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Prospects for shale gas production in China: Implications for water demand

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ABSTRACT

Development of shale gas resources is expected to play an important role in China's projected transition to a low-carbon energy future. The question arises whether the availability of water could limit this development. The paper considers a range of scenarios to define the demand for water needed to accommodate China's projected shale gas production through 2020. Based on data from the gas field at Fuling, the first large-scale shale gas field in China, it is concluded that the water intensity for shale gas development in China (water demand per unit lateral length) is likely to exceed that in the US by about 50%. Fuling field would require a total of 39.9–132.9 Mm^3 of water to achieve full development of its shale gas, with well spacing assumed to vary between 300 and 1000 m. To achieve the 2020 production goal set by Sinopec, the key Chinese developer, water consumption is projected to peak at 7.22 Mm^3 in 2018. Maximum water consumption would account for 1% and 3%, respectively, of the available water resource and annual water use in the Fuling district. To achieve China's nationwide shale gas production goal set for 2020, water consumption is projected to peak at 15.03 Mm^3 in 2019 in a high-use scenario. It is concluded that supplies of water are adequate to meet demand in Fuling and most projected shale plays in China, with the exception of localized regions in the Tarim and Jungger Basins.

Contents

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1. Introduction

At the Asia-Pacific Economic Cooperation (APEC) forum 2014, China committed to peak its CO_2 emissions by 2030 [1]. In order to achieve this goal, China must reduce the coal share of its primary energy use. China's Energy Development Strategic Action Plan [2], covering 2014–2020, and announced prior to the APEC commitment, seeks not only to raise the share of total energy consumption supplied by renewable sources, but includes also plans for increased supply from natural gas, rising from 5% of total primary energy supply in 2013 to at least 10% in 2020. In 2014, more than 32% of the gas consumed in China was supplied by imports, delivered either in the form of liquefied natural gas (LNG) or through long-distance pipeline [3]. Due to a lack of conventional gas reserves, China has sought to increase its production from unconventional resources, notably from shale. Production of gas from shale has increased rapidly in the US benefiting from two enabling technologies, horizontal drilling and hydraulic fracturing ("fracking"). Production of gas from shale increased from 6.7% of total US gas production in 2007 to 46.9% in 2013 [4]. The U.S. Energy Information Administration (EIA) has estimated China's technically recoverable shale-gas resources at 31.6 trillion cubic meters (tcm) [5], higher than those of the U.S., while China's Ministry of Land and Resources (MLR) estimated them at 25.1 tcm [6]. China's plan sets a goal for annual production of at least 30 billion cubic meters (bcm) annually by 2020 [2]. Achieving this objective will be critical to meet the stated goal of a peak in carbon emissions by 2030.

Influenced by the success of the recent shale-gas boom in the U.S., China's government has established a series of policies to support and promote extraction of gas from shale. A production subsidy of 0.4 RMB/m^3 was introduced between 2012 and 2015, though it is scheduled to decline to 0.3 RMB/m^3 between 2016 and 2018 and to decrease further to 0.2 RMB/m^3 between 2019 and 2020. These policies include also waivers of price controls and fees, and reclassification of shale gas as an independent mineral resource, which allows for development policies distinct from those for conventional gas [7]. Two rounds of auctions for exploration rights have been held, in 2011 and 2012. By April 2014, total investment had reached more than 2.42 billion U.S. dollars and 322 exploration wells had been drilled, including 96 with horizontal extensions [8]. Although China's shale-gas development has progressed more slowly than *anti*cipated and remains at an early exploratory stage, considerable progress has occurred at a few favorable fields in the Sichuan Basin of southwest China [9]. These are led by the Fuling field, which currently includes roughly one third of total existing horizontal wells in China and is the first to achieve large-scale production. In 2014, the Fuling field produced 1.08 bcm of gas from shale, accounting for 73.3% of China's total production [10].

A key challenge for shale gas development is the requirement for water employed both in drilling and fracking, with related concerns for economically feasible disposal of waste water. The International Energy Agency (IEA) estimates that the water volume required per unit shale gas production is, at a minimum, 200 times that for conventional gas [11,12]. The potentially large scale of unconventional gas development increases the risk for water contamination [12]. Experience in the U.S. is instructive. More than 1.1 million wells have been fracked in the U.S. [13], a number that is increasing. While use of water for shale-gas production accounts for less than 1% of total water consumption in a state such as Texas, which is both a center of the U.S. industry and largely arid, it could have serious impacts for water resources at more local levels depending on availability and competing demands [14–18]. And although federal regulations prohibit direct discharge of wastewater from shale-gas operations, discharges of shale-gas effluent from water treatment plants have been shown nonetheless to pose negative impacts on the local environment [19,20]. Additional impacts on water resources are also being studied [11]. The relationship between shale gas production and water consumption remains controversial in the U.S.

