Science of the Total Environment 630 (2018) 349–356

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

The water footprint of hydraulic fracturing in Sichuan Basin, China

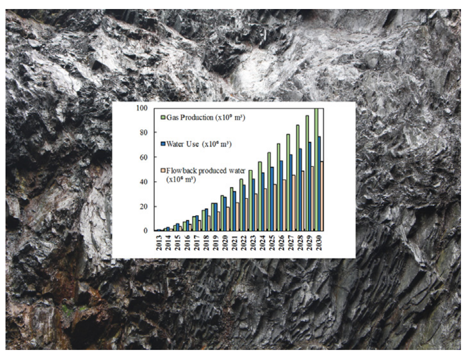
Caineng Zou [a], Yunyan Ni [a], Jian Li [a], Andrew Kondash [b], Rachel Coyte [b], Nancy Lauer [b], Huiying Cui [a], Fengrong Liao [a], Avner Vengosh [b,*]

[a] PetroChina Research Institute of Petroleum Exploration and Development, Beijing 100083, China
[b] Nicholas School of the Environment, Duke University, Durham, NC 27708, United States

HIGHLIGHTS

- New data for water use for hydraulic fracturing in Weiyuan gas field in Sichuan Basin (34,000 m^3 per well).
- The flowback volume during first year of shale gas production is 19,800 m^3 per well.
- Water use and production rates in Sichuan Basin are similar to those of recent shale gas operations in the U.S.
- China's goals for large-scale shale gas production are consistent with historical production rates in the U.S.
- Water is not a limiting factor for large-scale shale gas development in the Sichuan Basin.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 23 December 2017
Received in revised form 13 February 2018
Accepted 18 February 2018
Available online xxxx

Editor: J Jay Gan

Keywords:
Hydraulic fracturing
Shale gas
Flowback fluids
China
Sichuan Basin

ABSTRACT

Shale gas is likely to play a major role in China's transition away from coal. In addition to technological and infrastructural constraints, the main challenges to China's sustainable shale gas development are sufficient shale gas production, water availability, and adequate wastewater management. Here we present, for the first time, actual data of shale gas production and its water footprint from the Weiyuan gas field, one of the major gas fields in Sichuan Basin. We show that shale gas production rates during the first 12 months (24 million m^3 per well) are similar to gas production rates in U.S. shale basins. The amount of water used for hydraulic fracturing (34,000 m^3 per well) and the volume of flowback and produced (FP) water in the first 12 months (19,800 m^3 per well) in Sichuan Basin are also similar to the current water footprints of hydraulic fracturing in U.S. basins. We present salinity data of the FP water (5000 to 40,000 mgCl/L) in Sichuan Basin and the treatment operations, which include sedimentation, dilution with fresh water, and recycling of the FP water for hydraulic fracturing. We utilize the water use data, empirical decline rates of shale gas and FP water productions in Sichuan Basin to generate two prediction models for water use for hydraulic fracturing and FP water production upon achieving China's goals to generate 100 billion m^3 of shale gas by 2030. The first model utilizes the current water use and FP production data, and the second assumes a yearly 5% intensification of the hydraulic fracturing process. The predicted water use for hydraulic fracturing in 2030 (50–65 million m^3 per year), FP water production (50–55 million m^3 per year), and fresh water dilution of FP water (25 million m^3 per year) constitute a water footprint that is much smaller than current water consumption and wastewater generation for coal mining, but higher than those of conventional gas production in China. Given estimates for water availability in Sichuan Basin, our predictions suggest that water might not be a limiting factor for future large-scale shale gas development in Sichuan Basin.

* Corresponding author.
E-mail address: vengosh@duke.edu (A. Vengosh).

https://doi.org/10.1016/j.scitotenv.2018.02.219
0048-9697/

1. Introduction

Shale gas is likely to play a major role in China's transition away from coal (Qin et al., 2017; Liu et al., 2018), particularly since China has some of the largest global shale gas resources, with potential estimates ranging from 12.8 trillion m^3 to 31.2 trillion m^3 of natural gas (U.S. Energy Information Administration (EIA), 2015; Dong et al., 2016a, 2016b). The most productive and economically viable shale gas basin in China thus far has been the southern Sichuan Basin (Fig. 1), where exploration of the Upper Ordovician Wufeng Formation - Lower Silurian Longmaxi shale Formation has revealed ample shale gas resources. Several gas fields have been discovered in Sichuan Basin (Fig. 1), of which the Fuling, Weiyuan, and Changning fields have economically viable shale gas reserves and have become the major source of shale gas production in China (Zou et al., 2015, 2016; Dong et al., 2016a, 2016b). In 2016, the annual shale gas production from 356 wells from the southern Sichuan Basin was 7.8 billion m^3.

