Front. Earth Sci. 2021, 15(2): 406–422
https://doi.org/10.1007/s11707-020-0850-0

RESEARCH ARTICLE

# Environmental risks of shale gas exploitation and solutions for clean shale gas production in China

**Shikui GAO**[1], **Quanzhong GUAN (✉)**[2], **Dazhong DONG**[3], **Fang HUANG**[1]

1 School of Economics and Management, China University of Geoscience (Beijing), Beijing 100083, China
2 College of Energy, Chengdu University of Technology, Chengdu 610059, China
3 PetroChina Research Institute of Petroleum Exploration & Development, Beijing 100083, China

**Abstract** Shale gas is a relatively clean-burning fossil fuel, produced by hydraulic fracturing. This technology may be harmful to the environment; therefore, environmentally friendly methods to extract shale gas have attracted considerable attention from researchers. Unlike previous studies, this study is a comprehensive investigation that uses systematic analyses and detailed field data. The environmental challenges associated with shale gas extraction, as well as measures to mitigate environmental impacts from the source to end point are detailed, using data and experience from China's shale gas production sites. Environmental concerns are among the biggest challenges in practice, mainly including seasonal water shortages, requisition of primary farmland, leakage of drilling fluid and infiltration of flowback fluid, oil-based drill cuttings getting buried underground, and induced seismicity. China's shale gas companies have attempted to improve methods, as well as invent new materials and devices to implement cleaner processes for the sake of protecting the environment. Through more than 10-year summary, China's clean production model for shale gas focuses on source pollution prevention, process control, and end treatment, which yield significant results in terms of resource as well as environmental protection, and can have practical implications for shale gas production in other countries, that can be duplicated elsewhere.

**Keywords** shale gas, clean production, resource saving, environmentally friendly, China

## 1 Introduction

Shale gas, an unconventional natural gas, is a relatively clean-burning fossil fuel. Burning natural gas for energy results in fewer emissions of nearly all types of air pollutants (including carbon dioxide ($CO_2$), nitrogen oxides, and sulfur dioxide) than burning coal or petroleum products to produce energy. $CO_2$ emission resulting from burning natural gas is approximately 58.5% of that of coal-burning, and 73.1% of that of oil (Natural gas and the environment — U.S. Energy Information Administration (EIA), 2018). The clean-burning properties of natural gas have contributed to improving the ecological environment.

Shale gas extraction has attracted considerable attention in China following its energy transition toward decarbonization (Wu et al., 2019a). China mainly relies on coal energy generation, and according to the Economics and Technology Research Institute, PetroChina (ETRI)) Energy Statistical Review 2020, natural gas only accounted for 8.3% of energy sources in 2019, far below the world average of 24.5%. China's energy consumption has also been increasing, resulting in a 72.5% dependence on imports of crude oil, and a 45.2% dependence on natural gas imports in 2019. EIA (US Energy Information Administration (EIA), 2015) estimates that China's technically recoverable shale gas reserves are 1115 Tcf, the largest shale gas reserve in the world (World Shale Resource Assessments, 2015). China's government has introduced incentives for the extraction of shale gas (China adds incentives for domestic natural gas production as imports increase- Today in Energy- U.S. Energy Information Administration (EIA), 2015) to ensure national energy security and optimize the energy structure, and shale gas production was expected to be 15 billion cubic meters in 2019, making China the second largest producer outside the US.

Received November 11, 2020; accepted November 22, 2020

E-mail: muchang503@126.com

However, the process of shale gas development, including exploration, drilling, production, and transportation, inevitably causes damage to the environment. Natural gas mainly constitutes methane — a potent greenhouse gas, which may leak into the atmosphere from shale gas wells, storage tanks, pipelines, and processing plants (Chen et al., 2017; Gvakharia et al., 2017). Shale gas production requires clearing and leveling of land when constructing wells or laying pipelines, which can disturb local vegetation, soil, and wildlife (Baranzelli et al., 2015; Milt and Armsworth, 2017; Guo et al., 2020).

Advances in shale gas drilling technologies enable the opening up of large reserves of shale gas that were previously too expensive to develop, but also lead to adverse environmental effects. The fracturing of shale gas wells requires large amounts of water (Vengosh et al., 2014). It can also produce large volumes of wastewater and waste drill cuttings that need to be treated before discharge or reuse (Rozell and Reaven, 2012; Lutz et al., 2013; Warner et al., 2013; Estrada and Bhamidimarri, 2016). If mismanaged, drilling fluid and hydraulic fracturing fluid can contaminate surface or groundwater and surrounding areas through, for example, spills, leaks, and faulty well construction (Kahrilas et al., 2015). The injection of hydraulic fracturing (HF) fluids and formation water into the subsurface may lead to local earthquakes (Holland, 2013). Furthermore, operating equipment and compressors during shale gas production can cause air (Roy et al., 2014) and noise (Estrada and Bhamidimarri, 2016) pollution.

Considering the environmental problems caused by shale gas development, many scholars and governments are hesitant to support or are against shale gas development. Eaton (2013) suggested that a ban on drilling within the New York City water supply watersheds be appropriate, even if more strictly regulated Marcellus gas production is eventually permitted elsewhere in New York State. Many European countries, such as France, UK, have prohibited the extraction of shale gas because of environmental concerns (Van de Graaf et al., 2018).

Environmental concerns are among the biggest obstacles facing China's shale gas producers, and methods to produce shale gas cleanly remain a challenge. Existing literature focusing on environmental problems faced by China is mostly from a water resource protection perspective (Yang et al., 2015; Wu et al., 2019b; Xie et al., 2019), and not many studies comprehensively examine clean shale gas production practices. Therefore, this study included a broader and systematic analysis, and used detailed data, to address the entire range of environmental challenges as well as the treatment process from source to end, using China's shale gas production sites as a setting. China's shale gas companies have been attempting to improve methods and invent new materials and devices to implement cleaner, more environmentally friendly processes and preserve natural resources.

## 2 Environmental challenges associated with shale gas production

China began to commercially exploit shale gas in four national-level shale gas demonstration zones in 2013, subsequently forming two production bases with reserves of 100 billion cubic meters: Fuling Base and Changning–Weiyuan–Zhaotong (CHN–WY–ZHT) Base, extracted by PetroChina and Sinopec, respectively, two of China's national petroleum companies (Table 1). These two oil companies have had to face a host of environmental challenges in Sichuan and Chongqing, with high population densities contributing to pressure to protect the ecology.

### 2.1 Resource use

### 2.1.1 Water consumption

HF, which is a crucial technology to make mass shale gas production economical, requires significant amounts of water, far more than conventional gas extraction. Yang et al. (2015) stated that the average water consumption per well in the Fuling shale gas field was 27490 mm$^3$. However, the latest report from the site in 2018 placed consumption at $5 \times 10^4$ m$^3$ and $4.5 \times 10^4$ m$^3$ in Sichuan and Chongqing, respectively (Table 2) — much higher than consumption in the US, which is $1.06 \times 10^4 - 3.8 \times 10^4$ m$^3$ (Vengosh et al., 2014). Maximum figures reached $8.8 \times 10^4$ m$^3$ in 2019 in China (Table 3).

Unlike most of the US shales found in the plains of North Dakota, Pennsylvania, and Texas, and buried under a few hundred meters to 3000 m, China's promising Sichuan Basin is located in mountainous and harsh terrains, with vertical depths of shale formations ranging

**Table 1** China's two shale gas production bases

| | CHN–WY–ZHT base | Fuling base | Total |
|---|---|---|---|
| Area/km$^2$ | 529.33 | 575.92 | 10455 |
| Technically recoverable reserves/$10^8$ m$^3$ | 1062.86 | 1432.58 | 2495 |
| Cumulative output/$10^8$ m$^3$ | 112.31 | 214.53 | 326.84 |
| Producer | PetroChina | Sinopec | |

**Table 2** Average amount of fracturing fluid used per well in 2018

| Production area | Lateral length per well /m | Fluid amount per meter /($m^3 \cdot m^{-1}$) | Fluid amount per well /$m^3$ |
|---|---|---|---|
| Sichuan | 1591 | 32 | 50,912 |
| Chongqing | 1500 | 30 | 4,500 |

**Table 3** Maximum amount of fracturing fluid used per well in 2019

| Block or well | Fluid amount per well/$m^3$ |
|---|---|
| WEI 202 | 65063 |
| WEI 204 | 66066 |
| Wells in Changning | 85323 |
| Zhao YS113H1-7 | 88059 |

from 1000 m to 6000 m (Xie et al., 2019). This results in technical complexities, large-scale drilling and massive water consumption.

As shown in Table 4, assuming 4.5 × $10^4$ $m^3$ is the fluid consumption amount per well, for a total of 952 wells, the consumption will be 4284 × $10^4$ $m^3$, which accounts for 0.56% of the total industrial water use of 2018 in the four provinces ("Chongqing water resources bulletin 2018", "Guizhou province water resources bulletin 2018", "Sichuan water resources bulletin 2018", " Yunnan water resources bulletin 2018"). Even though Sichuan has the highest proportion of 1.51%, the number is still rather low. As Wan et al. (2014) and Xie et al. (2019) pointed out, although a large amount of water will be needed, there will be little impact on the local water supply.

Despite the above, the official reports on water resources in 2018 announced that China's overall annual water consumption per capita was 432 $m^3$, the GDP water consumption per 10000 yuan was 66.8 $m^3$, and the actual average farmland irrigation water consumption per hectare was 5475 $m^3$ (Ministry of Water Resources of the People's Republic of China, 2018a). Therefore, the water consumption of HF, 4,284 × $10^4$ $m^3$, would be equal to that of 10 × $10^4$ people, or 6.4 billion yuan of GDP, or 8 × $10^7$ $m^3$ of farmland irrigation.

