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Water Availability for Shale Gas Development in Sichuan Basin, China

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Supporting Information

ABSTRACT: Unconventional shale gas development holds promise for reducing the predominant consumption of coal and increasing the utilization of natural gas in China. While China possesses some of the most abundant technically recoverable shale gas resources in the world, water availability could still be a limiting factor for hydraulic fracturing operations, in addition to geological, infrastructural, and technological barriers. Here, we project the baseline water availability for the next 15 years in Sichuan Basin, one of the most promising shale gas basins in China. Our projection shows that continued water demand for the domestic sector in Sichuan Basin could result in high to extremely high water stress in certain areas. By simulating shale gas development and using information from current water use for hydraulic fracturing in Sichuan Basin (20 000−30 000 m^3 per well), we project that during the next decade water use for shale gas development could reach 20−30 million m^3/year, when shale gas well development is projected to be most active. While this volume is negligible relative to the projected overall domestic water use of ~36 billion m^3/year, we posit that intensification of hydraulic fracturing and water use might compete with other water utilization in local water-stress areas in Sichuan Basin.

INTRODUCTION

Unconventional natural gas extraction has captured the attention of global energy and natural resources managers, policy makers, environmental advocates, and the general public. The breakthroughs in horizontal drilling and hydraulic fracturing technologies are estimated to increase technically recoverable gas reserves worldwide by 47%.[1] The United States and Canada are in the midst of a remarkable natural gas boom due to the combination of hydraulic fracturing and horizontal drilling. China, a country with rapid economic growth, has generated a GDP with an average annual growth of 10.2% over the past 10 years.[2] This rapid economic development has increased energy demand (Supporting Information, A), and since 2009, China has become the world's largest energy consumer, importing oil, natural gas, and coal.[3] In order to enhance its energy security to meet growing domestic demand for energy, the Chinese government has encouraged companies to increase investments in upstream oil and gas operations, often through expanding overseas operations; yet, due to its abundant natural gas resources and desire to reduce domestic reliance on coal, the country is also moving to developing natural gas—both to improve its energy security and reduce air pollution from traditional fossil fuel combustion.[3] Since 2000, China's natural gas consumption has grown by 6-fold.[4]

Global shale gas exploration and production has had a profound impact on China's unconventional resources development. Possessing the most abundant, technically recoverable shale gas resources (32 trillion cubic meter) worldwide,[1] the country has initiated the National Shale Gas Development Plan (2012), which has placed great emphasis on development of unconventional energy. In the 13th Five-Year Plan (2016−2020), China's shale gas production goal is projected to reach 30 billion m^3 by 2020—this is anticipated to account for 15% of total natural gas consumption in the country.[4,5] In response to the nationwide development plan, the Ministry of Land and Resources of China has divided the territory into five shale gas resource districts and further assessed their exploration potential (Supporting Information B, C). With the highest estimated shale gas resources and relatively abundant water

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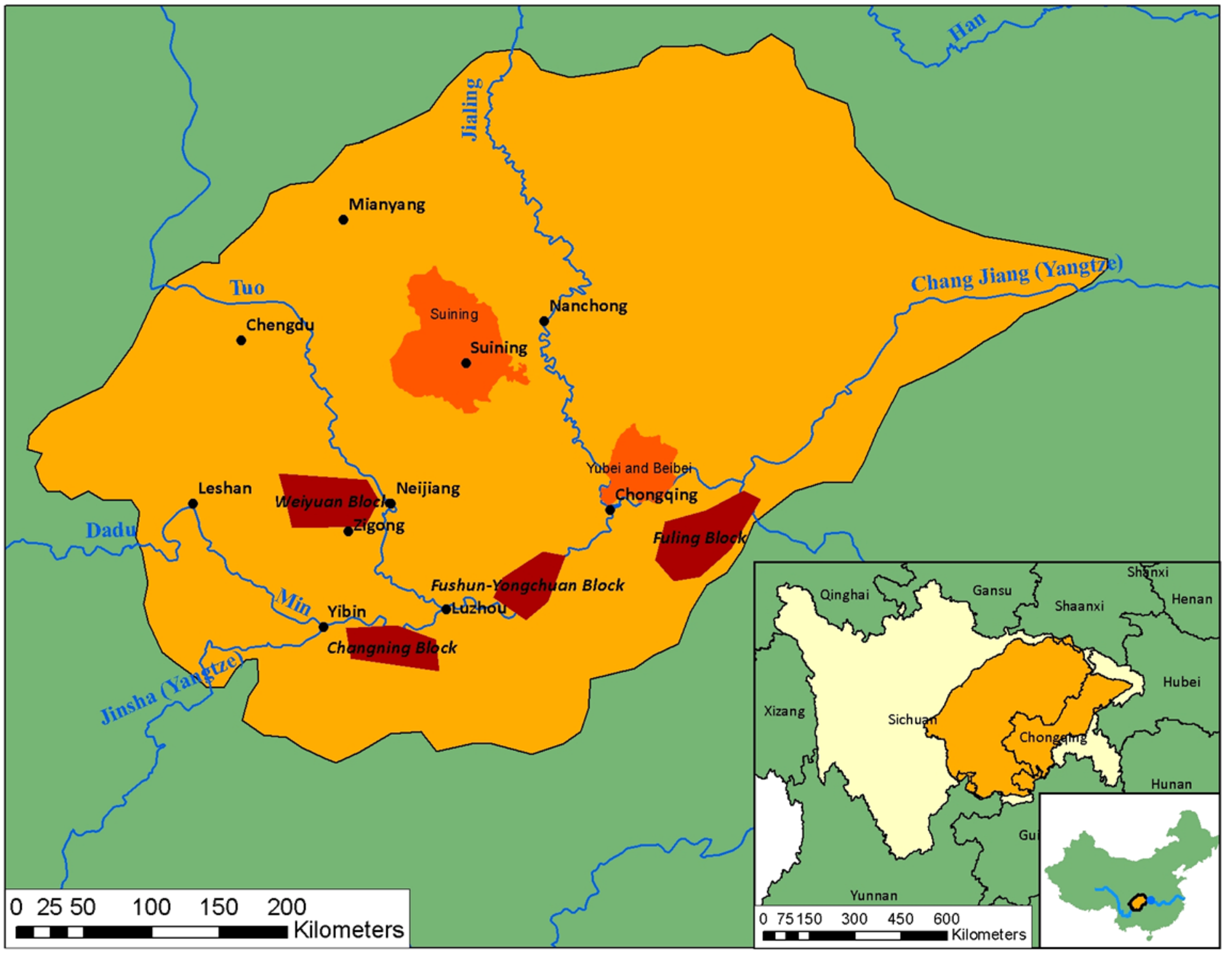

