Water Availability Assessment of Shale Gas Production in the Weiyuan Play, China

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Abstract: Innovations and improvements in hydraulic fracturing and horizontal well technologies have contributed to the success of the shale gas industry; however, the industry is also challenged by freshwater use and environmental health issues. Increasing water impact makes precise quantification of water consumption important. The objective in this study was to better understand water sustainability and availability of the projected shale gas from 2018 to 2030 in the Weiyuan play, China. The water footprint framework was used to quantify the potential water use and environmental impacts on different time scales. The results showed that the water use per well ranged from 11351.3 to 60664.73 m^3, with a median of 36013.94 m^3, totaling ~3.44 Mm^3 for 97 wells. Yearly evaluation results showed that the gray water footprint was the main contributor and accounted for 83.82% to 96.76%, which was dependent on different scenarios of treatment percentages. The monthly environmental impact results indicated that the annual streamflow statistics were more likely to prevent water withdrawal. Water quality issues may be alleviated through recycling and retreatment measures that improve current waste water management strategies. Resource regulators should manage their water resources by matching water demand to water availability or replenishment.

Keywords: water availability; shale gas; water sustainability; Weiyuan play

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1 Introduction

Fossil fuels (especially coal and oil) account for 65% of carbon emissions [1], and China is a country with a fossil-based energy system (Fig. S1), which has committed to peak its carbon emissions by 2030 at the Paris climate change agreement[2].Fuel switching is a pivotal and vital way to mitigate climate change and environmental pollution [3, 4].Shale gas, a clean-burning and efficient energy resource, has become a hot topic, particularly in regard to the advantages of reducing a country's overdependence on high-pollution energy resources [3, 5, 6]. China's shale gas reserves are 31.57 trillion m^3, ranking first in the world's shale gas reserves, and are the largest global reserves of technically recoverable shale gas [7, 8]. Shale gas is a promising option for China's decarbonized energy transition with respect to carbon emission reduction and abundant reserves. The Chinese government is focused on shale gas production development and also has set a target to increase the annul shale gas production from 30 billion m^3 in 2020 to 100 billion m^3 in 2030 [9].

The vigorous innovation and reform improvements in horizontal wells and hydraulic fracturing (HF) technologies have contributed to the flourishing development of the shale gas industry, while they also have caused environmental issues, including both water scarcity and contamination [10-14]. Nowadays, the main source of HF water is from regional water resources, and the volume of water used is increasing and place growing demands on regional water, which may cause a conflict with regional water consumption activities, such as irrigation and industrial water use. Water scarcity may be a limiting factor for sustainable shale gas development not only in semiarid regions globally but also in seasonally water-deficient areas in more humid settings [15-17]. In addition, water contamination caused by wastewater disposal, and determined by the volume and quality of flowback and produced (FP) water generated from shale gas wells, has also captured global attention [18-20]. Furthermore, water quality degradation is related to water depletion, and the problem of water quality can be expected to intensify as water scarcity increases.

Water footprint assessment (WFA) is a widely used analytical tool for quantifying

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the water quantity and quality impacts [21, 22]. The water footprint quantitatively evaluates water pollution and can more intuitively reflect the impact of water pollution on the amount of water available [22]. Previous studies have evaluated the water footprint of the shale gas industry and provided a wide range of water use, while they mostly focused on water consumption volume [23-25], and few studies have detailed quantified the volume of wastewater influence generated from shale gas production.

Some studies have attempted to evaluate the water issues regarding the sustainability of shale gas development in the Sichuan Basin [26-30]. However, due to lack of detailed onsite data, most of them focused on roughly evaluation of water use and production, only a limited number of recent studies provide onsite data on HF water use. This study builds on previous work in the major China Sichuan Basin and aims to focus on water use and wastewater generation and their impacts on local water resources by providing actual and systematic data on shale gas production. The water issues in-depth evaluation could provide valuable insights for managing water used and shale gas sustainability industry. We also evaluate water use on the county and province scales.

The Sichuan Basin is China's largest and most productive and economically viable shale gas basin, accounting for 40% of the country's shale reserves [27, 28, 30-32] (Fig. 1). China's first vertical shale gas well and horizontal well are in the Weiyuan play. The Weiyuan play is an ideal case study because it has the most complete geological, engineering, and economic information with an adequate history and detailed records on water use and gas and FP water production.

The objectives of this study were to evaluate 1) the historical trends in water use for HF and FP water; 2) the future trends in HF water demand and FP water in 2020 or 2030; and 3) the strategies for water use supply and management for FP water in regional shale gas plays. The data used in this study were from the Weiyuan play in southern Sichuan Basin (Fig. 1).

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2 Materials and Methods

2.1 Site description.

The Weiyuan shale gas play, one of the Chinese national shale gas demonstration zones, is the forerunner field for shale gas exploration in China. Encompassing an area of approximately 6500 km^2. As much of the production is mainly from Weiyuan County (Fig. 1), Weiyuan County was the focus for the current water supply and demand analysis in this study. The climate is a type of mid-subtropical humid climate, with an annual average precipitation of 1091.22 mm and evaporation of 603.68 mm. The annual mean temperature is 17.30 °C. Approximately 81.7% of the rainfall of the year is concentrated from May to October. The primary surface water source is the Weiyuan River, a tributary of the Yangtze River.

