important in groundwater quality. The total dissolved solid (TDS) presents values between 122 and 5500 mg/l, TDS exceeded the WHO permissible level in five samples from seven. All groundwater samples showed that it is not potable and it is not suitable for irrigation purposes, water is suitable for irrigation when the value TDS is less than 3000 mg /l (Khwedim *et al.*, 2017).

4. Conclusion and recommendation

This research presents a risk assessment analysis and evaluate the potential pollution of groundwater caused by the extraction of unconventional gas. The study established the necessary bases for estimating the vulnerability of water wells near spill locations to be polluted. The results indicated that the surface oil spills are a real concern for groundwater pollution. In addition, other surface water sources are also threatened by the same level of pollution, for example, there are 33 surface water, 17 wetlands, 23 livestock and 31 occupied building are threatened with pollution. About 80 % of cases of spills are due to equipment failures, the major cause of equipment failures was tanks battery by 56 %. Therefore, it is essential to carry out good planning and execution of preventive maintenance to guarantee the correct functioning of the equipment and, therefore, avoid breakdowns and unscheduled downtime. Livestock and intensive agriculture practices or the burning of fossil fuels are factors that have contributed in a decisive way to the fact that nitrate pollution, the negative effects of which are devastatingly felt in the environment, cease to be a problem. Environmental to become a potential health risk. All groundwater samples are not suitable for drinking or irrigation purposes.

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