Figure 1. Location of major cities and shale gas blocks in the Sichuan Basin. The Sichuan Basin includes the eastern part of the Sichuan Province and Chongqing Municipality. Areas where future high water stress is projected are marked in orange.

resources, Sichuan Basin (Figure 1) is one of the most promising areas for shale gas exploration in China.

Energy and water are increasingly interdependent resources, as water is a major input into the exploration and production of shale gas. For China, water availability, and alternatives for disposing wastewater could, however, constrain the country's ability to diversify its energy mix and enhance its energy security. This is most evident with the hydraulic fracturing process that uses a mixture of chemicals, sand, and water under high pressure to fracture the shale rocks and allow the flow of gas or oil into the well. Based on the U.S. experience, hydraulic fracturing requires 14 000 to 24 000 m^3 of water per well, depending on the well length and geological features of the formation.[6,7] Despite the increasing use of recycled flowback water, freshwater is still the industry's first choice because some chemical additives used for hydraulic fracturing perform better in low-saline water, induces less corrosion, causes minimum bacteriological contamination, and is overall easier to manage.[8,9] Although water requirements for shale gas production are significantly low when compared to the volume of water needs for cooling coal-fired power plants (e.g., about 40% of the water withdrawal in the U.S.[10]),[11] the impacts of water withdrawal for shale gas development could cause temporal reduction of natural stream flows and depletion of local groundwater.[7,12−16] Another challenge for water resources management associated with shale gas exploration is the wastewater generation. Together with the gas, shale gas wells generate large volumes of wastewater with typically elevated contents of salts and toxic elements.[7,17−19] Wastewater from shale gas production, generally classified into flowback and produced water, consists of injected fracturing fluids and deep formation waters.[20] For the Marcellus shale, currently the largest shale gas play in the U.S., the shale gas production activities have increased the total wastewater generation by approximately 570% since 2004, exceeding current wastewater disposal capacity.[21] If inappropriately handled, wastewater from shale gas production can contaminate surface and groundwater through surface leaks and spills, and inadequate treatment.[18,22,23] Although disposing wastewater through deep underground injection is a common practice in the U.S. (comprises >80% of disposal),[20] the increasing volume of injected wastewater has triggered seismicity and earthquakes in several areas.[24−26] Consequently, the feasibility of deep injection of wastewater in China—particularly in a seismic sensitive area such as the Sichuan Basin—may not be viable.

The water challenge in China is primarily driven by the uneven spatial and temporal distribution of freshwater resources, coupled with rapid industrialization, urbanization, growing agricultural demands, water quality degradation, and potential climate-related threats.[27−29] Most of the shale gas basins in China are located in arid or semiarid regions, and many of these basins are densely populated with growing water demand.[30] By the end of 2014, 780 shale gas wells were drilled for exploration and production purposes throughout the