Water is not an abundant resource in China, which is known for its uneven water distribution, and seasonal and regional water shortages (Wu et al., 2019a). Even though the main shale gas producing areas in the Sichuan Basin are rich in water resources, Sichuan, Yunnan, and Chongqing suffer from varying degrees of seasonal droughts yearly. At the peak of the drought in early April 2014, 40.467 × $10^4$ ha of arable land in Sichuan, Yunnan, and Chongqing was affected. By the end of April, 118.40 × $10^4$ people (accounting for 51% of China's population) and 62.55 × $10^4$ head of livestock in Yunnan had difficulty accessing drinking water (Ministry of Water Resources of the People's Republic of China, 2018b).

The water supply for Weiyuan Play and Fuling Play mainly comes from surface water or the Weiyuan River, and the Wujiang River, respectively (Lu et al., 2016; Wu et al., 2019b). Shallow karst water, the aquifer vital for local water supply, is widely distributed throughout the shale gas fields, and in some cases, significant use of water for HF may negatively impact aquatic habitats and the availability of water for other purposes.

The intense seismic waves caused by drilling can cause water in some surface karst caves to cut off, or even disappear. According to incomplete statistics, there have been more than 30 locations in Jiaoshiba Block of Fuling Play since October 2016, where karst water was reduced, 15 instances where the water in the caves stopped flowing, and 34 instances where small water conservancy projects (e.g., small pond dam, small water cellar, small pump station, small channels, or small weir gate) were damaged to some extent, affecting 1.5 × $10^4$ $m^3$ water, and resulting in 3300 people, 5000 livestock and 233.33 ha of farmland experiencing water shortages within a short period of time (Zhong and Fang, 2017).

### 2.1.2 Land occupation

China's key shale gas production bases are mostly in areas with developed agriculture and limited arable land per capita (Liang et al., 2014). As shown in Fig. 1, the arable land area per capita in the shale gas producing area of Changning, Weiyuan, Zhaotong, and Fuling is less than 500 $m^2$, lower than the national average, and much than the world average (Cultivated land area per capita (index), 2015).

At the stage during which hydrocarbon is extracted from unconventional deposits, shale gas production will continue for many years, though in the majority of cases, the technical infrastructure will occupy a smaller area than the rig area during the initial stage. The land area occupied by drilling platforms for shale gas, approximately 1.20×$10^4$ – 5.95×$10^4$ $m^2$ per well (Fig. 2), is more than a dozen times that of drilling platforms for conventional natural gas.

**Table 4** Shale gas drilling and completion (D&C) wells and water consumption

| | Chongqing | Sichuan | Yunnan | Guizhou | Total |
|---|---|---|---|---|---|
| D&C wells (as of 2018, 6 years in total) | 477 | 469 | 3 | 3 | 952 |
| Water consumption for shale gas/($10^4$ $m^3$) | 2146.5 | 2110.5 | 13.5 | 13.5 | 4284 |
| Industrial water consumption in 2018 (only one year)/($10^8$ $m^3$) | 30.37 | 14.01 | 7.405 | 25.19 | 76.975 |
| Proportion/% | 0.71 | 1.51 | 0.018 | 0.0054 | 0.56 |

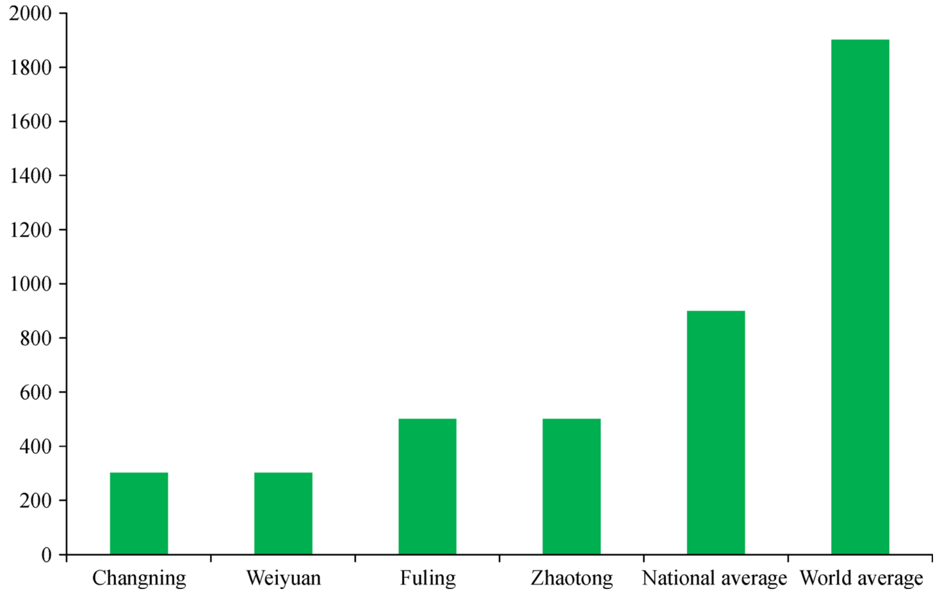


**Fig. 1** Comparison of arable land area per capita/m$^2$

Large areas of land are expropriated temporarily for well site construction, road infrastructure for of medium and large vehicles, placement of a large variety of equipment, and storage of chemical materials and toxic substances, which leads to a decline in local ecological functions. In practice, it is found that temporary ecological reclamation is difficult and requires a long recovery period (Mei et al., 2016). Gas recovery platforms, gas collection stations, dewatering stations, and certain other infrastructure occupy land permanently, and the nature of the land used for solidification and landfills for drill cuttings is changed forever.

According to the 2015 production capacity construction plans of the two shale gas production bases, Fuling and CHN–WY–ZHT (Table 5), the land areas occupied temporarily were 262.8 km$^3$ and 557.09 km$^3$, respectively, consisting mainly of dryland and woodland. A single drilling platform permanently covered an average area of 5080 m$^3$ and 7153.34 m$^3$ at the two bases, respectively. If the grain loss coefficient is 10.2 ton/ha (Yang et al., 2019), the permanent footprint of a single drilling platform can cause grain losses of 5.18 ton and 7.3 ton per year at the two bases, respectively.

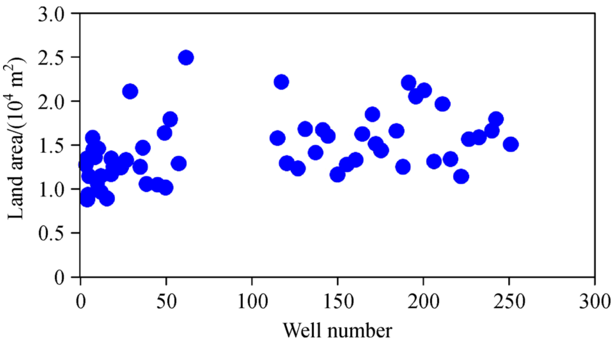


**Fig. 2** Statistics of drilling platforms in the Fuling Play (Xiong et al., 2016a)

As production continues to increase, larger areas of cultivated and forest land will become occupied. In addition to crop losses, there will be negative impacts on surface topography, vegetation, water and surface runoff, animal habitats, natural landscapes, species diversity, etc. The destruction of these natural ecological balances is difficult to rehabilitate effectively in a short period of time.

## 2.2 Environmental risks

The possible environmental risk caused by shale gas production is associated with water pollution, solid waste pollution, air pollution, noise pollution, and induced seismicity.

### 2.2.1 Water

HF is water-intensive (Fig. 3). In HF operations, a large amount of fracturing fluid (a mixture of water and additives) is injected under high pressure into low-permeability shale formations, to induce fractures and allow mobility of natural gas (Fig. 3). Common additives to water include proppants, drag reducers, clay stabilizers, corrosion inhibitors, biocides, scale inhibitors, surfactants, and gel agents (Gregory et al., 2011; Tang et al., 2010). The additives used in CHN–WY Play are listed in Table 6. More than 1000 possible chemicals can be used in fracturing fluid in the USA (Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources: Progress Report, 2012), of which many are harmful and

**Table 5** Land occupation of shale gas production bases in China

| Shale gas field | | | Fuling | CHN–WY–ZHT |
|---|---|---|---|---|
| Platforms | | | 71 | 65 |
| Wells | | | 235 | 388 |
| Temporary/km$^2$ | Forest land | | 73.928 | 212.513 |
| | Agricultural land | | 171.48 | 344.577 |
| | Other land | | 17.392 | |
| | Total | | 262.8 | 557.09 |
| Permanent/km$^2$ | Agricultural land | Primary farmland | 0.1873 | 0.279 |
| | | Other | 0.1732 | 0.186 |
| | Total | | 0.3605 | 0.465 |
| Area per pad/ha | | | 114.3 | 160.95 |
| Crop loss per pad/ton | | | 5.18 | 7.30 |