The Weiyuan shale discovery well was drilled in 2010, and today, there are more than 150 wells drilled and nearly 100 producing shale gas wells. Thousands of wells may be drilled and hydraulically fractured in the coming decades. The Upper Ordovician Wufeng Formation to Lower Silurian Longmaxi Shale Formation have revealed ample shale gas resources and are the primary target formations in the field. These formations occur at depths of 1.5–4.5 km, with an average thickness of 35~40 m.

2.2 Data collection and analysis.

The Weiyuan play is the first shale gas exploration field in Sichuan Basin, China. The data used to analyze Weiyuan's shale gas development were from an onsite production database, which is recorded and stored by Petro China, the Weiyuan field operator. The gas/water production data between August 2011 and December 2017, encompassing a total of 97 shale gas wells, were collected and analyzed. The sampled wells are represented as purple dots in Figure 1. Evaporation, precipitation, and temperature data from 1960 to 2017 were sourced from the China meteorological data network (http://data.cma.cn/data/detail/dataCode/). The and energy consumed were sourced from the Statistical Yearbook of China. The streamflow daily records data were derived from Hydrological Yearbooks published by the Hydrologic Bureau of the Ministry of Water Resources of China.

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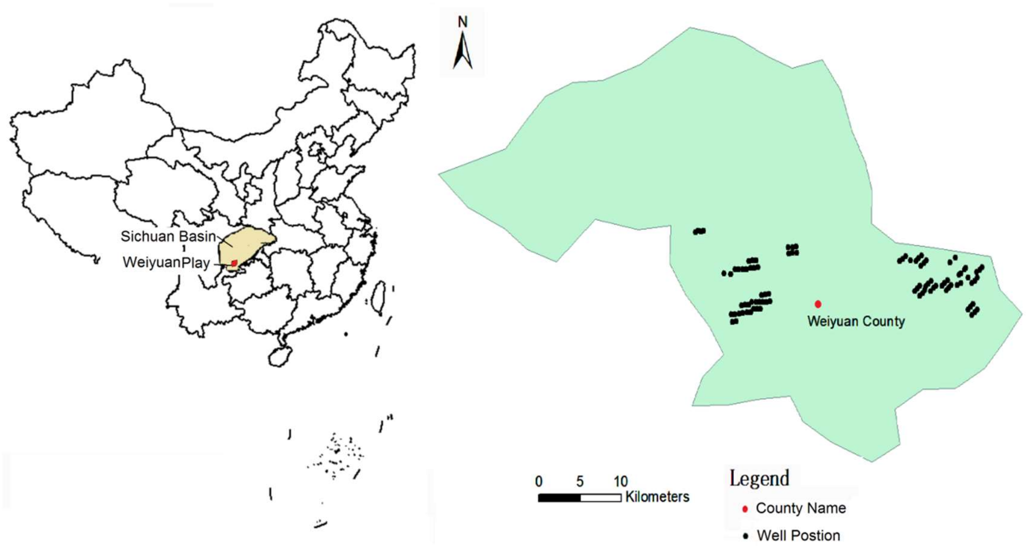

Fig. 1. Map of the study area—Weiyuan play with county line (highlighted in tan). Sampled wells are displayed in purple.

2.3 Water Footprint Assessment.

The water footprint framework, widely used for quantifying water quantity and quality impacts, was used to obtain a better understanding of the potential water and environmental impacts caused by the shale gas industry [33]. This study calculated the water footprint and evaluated the impact of expected shale gas expansion based on field data and the projected energy plan from 2018 to 2030; this study focused on water footprint accounting and environmental sustainability assessment.

2.3.1 Water footprint accounting.

Water footprint accounting includes the blue water footprint (WF-blue, directly measured actual water volume consumed), green water footprint (WF-green, associated with precipitation), and gray water footprint (WF-gray, indirectly measured water volume required to assimilate pollutants in wastewater generation). Because very small amounts of rainwater have been consumed in the shale gas industry, the water footprint accounting used in the shale gas industry only includes WF-blue and WF-gray. Data for the water footprint calculations were derived from the available records and verified by Petro China.

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2.3.1.1. Blue water footprint (WF-blue).

WF-blue is the water volume actually consumed by each well and was calculated by summing the drilling, equipment maintenance and HF water volume based on the actual field data. This analysis assumed that none of the FP water was treated for reuse for the development of new wells or any other beneficial reuse [34]. *WF-blue* was calculated as follows:

$$WF\text{-}blue = \text{HF water} + \text{Drilling water} + \text{Equipment maintenance water} \tag{1}$$

2.3.1.2. Gray water footprint.

WF-gray evaluates the water volume needed to assimilate the pollutant load of the wastewater discharge, and it is an indicator associated with the water pollution process. According to the Water Footprint Evaluation Manual, the gray water footprint is determined by the pollutants that need the most dilution; thus, the *WF-gray* is calculated by:

$$WF\text{-}gray = \max[WF1\text{-}gray, \ldots, WFi\text{-}gray, \ldots,] \tag{2}$$

where *WF-gray* is the total gray water footprint, m^3; and *WFi-gray* is the gray water footprint of the *i-th* pollutant, m^3.