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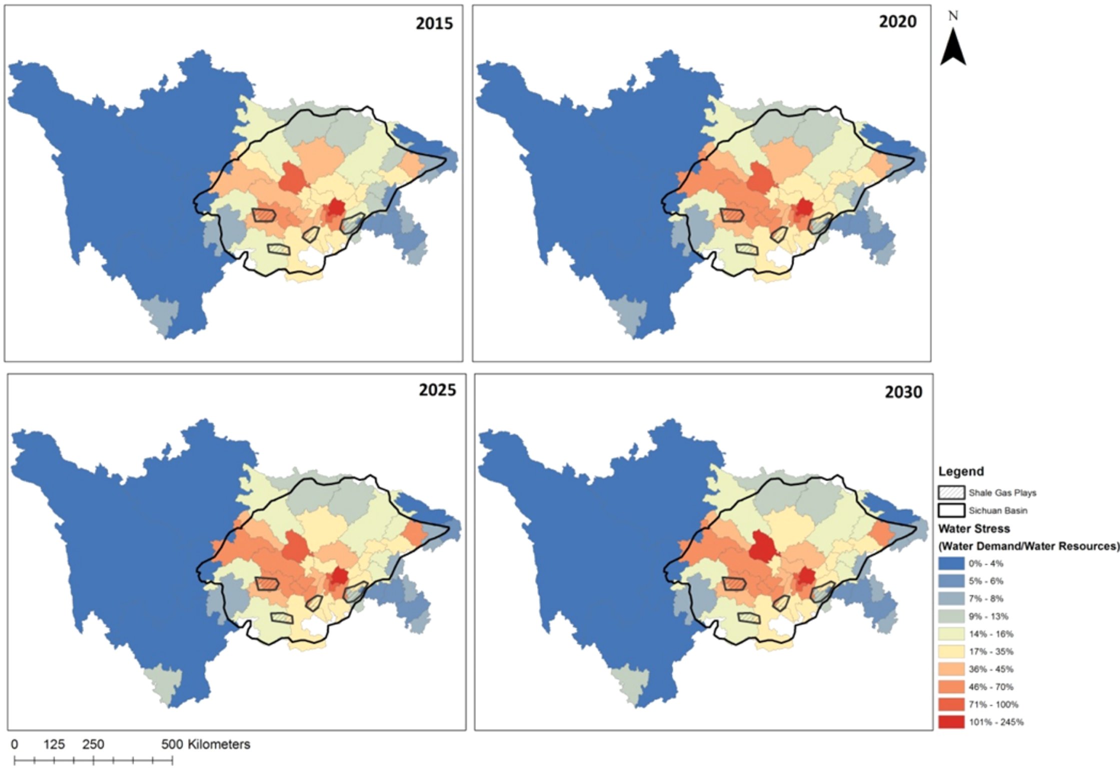

Figure 2. Water stress distribution in Sichuan Basin, calculated by using eq 2. Areas of high to extremely high water stress are located in the central and southern part of Sichuan Basin. The locations of the shale gas blocks coincide with high water stress areas.

country (Supporting Information, D).[31] The most promising resource in Sichuan basin is the Lower Silurian Longmaxi formation, composed of organically rich, black, graptolitic-bearing, siliceous shale (see details in Supporting Information, B). The southwest Sichuan Basin seems to meet the standard criteria for shale gas extraction including: favorable geology, thermal maturity of organic matter, overpressure of the reservoir,[32] existing pipeline infrastructure, and access to major urban gas markets.[33] However, only a limited number of studies have reported the current state of shale gas development in Sichuan Basin. With the largest technically recoverable shale gas reserves, Sichuan Basin has become the pilot target for shale gas development in China.[32,34] Although water is generally more abundant in southern China, Sichuan Basin has experienced significant variations in annual and seasonal precipitation,[35−37] historical extreme climatic events,[35] and degradation of the quality of surface water and groundwater[38] over the past few decades.

The objective of this study is to evaluate the possible impact of shale gas development in Sichuan Basin on water availability and the generation of wastewater in the region. We first estimate surface water availability and define an index of water stress in Sichuan Basin projected for the next 15 years under a baseline scenario. Next, we quantify projected volumes of water use and wastewater generation from shale gas production under different scenarios with different shale drilling rates and water use for hydraulic fracturing. Although commercial shale gas production in China is currently limited to Sichuan Basin, the projected water use and wastewater volumes presented in this study should serve as a guide for assessing potential water stress in other shale gas plays in China.

■ MATERIALS AND METHODS

Sichuan Basin. Sichuan Basin is located in the southwest of China, including the entire Chongqing Municipality (Figure 1). Encompassing approximately 260 000 km^2, the basin is a fertile and productive agricultural area. Over the past 15 years (1991−2014), Sichuan's total population grew from 78.9 to 91.3 million, in which the urban population grew from 11 to 26.3 million at an average annual rate of 3.9%, while the rural population decreased from 67.9 to 65 million. The major two municipalities within the basin, Chengdu and Chongqing, have a population of around 14 and 30 million, respectively, making Sichuan Basin one of the most densely populated areas in the country. Located at the upper reach of the Yangtze River, Sichuan Basin has a southern subtropical warm and humid climate.[37] The major tributaries of the Yangtze River, namely Minjiang River, Tuo River, Jialing River, and Qu River, run through the Basin from north to south into the Yangtze River.[39] The Sichuan Basin is one of the earliest and currently largest conventional gas-producing regions in the country.[40−42] Recent evaluations of shale gas resources have targeted Sichuan Basin as a focus of shale gas exploration in China. Weiyuan, Changning, Fushan-Yongchuan, and Fuling Shale Gas Blocks are the four key areas for shale gas exploration in Sichuan Basin (Figure 1).[32]