Given China's existing water scarcity and water quality problems, the effect of potentially large-scale development of shale gas on water resources is of critical concern, requiring more intensive investigation. Per capita renewable internal freshwater resources amount to only a third of the world average while about 400 of 660 cities in China suffer from water shortages, close to 50% of Chinese rivers are severely polluted, and availability of safe drinking water is inadequate to meet the needs of 300 million rural people [21,22]. Some have concluded that water constraints represent the key obstacle to China's shale-gas development [23,24], with one commentator suggesting that this could lead to a national disaster [25]. Such pessimistic assessments tend not to be based on quantitative analyses, however, but rather on inferences from water use in the U.S. shale-gas industry and general characteristics of China's water resources such as its uneven distribution and low per capita consumption rates. The few quantitative assessments of water availability in China's shale-gas regions, moreover, fail to estimate water use based on actual shale-gas production [26–28]. Some studies suggest that water supply is less of a concern [29], at least in the short-term [7], but that the lack of regulations to limit wastewater discharge from shale-gas operations means that impacts on water quality deserve greater attention. Few of the existing findings result from quantitative analysis, reflecting lack of data for water use and wastewater treatment on current China's shale-gas operations.

This paper focuses on the requirements for water if China is to meet the anticipated production targets for shale-derived natural gas (30 bcm by 2020). It begins by developing a methodology that can be used to project the demand for water in the development of shale-gas wells in China, a function both of the geological conditions defining particular sites and the extent and spacing of the horizontal drilling wells. Values for water intensity, defined as the water demand per unit lateral length (i.e., the length of the horizontal bore section in which fracking is performed), were derived from water use data published for major U.S. shale plays and collected also in the field at China's Fuling shale gas development. The paper continues with assessment of the future demand for water through 2020 for the Fuling field and more extensively for the seven shale gas basins identified for future development in China. The demand for water to supply these shale developments is compared with available supplies and current aggregate consumption. With a few local exceptions, the conclusion is that China's future development of shale gas is unlikely to be limited by the availability of water. It will be important nonetheless to impose regulatory requirements to ensure safe disposal of the resulting wastewater.

2. Data and methods

The quantity of water consumed by shale-gas drilling and production varies with geological, technological, and economic factors. Instead of estimating water use on a well-by-well basis, we employ the metric of water intensity, the volume of water used per unit lateral bore length (m^3/m). The data used to estimate the water intensity of China's shale-gas development are compiled using a combination of sources from the U.S. and China. For the U.S., we rely on well completion reports from Pennsylvania [30], West Virginia [31], and Texas [32], and the FracFocus Chemical Disclosure Registry [33]. For the Fuling field in China, we use data developed during field interviews with on-site well managers, conducted in July 2013 and June 2014, encompassing reports for 24 shale-gas wells completed by April 2014 by Sinopec, the Fuling field developer.

We create first a regression model for water consumption associated with well drilling and fracking to estimate the water intensity of wells in two major U.S. shale-gas plays, the Barnett and the Marcellus. We apply the model then to the Fuling well data to estimate the water intensity of these wells. Based on the estimated water intensity results and a Sinopec technical plan [34] for well spacing, we predict the total water demand for full development of the Fuling field.

To evaluate the potential impact that the large amount of water used for shale-gas production might have on local water resources, we project temporal water consumption for shale-gas development in Fuling through 2020 under high, medium, and low development scenarios. Parameters and constraints include the estimated water intensity, the average lateral length and the gas production curve for wells at Fuling, the well construction plans of Sinopec, the availability of drilling rigs, and drilling water consumption. The detailed methods are outlined for the Fuling case study in Sections 2.1–2.3. In addition to the Fuling assessment, we apply the same methods to estimate the total water demand and temporal water consumption nationwide for China, covering seven prospective shale gas basins. Potential impacts of shale-gas production on local water resources are analyzed by comparing peak water consumption with available local water resources and other competing demands for water.

2.1. Water intensity of Fuling shale gas field

Fuling is the first operational large-scale shale gas field in China [35]. It is part of the Lower Silurian Longmaxi Shale deposit in the Sichuan Basin, present at depths of 2.7–4.7 km, with an average thickness of 120 m (see Fig. 1) [5]. Sinopec's initial evaluation suggested that the Fuling field should cover nearly 4000 km^2 of land area with high-quality marine-type shale gas resources of up to 2.1 tcm [36]. In November 2012, Sinopec drilled the first high yield shale gas well in the Jiaoshiba Block in Fuling, producing approximately 203,000 m^3 natural gas per day [36]. In 2013, China's National Energy Administration [37] officially approved the establishment of the Fuling State Shale Gas Demonstration Area [36]. In March 2014, Sinopec announced plans for Fuling Field to enter into large-scale commercial development [36].

Shale-gas production requires water mainly for well drilling and fracking. In the U.S., drilling has been estimated to account for 1.6% up to as much as 25% of total water use per well, varying according to drilling technique and shale-gas play [38]. Fracking requires much more water, estimated at 11,755 m^3 to 17,214 m^3 per well across major U.S. shale-gas plays, from the Marcellus to the Barnett [33].