FP water discharge was directly released into the fixed drainage pipes, without partial loss of pollutants, which could be considered point source pollution. And the load can be estimated by measuring the effluent volume and the concentration of a chemical in the effluent. Thus, the calculation is as follows:

$$W_{Fi-gray} = \frac{Li}{C_{i-max} - C_{i-nat}} \tag{3}$$

where *WFi-gray* is the gray water footprint of the *i-th* pollutant, m^3; *Li* is the emission of the *i-th* pollutant; and *Ci-max* (kg/m^3) is the maximum mass concentration of the *i-th* pollutant allowed by the local water quality environmental standard of the discharge zone and calculated with reference to the Chinese ambient water quality standards to evaluate the ability of the receiving water body [33]. The Class III water quality standard of the Surface Water Environmental Quality Standard of China (GB3838-2002) was the maximum concentration allowed by the water quality environmental standard. *Ci-nat* (kg/m^3) is the natural concentration of the *i-th* pollutant in the receiving water

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body. Due to the lack of basin-specific natural background concentration data and to keep *WF-gray* conservative, the *Ci-nat* value was assumed to be zero for the analysis [33]. The gray water footprint of a pollutant is determined by the emissions of the pollutant, the initial concentration in the water, and the allowable concentration. A summary of the collected FP water quality data sources is presented in Table S1 (SI Section 1).

2.3.1.3. Scenarios for FP water recycling and reuse.

Equation 3 shows that the *WF-gray* volume is linearly correlated with the mass of pollution with respect to the volume of the FP water. After treatment and recycling or reuse, the volume of the FP water may be reduced. In the field investigation, most of the FP water returning to the surface was processed by an onsite treatment facility, and approximately 50–80% of the generated FP water was recycled or reused. Given that up to 50–80% of the FP water was estimated to be recycled, the actual returned and discharged liquid was set to calculate the volume of the gray water in different scenarios: (1) the returned liquid is directly discharged without treatment; (2) 50% of the total liquid volume is recycled; and (3) the amount of recycled liquid discharged reaches 80% of the total liquid volume. The calculation results of *WF-gray* in the different scenarios are listed in the following Results section.

2.3.2 Sustainability assessment.

2.3.2.1. Environmental sustainability of WF-blue scarcity.

WS-blue refers to the shortage of water resources for local water consumption in this study, and it can be expressed as the ratio of the blue water footprint to the available blue water. Because water consumption for the Weiyuan play is mainly withdrawal from the Weiyuan River, the amount of blue water available is calculated as the natural runoff (*Rnat*) minus environmental flow requirements (EFR).

$$WA_{blue}=Rnat\text{-EFR} \tag{4}$$

$$WS-blue=\frac{WF-bl}{WA_{blue}} \tag{5}$$

WS-blue is equal to or greater than 100%, which means that *WF-blue* exceeds *WA-blue* and that *WA-blue* has been fully consumed and is not sustainable.

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Due to the poor streamflow gauging stations and the lack of consistent and long-term records of streamflow observations, flood frequency analysis was difficult in the Weiyuan River. Precipitation is less affected by human activities and could be used for improving the 7Q10 model for the EFR assessment (SI Section 2; hereafter, 7Q/75% model). The results showed that the reference year was Year 2015 with an annual precipitation of 1075.78 mm; thus, the streamflow of Year 2015 was the representative hydrological year.

2.3.2.2. Environmental sustainability of the WF-gray pollution level.

The water pollution level (*WPL*) is an indicator of the sustainability of *WF-gray*, and it is the ratio of *WF-gray* to the actual runoff (*Rac*t) of the catchment. *WPL* refers to the shortage of water resources caused by pollutant discharge:

$$WPL = \frac{WF-grey}{Ract} \tag{6}$$

where *WF-gray* is the gray water footprint and *Ract* is the actual runoff. *WPL* is the sustainability criteria level of *WF-gray.* If *WPL* >100%, the available water resources are not sufficient to assimilate pollutants and the catchment is not sustainable. Since the streamflow of Year 2015 was selected as the representative hydrological year, it has also been used for *Ract* calculated in *WF-gray* sustainability evaluation.

3 Results and Discussion

The onsite historical water use and shale gas production range from 2015 to 2017 in the Weiyuan play was analyzed, and the potential impacts of shale gas production on local water resources and future trends from 2018 to 2030 under the plans of Petro China and China's policy were also estimated by the water footprint model. This study included an estimate of future water need and FP water volumes based on the future well inventory by 2020 and 2030 under the plans of Petro China and China's policy projections derived from ~3 years of historical onsite field data (from 2015 to 2017). WFA is a useful tool to quantify local water consumption from a water quantity and quality perspective to evaluate local water resource sustainability and to identify options for time-dependent water adjustment and management.

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3.1 Energy use recovery.

Monthly median gas production rates (m^3 per day) were calculated from shale gas wells in the Weiyuan gas field over the first 31 months of production (Fig. 2). Decline curves were developed for shale gas production to determine the EUR. Due to the characteristics of shale formation, the estimated ultimate recovery (EUR) assumes that the wells will be productive for a 30-year period [28]. The EUR of a gas production without any restimulation was assumed to be between 0.33 and 0.49 million m^3 per well, with a median of 0.41million m^3 per well and a mean of 0.46 billion m^3/well (SI, Section 3). The projected number of future wells in Weiyuan play can be inferred by the Petro China's annual production goals of 5 billion m^3 by 2020 and 2030, respectively (SI, Section 4); the number of projected wells in the production period (2018~2020) should be approximately 225, an average of 75 wells per year, and the new production wells in the stable production period (2021~2030) will be approximately 540, an average of 54 wells per year.