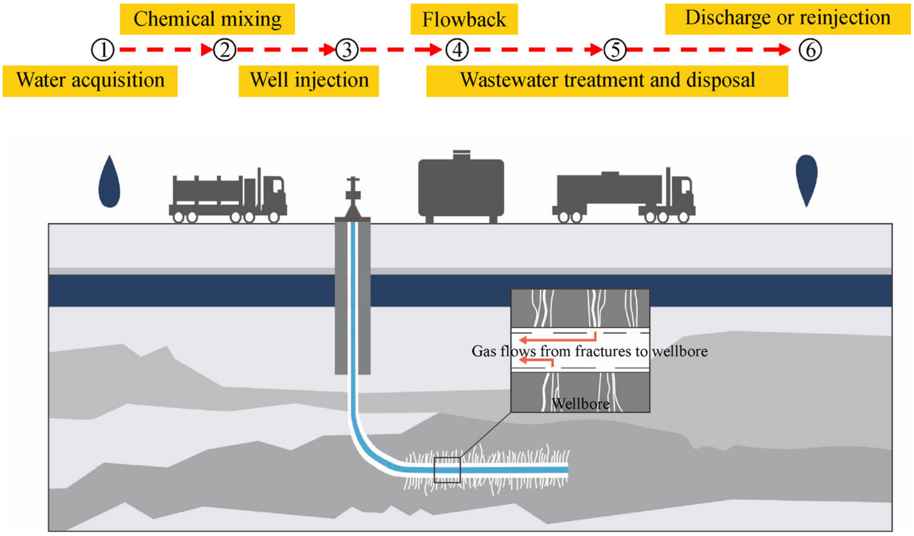


**Fig. 3** Water life cycle during shale gas extraction.

**Table 6** Main additives of fracturing fluid used in CHN–WY (adapted from Huang, 2019)

| Additive | Example of the chemical |
|---|---|
| Acids | Hydrochloric acid |
| Antimicrobials | Glutaraldehyde |
| Corrosion inhibitors | N, N-dimethylformamide |
| Cross-linkers | Sodium carbonate/potassium carbonate |
| Deoxidants | Ammonium |
| Disincrustants | Glycol |
| Drag reducers | Petroleum Distillates |
| Gel breakers | Sodium chloride |
| Iron ion inhibitors | 2-hydroxyl – 1,2,3- tricarballylic acid |
| Proppants | Silica, quartz sand |
| Tackifiers | Guar gum, hydroxyethyl cellulose |

dangerous to the environment. Large volumes of flowback and produced water (FPW) are typically generated, and can account for 30%–70% of the original fracturing fluid volume (Li et al., 2014). FPW contains some formation water (i.e., naturally occurring saline water in the formations, as well as naturally occurring radioactive materials), byproducts, and gases.

FPW is characterized in terms of total suspended solids (TSS) and total dissolved solids (TDS), as shown in Fig. 4 (Mohammad-Pajooh et al., 2018). The main pollutants in the flowback (Chen et al., 2016; Wei et al., 2018) are: 1) Organic substances: oily substances and chemical additives; 2) Cations: a large amount of calcium, magnesium, barium, and strontium plasma (Table 7); and 3) Suspended solids. Research reports on the Fuling shale gas field in Chongqing indicate that the flowback was characterized by high chemical oxygen demand (COD), high salinity, high TSS, extremely large volumes of

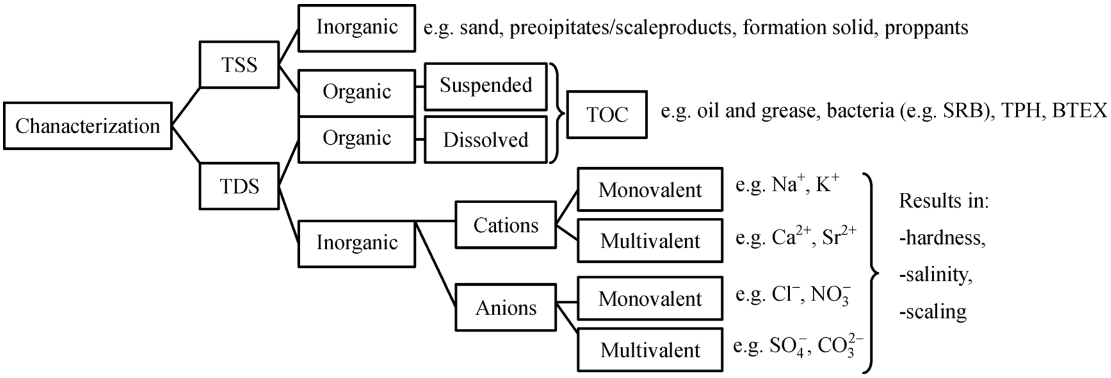


**Fig. 4** Flowback and produced water (FPW) characterization (Mohammad-Pajooh et al., 2018).

flowback and long duration of flowback. The salinity of the wastewater was up to 38150 mg/L, which can affect the healthy growth (or even death) of plants that are not salt tolerant. TSS was too high, usually above 2000 mg/L, and up to 4760 mg/L. If discharged directly into the river soil, TSS can be harmful to plants and animals in the water and soil.

In unconventional shale gas extraction, fracturing fluid and FPW generated can severe pollution if chemicals, brine, and other natural radioactive materials are left untreated or are poorly treated (Table 8).

The obtained results in Jiaoshiba Block of Fuling Play suggest that even small failures or rough operation in the rig area may result in the fluids seeking surface water or shallow groundwater. For example, Well 51-3HF had a leakage of over 400 $m^3$ of drilling fluid in an hour (Lu et al., 2016). Since October 2016, water source pollution has occurred more than 30 times within a short time, and more than 20 water sources became milky white, often with bubbles. The water coming out of the karst caves smelled like oil and diesel oil, and in severe cases, the water from the karst caves was colored black (Zhong and Fang, 2017).

The flowback rate of fracturing fluid in the Fuling shale gas field in Chongqing is relatively low, with an average flowback rate of approximately 2.6% and a maximum flowback rate of less than 5% (Yang et al., 2019). The average flowback rate of CHN–WY–ZHT in Sichuan and Yunnan is higher, between 25.3% and 52.6% (Table 9).

During the early stages of the Changning and Weiyuan shale gas fields in Sichuan Province, the fracturing flowback had medium salinity, with scale-forming ions, suspended substances, and a large number of bacteria, such as SRB, IB, and TGB. During the later stages, with increasing reuse times, as well as the cross-application of different fracturing fluid systems, the water quality of flowback fluid changed considerably, indicating that the concentration of TDS ($6\times10^4$ – $9\times10^4$ mg/L) and multivalents such as calcium, magnesium, and iron increased, and the flowback became black and smelly (Xiong et al., 2016b).

The produced water can be generated in the well site, gas collection station, or dewatering station, and its pollutant composition is similar to that of fracturing flowback. In the Fuling shale gas field, the yield of produced water from a single well is approximately 8–10 $m^3$/d, and the field's

**Table 7** Metal elements and pH value of flowback in Well Ning 201 (Lu et al., 2016)

| Metal cation/($mg\cdot L^{-1}$) | Ning 201-H1 | Ning 201-H2 | Ning 201-H3 |
|---|---|---|---|
| $K^+$ | 418.48 | 464.9 | 460.28 |
| $Na^+$ | 4,839.06 | 6,292.01 | 6,601.55 |
| $Ca^{2+}$ | 549.22 | 1,843.23 | 930.00 |
| $Mg^{2+}$ | 143.01 | 285.23 | 282.64 |
| $Fe^{3+}$ | 17.81 | 6.79 | 23.22 |
| $Sr^{2+}$ | 213.00 | 301.20 | 313.41 |
| $Cr^{3+}$ | 0.11 | 0.04 | 0.03 |
| $Zn^{2+}$ | 0.13 | 0.19 | 0.18 |
| $Mn^{2+}$ | 4.09 | 8.63 | 100.10 |
| $Hg^{2+}$ | 20.45 | 33.31 | 34.08 |
| pH | 6.94 | 6.96 | 6.71 |

**Table 8** Possible risks associated with water (Sun et al., 2019)

| Stage | Possible risks |
|---|---|
| Chemical mixing | Chemical spills, surface water and/or groundwater contamination |
| Well injection | Casing failure or induced fractures in the rocks, serving as a pathway for HF fluid migration into water resources |
| Flowback | Surface spills, infiltration into the ground from the reserve pits or tanks, and leaks from pipes |
| Wastewater treatment and disposal | Spills and leakage during on-site treatment, storage, and transportation to off-site treatment facilities or disposal |
| Discharge or reinjection | Inability of the treatment plants to effectively eliminate contaminants, which can reach streams and impair drinking water sources |

**Table 9** Fracture flowback volumes in shale gas field in Sichuan

| Play | Period | Well | Fracturing fluid volume/$m^3$ | Flowback volume/$m^3$ | Flowback rate /% |
|---|---|---|---|---|---|
| Changning | 2009–2018 | 107 | 42,658 | 14,612 | 35.2 |
| Weiyuan | 2014–2018 | 152 | 38,991 | 20,504 | 52.6 |
| Zhaotong | 2014–2018 | 86 | 41,872 | 10,503 | 25.3 |

total daily yield is approximately 2500 $m^3$, whereas the generated water amount of a single well in Changning–Weiyuan is approximately 5–30 $m^3$/d (Yang et al., 2019).

### 2.2.2 Waste

The solid waste produced during shale gas extraction mainly consists of waste drill cuttings, which can endanger the environment, as drill cuttings do not easily degrade naturally. If dumped untreated, it will cause not only the salinization of soil but also the destruction of natural vegetation. When buried underground, it will occupy a considerable amount of land at a high cost. Furthermore, with long-term burial, the solidified blocks will undergo a series of physical, chemical, and biological transformations, and thus cause secondary pollution (Wang et al., 2017).

Drill cuttings can be divided into two types: water-based drill cuttings (WBDCs) and oil-based drill cuttings (OBDCs), depending on the type of drilling fluid used. In the Sichuan Basin, oil-based drilling fluid is applied widely in horizontal wells applying multi-interval fracturing technology for gas extraction (Wang et al., 2017), whereas water-based drilling fluid is often used in vertical sections. The cuttings produced during drilling are relatively large. Approximately 200 – 300 $m^3$ of OBDC would be generated per well in the Fuling field, and approximately 260 – 350 $m^3$ of OBDC would be generated per well in the CHN–WY–ZHT field (Table 10).

However, WBDC is a solid waste, whereas OBDC is classified as hazardous waste. Chen et al. (2020) believe that heavy metal pollution from WBDC in the Fuling area poses a threat to the environment, despite the leaching toxicity being relatively limited. The contaminants in OBDC are petroleum, chemical agents, salt, and heavy metal ions, including Hg, Cd, As, Pb, and Cr. The oil content usually ranges from 10% to 20%, and its aromatic hydrocarbons are highly toxic. Chemical agents include emulsifiers and wetting agents, and salt is composed of inorganic salt in the drilling fluid and mineral salt dissolved in the formation. Therefore, the Chinese government has implemented a unified and strict management regime by classifying OBDC as a “HW08 category of hazardous solid waste” in the national hazardous waste list (Shi et al., 2019). Due to it being an oily solid waste, pyrolysis procedures are often used to ensure the safe discharge of OBDC.