At Fuling, based on limited data from field interviews in 2013 and 2014 at the 24 shale-gas wells, well drilling accounted for less than 1% of the total water demand while fracking accounted for the balance, averaging 30,366 m^3 per well, as shown in Table 1. For drilling water use, the average for the 24 wells was only 300 m^3, considerably less than implied by the average depth and the standard intensity coefficient of 0.85 m^3 per meter of depth used in Environmental Impact Assessments, based possibly on outdated guidelines from the Ministry of Environmental Protection (MEP) of China [39]. The reason for the difference may reflect a recent shift to more efficient oil-based drilling fluid (comprised of only 20–30% water) in Fuling compared to the water-based fluid assumed in the MEP guidelines, and also an improved reuse rate (50% in Fuling) for drilling fluid. Advanced techniques to drill multiple wells sequentially (linked to a factory assembly line) are believed to have improved efficiencies, and to have helped also increase the reuse efficiency for drilling fluid.

Given the limited drilling water requirements in both countries, we focus on the much larger water demands for fracking. The

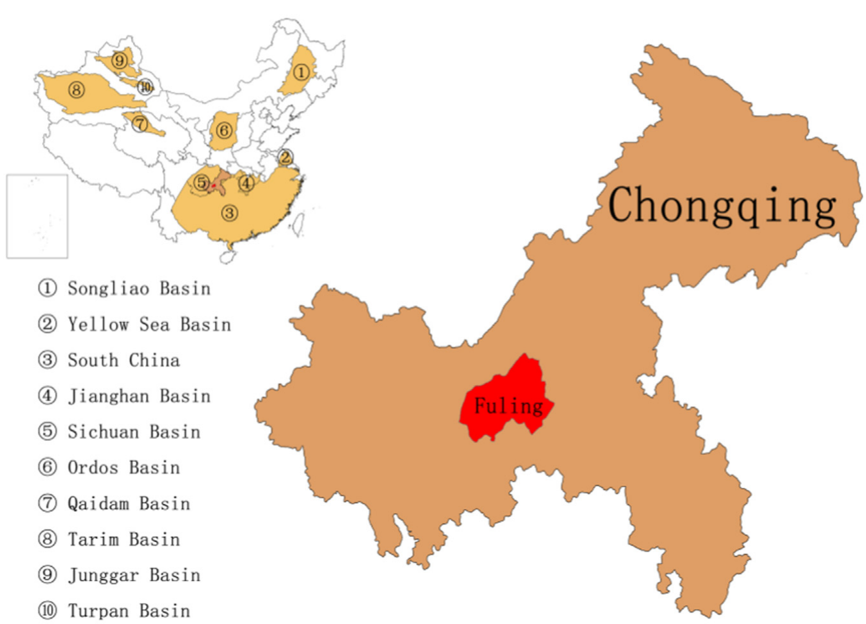

Fig. 1. Shale gas plays in China and Fuling shale gas field adapted from ARI/EIA [5].

Table 1
Characteristics of and water use for shale-gas formations and wells in the Marcellus and Barnett plays in the U.S and for the Fuling play in China.Sources: For Marcellus and Barnett, depth data are from reference [37]; well numbers are from http://www.depreportingservices.state.pa.us/ReportServer/Pages/ReportViewer.aspx?/Oil_Gas/OG_Well_Formations and http://www.rrc.state.tx.us/media/2105/oilwellct_022014.pdf, respectively; drilling water use data are from reference [37]; fracking water use data are from reference [33]. For Fuling, all data are from field interviews of on-site well managers in 2014.

Shale play	Geological formation depth [40]	Wells (number)	Drilling water use (m^3/well)	Fracking water use (m^3/well)
Marcellus	1.2–2.6	8902	379	17,214
Barnett	2.0–2.6	20,937	1514	11,755
Fuling	1.5–4.0	24	300	30,366

main reason for China's higher fracking water use per well relates to geological and/or technological differences, as well as the longer average lateral length in the Fuling wells compared to the U.S. average (greater by about 100 m).

We apply an ordinary least squares (OLS) linear regression to well data for two major U.S. shale-gas plays, the Marcellus and Barnett, to estimate the water intensity (I) in m^3/m, i.e., the coefficient I in Eq. (1):

$$W_F = \alpha + IL + \mu \quad (1)$$

where W_F is fracking water use (in m^3), L is lateral length [41], α is a constant, and μ is the residual error. Well lateral length is calculated as the difference between what are identified as the top and bottom "perforation depths" (the points in the well casing at which perforations for fracking begin and end) based on well completion reports from state authorities in Pennsylvania, West Virginia, and Texas. The sample for the Marcellus and Barnett encompasses 902 wells that commenced operation between 2011 and 2013.

The regression results in Fig. 2 show highly significant positive relationships between well lateral length and fracking water use. Our results are consistent with water intensities estimated by Nicot and Scanlon [16] and Jiang et al. [17] for two shale-gas plays in Texas and the Marcellus respectively. We tested other regression model forms and found that the OLS procedure yielded the best fit.

The high significance of the results with the OLS regression for the U.S. plays suggests that the model for estimation of the water intensity for fracking elsewhere, including China in general and Fuling in particular, is reliable.