Estimation of Future Baseline Water Stress. Historical population[43,44] and water resources[45,46] data are reported at the county/district level by provincial agencies. While water resources information based on administrative units may not reflect the region's natural hydrologic conditions, this database represents the best available census and water resources information. Additionally, shale gas production in Sichuan Basin is at an early stage, and data on current shale gas extraction activities are neither clear nor readily available. Given

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the lack of information on specific drilling areas, we used and digitized the general boundaries of shale gas blocks in the basin by applying ArcGIS software. In order to project domestic water use (which includes household, government offices, public parks, and other withdrawals related to public supply), we used Equation 1:

$$\text{domestic withdrawals} = \text{population} \times \text{domestic withdrawal per capita} \quad (1)$$

The future population of each region is projected using the average annual growth rate from historical data. This projection is also based on domestic water use per capita.[47] Our data indicated that the average urban domestic withdrawal in the region during the period 2001−2013 was 153 L/person/day, while rural residents consumed on average 73 L/person/day of water. Therefore, we separated urban and rural populations for total domestic withdrawals. The Holt-Winters Exponential Smoothing Method was used to fit this historical data and generate estimates of future per capita domestic withdrawals for urban and rural residential water use (Supporting Information, E).[48] In general, the prediction model with the normally distributed forecast errors and constant variance of errors over time was identified as the best forecast model for this data.

The total water demand is documented by Sichuan and Chongqing Water Resources Bureau for four different categories: domestic and public, industrial and commercial, agricultural (livestock and irrigation), and environmental water utilizations.[45,46] Due to insufficient data for each category, the future total water demand of Sichuan Province and Chongqing Municipality was estimated by first estimating domestic water use and then by assuming that domestic water demand will continue to account for a fixed percentage of the total water use (i.e., assuming that total water demand will grow at the same pace as domestic water demand). We found the average of annual domestic water use as a percentage of total water demand for the years 1998−2001,[49] and then used these percentages, together with the projection of future population, to estimate total water demand for each county/district. While the baseline projection of future water demand is based on the observed average trends for population growth, per capita domestic water use, and the fraction of domestic water use in total water demand, in order to bound the uncertainty surrounding this estimate, we also calculated the maximum, and minimum total water demand values for each year that would result from combining extreme values of these three factors (Supporting Information, F). The baseline water stress across the region is quantified with the Water Stress Index calculated as

$$\text{water stress index (\%)} = \frac{\text{total water demand per year (million cubic meters)}}{\text{average total water availability per year (million cubic meters)}} \times 100 \quad (2)$$

where the average total water availability was obtained as the sum of surface and groundwater resources reported by the best available regional water resources bulletins.[45,46] Figure 2 shows the projected water stress indices across Sichuan Basin under our baseline (i.e., average based) water demand projection.

Projection of Water Use and Wastewater Generation from Shale Gas Production. The projection of water use for shale gas production is based on the U.S. history of unconventional shale gas and oil exploration that includes the number of wells drilled per year (i.e., rate of exploitation) and water usage for hydraulic fracturing per well.[6,50] The rate of exploitation depends on target production volumes, shale gas production declining rates, and the anticipated shale gas well lifespan.[51] As of 2015, 780 wells have been drilled in China, resulting in 1.3 billion m^3 of shale gas production.[31] Most shale gas drilling has been conducted in Sichuan Basin, and about 300 shale gas wells have been completed in Fuling, Changning, Weiyuan, Zhaotong, and Fushun-Yongchuan shale gas blocks of Sichuan Basin. Although we found widely divergent views about the medium/long-term prospects for shale gas production in China (Supporting Information, G), we used the most recent target production rates established by the central government—6.5 billion m^3/year by 2015 and 30 billion m^3/year by 2020—to estimate the rate of drilling and the corresponding water withdrawal and wastewater generation. An updated evaluation suggests that the annual production from shale gas in Sichuan Basin could reach 20−30 billion m^3/year in 2020.[32] Another key variable affecting projected water use and wastewater generation from shale gas activities is the average lifespan of Sichuan Basin wells. Several studies have reported the average lifespan of shale gas production wells is between 7 and 10 years;[50,52,53] thus, we assume a lifetime of 10 years for our analyses. For the gas production characteristics over the lifespan of a shale gas well (which has been observed in major U.S. shale gas plays and Sichuan shale gas production wells.[51,54]), we used the initial production and declining rates reported by Liu et al.[54] for our projection.