### 2.2.3 Exhausts

In terms of air pollutants, potential compounds associated with shale gas development processes include: 1) criteria air pollutants (particulate matter, nitrogen oxides, sulfur oxides, and carbon monoxide), due to compressor engines; 2) volatile organic compounds, many of which are precursors to ground-level ozone formation, as well as

**Table 10** Solid waste volumes from a single well in each shale gas field/$m^3$

| | WBDC | Wastewater-based mud | OBDC | Pyrolysis residue of OBDC | Source |
|---|---|---|---|---|---|
| Fuling | 450–600 | 220–270 | 200–300 | 150–200 | Mei et al. (2016) |
| CHN–WY–ZHT | 610 | 330–450 | 260–350 | 120–220 | Huo et al. (2019) |

hazardous air pollutants, including benzene and formaldehyde; 3) methane, a greenhouse gas; and 4) odor-causing compounds, such as hydrogen sulfide and other reduced sulfides (Rich et al., 2014).

Methane, the primary shale gas constituent, contributes substantially to climate change, and other shale gas constituents are known to have adverse health effects. Methane is a powerful greenhouse gas, with a global warming potential that is far greater than that of carbon dioxide, particularly over the first few decades following emission. Approximately 3.6%–7.9% of the methane from shale gas production escapes into the atmosphere through venting and leaks over the lifetime of a well. These methane emissions are at least 30% higher than, and perhaps more than twice as high as those from conventional gas. Methane leakage mainly occurs during drilling, hydraulic fracturing, and gas extraction. The higher emissions from shale gas occur when time wells are hydraulically fractured, as methane escapes from flowback fluids, and during drill-out following the fracturing (Howarth et al., 2011).

In China, the methane emitted into the air during shale gas development mainly emanates from exhaust-associated produced water, shale gas released directly during gas processing, and the exhausts when cleaning gas tubes, which is released after combustion through the pipe adjacent to the equipment or the torch at the station (Table 11) (Yang et al., 2019).

### 2.2.4 Seismicity

According to the US Geological Survey, HF and the injection of wastewater (HF fluids and formation waters) into the subsurface can induce earthquakes. The abnormal increase in seismicity in areas such as the central United States and western Canada is considered to be a direct result of the rapid increase in injections for several applications including wastewater disposal, enhanced oil recovery, and shale gas HF. In late August 2019, small earthquakes continued to occur in areas where UK oil and gas company Cuadrilla was engaged in HF for shale gas, with some residents saying they felt strong tremors. The Cuadrilla project was the only active shale gas project in the UK, and was ordered to suspend operation due to protest.

Since 2014, with increased demand for clean energy and the implementation of China's national energy structure adjustment, the demand for shale gas production has increased significantly. Therefore, exploitation activities such as drilling, completion and fracturing are common in the Sichuan Basin. Table 12 shows that the extraction of shale gas has considerably increased seismic activity in the shale gas plays, from approximately 17% before 2015 to 50% in 2020. However, the impact of shale gas production on local seismic activity needs to be investigated further, because it has generally not resulted in large seismic events.

### 2.2.5 Noise

Noise related to shale gas production originates from: 1) pre-drilling: the mechanical rumble from the earth-rock construction on the platform; 2) drilling: noise generated by diesel engines, drilling equipment, mud pumps, vibrating screens, and other machinery; and 3) post-drilling: noise from the fracturing pump set, as shown in Table 13.

National law on the prevention and control of environmental noise pollution stipulates that noise from construction sites should be limited to 85 dB during the day and 55 dB during the night. Monitoring data on noise in shale gas production areas in the Sichuan Basin reveals that noise from diesel generator sets, which are generally used as the drilling power source, exceeds the standard by more than 16 dB (Mei et al., 2016). More than a dozen diesel fracturing trucks operate 24 h a day, generating noise at the same time, which has a significant impact on the lives of the people in surrounding areas. According to data from the Administrative Department of Environmental Protection in the production area, complaints about noise nuisance account for more than 60% of environmental pollution complaints, and approximately 10000 related

**Table 11** Main routes of methane emissions in shale gas fields (Yang et al., 2019)

| | Exhaust-associated/produced water | Shale gas directly released during gas processing | Exhaust from cleaning/gas tube |
|---|---|---|---|
| Fuling | 2–5 $m^3$/time | — | 1000 $m^3$/time |
| CHN–WY–ZHT | 2–5 $m^3$/time | 62500 $m^3$/(time·year) | 10–25 $m^3$/(time·tube) |

**Table 12** Earthquakes in the Sichuan Basin and its shale plays

| | **Sichuan Basin** | **Shale plays** |
|---|---|---|
| 2012–2014 | 2.8–7.0/3.46 (422) | 2.8–5.3/3.53 (57) |
| 2015–2020 June | 1.4–7.0/3.35 (536) | 1.9 – 6.0/3.36 (273) |
| Total | 1.7–7.0/3.39 (958) | 1.9 – 6.0/3.39 (330) |

Note: Minimum Magnitude – Maximum Magnitude/Average Magnitude (occurred times)

**Table 13** Noise sources associated with shale gas development in the Sichuan Basin

| Sound source | Sound power of a single device/dB |
|---|---|
| Pre-drilling: earth-rock construction | |
| bulldozer | 96 |
| Drilling: drilling well | |
| diesel motors | 113 |
| rig | 95 |
| mud pump | 90 |
| vibrating screen | 90 |
| centrifuge | 90 |
| air compressor | 95 |
| supercharger | 100 |
| Post-drilling: hydraulic fracturing | |
| fracturing truck | 100 |

conflicts and disputes need to be mediated every year (Zhong and Fang, 2017).

# 3 Cleaner shale gas production practices in China

In the production areas of the shale gas plays in Sichuan and its periphery, Chinese shale gas corporations have explored a cleaner production model of "source pollution prevention, process control, and end treatment" in practice, and have achieved good application results.

## 3.1 Source pollution prevention

Source pollution prevention refers to the design and planning before drilling and fracturing commence — the deployment of the development plan to configure drilling and fracturing.

### 3.1.1 Deployment of the development plan

1) Plan the development space carefully

Among the eight shale gas producing blocks in Sichuan, there are more than 60 nature reserves at or above provincial level, and more than 40 drinking water source reserves at or above county level. The ecological protection red line overlaps with shale gas mining rights by approximately 1.6% (Huo et al., 2019). For example, the Fuling shale gas field in Chongqing is located near five nature reserves and four tourist areas (Xiong et al., 2016a). Therefore, shale gas companies must attempt to avoid these sensitive ecological areas. On the other hand, they need to contribute to and adhere to the determination and adjustment of the government department's territorial space planning (Huo et al., 2019).

2) Position the drilling platform optimally

China's discovered shale gas fields are mainly located in the mountains of southwest China, where karst formations have led to large numbers of gullies on the surface and buried caves and rivers (Liu, 2016; Wan et al., 2018; Huo et al., 2019; Wan, 2019). When positioning the drilling platform by using the high-density resistivity technique (HDRT), hydrogeological exploration to determine the distribution of karst caves within 100 m underground were conducted for all 251 of the wells during the first phase of construction of the Fuling Play, to avoid the hidden river (Liu, 2016). The same was done at the Changning Play (Wan, 2019). Through the HDRT, the risk of leaking of drilling fluid and pollution of groundwater at the source was effectively reduced.

3) Utilize land intensively

It is difficult for shale gas producers to expropriate agricultural land in the densely populated Sichuan and Chongqing because 80% of the farmland is designated as primary farmland under permanent protection in China (Huo et al., 2019). To maximize available land resources, an approach of designing intensive drilling platforms, "well factory operation", standardized station design, and combining the gas recovery, and gathering and transportation stations on the same platform, was adopted.

According to data from the Wei202 and Wei204 blocks in Sichuan Province, compared with conventional oil and gas drilling, $5.84 \times 10^5$ $m^2$ land has been saved by the standardized deployment and construction of 27 horizontal wells on the five "factory" platforms (Tang, 2016).

Data from Fuling in Chongqing revealed that, compared with the conventional average land area of a single drilling well of $7.92 \times 10^3$ $m^2$, the "well factory" platform for four wells covers an area of $6.6 \times 10^3$ $m^2$, with an average land use saving of 79.2% per well. This "well factory" technology not only saves land, but also drilling fluids. According to data from 30 drilling platforms in the Fuling Play, a total of $2.184 \times 10^4$ $m^3$ of water-based drilling fluids and $3 \times 10^4$ $m^3$ of oil-based drilling fluids were saved (Mei et al., 2017a).

The land-use mode of "expropriate temporarily first and permanently later" was implemented. The temporary land is reclaimed and turned back into farmland completely (Fig. 5), with an average of 8.44 ha of reclaimed land per platform (Mei et al., 2017a).

4) Use water reasonably

In China it is forbidden to take water from small–medium rivers nearby for hydraulic fracturing operations, as this will exert pressure on residents' water availability. Special water pipelines in the Fuling field were built from the Wujiang River — the biggest river in the area — to fracturing platforms more than 20 km away (Fan, 2016). Other ways of water acquisition include recycling fracturing fluids, using reclaimed water from urban wastewater treatment plants, and building water reservoirs in gas fields for water storage.

**Fig. 5** Aerial photograph of reclamation effect on farmland.

### 3.1.2 Configuration of drilling and fracturing design

1) Drilling design optimization

In the Fuling shale gas field, a wellbore configuration of "one pipe and three stages" with four layers of casing was adopted. High-quality casing with 117 MPa pressure resistance is selected for cementing to ensure that the drilling hole is wholly separated from the water and shallow rock (Liu, 2016). Downsizing of the wellbore was also carried out, reducing water consumption per well by 12% and drilling waste by 17% (Mei et al., 2017a). The Changning field even designed different well structure schemes for three various topographical features: complex mountainous area, stacked mountainous area, and mountainous area with a highly damaging surface water source (Wan, 2019).