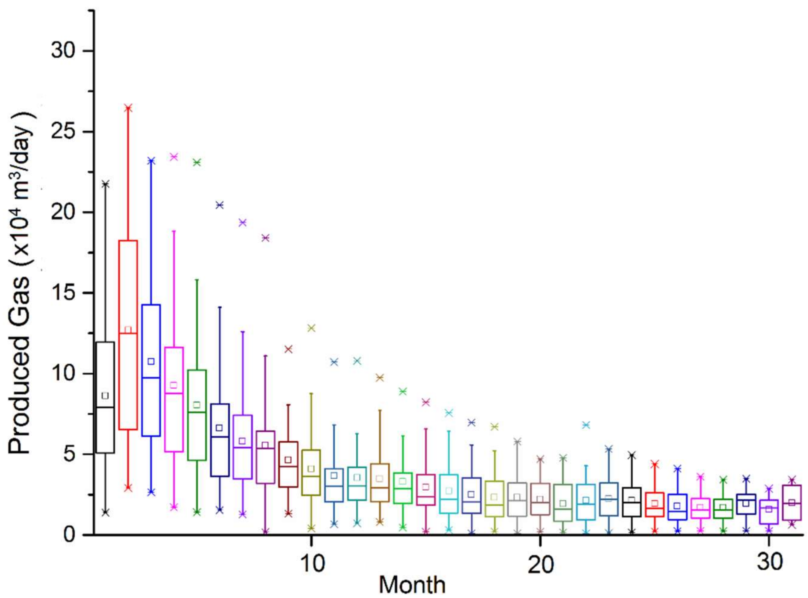

Fig. 2. Box plots for each month of shale gas production in the Weiyuan play

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3.2 Water use Trends.

3.2.1 Water use.

Basic parameters such as fracturing fluid volume, horizontal lateral length, well depth and number of design segments were analyzed (Table 1). The depth of the shale gas wells ranged from 2677 m to 4380 m, with a median of 3678 m; the fractured horizontal lateral length was between 502 m and 2006 m, with a median of 1420 m; the number of design segments ranged from 3 to 33 segments, with a median of 20; and the injected fluid volume ranged from 11351.3 to 60664.73 m^3 /well, with a median of 36013.94 m^3 /well, similar to the average (35509.69 m^3/well) (Table 1). Most of the injected fluid was composed of low-viscosity slick water.

Water intensity was employed for estimating HF water use per meter, and every segment was also calculated (Table 2). The volume of fracturing fluid ranged from 1107.60 to 6456.46 m^3 /segment, with a median of 1874.93 m^3 /segment; the average was approximately 1986.78 m^3/segment; the volume of fracturing fluid per meter ranged from 13.47 to 38.59 m^3, with a median of 25.88 m^3, and the average was approximately 26.18 m^3. The lengths of single horizontal segments ranged from 57.36 to 479.33 m, with a median of 71.44 m and an average of 79.87 m.

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Tables:Table 1-1. Basic analysis parameters for hydraulic fracturing

Year	Wells	HF water use (m^3/well, percentile)						Lateral Length (m, percentile)						Number of HF segments (percentile)					
		Mean	5th	25th	50th	75th	95th	Mean	5th	25th	50th	75th	95th	Mean	5th	25th	50th	75th	95th
2015	47	32727.11	19369.38	27548.11	33885.13	37886.06	44043.48	1350.84	919	1300	1400	1441	1600	17	8	15	19	20	22
2016	30	38478.74	24985.30	29015.91	39909.24	46711.09	53412.90	1347.63	846	1373	1435	1457	1554	20	13	18	21	23	25
2017	18	37768.60	21416.60	33692.90	39692.36	44051.30	49498.58	1374.50	788	1233	1452	1595	1929	21	12	18	22	24	27

Table 1-2. Basic analysis parameters for hydraulic fracturing

Year	Wells	Proppant(t, percentile)						Depth(m, percentile)					
		Mean	5th	25th	50th	75th	95th	Mean	5th	25th	50th	75th	95th
2015	47	1823.30	1056.82	1489.8	1860.07	2218.98	2430.27	3621.03	2880	3208	3678	4111	4320
2016	30	2121.07	1220.25	1852.2	2178.27	2490.8	2898	3712.33	3273	3451	3738	3876	4345
2017	18	2309.59	1269	1776	2374.3	2726.4	3682.02	3534.06	2804	2821	3638	4003	4217

Table 2. Water use for hydraulic fracturing (HF) per metric and per segment

Year	Wells	HF water use(m^3/m, percentile)						HF water use(m^3/stage, percentile)					
		Mean	5th	25th	50th	75th	95th	Mean	5th	25th	50th	75th	95th
2014	13	22.67	19.17	20.92	23.65	24.99	25.94	1830.07	1740.82	1822.33	1850.22	1885.17	1894.70
2015	19	26.54	25.12	25.95	26.35	26.98	28.85	1887.38	1845.06	1851.65	1882.05	1919.76	1932.92
2016	23	28.39	26.05	27.01	27.90	28.85	35.43	1949.49	1841.89	1893.76	1911.95	1980.00	2233.90
2017	12	27.73	25.61	26.53	27.46	28.04	29.50	1905.50	1870.07	1890.53	1905.29	1928.23	1937.73

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The comparative analysis showed that the mean injected fluid volumes increased from 32727.11 m^3 /well in 2015 to 37768.60 m^3 /well in 2017, and the mean water consumption per meter of the shale gas wells also increased from 24.23 m^3/m in 2015 to 27.24 m^3/m in 2017. The number of design segments also increased from 16 in 2015 to 21 in 2017 (Table 2). However, the lateral length, shale gas well depth and volume of fracturing fluid for a single fracturing segment were slightly different. The water intensity changed with the number of HF stages, and both the water consumption and energy recovery increased with more HF stages. These results may be related to factors of the fracturing technology and operators.