A review of the available literature indicates considerable variability in water requirements for shale gas production.[6,7,21,55,56] Differences in wellbore depth, length of horizontal well, and the geology of the shale formation can lead to wide variation in water usage. Additionally, shale gas wells may be repeatedly hydraulically fractured to maximize productivity upon completion of the drilling process.[52,57]

The volume of wastewater, typically composed of highly saline water, also varies significantly across shale gas plays.[6] Therefore, we reviewed the comprehensive characterization of water withdrawal and wastewater volumes from publically accessible data[6] and estimated the water withdrawal for shale gas development in the region. Because of the wide variation in reported water use for hydraulic fracturing, we used a range of water requirement per hydraulically fractured well to account for these variations in our projections for water withdrawal. Our own information indicates that current water use for hydraulic fracturing in Sichuan Basin varies from 20 000 m^3 to 30 000 m^3 per shale gas well. A recent study shows that Sichuan Shale Basin has the most similar geological properties with the Haynesville Shale in the U.S.,[54] and therefore we adopted the wastewater type curve of Haynesville Shale Basin's to estimate the quantity of wastewater that Sichuan Shale Basin may generate during the next 15 years.

RESULTS AND DISCUSSION

Baseline Water Stress Projection 2015−2030. The historical population and per capita domestic water use were analyzed in order to project the domestic water demand in Sichuan Province and Chongqing Municipality for the next 15 years. The estimation of total water demand was obtained by estimating domestic water demand and assuming that future growth in domestic water demand will be the same as growth in total water use in the region. Further, the level of water stresses across the region was calculated by normalizing the total water demand by available water resources (eq 2).

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Table 1. Summary of Baseline Projections of Domestic and Total Water Withdrawals in Sichuan Province and Chongqing Municipality

baseline projection (based on average historical trends)		population (million)		domestic water per capita (L/day)[a]		domestic water withdrawals (Bm^3/year)			total water withdrawal (Bm^3/year)
		urban	rural	urban	rural	urban[b]	rural[c]	total	
Sichuan	2015	27.42	64.91	142.66	80.83	1.43	1.92	3.34	25.39
	2020	33.69	64.48	136.43	83.17	1.68	1.96	3.63	27.61
	2025	41.53	64.13	130.20	85.50	1.97	2.00	3.98	30.19
	2030	51.38	63.85	123.97	87.83	2.33	2.05	4.37	33.21
Chongqing	2015	14.34	19.87	142.66	80.83	0.75	0.59	1.33	7.15
	2020	20.15	18.59	136.43	83.17	1.00	0.56	1.57	8.41
	2025	29.15	17.42	130.20	85.50	1.39	0.54	1.93	10.35
	2030	43.43	16.35	123.97	87.83	1.97	0.52	2.49	13.35

[a]Projected values using data from Changjiang and Southwest Rivers: Water Resources Bulletin (2001−2013). [b]Urban domestic water withdrawals = urban population × urban water use per capita. [c]Rural domestic water withdrawals = rural population × rural water use per capita.

The county-level data shows that more developed and industrialized areas such as Chengdu City and Nanchong City (Figure 1), have had higher growth rates of urban population than less developed regions. According to our projection, Sichuan's total population will continue to grow during the next 15 years, reaching about 101.5 million in 2030. Although urbanization is anticipated to contribute to the province's total population, Sichuan is expected to continue to be a rural-dominated province until 2030 (Supporting Information, H). Chongqing Municipality has had a relatively stable total population since 2000 and some rural-to-urban migration in the region.[58] Increased urban population in areas such as Yubei District and Jiangjin City has significantly contributed to the overall urban population growth. Our projection estimates show that Chongqing's urban population will likely grow to 43.4 million in 2030, continuing its urbanization and surpassing rural population by 2020 (Supporting Information, H).

The historical trend of domestic water use per capita differs between urban and rural communities. Between 2001 and 2013, the per capita urban water withdrawal slightly dropped from 164 L/day to 161 L/day in the area. In contrast, a consistent annual growth of 0.6% in per capita rural water withdrawals was observed since 2001. In our projection, the Holt-Winters smoothing method was performed to fit historical data and generate future withdrawal efficiency for urban and rural residential water uses (Supporting Information, E). The per capita urban water demand is expected to continue to decrease, while per capita rural water demand is expected to increase steadily. Many factors can possibly contribute to the increase in per capita rural water use, including the upgrading of older or rural households, an increase in lawn and garden watering, and the increase of water-using amenities.

Despite declining per capita water use, overall urban water withdrawal in the area is projected to increase for the next 15 years, from 1.43 to 2.33 billion m^3/year in Sichuan and from 0.75 to 1.97 billion m^3/year in Chongqing (Table 1), due to rapid urban population growth in the areas. In addition, rural domestic water withdrawal of Sichuan Province will continue to increase even with a diminished rural population. Rural water demand in Chongqing, however, is projected to remain relatively stable. The combined domestic water withdrawal in Sichuan and Chongqing is expected to grow from 3.34 to 4.37 billion m^3/year and from 1.33 to 2.49 billion m^3/year, respectively. In order to estimate the total water demand from our projected domestic water demand, profiles of the region's historical water use were further investigated. On average, between 1998 and 2013 Sichuan Basin as a whole used 13.2%, while Chongqing used 18.6% of its total water withdrawal for domestic and public purposes. Extrapolating this trend, at the county/district level, the total water demand is projected to increase for the next 15 years (Supporting Information, I); Specifically, water withdrawal will continue to be concentrated in the eastern part of the Sichuan Basin (Figure S6).