2) Drilling with gas or clean water

The geological characteristics of shallow fractures and karst caves in shale gas-rich areas may lead to serious and frequent well leakages. The current gas atomization drilling technology has been applied on a large scale in the Changning–Weiyuan shale gas fields (Fig. 6), limiting well leakage, and also improving drilling speed and shortening the drilling cycle. As a result, the protective effect on the environment is significant (Sun et al., 2017). For example, when it was drilled to 65.5 m with clear water, Well Wei-E202 began to leak, but continued drilling until 200.93 m, and then switched to air drilling. After that, it only took 1.5 days to drill to 600 m deep.

However, it is easy to block, and challenging to carry sand when gas drilling is used in a stratum with a high water content, therefore risking easy collapse. Instead, use of a clearwater drill is recommended. By the end of 2016, 271 wells in the Fuling shale gas field in Chongqing had been drilled with clear water in the 1500 m deep formations, reducing the amount of water-based drilling fluids by $1.355 \times 10^4$ $m^3$ (Mei et al., 2017a).

3) Use of environmentally friendly drilling fluids and fracturing fluids

- Drilling fluid

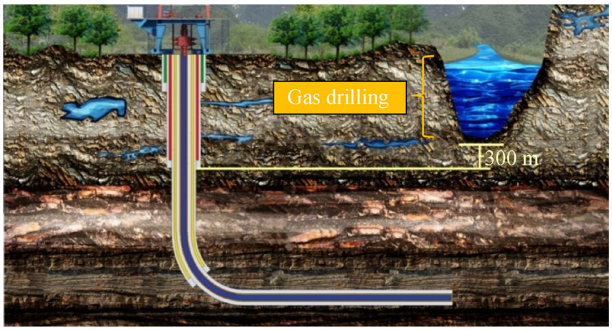


**Fig. 6** Schematic diagram of shallow drilling structure to protect underground water reservoirs.

In Fuling gas field, water drilling fluid is used in the 1500 m deep vertical section, water-based drilling fluid in the 1500–2500 m vertical section, and oil-based drilling fluid in the 2500–4500 m horizontal section.

The geological conditions in Sichuan and Chongqing are too complicated to transform drilling fluid to being completely harmless. In the Leikoupo Formation and upper strata, PAC, CMC, CMS, HPAM, and other treatment agents were used to prepare water-based polymer drilling fluid with little impact on the environment. When drilling the strata prone to collapse in the lower part of the vertical well section, the drilling fluid is usually converted to the sulfonated polymer drilling fluid system with strong sealing capabilities. Due to the in-degradability of polymers, the toxicity of catalysts and crosslinking agents, and the pollution of heavy metal ions, drilling fluids with low-toxicity treatment agents are used as far as possible to prepare polymer (Wei et al., 2018). At the Changning shale gas field in Sichuan, the high-performance water-based drilling fluids used in more than 30 wells can reach the same results as the oil-based drilling fluids (Sun et al., 2017).

- Fracturing fluid

Shale gas producers in China have been working to develop fracturing fluids that are free of heavy metals and high-risk substances, and easy to degrade.

Environmentally friendly additives, such as guanidine, hydroxyethyl cellulose, and sodium carbonate/potassium are selected for use in fracturing fluid in the Changning block (Wei et al., 2018). This recoverable oligomer fracturing fluid system has the advantages of reusability, continuous mixing, temperature resistance, strong sand-carrying capacity, low residue, and low damage, and the utilization rate of flowback is 98.0% (Sun et al., 2017). The fracturing flowback in the Changning area consists mostly of calcium chloride with high salinity (the average salinity of a single well in the region is approximately 30000 mg/L). Therefore, a salt-resistant friction reducer was developed in the Changning block to improve the performance of fracturing fluid (Wei et al., 2018).

In Chongqing's Fuling shale gas field, a new efficient and clean fracturing fluid system with stable performance, no corrosion, no residue, and low damage, suitable for the shale gas reservoir, has been developed. The chemicals used during fracturing has been published for public review and submitted to the local environmental protection department for approval. After entering the formation, the fracturing fluid will automatically degrade with an increase in temperature and over time, causing less damage to the rock. A total of 276 wells have used this environmentally friendly fracturing fluid system and achieved good fracturing results (Mei et al., 2017a).

### 3.2 Process control

#### 3.2.1 Fluids

The waste fluid during shale gas production includes: 1) the wastewater in contact with drilling fluid and oil; 2) the waste drilling fluid after drilling; and 3) fracturing flowback and produced water (Fig. 7).

Deep-well injection and reuse are the most commonly employed strategies for water control. Reuse is the preferred option where feasible (Zhang et al., 2016). Other techniques, such as mechanical vapor compression, thermal distillation, or forward osmosis may be needed to meet the requirements for discharge.

1) Wastewater

Oil-based drilling fluid is widely used in horizontal shale gas drilling in the Sichuan Basin, and no drilling wastewater is generated. Clearwater and/or water-based drilling fluids are used in the straight and inclined section, and the wastewater generated is non-toxic and alkaline. The average wastewater volume per meter in depth is approximately 0.4 m$^3$. All the wastewater generated by drilling is dealt with on-site without being discharged, and all shale gas fields have realized 100% reuse of drilling wastewater (Yang et al., 2019).

- Establishing a rain–sewage diversion system.

Each shale gas well is equipped with a 1000 m$^3$ wastewater tank with anti-seepage hardened ground. Because Sichuan and Chongqing have a high annual rainfall, clean water, including rainwater, easily become contaminated with sewage, with sewage overflows occurring especially after heavy rain. A rain–sewage diversion system has been developed (Fig. 8) in which the wastewater pool is isolated by a closed cofferdam, with rain shelter in the upper part. The rainwater flows into the surrounding oil interceptor along the slope and into the natural water system (Sun et al., 2017; Wei et al., 2018; Huang, 2019). Data shows that this sewage diversion system has resulted in a 34.8% reduction in the amount of wastewater compared with those of conventional wells during the rainy season (Wang et al., 2018).

- Centralized processing.

After the sewage is coagulated, precipitated or separated from the oil, slag removed, deodorized, softened, PH-adjusted, and filtered, it is used to prepare water-based drilling fluids or fracturing fluids, or to clean equipment and remove dust (Yang et al., 2019).

2) Waste drilling fluid

Generally, in the same shale gas development area, the geological conditions at the well site or block are similar, and the re-use of drilling fluid can quickly and easily adapt to the underground requirements, which is conducive to optimal drilling. The recycling process is illustrated in Fig. 9. The surplus drilling fluid (water drilling fluid, water-based drilling fluid, and oil-based drilling fluid) is collected for centralized storage and collection, and then the drill cuttings and drilling fluid are separated by a waste fluid disposal system (such as vibrating screen, sand remover, mud remover, and centrifuge). The separated clear liquid is used to prepare drilling fluid for recycling. The drilling fluid is secured in order not to spill on the ground during drilling. According to data of 13 platforms in Changning–Weiyuan, the re-utilization amount of water-based drilling fluid reached 7671 m$^3$, and the reuse rate was 81.17%, which reduced the single well cost by approximately 30% (Wei et al., 2018).