Linear regression analysis was carried out between water consumption for single well fracturing and the fractured horizontal lateral length and between water consumption for single well fracturing and the number of fracturing segments (Fig. 3). Figure 3 (a) shows the relationship between the fractured horizontal lateral length and the water consumption per well; the results show that the correlation coefficient R-Squared was 0.451, and the corresponding water intensity (I) was 26.73 m^3/m. Figure 3 (b) displays the relationship between water use per well and the number of stages; the correlation coefficient R-Squared was 0.717, and the corresponding slope coefficient was 1700.00 m^3/segment. The correlation between water consumption for single well fracturing and the fractured horizontal lateral length was better than that between water consumption for single well fracturing and the number of fracturing stages. The result was likely related to the construction technologies, and the HF design may be on the segmented construction.

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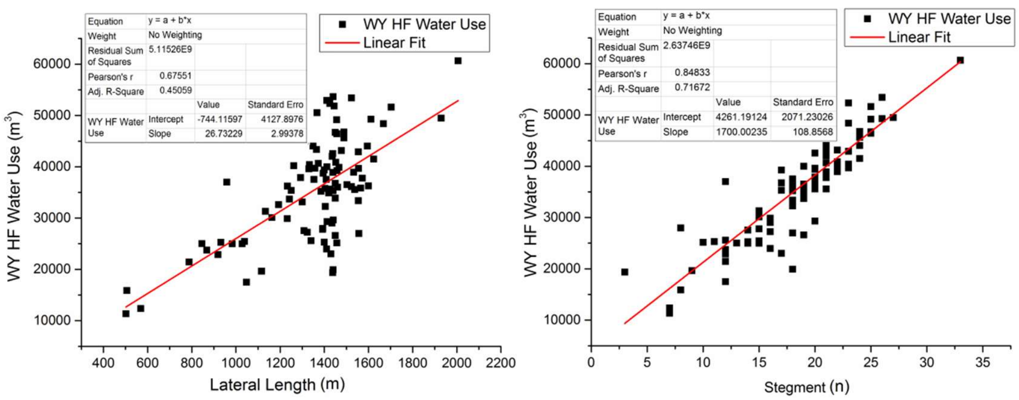

Fig. 3. Hydraulic fracturing water consumption per well: (a) relationship between the length of the fracturing horizontal section and water consumption, and (b) relationship between water use and number of stages per well.

The results showed that HF construction may be more inclined to the number of segments to calculate the volume of the fracturing fluid. Thus, the linear regression model of single well fracturing water consumption to the fracturing segment was established. The current single-stage injection volume was normalized to a water intensity (I) of 1700 m^3 per segment plus an intercept value of 4261.19 m^3 (Fig. 3b).

$$Y=1700*X+4261.19 \tag{7}$$

where Y is HF water consumption per well, m^3 and X is the number of segments for each well.

Based on the estimated water intensity results and the Petro China technical plan for shale gas production, the total water demand for the development of the Weiyuan field was predicted. The wide range of water use values for individual wells can be accounted for by the number of HF stages. As the number of segments and horizontal length increase, the water use also increases.

3.2.2 Water footprint accounting.

3.2.2.1. Evaluation of WF-blue during shale gas production.

The segment fluctuation tendency and the fractured horizontal lengths divided into 15 to 25 segments, where most of them were focused in the range from 18 to 22. According to equation 7, the water consumption for single well fracturing ranged from

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29761.19 to 46761.19 m^3. Based on the field data, *WF-blue* was the sum of the HF fluid volume (the main water-consuming activity), drilling water consumption and equipment maintenance water consumption. Based on the onsite data from 2015 to 2017, the water consumption of drilling and equipment maintenance accounted for a small proportion, which ranged from 2% to 5%, and to keep *WF-blue* conservation, this calculation takes the maximum value of 5% (Table 3).

Table 3. Water footprint of shale gas production in Weiyuan play

Periods	Scenarios	*WF-gray* (10^4 m^3/year)	*WF-blue* (10^4 m^3/year)	*WF-blue*/*WF-gray* (%)	Total WF (10^4 m^3/year)
2018-2020	Scenario A	9312.44	301.31	3.24	9613.74
	Scenario B	4656.22	301.31	6.47	4957.53
	Scenario C	1862.49	301.31	16.18	2163.80
2021-2030	Scenario A	6704.95	216.94	3.24	6921.89
	Scenario B	3352.48	216.94	6.47	3569.42
	Scenario C	1340.99	216.94	16.18	1557.93

Surface water is the dominant water source for Weiyuan's shale gas production, similar to the other shale plays [35, 36]. The water source for Weiyuan's play is derived from the Weiyuan River. A pair of major pipeline projects has been developed by operators for providing water. Cumulative water use for 97 wells from 2015 to 2017 totaled ~3.44 Mm^3, representing ~0.99% of the average annual surface runoff of the Weiyuan River of ~346 Mm^3, and ~0.78% of the total surface water resources of Weiyuan County of ~440 Mm^3. In the projected 2018-2020 and 2021-2030 periods, the estimated *WF-blue* was 3.01 Mm^3 per year and 2.17 Mm^3 per year, which was 0.68% and 0.62%, respectively, of the total surface water resources of Weiyuan County and was 0.87% and 0.63%, respectively, of the average annual surface runoff of the Weiyuan River. These results showed that this volume was negligible relative to the average annual surface runoff of the Weiyuan River and the total surface water resources of Weiyuan County and Sichuan Province (with an annual total surface water resource of 261.6 billion m^3 in Sichuan Province).