In order to quantify the water stress for each county/district and changes over time, the water stress index (eq 2) was calculated by dividing the total water demand in different time intervals by the regional water resources. Figure 2 shows water stress indices for each county/district of Sichuan Province and Chongqing Municipality over 5-year intervals from 2015 to 2030. Based on these indexes, areas using between 40 to 100% of their total water resources were defined as high to extremely high water stressed. In general, these areas are located in the central and southern parts of the Sichuan Basin. Areas with water stress indices greater than 100% will likely require external water sources for regional development, if no water conservation or reuse program is implemented. As shown in Figure 1, the water stress areas coincide with the areas that are currently undergoing shale gas exploration and extraction (shale gas blocks). Although it is unclear to what extent shale gas activities in Sichuan Basin will rely on regional water resources, large-scale water transfer in the region is less likely mainly due to the region's complex and mountainous terrain. Therefore, the water withdrawal for shale gas extraction activities can potentially compete with other water users in the regions of high water stress.

The many uncertainties in the water stress estimation require future investigation. As mentioned above, the total water demand is estimated by assuming that domestic water demand accounts for a fixed portion of the total water withdrawal. However, this portion is likely to change over time, especially with different regional development as well as increasing efficiency in water use in different sectors. Thus, more detailed projections on agricultural and industrial water use or the examination of multiple water demand scenarios can provide a better uncertainty characterization. Also, stressors such as water quality degradation and climatic variability may also contribute to variability in regional water use and availability. Finally,

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future investigation should include an analysis of different scenarios of freshwater use for shale gas extraction, which will greatly affect the shale gas impact on regional water resources.

Projection of Shale Gas Water Use. The second component of this study considers a shale gas well development scenario by reviewing historical well drilling rates across the U.S. major shale plays and validation with actual water use data in Sichuan Basin. Further, this section incorporates the well production profile of Sichuan Basin shale gas well and estimates the expected natural gas production under this scenario. In order to link the potential of shale gas development and future water use and thus its effect on regional water resources, the water withdrawal for shale gas extraction is quantified by developing a few hypothetical water impact scenarios. In addition, we calculate the quantity of wastewater that could be generated from the development of shale gas extraction rate by using the produced water data from the U.S. Haynesville Shale that has similar geological properties to the shale formation in Sichuan basin.[54]

Our data indicate that up to the end of 2015 about 300 shale gas wells have been installed in Sichuan Basin. Well development is one of the most important factors for determining water withdrawal and wastewater generation from shale gas production. Yet previous studies have shown large variations in water use for hydraulic fracturing, gas production rates, and volume of wastewater generated for the different shale gas plays in the U.S.[6] Each shale gas play has its own set of geological and geographical characteristics, and variability in factors including production rates, development and economical incentives, geographical constraints, and infrastructure availability. Therefore, the drilling rates have also varied significantly across the U.S. shale plays (Supporting Information J). Barnett play, for example, had its drilling rate peak in 2008 at 2707 wells per year, and as of 2014 drilling has slowed down at less than 1000 wells per year.[51] In the Marcellus shale, the drilling rate peaked in 2013 at approximately 1350 wells per year and has fallen to 1200 wells per year in 2014.[51] Although annual drilling rates vary across plays, a peak drilling rate is likely to occur in the fifth to seventh year of a play's gas production. In addition, the well development is expected to slow down one to two years after the peak rate and further stabilize. Shale gas development depends on both physical parameters such as gas flow rates from the shale formations and economic factors such as gas prices that are the major driving force for hydraulic fracturing. In this study we assume development rates as those observed in the U.S. from the mid-2000s until 2014.

For Sichuan Basin, it is difficult to foresee a well development scenario simply by comparing the scale of shale plays, shale gas estimates, and geologic properties to those in the U.S. The oil and gas industries, research and development policy, pipeline policy, natural gas pricing policy, fiscal policy, and incentive pricing are also fundamentally different between China and the U.S.[59] Nonetheless, given the similarity of the Haynesville Shale Play in the U.S. (e.g., geology, depth, gas yield) to Sichuan Basin,[54] we built a single well development model based on the Haynesville Shale Play drilling rates. We assume that the drilling rate in Sichuan, will follow the same pattern as Haynesville but with a 2−3 years time lag before the rapid increase in drilling rate (Figure 3). We assume this time lag because during the early stages of shale gas extraction, the industry needs to invest in technology innovations which slows rates of drilling.[59] Further, the drilling rate is projected to peak