Applying the regression model to data from the 24 Fuling Jiaoshiba shale-gas wells implies an estimated water intensity of 19.90 m^3/m, as illustrated in Fig. 2. With other factors held constant, each additional meter of lateral length for a shale-gas well in Fuling requires an average of 19.9 m^3 of extra fracking water, roughly 50% more than required in the two U.S. plays. The difference in fracking water intensity for the two countries reflects a combination of geological, technological, and economic factors. The quantity of water used in fracking is selected generally to provide for the optimal projected economic return from gas production. The fracking water intensity is a comprehensive reflection thus of geological potential, the technical capability of drillers, and the economic prospects for production. Geological factors aside, the relatively high Fuling water intensity could be reduced over time in response to technological progress, higher water prices, higher wastewater treatment costs, and other factors.

2.2. Method for evaluation of total water demand at Fuling field

According to the Sinopec shale-gas development plan for Fuling, only 200 km^2 will be developed through 2017 [42], compared with the total size of the field of 4000 km^2 according to An and Zhu [43]. The water demand for a fully developed Fuling play can be estimated using the method introduced by Nicot and Scanlon to project use of water for shale-gas production in Texas [16]. The fracking water use (W_U) for a shale-gas field is estimated by dividing the domain of the entire field (D) by the average lateral spacing between horizontal wells (d) in a fully developed field, multiplying by the water intensity (I) derived above for Fuling using equation (1), and the prospectivity (p):

$$W_U = D/d \times I \times p \quad (2)$$

The last term in equation 2, p, is a composite taking account of a number of geological and other characteristics that limit the fracking potential of a given play [16]. The characteristics influencing p include shale depth and thickness, amount and type of organic matter, thermal maturity, burial history, microporosity,

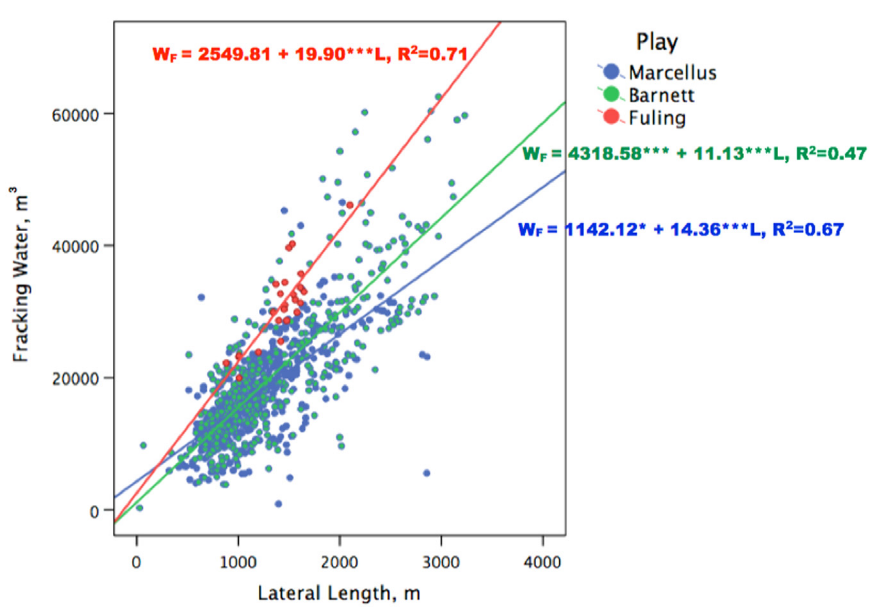

Fig. 2. Curve fitting for use of water for fracking in the Marcellus, Barnett, and Fuling plays. * significant at 0.1 level ($p < 0.1$); ** significant at 0.05 level ($p < 0.05$); *** significant at 0.01 level ($p < 0.01$).

fracture spacing, and orientation. Values for p, which are generally close to 1 in the core of a play and decrease to 0 at the margin, represent educated estimates based on the judgments of expert geologists. The p values for the seven perspective shale gas basins in China are respectively 0.86 (Junggar), 0.50 (Sichuan), 0.49 (Jianghan), 0.01 (Yangtze Platform), 0.34 (Greater Subei), 0.27 (Tarim), and 0.06 (Songliao) [5]. Since no expert advice on local prospective is available for the Fuling field, the p value for Sichuan basin of 0.5 was applied for this evaluation. Thus $p=0.5$, $D=4000$ km^2, and $I=19.9$ m^3/m (assumed constant in time). To estimate W_U we consider two possible values for the lateral well spacing d. One derived from the Sinopec technical proposal for the Jiaoshiba block, which indicates a minimum spacing of 700 m with a maximum of 1300 m, as illustrated in the schematic diagram in Fig. 1 in the Supplementary Information (*SI*), corresponding to an average value of 1000 m [34]. This value for d leads to a value for W_U of 39.9 Mm^3. A second value for d is 300 m, based on well-spacing experience in the more mature U.S. shale-gas industry [16]. This value ignores possible geological differences and assumes that future development of Fuling could eventually realize American well spacing practices, raising W_U to 132.9 Mm^3.

2.3. Scenarios for water consumption at Fuling

The projection for the temporal trajectory of water consumption for shale-gas development at Fuling through 2020 relates closely to the development plan for shale gas. In 2013, Sinopec set shale-gas production targets for Fuling of 5, 10, and 15 bcm by 2015, 2017, and 2020 respectively [44]. Based in part on this plan, we define high, medium, and low scenarios for shale-gas production and associated water consumption through 2020, as displayed in Table 2.