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3.2.2.2 Evaluation of WF-gray during shale gas production.

Monthly water production rates (m^3 per day) were calculated over the first 29 months of production (Fig. 4). Decline curve analysis was also applied to analyze FP water generation, similar to the decline curves applied to shale gas production (SI Section 5). The generation of FP water peaked in the first few months and then declined, predominantly reflecting the flowback water volume (Fig. 4). The accumulated volume of wastewater was 107.24×10^4 m^3, varying from 4625.44 to 33224.53 m^3 per well, with an average of 18813.51 m^3 per well. The ratio of FP to HF water was calculated and ranged from 12.84% to 109.64%, with an average of 55.34% (Fig. 5).

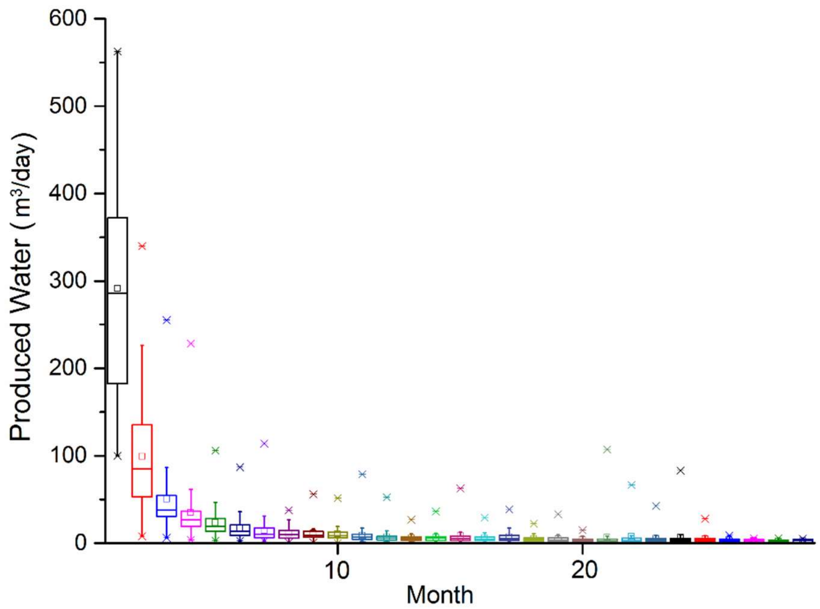

Fig. 4. Box plots of monthly average flowback and produced (FP) water production in the Weiyuan play

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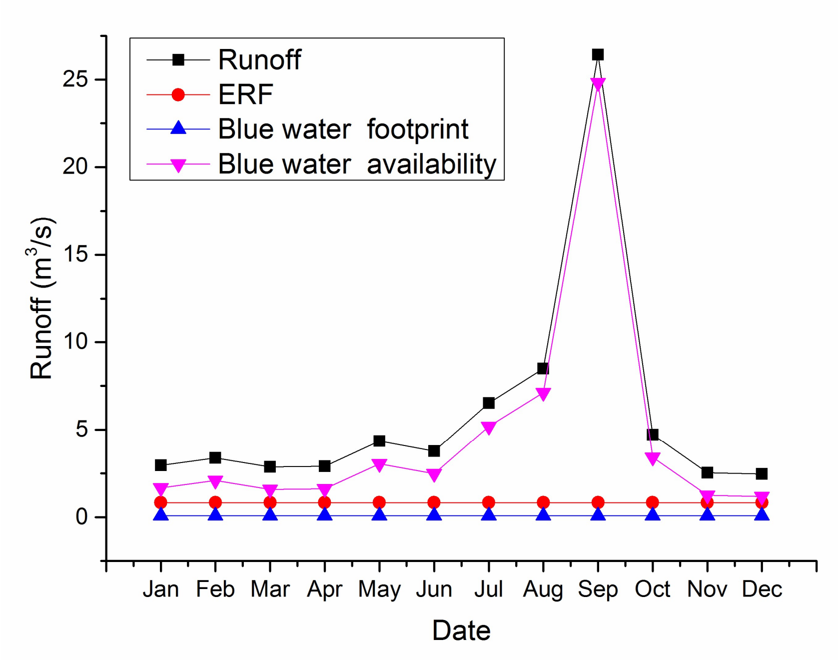

Fig. 5 The blue water footprint over a year compared to the blue water availability and environmental flow requirements (ERF).