The ability of China to continue shale gas development depends on multiple factors, including natural gas production rates from the shale formations, adequate technology to support hydraulic fracturing, infrastructure and transportation, and environmental protection (Dong et al., 2016a, 2016b; Jiang et al., 2017). One major challenge facing unconventional shale gas development is the large water footprint of hydraulic fracturing relative to conventional oil and gas development (Scanlon et al., 2014a, 2014b; Gallegos et al., 2015; Kondash and Vengosh, 2015; Guo et al., 2016; Wilkins et al., 2016; Yu et al., 2016; Kondash et al., 2017). Consequently, some have suggested that water scarcity could be a limiting factor for sustainable development of shale gas, particularly in the water-scarce areas of China (Chang et al., 2014; Scanlon et al., 2014a, 2014b; Guo et al., 2016). In addition, the volume and quality of flowback and produced (FP) water generated from shale gas wells are critical factors in the ability to reuse and manage wastewater without harming the environment (Gregory et al., 2011; Warner et al., 2013; Vengosh et al., 2014; Kahrilas et al., 2015; Kondash et al., 2017), or increasing the risk of induced seismicity upon disposal of wastewater through deep injection wells (Ellsworth, 2013; Lei et al., 2017). Previous attempts to evaluate the role of water availability on the sustainability of shale gas development in China (Chang et al., 2014; Guo et al., 2016; Yu et al., 2016) were limited due to the lack of actual water footprint and natural gas production rate data. This paper aims to fill this gap by providing, for the first time, actual and systematic data of shale gas production, water use for hydraulic fracturing, and FP production rates from 36 representative shale gas wells from the Weiyuan gas field of the southern Sichuan Basin. By using empirical gas production and water footprint data, we estimate both the water need and the wastewater generation upon implementation of China's goals for large-scale shale gas production by 2020 and 2030.

2. Methods

Monthly gas and FP water production rates (m^3 per day) were calculated from 36 shale gas wells in the Weiyuan gas field over the first 19 months of production (Figs. 1, 2). The median value for each day of production was calculated, then summed by production month (i.e., day 1–30 were considered first month, day 31–60 were considered second month, and so on) to get a production per month estimate. Data were available up to 19 months in 11 wells and up to 12 months in the rest of the wells investigated in this study. Data from all 36 wells were combined to form an overall decline curve (Figs. 2, 3), then the Arps decline curve estimate (Arps, 1945) was used to extrapolate monthly production data past the initial 19 months. We define the Arps equation as:

$$q(t) = \frac{q_o}{[1 + bD_o t]^{1/b}} \quad (1)$$

where q_o is the initial gas (or water) production rate, D_o represents the initial decline rate, and b is a curvature constant (Ho et al., 2016). Gas production dropped off fairly quickly with a curvature constant (b) of 0.013, while the FP water data dropped at a similarly rapid rate with a curvature constant (b) of 0.364. Using the generated Arps decline

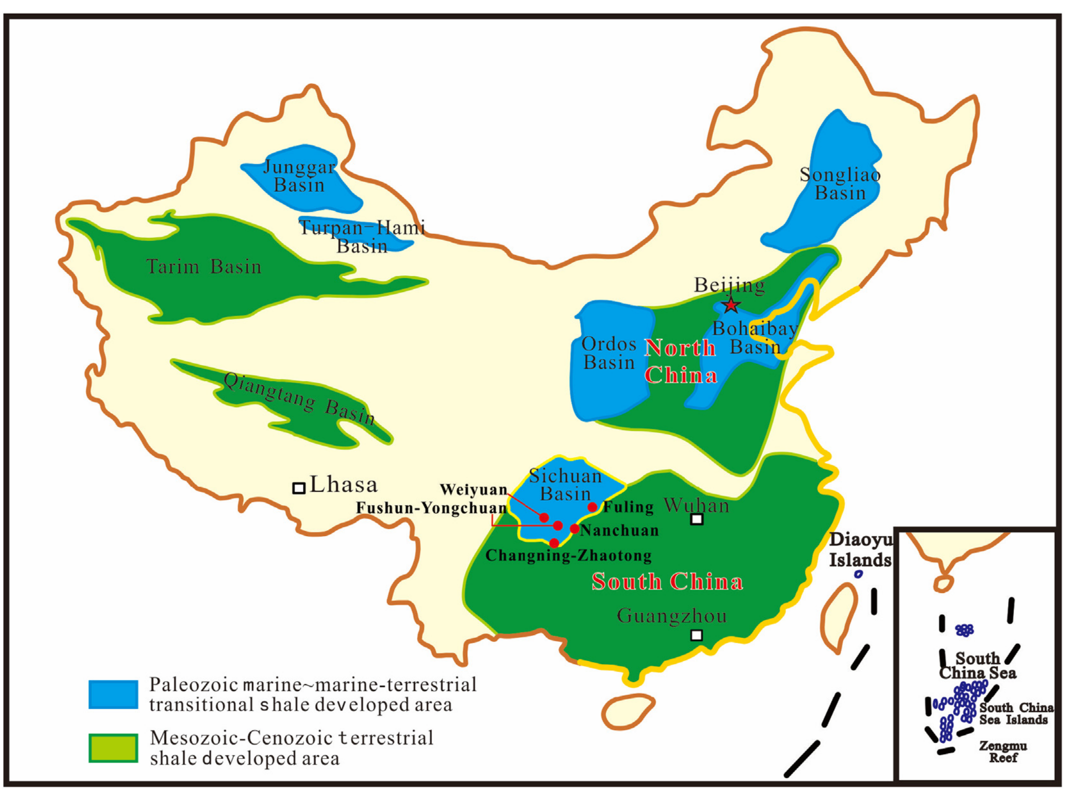


Fig. 1. Distribution of major shale plays in China and the location of Weiyuan and other shale gas fields in the Sichuan Basin of Southern China.