To estimate drilling and fracking water use over time for these scenarios, we must determine the number of new wells initiated each year from 2015 to 2020. (The number constructed in 2013 is known and the number planned for 2014 was set in the Sinopec plan.) This in turn depends on the gas production of both existing and new wells over time. The Sinopec plan includes an estimated well production decline curve, shown in the *SI* [45]. A Fuling shale gas well has its maximum output during the first two years following completion, with production decreasing by a factor of 2 over the following three years. In order to meet the production targets under the three scenarios, this curve can be employed to back out the number of new wells needed for each year, subject to the additional constraint of a smooth drilling trajectory from 2014 to 2020 (minimizing the difference of new well numbers between two years). The drilling schedule is constrained potentially also by the availability of drilling rigs, but Sinopec's existing and planned equipment deployment at Fuling is shown to be adequate. See the *SI* for details on the estimation of new wells.

Table 2
Shale-gas production and water consumption scenarios for the Fuling field.

	Scenarios	Parameters
Medium	Meet the planned production goal in the three target years, with medium water intensity (i.e., at the historical rate of decline from 2013 to 2014, 6.5%)	Production goals: 2015, 5 bcm; 2017, 10 bcm; 2020, 15 bcm Rate of decline of water intensity: 6.5%
High	Exceed the planned production goal by 30% in the three target years, with high water intensity (i.e., at a lower rate of decline, 2%, than the historical value assumed in the Medium Scenario)	Production goals: 2015, 6.5 bcm; 2017, 13 bcm; 2020, 19.5 bcm Rate of decline of water intensity: 2%
Low	Fall below the planned production goal by 30% in the three target years, with low water intensity (i.e., at a higher rate of decline, 8%, than the historical value assumed in the Medium Scenario)	Production goals: 2015, 3.5 bcm; 2017, 7.0 bcm; 2020, 10.5 bcm Rate of decline of water intensity: 8%

3. Results

3.1. Fuling analysis

In this section we project the temporal trajectory of water consumption for shale-gas development at Fuling through 2020, based on Sinopec's plans. With the number of new wells estimated each year through 2020, water demands can be calculated. We assume that the modest drilling water consumption noted above, 300 m^3 per well, will remain constant through 2020. The fracking water consumption per well is estimated first by assuming a constant lateral well length through 2020 based on the current average at Fuling Jiaoshiba, 1420 m; an initial water intensity of 19.9 m^3/m as estimated in section 2.1; and high, medium, and low rates of decline in water intensity as noted in Table 2. The projected declines in water intensity are attributed to gradually improving fracking techniques and improvements in the efficiency of future fluid reuse.

Details, including equations, production curve, and the projected number of new wells, are described in SI. The projected results for water consumption under high, medium, and low scenarios for each year from 2013 to 2020 are displayed for Fuling in Fig. 3.

The analysis suggests that Fuling's annual water consumption for shale-gas development continues to increase from 2014 to 2017 in the medium scenario, declining gradually subsequently. Water consumption peaks in 2017, at a value of 4.70 Mm^3, reflecting the fact that the fastest capacity growth occurs in the period when most wells are drilled and fracked for shale-gas production. The water consumption curve under the low scenario averages less than 1.61 Mm^3 for water consumption per year from 2015 to 2020. The assumption of lower water intensity, as well as production falling below the planned goal, is responsible for the dip in water consumption for 2015 in the low scenario. In the high scenario, water use begins to plateau after a rapid rise in 2015, in the range of 6.18 and 7.22 Mm^3 through 2020, reflecting a slowdown in the development of new wells in addition to a decline in water intensity.

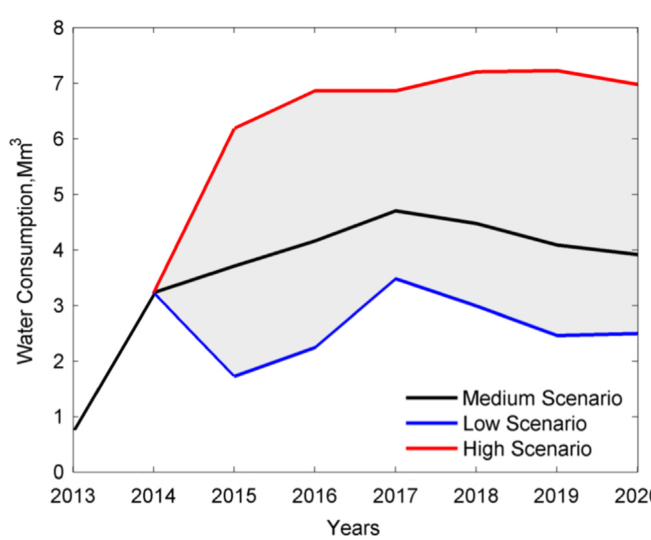

Fig. 3. Projections for shale-gas water consumption at Fuling.

Table 3
Comparison of maximum water demand for Fuling shale gas development with availability and current consumption of water in Fuling and Chongqing.