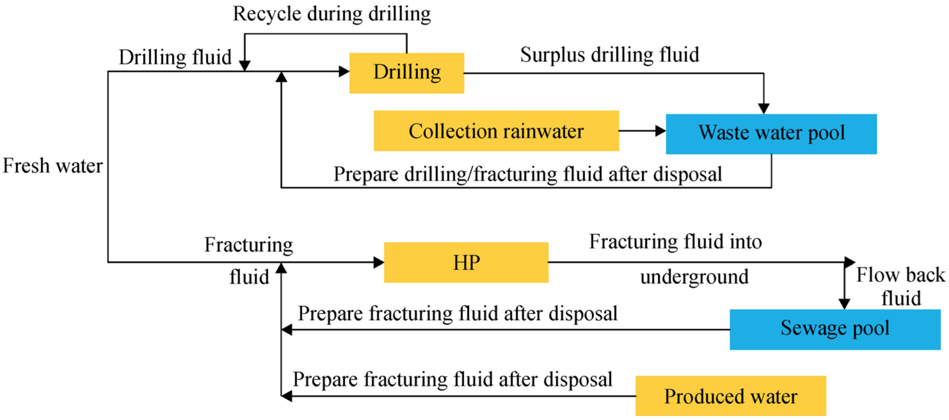


**Fig. 7** Flow diagram of water treatment in shale gas field.

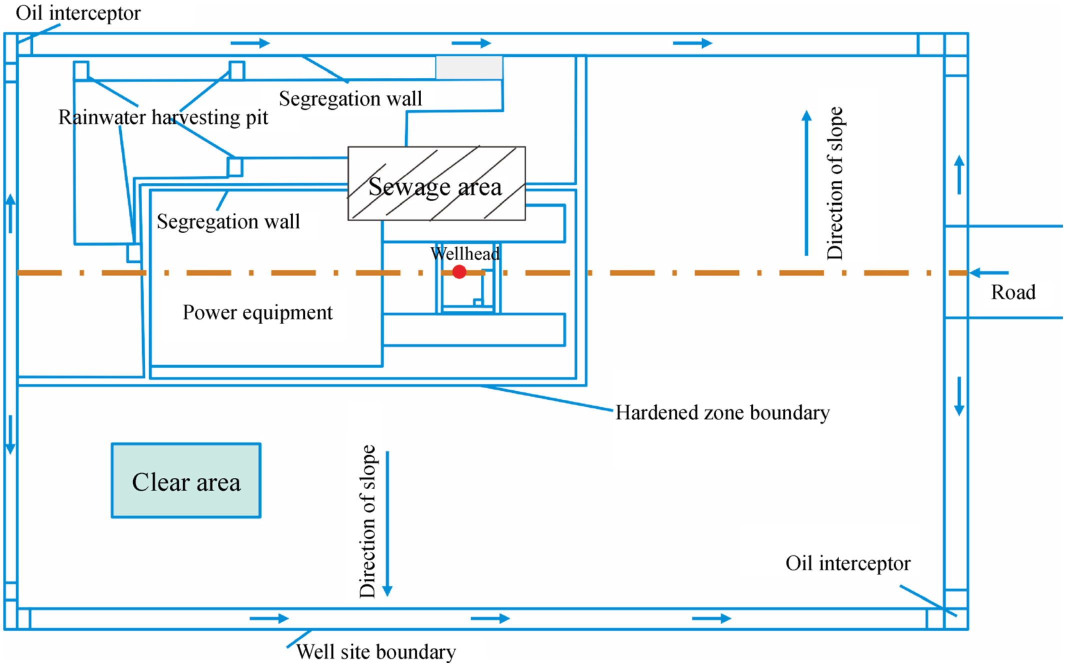


**Fig. 8** Rain–sewage diversion system (adapted from Huang, 2019 and Sun et al., 2017)

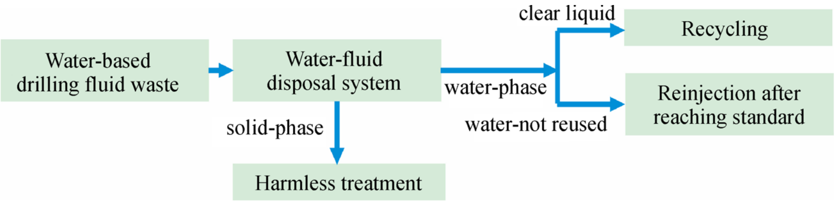


**Fig. 9** Flow diagram of drilling fluid waste disposal (adapted from Wei et al., 2018).

Of the solids in drilling waste fluid, some complicated organic matter is converted into humus components, with the remainder left to degrade into simple inorganic matter (including $CO_2$ and $H_2O$), in order to render the pollutants in the drilling waste fluid harmless (Wei et al., 2018).

3) Flowback and produced water

The treatment of hazardous FPW is a significant challenge for the oil and gas industry because of stringent regulations (Li et al., 2014). Various treatment or disposal options are available for FPW management, such as underground injection, treatment at hazardous wastewater treatment plants, and/or reuse (Zhang et al., 2016).

Chinese enterprises mainly adopt aeration, coagulation and flocculation-filtration technologies in the treatment of fracturing flowback wastewater from shale gas wells (Fig. 10). After coagulation, precipitation, and sterilization, the quality of flowback water reaches the standard and can be reused to prepare new fracturing fluid.

In the Fuling shale gas field, the disposed flow-back was mixed with fresh water at a ratio of ⩽3:7, to prepare a new fracturing fluid. All the flowback and produced water have been reused for new fracturing fluid in Fuling (Yang et al., 2019). At the CHN–WY–ZHT shale gas field, the handled water quality of fracturing flow-back fluids (Table 14) significantly improved (Wei et al., 2018). By the end of 2018, the average reuse rate had reached 60.3% –75.8% (Table 15). Well No. 141 has returned $63.6\times10^4$ $m^3$ of fracturing flowback fluid, and recycled $60.5\times10^4$ $m^3$, with a reuse rate of 95%.

### 3.2.2 Solids

Solid waste consist of drilling waste muds (including WBDC, OBDC) and sludge from wastewater treatment, and different treatments are applied in practice depending on the type of solid waste. Sludge is incorporated into WBDC for simultaneous disposal. Oil-based cuttings are strictly prohibited from being discharged into the waste-water pool. All the solid waste is prevented from falling on the ground during treatment, including collection, transfer, and storage (Mei et al., 2017b; Sun et al., 2017; Liu, 2018).

1) Water-based drill cuttings (WBDC)

A vibrating screen for solid–liquid separation, a device independently developed by Chinese shale gas enterprises,

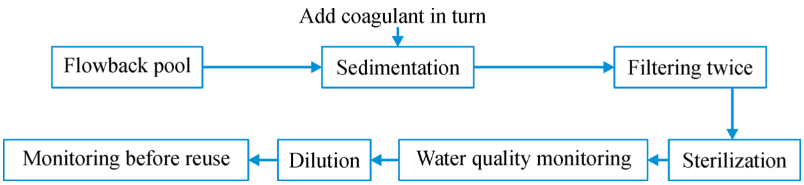


**Fig. 10** Flow diagram of treatment of fracturing flowback fluid.

**Table 14** Water quality before and after treatment

| Water quality | pH | $\rho$ (total iron) /(mg·L$^{-1}$) | COD/mg·L$^{-1}$ | $\rho$ (petroleum) /(mg·L$^{-1}$) | $\rho$ (TSS)/(mg·L$^{-1}$) |
|---|---|---|---|---|---|
| Before treatment | 7.8 | 12.2 | 287 | 22.68 | 73 |
| After treatment | 7.3 | 0.8 | 98.4 | 1.14 | 29.75 |

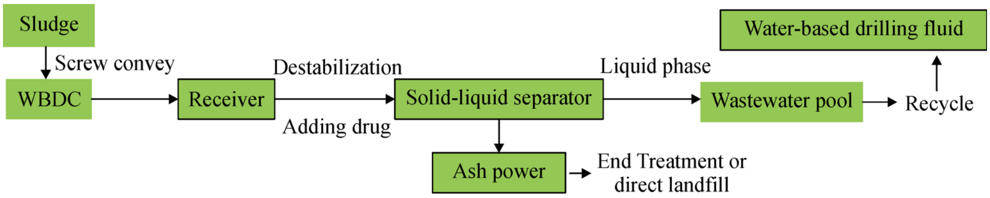
**Table 15** Return and reuse of fracturing fluid in the Sichuan Basin

| Gas field | Period | Flowback volume/m$^3$ | Reuse volume/m$^3$ | Reuse rate/% |
|---|---|---|---|---|
| Changning | 2014–2018 | 1563503 | 1128926 | 60.3 |
| Weiyuan | 2015–2018 | 1931759 | 2549744 | 75.8 |
| Zhaotong | 2014–2018 | 521618 | 343492 | 65.9 |

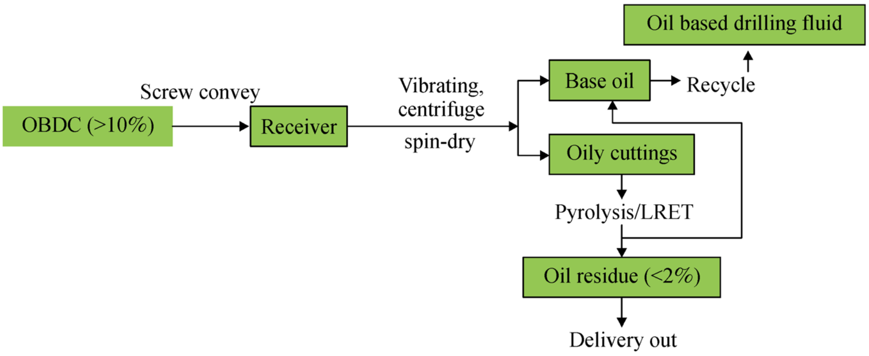
achieves real-time processing of water-based cuttings while drilling (Wang et al., 2018). After solid–liquid separation, the liquid enters the wastewater pool to be recycled to prepare water-based drilling fluid, and the solid ash powders can be processed at the end or directly buried (Fig. 11).

2) Oil-based drill cuttings (OBDC)

Traditional solidification and landfill disposal of OBDC has gone out of use due to the large areas of land it requires and the potential for pollution. OBDC can be handled on-site (Fig. 11). After three treatments by a shaker, dryer, and centrifuge, the oil content of oil-based cuttings is reduced from more than 10% to approximately 3.5%, and then, through pyrolysis adsorption or LRET, the oil content of the remaining residue is reduced to less than 2%, after which it is delivered to a qualified environmental company for further disposal. The recovered base oil can be recycled to prepare oil-based drilling fluid (Liu, 2016). This



WBDC treatment process



OBDC treatment process

**Fig. 11** Flow diagram of the treatment of WBDC and oil-based drill cuttings (OBDC).

technology has treated more than 8000 ton of oil-based cuttings and recovered 900 ton of oil-based drilling fluid in Changning–Weiyuan Field (Sun et al., 2017).

### 3.2.3 Noise and exhausts

1) Noise

Conventional drilling and fracturing are powered by diesel generators, which are energy-intensive and inefficient, especially due to the $CO_2$ and other greenhouse gases they emit, and the loud noise they generate.

According to the power supply facilities in shale gas areas, China's companies lay exclusive power supply lines to use high-voltage grid electric rigs, instead of using diesel-driven ones. Data on 171 wells in Chongqing's shale gas producing area show (Mei et al., 2017a) that 81% of the drilling rigs have been switched to be electricity-driven, saving $5.47 \times 10^4$ ton of diesel, reducing $1.705 \times 10^5$ ton of $CO_2$ emissions, and reducing equipment noise from 93.1–94.3 dB to 76.1 dB.

At the same time, electricity-driven fracturing devices have been widely adopted. A conventional fracturing truck consumes 300 L of diesel oil per hour and generates noise of 103 dB, whereas an electric fracturing pump, using 2400 kWh and generating only 90 dB of noise, does not produce any harmful gases such as nitrogen oxides and sulfur dioxide. Furthermore, for wells that are in close proximity to residential areas, installing a noise screen may be a good option.

2) Exhausts

The switch from diesel to electricity mentioned above not only reduces noise but also reduces the discharge of greenhouse gas, solid particles, and other waste gases. In addition to this, the emission of natural gases during the process of testing and extracting gas is under strict control.