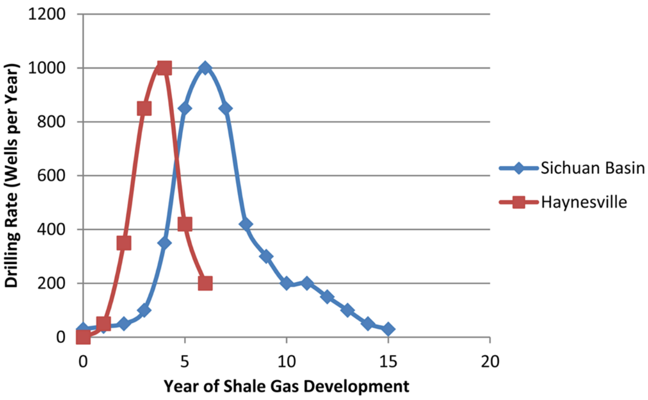

Figure 3. Variations of shale gas drilling rates observed in the Haynesville shale, U.S., used to project hypothetical shale gas well development during the next two decades in the Sichuan Shale Basin.

at about 1,000 wells per year in the sixth year of production, since the production of shale gas is rapidly increased and has a rate of exploitation to plays of similar geology during the scaling-up stage.[59] Based on our own information, it is expected that 1000−1500 shale gas wells will be drilled in the Sichuan Basin in the next five years. According to our projection model, a total of 1420 wells is expected to be drilled by the end of 2020, which is consistent with the official well development plan of up to 1500 wells during the next five years.

On the basis of the hypothetical scenario for well development in Sichuan Basin, we further calculate the annual production and cumulative production that can be achieved under the well development model. Two metrics widely used in describing shale well performance are the initial per well production (IP) rate and the well production decline rate. Together, these contribute to the variability in shale well production performance across five most active U.S. shale gas plays (Supporting Information, K). Due to the limited existing wells that have been producing, data on the IP rate and decline characteristics are still sparse in Sichuan Basin. In this study, we applied the development indices developed by Liu et al. (2014) and calculated the annual and cumulative production based on initial production data of 50,000 m^3/d and the unique decline curve for Sichuan Basin (Figure 4).[54] By summing up the production of existing wells and the new wells being drilled for that particular year, the annual and cumulative shale gas production were calculated based on our hypothetical well development model (Supporting Information, L). According to China's National Energy Administration (NEA), the government's shale gas production targets are 6.5 billion m^3/year by 2015 and 30 billion m^3/year (recently updated) by 2020. In this case, the projected shale gas production in Sichuan Shale Basin can contribute between 7% and 63% of the national production target in 2015 and 2020, respectively.

Despite the wide variation in reported water requirements for hydraulic fracturing[6] (Supporting Information, M), we estimated the water use for shale gas development using actual data of water use for hydraulic fracturing in Sichuan Basin of 20,000 to 30,000 m^3 of surface freshwater withdrawal per hydraulic fracturing single activity. This water use range is consistent with the water use data reported for the Haynesville Shale Play in the U.S.[6] Due to limited information, it is assumed that the most likely source of freshwater is the surface water from adjacent streams and rivers. Figure 5 illustrates the shale gas water withdrawals from 2015 through 2030 under two

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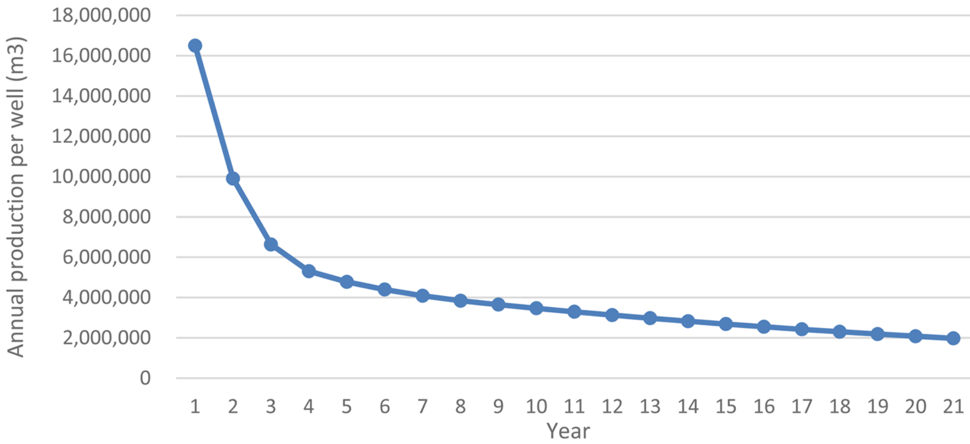

Year	1st	2nd	3rd	4th	5th	6th	7th	8th and thereafter
Decline Rate	40%	33%	20%	10%	8%	7%	6%	5%

Figure 4. Simulated gas production of shale gas wells in Sichuan Basin (data retrieved from Liu et al., 2014).[54] The table reflects the relative percentage of gas production in each year.