Year	Fuling precipitation (mm)	Fuling total water resource (Mm^3)	Fuling water use (Mm^3)	Maximum shale-gas water use / Fuling total resource (%)	Maximum shale-gas water use / Fuling total use (%)	Maximum shale-gas water use / Chongqing total use (%)
2009	1056.3	1497.27	350.67	0.48%	2.06%	0.08%
2010	929.0	1179.64	277.81	0.61%	2.60%	0.08%
2011	795.4	882.63	451.27	0.82%	1.60%	0.08%
2012	982.5	1304.69	358.49	0.55%	2.01%	0.09%
2013	954.6	1229.52	257.14	0.59%	2.81%	0.09%

In order to analyze the potential impacts of shale-gas production on local water resources, we considered the availability of water in the Fuling district and in Chongqing, the province-equivalent "municipal" jurisdiction in which the shale development is located. The Yangtze River transits from west to east in Fuling (north of the Jiaoshiba block) and the Wujiang River flows north into the Yangtze to the west. Sinopec currently meets the demand for water for shale-gas production at Fuling through an arrangement with a local chemical plant, which has water withdrawal rights from the Wujiang [36]. Our survey subjects, interviewed at the outset of shale-gas development of Fuling, did not consider local water availability as a significant constraint on production. Whether it may develop as such in the future as the play enters full-scale development is an open question. We use the peak value for the projected amount of water consumption for shale gas in Fuling, which could reach 7.22 Mm^3 for 2018 in the high scenario, to study the potential future impact on local water resources.

In Table 3, we present the changes in Fuling's precipitation and total water resources from 2009 to 2013, together with the percentage of total current annual water use for Fuling and Chongqing represented for the projected maximum Fuling shale-gas water consumption (i.e. for 2018). The maximum projection corresponds to less than 1% of Fuling water resources for all years, even if the declining precipitation observed in recent years should persist. According to the water use data from 2005 to 2013 in the Fuling Statistical Yearbook [46], maximum shale-gas water use represented less than 3% of the total demand. This compares with values of 0.9–136% for 15 shale-gas-mining counties in Texas, with a mean of 7.41% [16]. The much higher population density in Fuling compared to the fifteen Texas counties (Table 4) results in a much higher annual total water use. Hence, even with a higher projected maximum shale-gas water use, the proportion of total water use in Fuling (2.13%) is still less than the average for involved Texas counties (7.41%) and may have relatively lower impact on local water resources and competing demands. At the scale of Chongqing, Fuling water demands account for only 0.08–0.09% of total water use, comparable to the U.S. statewide result for Pennsylvania (0.2%) [11].

3.2. Nationwide analysis

To extend the analysis to national scale, we consider China's 7 currently identified prospective shale-gas basins (geologic properties are shown in the *SI*) and related demands for water. Besides the Sichuan Basin, which accounts for more than 56% of China's total technically recoverable shale gas, the EIA/ARI's assessment report has investigated also other six promising shale-gas basins in China (shown in the inset of Fig. 1) [5]. At present, development of shale gas in these six basins remains at the stage of resource exploration and evaluation. Here we assume that: (1) the projected well spacing (d) at Fuling, 300–1000 m, that (2) the average length of a fracking stage at Fuling, 80 m, applies to wells in all plays, and that (3) that the fracking water use per unit stage is estimated at 1000–2000 m^3 based on experimental fracking results [45] for China, yielding an estimated water intensity (I) of 12.5–25.0 m^3/m. Applying the low (high) well spacing, high (low) water intensity and the prospectivity (p) values in section 2.3 to equation 2 for all plays, we derive an upper [47] estimate of projected total water use for all major shale-gas basins in China upon full development. The potential demand for water is estimated greatest in the Tarim basin reflecting its significantly larger prospective areas for development compared to other major basins in China. Results of total water demands for all 7 basins are described in *SI*.

While the estimated aggregate fracking water use for a shale-gas basin represents its water demand in long-term development terms, to understand the potential impacts on local water resources – e.g., exacerbating scarcity during droughts or competing with demands for other uses – requires a more temporal perspective [11,16]. Based on the national shale-gas production goal of 30 bcm by 2020, we can project the potential trajectory of nationwide water use for shale-gas production using the method applied to Fuling (shown in the *SI*).

Since Sinopec and PetroChina have already announced 2020 production targets for the comparatively more developed Sichuan Basin (15 bcm and 11 bcm, respectively), we assume that these plans will be met and will account for 26 bcm of the 30 bcm national production goal for 2020. We assume further that the balance of the target (4 bcm) will be met from the other six basins in proportion to their technically recoverable resources (TRR) as reported in the EIA/ARI's assessment report [5], and that this production will increase from zero in 2014, again subject to the constraint of a smooth drilling trajectory from 2014 to 2020 as required for practical logistical and financial reasons.

To achieve the goal of 30 bcm shale-gas production by 2020, the peak volume of China's water consumption (an estimated 15.03 Mm^3 in the high scenario) for shale-gas development will occur in 2019 (Fig. 4). Using global water resource data according to catchment areas compiled by the World Resources Institute [26], we compare the peak volume of water employed for shale gas development in 2020 to the total water resource available and

Table 4
Comparison of water use in Fuling with use in 15 shale-gas-mining counties in Texas.