During fracturing fluid flowback and gas-testing, a counterbalance valve is set to minimize discharge time to extract shale gas while gas-testing, through the self-developed ground process testing system for shale gas (Xiong et al., 2016a). The technology has been applied in 32 wells in the Fuling field, with a reduction in shale gas combustion of $3.0 \times 10^5$ $m^3$ per well, and a total recovery of $9.6 \times 10^6$ $m^3$ for 32 wells (Mei et al., 2017a).

During gas extraction, sealed gathering and transportation has been adopted to separate the gas–liquid flowback, and the separated shale gas is transferred into the pipe with no methane escaping directly into the atmosphere.

## 3.3 Residues treatment

China's shale gas companies have been attempting to turn residue into alternative resources or render the waste harmless as much as possible, and this is referred to as "end treatment."

### 3.3.1 WBDC residue

1) Manufacturing building materials

When the water content of clean water and water-based drill cuttings drops to 16%–20%, it can be used as fire-fighting sand or paving for well sites. Water-based cuttings mixed with cementitious materials can be used as road-base bedding cushions and concrete (Mei et al., 2017a). Water-based cuttings can also be used to manufacture baking-free bricks, with high hardness after dehydration and mechanical compaction. These bricks have been approved by the environmental protection department. More than 55,000 t of water-based cuttings have been disposed of in this way in Changning–Weiyuan Fields (Sun et al., 2017). In Chongqing's shale gas producing area, ash powder from oil-based waste replaces fine sand in the manufacturing of concrete and baking-free bricks for surface construction in gas fields.

2) Microbial degradation

Water-based drilling waste has been dealt with by adding an appropriate proportion of soil and highly efficient degradation strains. After more than three months of degradation treatment of drill cuttings, the degradation rate of the main indicators such as COD and petroleum in the solid waste exceeded 90%, reaching the sewage discharge standard. Pb, Cd, and other heavy metal indexes in soil-waste mixtures disposed of by biological degradation conform with soil environmental quality standards. This microbial treatment technology has been approved by the local environmental protection agency and will continue to be applied in the clean production of shale gas (Sun et al., 2017).

### 3.3.2 Oil-based drill cutting (OBDC) residue

1) Thermal desorption

Chinese petroleum companies have self-developed a "hammer-mill" thermal desorption treatment method of oil-based cuttings, which separates water from oil through distillation and condensation. The performance of this method meets the requirements of preparing oil-based drilling fluid. The oil recovery rate is 95%, with the oil content of treated OBDC less than 1%. The capacity of thermal desorption to treat OBDC is up to 40 ton/d in shale gas fields in China (Huang, 2019).

2) LRET

Solvent extraction technology (LRET) combines physical separation with deep separation of the treatment agent to recover base oil and drilling fluid additives from oil-based drilling waste. The oil content of cuttings after treatment is less than 1%, and the recovered oil-based drilling fluid meet recycling requirements. LRET has been used on-site in the Changning play, where 12000 ton of OBDC have been disposed, and 1400 $m^3$ of oil-based drilling fluid has been recovered (Sun et al., 2017). The treatment capacity of LRET is up to 150 ton/d, with an oil recovery rate of 98% (Huang, 2019).

3) Making fuel slurry

With this technology, oil-based cuttings are used as matrix material by adding combustion improver to form reliable fluid fuel products, which are mainly used as auxiliary materials in brickmaking. After that, the oil content of fuel slag is less than 1%. The advantages of making fuel slurry are lower costs, simpler process, and significantly better disposal. The treatment capacity of making fuel slurry is up to 15 ton/d. (Huang, 2019).

4) Co-combustion in cement-producing kilns

This technology means the harmless treatment process of solid waste is synchronized with cement clinker production. OBDC and semi-solid materials are mixed and adjusted in a particular proportion to make semi-solid homogeneous pretreatment products, which can enter the cement kiln for disposal after reaching the quality standard of the furnace. For example, OBDC generated in Well JY199-4HF and Well JY199-5HF in Fuling field were treated with cement kiln technology (Xia et al., 2019).

## 4 Conclusions

This study demonstrates environmental risks of shale gas exploration in the Sichuan Basin in the southern part of China and then provides corresponding solutions for clean shale gas production. Three shale gas fields were in detail analyzed on environmental problems from wells drilling to natural gas development. Main environmental risks includes water resources consuming, underground water pollution, noise, seismicity and so on. By 10-year advances in technologies, the clean production model developed by China's Petroleum Companies can be summarized as follows:

1) Reducing the consumption and occupation of resources, and reducing pollution and damage to the environment. For example, "well factory operation" may occupy less land, and the recovery and recycling of drilling fluid and fracturing flowback fluid can reduce the demand for water resources. Gas drilling or clear water drilling, as well as using environmentally friendly drilling fluid and fracturing fluid, may decrease the water pollution risk caused by drilling fluid leakage. Using grid power for drilling and fracturing operations can reduce noise. A ground process testing system of shale gas can reduce carbon emissions from $CH_4$ combustion.

2) Degradation or decomposition of harmful components of liquid, gas, and solid materials associated with shale gas exploration. By using the rain–sewage diversion system or by ensuring drilling fluid and drill cuttings do not to fall on the ground, the well site and surrounding environment will not be polluted. Microorganism treatment can degrade water-based drill cuttings, and co-combustion in cement-producing kilns deals with oil-based cuttings cleanly.

3) Reusing harmless waste residues as different resources. The manufacturing of fuel slurry and baking-free bricks have turned solid drill cuttings into fuel and building materials.

The shale gas industry in China has been exploring ways to achieve clean production by saving resources and employing environmentally friendly technologies to achieve the two controls (reducing greenhouse gas emissions and noise), three utilizations (WBDC, oil cuttings, fracturing fluid flowback), and four protections (surface water, groundwater, soil, vegetation). However, in the future, it is necessary to develop advanced clean technologies for drilling fluid and fracturing flowback, implement dynamic environmental risk assessment and monitoring of the ecological environment, and establish a safety and environmental protection standard system.

**Acknowledgements** This work was supported by the National Key Technology R & D Program of China (No. 2011ZX05028-002). The authors acknowledge colleagues from the PetroChina Research Institute of Petroleum Exploration and Development for their help with this study.

## References

Baranzelli C, Vandecasteele I, Ribeiro Barranco R, Mari i Rivero I, Pelletier N, Batelaan O, Lavalle C (2015). Scenarios for shale gas development and their related land use impacts in the Baltic Basin, Northern Poland. Energy Policy, 84: 80–95

Chen L, He M, Wang D, Zhang S, Yang F (2016). Discussion on pollution control technologies of fracturing waste water in fuling shale gas exploitation. Fine Spec Chem, 24: 26–31

Chen Y, He L, Guan Y, Lu H, Li J (2017). Life cycle assessment of greenhouse gas emissions and water-energy optimization for shale gas supply chain planning based on multi-level approach: case study in Barnett, Marcellus, Fayetteville, and Haynesville shales. Energy Convers Manage, 134: 382–398

Chen Z, Zheng Z, Li D, Chen H, Xu Y (2020). Continuous supercritical water oxidation treatment of oil-based drill cuttings using municipal sewage sludge as diluent. J Hazard Mater, 384: 121225

Chongqing Provincial Water Resources Bureau (2018). Chongqing water resources bulletin, 2018. Available at Chongqing Government website

Eaton T T (2013). Science-based decision-making on complex issues: Marcellus shale gas hydrofracking and New York City water supply. Sci Total Environ, (461–462): 158–169

EIA (2018). Natural gas and the environment. Available at EIA website

EIA (2015a). World Shale Resource Assessments. Available at MWR website

EIA (2015b). China adds incentives for domestic natural gas production as imports increase- Today in Energy. Available at EIA website

EPA (2012). Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources: Progress Report

Estrada J M, Bhamidimarri R (2016). A review of the issues and treatment options for wastewater from shale gas extraction by hydraulic fracturing. Fuel, 182: 292–303

Fan H (2016). Approaching jiaoshiba – focusing on geological environment impact assessment in the development of fuling shale gas field in chongqing. Hydrogeol. Eng. Geol, 171–172

Gregory K B, Vidic R D, Dzombak D A (2011). Water management challenges associated with the production of shale gas by hydraulic fracturing. Elements, 7(3): 181–186

Guizhou Provincial Water Resources Department (2018). Guizhou province water resources bulletin. Available at Guizhou Goverment website

Guo Y, Zhang X, Wang Q, Chen H, Du X, Ma Y (2020). Temporal changes in vegetation around a shale gas development area in a subtropical karst region in southwestern China. Sci Total Environ, 701: 134769

Gvakharia A, Kort E A, Brandt A, Peischl J, Ryerson T B, Schwarz J P, Smith M L, Sweeney C (2017). Methane, black carbon, and ethane emissions from natural gas flares in the Bakken Shale, North Dakota. Environ Sci Technol, 51(9): 5317–5325

Holland A A (2013). Earthquakes triggered by hydraulic fracturing in south-central Oklahoma. Bull Seismol Soc Am, 103(3): 1784–1792

Howarth R W, Santoro R, Ingraffea A (2011). Methane and the greenhouse-gas footprint of natural gas from shale formations. Clim Change, 106(4): 679–690

Huang W (2019). Cost-reduction and Profit-increase Cases of Shale Gas Drilling Engineering. Beijing: Petroleum Industry Press (in Chinese)

Huo X, Jiao Y, Li Y, Yang Z, Luo F (2019). Current status of environmental protection and countermeasures of shale gas exploitation in southern Sichuan. Environ Prot Oil Gas Fields, 29: 1–3

Kahrilas G A, Blotevogel J, Stewart P S, Borch T (2015). Biocides in hydraulic fracturing fluids: a critical review of their usage, mobility, degradation, and toxicity. Environ Sci Technol, 49(1): 16–32