WF-gray water use results are shown in Table 3 and are consistent with the average *WF-blue* consumed and the total water footprint in the Weiyuan field. The ratio of *WF-blue* to *WF-gray* was also calculated (Table 3). Scenarios A, B and C present a similar trend, with *WF-blue* accounting for a small percentage, ranging from 3.24% to 16.18%, while *WF-gray* accounted for a large percentage (ranging from 83.02% to 96.76%). The *WF-gray* changed greatly from 18.63 to 93.12 million m^3 per year in the period from 2018 to 2020 and from 13.41 to 67.05 million m^3 per year in the period from 2021 to 2030. The total water footprint varied from 21.64 to 96.14 million m^3 per year in the period from 2018 to 2020 and varied from 15.58 to 69.22 million m^3 per year in the period from 2021 to 2030. The *WF-gray* volume in projected years was estimated to approximately 3.88% to 26.91% of the average annual surface runoff of Weiyuan River, approximately 3.05~21.16% of the total surface water resource in Weiyuan County, and approximately 0.05% to 0.36% of the total surface water resource in Sichuan Province.

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3.3 Environmental impact assessment.

The water consumption of the Weiyuan play shale gas development mainly originated from surface water resources and withdrawal from the Weiyuan River. The average annual surface runoff of the Weiyuan River is approximately 346 million m^3. Due to the limited streamflow data, the flood frequency analysis was difficult, and the 7Q/75% method was used for the EFR assessment calculated in Weiyuan River (SI, Section 2).

Because the runoff is time-dependent, it varies within the year and from month to month; thus, a yearly basis is often not accurate enough to cover the severity in individual periods, and the *WS-blue* and WPL calculation may also be monthly (Table 4). During six months of the year (wet season: May-October), the water scarcity was clearly lower than the other six months (dry season: January-April, November and December) (Table 4 and Fig. 5). During all twelve months, *WF-blue* had a slight effect on *WA-blue*; the available water resource was sufficient, and the water resource was sustainable. The monthly EFR over all months of the year in Figure 5 were far below the monthly blue water availability in this catchment of approximately 0.84 m^3/s. The monthly *WS-blue* calculation was used to assess the *WF-blue* sustainability (Table 4). The values ranged from 0.39% (September) to 8.07% (December). These results suggest that both the yearly and monthly *WF-blue* may have a negligible influence on local water resources.

WF-gray was used to indirectly evaluate water use sustainability with respect to the environmental impacts caused by FP water. The monthly division of the time dimension was considered in this study, and the monthly evaluation WPL results of *WF-gray* for different scenarios are listed in Table 4. Monthly WPL results showed that in different scenarios, WPL varied substantially and showed a gradient decline with the retreatment FP water volume. In scenario A, B and C, the WPL in the wet season (May-October) was lower than that in the dry season (January-April, November, and December), consistent with the actual situation. Scenario A results showed that the WPL in dry season was similar to or surpassed the limited WPL (100%), indicated that the available water resources are not sufficient to assimilate pollutants and that the

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catchment is not sustainable. While in scenarios B and C, the whole WPL was less than 100% from 2018 to 2030, WPL was positively correlated with the volume of FP water. These findings indicated that the FP water volume of the Weiyuan play has a great influence on local water resources, and additional water treatment and reuse strategies should be implemented and refined before discharge; thus, the ecological environment is less impacted. The monthly basis calculation can more accurately and effectively evaluate the water resource sustainability, reflecting the actual pollution of water bodies at various time periods.

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Table 4 Environmental impacts assessment of shale gas production in Weiyuan play

Month	*WAblue*	Ract	2018-2020				2021-2030			
			Ws-bule (%)	WPLA (%)	WPLB (%)	WPLC (%)	*Ws-bule* (%)	WPLA (%)	WPLB (%)	WPLC (%)
1	439.70	776.78	5.71	99.90	49.95	19.98	4.11	71.93	35.97	14.39
2	548.65	887.18	4.58	87.47	43.74	17.49	3.30	62.98	31.49	12.60
3	416.35	753.12	6.03	103.04	51.52	20.61	4.34	74.19	37.10	14.84
4	428.03	764.95	5.87	101.45	50.72	20.29	4.22	73.04	36.52	14.61
5	797.69	1139.54	3.15	68.10	34.05	13.62	2.27	49.03	24.52	9.81
6	649.82	989.70	3.86	78.41	39.21	15.68	2.78	56.46	28.23	11.29
7	1361.90	1711.28	1.84	45.35	22.67	9.07	1.33	32.65	16.33	6.53
8	1871.65	2227.82	1.34	34.83	17.42	6.97	0.97	25.08	12.54	5.02
9	6521.58	6939.75	0.39	11.18	5.59	2.24	0.28	8.05	4.03	1.61
10	894.97	1238.11	2.81	62.68	31.34	12.54	2.02	45.13	22.56	9.03
11	330.75	666.37	7.59	116.46	58.23	23.29	5.47	83.85	41.92	16.77
12	311.29	646.66	8.07	120.01	60.00	24.00	5.81	86.41	43.20	17.28

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3.4. Flowback-produced water volume trends and management.

FP water, which typically contains salts and high levels of toxic elements, has become a major challenge for local water resource sustainability owing to the increase in induced pollution and the environmental and human health risks. *WF-gray* was used to indirectly evaluate water use sustainability with respect to the environmental impacts caused by FP water. The monthly division of the time dimension was considered in this study, and the monthly evaluation WPL results of WF-gray for different scenarios are listed in Table 4. These findings indicated that the FP water volume of the Weiyuan play has a great influence on local water resources, and additional water treatment and reuse strategies should be implemented and refined before discharge; thus, the ecological environment is less impacted. The monthly basis calculation can more accurately and effectively evaluate the water resource sustainability, reflecting the actual pollution of water bodies at various time periods.