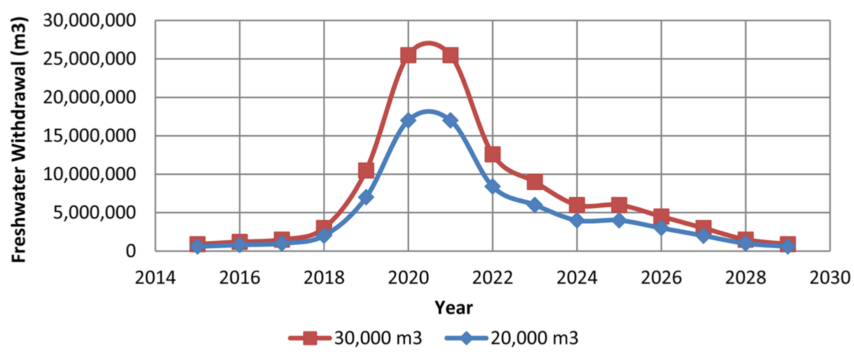

Figure 5. Simulation of water withdrawals for shale gas development and hydraulic fracturing in Sichuan Basin based on the estimate of water use in the range of 20 000 m^3 per shale gas well (blue line) and 30 000 m^3 per shale gas well (red line) for 2015 to 2030.

water impact scenarios corresponding to low and high water withdrawal assumptions of 20 000−30 000 m^3 per well. During the early development stage, water withdrawal is relatively insignificant, especially compared to the total available water resources in the region. With the anticipated rapid expansion of shale gas extraction, water withdrawal will increase significantly and will peak in the year when shale gas production is projected to be most active. In 2021, the projected water use is estimated to peak at 17 to 26 million cubic meters. Over the subsequent years, reduced drilling activity will generally decrease water use. Our projection is based on the assumption that fresh water will be the predominant source for hydraulic fracturing. Yet utilizing alternative water sources[60] or recycled flowback water would reduce the amount of fresh water need for hydraulic fracturing in Sichuan Basin.

Projection of Wastewater Generation from Shale Gas Development. Wastewater is a byproduct of shale gas extraction. Upon the completion of hydraulic fracturing, the reduction of injection pressure allows water to flow back to the surface. The water (flowback water) that initially flows back is a blend between the injected water and formation water, and once the well is in the production mode, it generates produced water, which is composed mainly by the formation water.[7,61] In this study, we considered both flowback and produced water as wastewater. Preliminary water quality data of flowback from Sichuan Basin indicate a TDS range of 10 000 mg/L to 44 000 mg/L, which is similar to the range of TDS measured in flowback from U.S. shale plays.[7] The volume and chemical composition of shale gas wastewater from a well can vary significantly depending on the type of hydrocarbon produced, the geologic properties of the formation, and operational factors.[61] Similar to gas production, water production from a well also follows a decreasing trend with time.[6,62,63] We used the wastewater type curve from Haynesville Shale that showed a total flowback and produced water volume of a range of 10 000 to 20 000 m^3 per shale gas well (Supporting Information, N).[6] Similar to annual and cumulative gas production, the water production of existing wells and new wells being drilled for that particular year were summed up in our analyses (Supporting Information, O). On the basis of the Haynesville example for produced water generation, we estimate that over 11 million m^3 of wastewater will be generated during the years of most active shale gas extraction in the Sichuan Basin (i.e., 2022), and the volume of wastewater will stabilize in the subsequent years due to a lower extraction rate (Supporting Information, O). Cumulatively, we estimate that by 2030 over 73 million m^3 of shale gas wastewater will be generated and will require treatment, disposal or recycling for hydraulic fracturing. If the flowback salinity level below 50 000 mg/L suggested by preliminary data is confirmed, then

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recycling could become feasible for future management of unconventional shale gas production in Sichuan Basin, particularly during peak periods of high drilling rates.

Overall, while China's demand for energy is growing, water availability and quality will constrain China's ability to enhance its energy security through shale gas production. A recognition of the water-energy nexus, that is, energy's impact on water quality and water availability's on energy exploration and production is fundamental for furthering policies to expand shale gas and hydraulic fracturing in China.[64] Yet, taking a more holistic and integrated approach to the water-energy nexus will also require China to pay particular attention to the environmental impacts associated with shale gas development, particularly to enhanced seismic activity associated with deep-well injection of oil and gas wastewater and potential water contamination. Thus, as in the U.S., China will also need to bolster its environmental regulations, monitoring capacities, and judicial oversight.[65] Our projections indicate that the continued demands from the domestic sector in Sichuan Basin could result in high to extremely high water stress in certain areas that are also associated with shale gas exploration. In particular, we have identified potential high to extremely high water stress in Yubei, Beibei, and Suining districts and Chongqing Municipality that some are located near shale gas blocks in the southern part of Sichuan Basin (Figure 1). We used a range of water use currently applied for hydraulic fracturing in Sichuan Basin to project water use for shale gas development over the next decade, and our calculation shows that water use could peak up to 25.5 million m^3 in 2020. This volume is negligible relative to the overall projected domestic water use of ~36 billion m^3 per year. Yet, we posit that the amount of water needed for hydraulic fracturing in the specific water-stress areas in the southern part of Sichuan Basin (Figure 1) during periods of intensified drilling and hydraulic fracturing might be limited, requiring external or alternative water sources for hydraulic fracturing.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b04669.

Further information on the analytical techniques is provided. Ten figures and eight tables are also available (PDF)

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Notes

The authors declare no competing financial interest.

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