Li X M, Zhao B, Wang Z, Xie M, Song J, Nghiem L D, He T, Yang C, Li C, Chen G (2014). Water reclamation from shale gas drilling flow-back fluid using a novel forward osmosis-vacuum membrane distillation hybrid system. Water Sci Technol, 69(5): 1036–1044

Liang R, Tong L, Xiang Q, Zhuang S, Zhou X (2014). Management of and proposals on environmental impact assessment (EIA) for shale gas development in China. Nat Gas Ind, 34: 135–140

Liu C (2016). Research and practice of the key technologies for “green” drilling. Explor Eng (Rock & Soil Drill Tunneling), 43: 9–13

Liu Y (2018). Key technologies for green development in the Fuling shale gas field. Pet Drill Tech, 46: 8–13

Lu T, Hu M, Liu M, Ding C, Wang X (2016). On the impact of shale gas development on water resource and environment in Sichuan and Chongqing. Sci Technol Rev, 34: 51–56

Lutz B D, Lewis A N, Doyle M W (2013). Generation, transport, and disposal of wastewater associated with Marcellus Shale gas development. Water Resour Res, 49(2): 647–656

Macro Data on the Global Economy (2015). Cultivated land area per capita (index). Available at Sina website

Mei X, Jin J, Wang C, He Y, Wang D, Zhang C (2017a). Practice and research of green development in Fuling Shale Gas Field. J Southwest Pet Univ Sci Ed, 19: 9–14

Mei X, Wang C, Zhang S, Xiong D, Zhang C, He M (2017b). Main environmental risk analysis and countermeasure for shale gas mining in Fuling. Environmental Science and Management, 42: 63–66

Mei X, Zhang S, Xiong D, Wang C, He M (2016). Impacts of Shale Gas Exploitation on Ecological Environmengt in Fuling and Countermeasures. J Southwest Pet Univ Sci Ed, 18: 7–12

Milt A W, Armsworth P R (2017). Performance of a cap and trade system for managing environmental impacts of shale gas surface infrastructure. Ecol Econ, 131: 399–406

Minstry of Water Resources of the People’s Republic of China (2018a). Water resources bulletin. Available at Ministry of Water Resources of the People’s Republic of China Website

Minstry of Water Resources of the People’s Republic of China (2018b). Bulletin on flood and drought disasters in China. Available at Ministry of Water Resources of the People’s Republic of China Website

Mohammad-Pajooh E, Weichgrebe D, Cuff G, Tosarkani B M, Rosenwinkel K H (2018). On-site treatment of flowback and produced water from shale gas hydraulic fracturing: a review and economic evaluation. Chemosphere, 212: 898–914

Rich A, Grover J P, Sattler M L (2014). An exploratory study of air emissions associated with shale gas development and production in the Barnett Shale. J Air Waste Manag Assoc, 64(1): 61–72

Roy A A, Adams P J, Robinson A L (2014). Air pollutant emissions from the development, production, and processing of Marcellus Shale natural gas. J Air Waste Manag Assoc, 64(1): 19–37

Rozell D J, Reaven S J (2012). Water pollution risk associated with natural gas extraction from the Marcellus Shale. Risk Anal, 32(8): 1382–1393

Shi Z, Xu Y, Shao Z, Sun J, Liu J, Ke Y (2019). Research and Application of Thermal-desorption Treatment of Oil-based Cuttings from Shale Gas Produtiion. Environ Prot Oil Gas F, 29: 37–40

Sichuan Provincial Water Resources Department (2018). Sichuan water resources bulletin. Available at Sichuan Provincial Water Resources Department website

Sun H, Wang C, Liu W, Xie Y (2017). Cleaner production in the Changning-Weiyuan national shale gas demonstration area. Nat Gas Ind, 37: 105–111

Sun Y, Wang D, Tsang D C W, Wang L, Ok Y S, Feng Y (2019). A critical review of risks, characteristics, and treatment strategies for potentially toxic elements in wastewater from shale gas extraction. Environ Int, 125: 452–469

Tang Y, Jinchuan Z, Qin Z, Pengyu L (2010). Hydraulic fracturing of shale gas Wells and its application analysis. Nat gas Ind, 30: 33–39

Tang Z (2016). A brief analysis of the application and practice of factory operation mode in shale gas development in weiyuan. China Pet Chem Ind Stand Qual, 36: 78–79

Van de Graaf T, Haesebrouck T, Debaere P (2018). Fractured politics? The comparative regulation of shale gas in Europe. J Eur Public Policy, 25(9): 1276–1293

Vengosh A, Jackson R B, Warner N, Darrah T H, Kondash A (2014). A Critical Review of the Risks to Water Resources from Unconventional Shale Gas Development and Hydraulic Fracturing in the United States. Environ Sci Technol, 48(15): 8334–8348

Wan F (2019). Research on plugging technology for surface casing drilling of changing shale gas. Drill & Prod Technol, 42: 28–31

Wan F, Liu H, Qi Y (2018). Environmental surface driling on well pad N213. Drill & Prod Technol, 41: 13–15

Wan Z, Huang T, Craig B (2014). Barriers to the development of China's shale gas industry. J Clean Prod, 84: 818–823

Wang C Q, Jin J Z, Lin X Y, Xiong D M, Mei X D (2017). A study on the oil-based drilling cutting pyrolysis residue resource utilization by the exploration and development of shale gas. Environ Sci Pollut Res, 24: 17816–17828

Wang Q, Zhu D, Xia G, Zeng G, Li X, Chen H, Wei L, Liu Y (2018). Technological series supporting the "green-development" of shale gas in China: a case study. Nat Gas Ind, 38: 125–130

Warner N R, Christie C A, Jackson R B, Vengosh A (2013). Impacts of shale gas wastewater disposal on water quality in western Pennsylvania. Environ Sci Technol, 47(20): 11849–11857

Wei Y, Wang S, Ma Q, Wu W, Lu X, Yan X (2018). Waste water management in Sichuan Changning-Weiyuan shale gas field. Chem Eng Oil Gas, 47(4): 113–119

Wu X, Xia J, Guan B, Liu P, Ning L, Yi X, Yang L, Hu S (2019a). Water scarcity assessment based on estimated ultimate energy recovery and water footprint framework during shale gas production in the Changning play. J Clean Prod, 241: 118312

Wu X, Xia J, Guan B, Yan X, Zou L, Liu P, Yang L, Hong S, Hu S (2019b). Water availability assessment of shale gas production in the Weiyuan play, China. Sustain, 11(3)

Xia H, Bao K, Wang Y, Zhou C, Yang Y (2019). An Integrated Drilling Cuttings Utilization Technique in the South Pingqiao Block of the Fuling Shale Gas Field. Pet Drill Tech, 47: 63–67

Xie X, Zhang T, Wang M, Huang Z (2019). Impact of shale gas development on regional water resources in China from water footprint assessment view. Sci Total Environ, 679: 317–327

Xiong D, Zhang S, Feng B, Wang C, Mei X, Zhang C (2016a). Present status analysis of environmental protection in exploration and development of fuling shale gas. J Xi'an Shiyou Univ Nat Sci Ed, 31: 48–53

Xiong Y, Liu Y, Liu Y, Wu W, Dai Y, Chen N (2016b). Recycling disposal technology and application of shale gas fracturing flowback fluid in Changning-Weiyuan area. Chem Eng Oil Gas, 45: 51–55

Yang D, Yu Y, Liang R, Yuan J (2019). Development progress and environmental protection status in China's key shale gas construction areas and suggestions. Mod Chem Ind, 39: 1–6

Yang H, Huang X, Yang Q, Tu J, Li S, Yang D, Xia H, Flower R J, Thompson J R (2015). Water requirements for shale gas fracking in Fuling, Chongqing, Southwest China. Energy Procedia, 76: 106–112

Yunnan Provincial Water Resources Department (2018). Yunnan water resources bulletin. Available at wcd.yn.gov.cn website

Zhang X, Sun A Y, Duncan I J (2016). Shale gas wastewater management under uncertainty. J Environ Manage, 165: 188–198

Zhong Y, Fang J (2017). Environmental protection during the development of fuling national shale gas production demonstration area. China Petrochem, 34–35

## AUTHOR BIOGRAPHIES

**Shikui Gao** received her B.Sc. and M.Sc. Degrees in Economics from China University of Geosciences, China and a Ph.D. in Economics and Management from China University of Petroleum (Beijing), China. She is an associate professor at China University of Geosciences (Beijing), China. associate prof. Gao's research is broadly interdisciplinary, anchored on a core expertise in economic evaluation and in environmental systems. She has published about 30 peer-reviewed articles, often collaboratively, in areas including environmental science; economics and management; and petroleum science.
E-mail: gaoshikui@cugb.edu.cn

**Quanzhong Guan** received his M.S. and Ph.D. in Geological Resources and Geological Engineering from PetroChina Research Institute of Petroleum Exploration and Development, and China University of Petroleum (Beijing), China. He is a lecturer in Petroleum Geology at the College of Energy, Chengdu University of Technology, China. His research explores the unconventional reservoirs of gas shales, and environmental risks. He has published 45 peer-reviewed articles and is an editor for Natural Gas Industry Journal.
E-mail: muchang503@126.com

**Dazhong Dong** received his M.S. and Ph.D. in Geological Resources and Geological Engineering from PetroChina Research Institute of Petroleum Exploration and Development, and China University of Petroleum (Beijing), China. He is a professor in Petroleum Geology at the PetroChina Research Institute of Petroleum Exploration and Development, China. His research focuses on petroleum geology and energy exploration evaluations. He has published 73 peer-reviewed articles and is an editor for core journals on petroleum science.
E-mail: ddz@petrochina.com.cn

**Fang Huang** earned his BA in management from China University of Geosciences (Beijing) and is currently a master's student in the University.
E-mail:hhfangs@163.com