Currently, the primary approach for managing FP water is recycling, treatment and reuse or rejection. The onsite treatment facility for FP water (by chemical precipitation, flocculation sedimentation, multistage filtration, sterilization, etc., to remove or reduce the concentration of suspended solids) is employed by Petro China [31]. However, there are several challenges with reusing FP water. The variability in FP water quality throughout the different field wells and at different times after hydraulic fracking (transition from a water quality that resembles the HF fluid to a water quality that is similar to the formation water quality) may create challenges for waste water management when considering the complex and various additives [38].

Furthermore, the technologies for recycled flowback water do not work very well, and high total dissolved solids with some chemical additives are still present; the high salinity in recycled FP water could not match the hydraulic fracking fluid quality requirements, and thus, freshwater is the main source in the shale gas industry [39].

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3.5. Potential research needs for managing the water availability of shale gas production.

Shale gas is the promising energy option for the Chinese energy system transition for the Paris Agreement carbon emission goal of 2030. The Chinese government is focused on shale gas production, while it also participates in many debates in regard to exploration technologies neglecting effects related to water scarcity and environmental health. Water sources are mainly fresh river surface water. Parameters and trends, including lateral length, fracking segment, well depth, fracking fluid volume and water intensity, were analyzed to understand the controls on determining the primary dynamic drivers of water use for shale gas production in the Weiyuan play. Our analysis indicated that in the Weiyuan play, water use for HF varies with lateral length, especially with the number of design segments, indicating that the operators' technologies played a critical role in HF and shale gas production.

The consumed water volume by shale gas drilling and production was found to vary with different wells. Water intensity was employed to estimate the water use volume in water used per unit lateral segment (m^3/segment). Based on the water footprint accounting, the estimated *WF-blue* was 3.01 Mm^3 per year and 2.17 Mm^3 per year in the projected 2018-2020 and 2021-2030 periods, respectively, which was highly positive correlated with the lateral lengths and fracking segments [34]. Although the water volume requirements for shale gas production are significantly lower than the volume of total local water resources (e.g., approximately 0.68% and 0.62% of the total surface water resource in Weiyuan County and approximately 0.0012% and 0.0010% of the total surface water resource in Sichuan Province for the projected 2018-2020 and 2021-2030 periods, respectively), the impacts of water withdrawal for shale gas development could cause a temporal reduction in monthly natural stream flows and depletion of local seasonal water resources (Table 4). In addition, mean total annual water use in Sichuan Province is dominated by irrigation (approximately 60%, Table S3), and shale gas production may have a conflict with seasonal water quantity scarcity.

In addition, although freshwater sources are abundant in Sichuan Basin, future water availability is uncertain because of potential regulatory and legal constraints

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provided by the Ministry of Water Resources of China, including the 'Applying the Strictest Water Resources Control System', 'Three red lines', and 'The Action Plan for Prevention and Treatment of Water Pollution'. In the past 40 years, therainfall and runoff in the Sichuan Basin have shown a long-term decline, which shows a drying trend that could lead to increasingly serious drought events [40, 41]. For example, two droughts in 2006 and 2011 caused a severe short-term water crisis and serious losses to the human economy and life in this region [42]. In summary, regional water resources are declining, which may limit shale gas development. Reasonable management strategies are essential and will play a critical role in continued shale gas production.

Furthermore, due to the high proportion for the whole water footprint, the *WF-gray* volume in projected years attracted great attention (approximately 3.05~21.16% of the total surface water resource in Weiyuan County and approximately 0.05% to 0.36% of the total surface water resource in Sichuan Province). In addition, the monthly WPL results indicated that the WPL may threaten local water resource sustainability in the dry season. The technology for treatment, reuse and recycling of FP water should be a focus of future research. However, the high salinity of the FP water and disposal of FP water may preclude this option. Additionally, some of the parameters exceed the desired range for reuse and recycling, making reuse and recycling challenging (Table S1). An onsite treatment facility and earthen pits were used in Weiyuan play for FP water disposal, and these methods could decrease the risk of contamination from spills and significantly reduce truck traffic. After most FP water disposal is currently retreated, and considering advances in desalination technology, FP water could serve as a potential water source for HF in the future, which would help to dispose of FP water, minimize the short-term total freshwater use and alleviate the pressure on regional water sources [43]. All of these issues point out the need for further research on future water management with respect to water scarcity and wastewater salinity disposal in reuse and recycling to optimize the management of increasing volumes of FP water. Advances in desalination and treatment technologies may allow reused and recycled FP water to serve as a water source for HF in the near future.

This study provides insights for quantifying the water footprint on different time

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scales (yearly and monthly). These results showed that *WF-gray* made the main contribution, accounting for 83.02% to 96.76% of the whole water footprint, and the monthly WPL results indicated that *WF-gray* may threaten the sustainability of local water resources in the dry season. The approaches of reuse and retreatment for managing the water footprint are considered an urgent environmental health issue. The *WF-blue* (3.24% to 16.18%) and monthly *WS-blue* calculation deduced that *WF-blue* may have a negligible influence on the sustainability of local water resources. However, the regional water resources are declining, and reasonable management strategies are essential for increasing shale gas production. The operators are responsible for their water footprint and should take actions to ensure that their water footprint is sustainable.

Supporting Information

Additional supporting information may be found online under the Supporting Information for this article. The Supporting Information includes additional information on methodology, background information, maps and tabulated data.

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