		Population	Area (km^2)	Total water use (Mm^3)	Maximum shale-gas water use (Mm^3)	Shale-gas use / total use (%)
Average of Fuling (2009–2013)		1,160,000	2941	339	7.2	2.1%
Fifteen Texas counties (2008)	Range	6000–637,400	1530–8790	3–453	2.1–7.1	0.9–136%
	Average	104,093	2855	54	4	7.4%

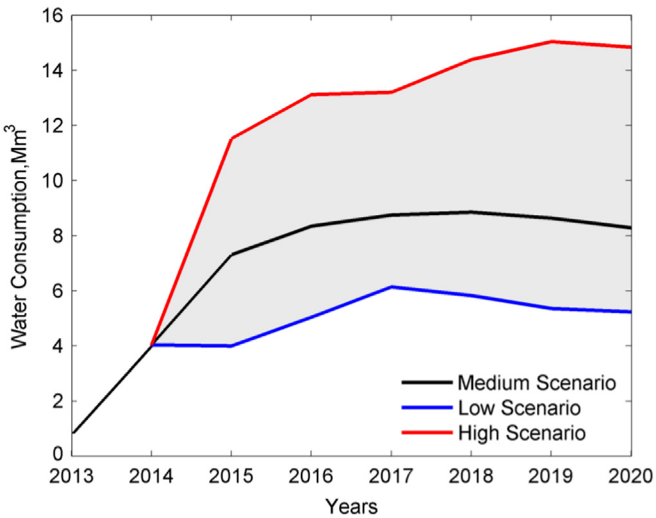

Fig. 4. Water consumption for shale-gas development in China.

existing water withdrawals (to represent competing water use). Results are shown in Fig. 5.

Each scatter point refers to a unit area, in which the hydrological catchment area and shale-gas plays overlap. It indicates that for most areas, shale-gas water use accounts for less than 10% of locally available water resources even under the high scenario, and these areas account collectively for 95.7% of the total estimated TRR of shale gas in China. However, for several areas with relatively low TRR and/or arid natural conditions, the projected water use for shale-gas development can account for more than 10% of local water resources, potentially exceeding 600% for an area in the Junggar Basin. Compared to current water use, maximum shale-gas water use generally represents less than 10%; the largest percentage is over 3000% for an area in the Junggar Basin. For context, recall that the analogous value for 15 counties in shale-gas regions of Texas averaged 36% in 2008 [16].

Given these relatively small percentages, it appears that most of the shale-gas plays in China with the highest estimated gas resources should be able to accommodate the water demand required for China to achieve the 2020 shale-gas production goal. For several specific areas in the Tarim and Junggar Basins, shale-gas development could require more water than would be locally available, requiring significant changes for the local water system, risking serious exacerbation of water scarcity problems. Development of these areas, if justified for other reasons, would require transfer of water from areas with more abundant resources.

4. Discussion

Roughly 50% higher water intensity was estimated for shale-gas wells at Fuling in China as compared with plays in the U.S. Pursuit of maximum economic return is the most direct determinant of water intensity, involving a tradeoff between water costs and gas production benefits. One way to decrease water intensity is to increase water costs, including water consumption costs and wastewater treatment costs, to incentivize operators to improve water use and recycling efficiencies. Costs for both of these activities in China's shale-gas industry are much lower than in the U.S. (Table 5).

Wastewater management in China's Sichuan Basin depends mainly on on-site recycling and wastewater treatment plants. Only a few injection wells are used by PetroChina to dispose of shale-gas wastewater in Sichuan and so far, none have been drilled in Fuling [53]. About 60% of the wastewater is recycled by on-site installations [54], and the balance is delivered by trucks to wastewater treatment plants. Sinopec and PetroChina generally operate their own treatment plants, but there are a few plants operated by commercial wastewater treatment companies, such as Veolia. The estimated cost in Fuling is about US$45/$m^3$ [51], much of which is associated with expense for delivery to the treatment plants. Based on the water-use projection in Fuling and assuming a 10–15% flow back rate, 40% recycling rate [54], and the same ratio between produced water and flow back water as in the U.S. Marcellus play [55], the cost for wastewater treatment in 2015 would be US$96.2 million. The average wastewater treatment cost per new drilled well would be US$230,000, and the water use cost would be US$23,000 based on the estimate for the water use per well in Table 1 and the average water price of US$0.75/$m^3$. The total water cost for a shale-gas well in China, US$253,000, would account for roughly 2% of the total cost of a shale-gas well

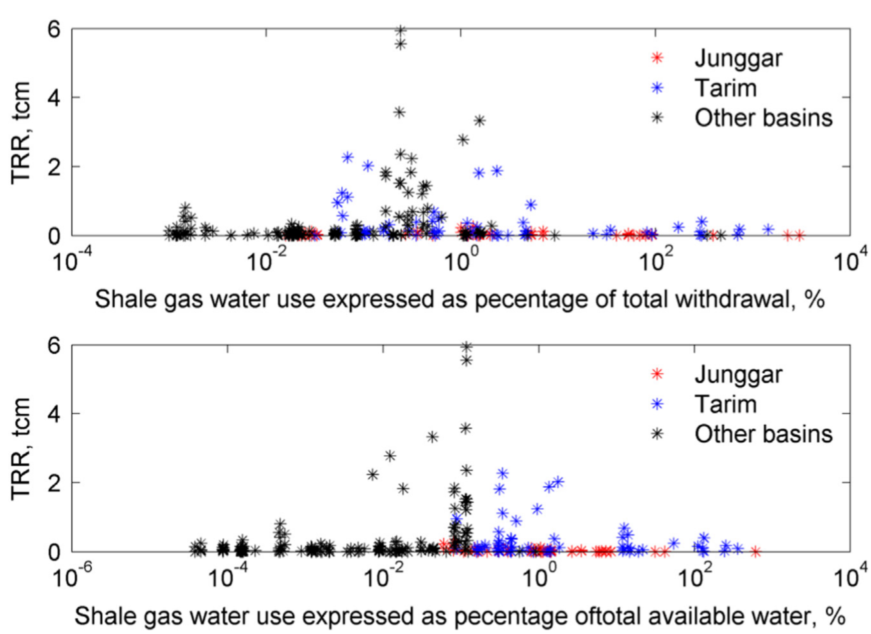

Fig. 5. Shale-gas water use as a share of total available water and total withdrawal.

Table 5
Costs of major options for drilling and fracking water supply and wastewater management in the U.S. and China.

		U.S.		China	
		Options [48]	Cost	Options	Cost
Supply	Fresh water		\$2–3 m^3		\$0.5–1.0 m^3 [49]
Wastewater Management	Drilling fluid	Recycle: 70.7% Treatment plants: 19.8%	\$32–66 m^3 [50]	Recycle Treatment Plants	\$45 m^3 [51]
	Flowback fluids	Recycle: 89.8% Treatment plants: 6.8%	\$32–66 m^3 [50]	Recycle Treatment Plants Injection	\$45 m^3 [51]
	Produced water	Recycle: 55.7% Injection: 27.8%	\$25–59 m^3 [52]	Recycle Treatment Plants Injection	\$45 m^3 [51]

Notes: the U.S. wastewater treatment options and proportions are from reference 48, cost of those options are from references [50,52]; China's wastewater treatment information is from our field interviews in Fuling in 2014 and the reference [51].

according to the most recent cost estimate of US\$13 million [8].

The relatively low costs for water withdrawal can provide only limited incentives for large state-owned operators to improve wastewater recycling efficiency and fracking technology to reduce water demand. In addition, the coverage and implementation of regulations on water withdrawal and wastewater treatment for shale-gas production are insufficient in the two countries, especially in China [56]. For the U.S. regulatory framework on shale-gas development, improvements should be made to extend the coverage of regulations on water consumption, particularly groundwater [56]. The potential impacts of shale-gas wastewater on local water quality is still underappreciated in China. Shale-gas operators currently manage wastewater treatment in accordance with their internal procedures. It is important to establish specific regulations and standards for waste water treatment from shale-gas production in China.

Proper technologies, including wastewater treatment technologies, could address many of major environmental concerns. These controlling technologies increase the overall drilling costs by about 7% in the United States [12]. Under current circumstances, Chinese government is working to establish uniform wastewater treatment and disposal standards for shale-gas production in China. More stringent regulations and requirements on wastewater treatment are expected to increase the overall costs for water in shale-gas production. By the same token, it may encourage the operators to improve the water use efficacy and reduce water demand in the future.

Uncertainties are inevitable in the projections of China's total and temporal water use for shale-gas development. The actual water intensity and well spacing vary with shale-gas plays. Estimates based solely on the Fuling data might result in gaps between the projected and actual total water use. However, the constraints of different scenarios explored here help define the potential limits under different development scenarios.

In order to realize the 2030 carbon commitment and achieve the production goal, it is likely that most Chinese shale gas will be produced in the Sichuan Basin, with a small proportion from other basins. Most of the shale plays appear to have sufficient water resources for shale-gas production by 2020 with at most minor impact on other competing water uses. However, several specific areas with limited water resources in the Tarim and Jungger Basins would have difficulty in meeting their production goals, although the production proportions in these areas are relative small.

The "one-time" use character of water employed in shale-gas development makes the temporal water consumption volume highly correlated with well drilling and fracking numbers. Hence, drilling and fracking a large number of wells in a short-term period could result in an extremely high consumption of water, which could have serious impacts on local water resources. Operators can address the related problems by considering the local availability of water when they formulate their capacity development plans.

Water use is unlikely to pose a widespread constraint on China's future shale gas development. However, the potential for water pollution poses separate and potentially more serious problems. The large volumes of water use, as well as the high concentrations and multiplicity of effluent contaminants, make the safe disposal of wastewater from shale-gas production a major challenge. Lack of specific regulation relating to water management in the shale-gas industry is a critical gap in policy that must be addressed for large-scale development to proceed safely.

Supporting information

Schematic diagram for lateral well spacing at Fuling, description of methodology to estimate future water use for production of shale gas at Fuling, summary of geologic properties of China's seven most prospective shale basins, summary of results of water demand and key parameters used in the scenarios for China's national analyses.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2016.08.026.

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