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# Water Availability and Shale Gas Development in Sichuan Basin, China

Presented by

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Duke University

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## **Executive Summary**

Extraction of shale gas, a type of unconventional natural gas formed in shale formations, has captured the attention of global energy and natural resources managers, policy makers, environmental advocates, and the general public. Globally, shale gas represents an opportunity to increase energy demand with reduction in greenhouse gases emission from coal combustion. Technological advances such as hydraulic fracturing has driven the rapid development of shale gas extraction across the United States and Canada. China holds the world's largest technically recoverable shale gas resources and the third largest technically recoverable tight oil resources. Sichuan Basin, with the largest shale gas resources in the country, is China's most promising shale basin. China's current policies has put strong emphasis on the development of unconventional energy, indicating a national transition to "green" energy.

Based on the U.S. experience, shale gas production has posed a number of risks on the water resources. The withdrawals of freshwater for hydraulic fracturing, in particular, have become a limiting factor for shale energy development in regions under significant water stress. With its large population and rapid economic growth, China has experienced different levels of water stress. A World Resources Institute report with a focus on water availability and global shale gas development has highlighted that shale gas resources in China are not always located in water-abundant areas. Although interest in China's shale gas development is growing, the nexus between water availability and regional shale gas development is rarely studied. In order to fill this gap, this thesis examines possible links between water availability and shale gas development in Sichuan Basin by projecting baseline water stress and estimating water utilization for Sichuan Basin shale gas development under hypothetical water impact scenarios.

The first section of this thesis provides an estimation of total water demand by extrapolating domestic water demand, and further evaluates the level of water stresses across the study regions. Specially, it reviews the population growth and historical per capita domestic water use in order to project the domestic water demand in Sichuan Basin for the next 15 years. By extrapolating domestic to total water demand, this thesis further shows the distribution of the future baseline water stress in the study region.

The second section of this thesis evaluates the shale gas well development scenario by reviewing historical well drilling rates across the U.S. major shale plays. Further, this section incorporates the well production profile of Sichuan Basin shale gas well and estimates the expected natural gas production under this well development scenario. The section then

quantifies the water withdrawals for shale gas extraction by developing three hypothetical water impact scenarios.

Ultimately, the baseline water stress and the projected water utilization for shale gas extraction are integrated into a discussion on water availability for shale gas development in Sichuan Basin. Using statistical and geospatial analysis to combine the water stress indices and the locations of shale gas plays in the basin, the thesis highlights several key points and recommendations:

- The areas of high to extremely high water stress are projected to concentrate in areas with major urban centers and industrial activities. Shale gas development will also overlay with these areas, indicating that shale gas development in Sichuan Basin may pose potential risk on local water resources.
- Water withdrawals for shale gas development is relatively insignificant compared to the total water resources available in Sichuan Province and Chongqing Municipality. However, water withdrawal for shale gas extraction is likely to localize due to the region's complex and mountainous terrain. Therefore, the results of this study can be used to identify areas that are most at risk and, in these areas, identify alternative water sources for hydraulic fracturing such as industrial wastewater or brackish water that could substitute deficient freshwater resources.
- This study provides a general framework for evaluating water risks associated with a regional shale gas development. In order to refine future projections, detailed projections of other water use sectors as well as development of multiple water demand and water resources scenarios could help to reduce the uncertainties for natural resources planning purposes.

## **Acknowledgements**

I would like to acknowledge those individuals and organizations, which provided information, data, and support and without whom the process would have been insurmountable at best. In addition, I would like to thank my Master Project advisor, Dr. Avner Vengosh, who provided valuable advice throughout the project. Finally, thanks to my mom Ms. Jiashan Yang who have supported me throughout entire process, both by keeping me harmonious and helping me putting pieces together.

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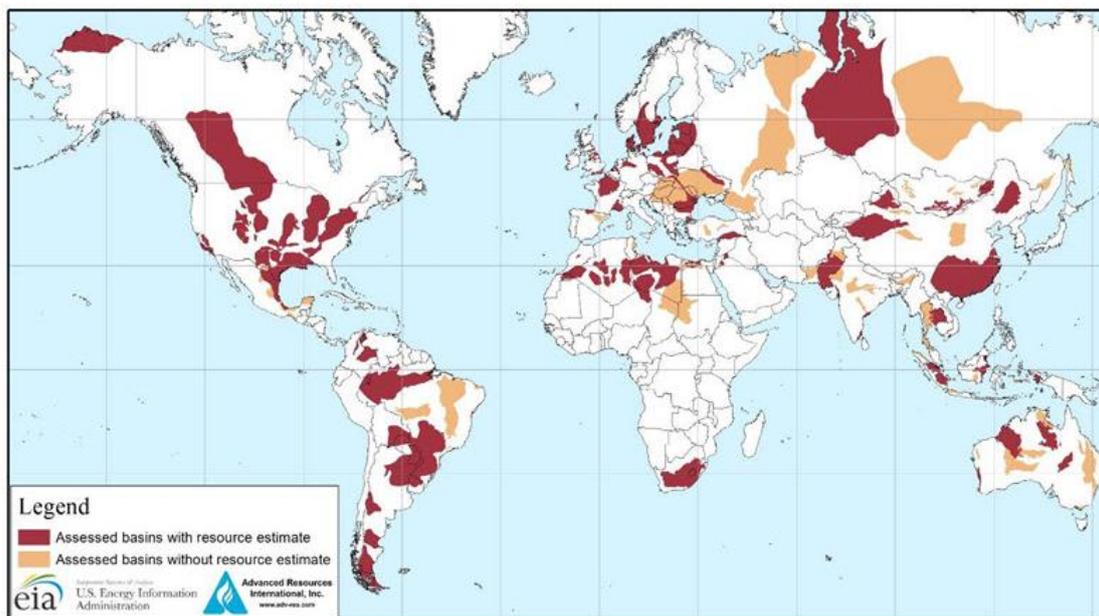
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## Introduction

Unconventional natural gas extraction has captured the attention of global energy and natural resources managers, policy makers, environmental advocates, and the general public. Shale gas is a type of natural gas that is formed in the fine-grained formations. According to U.S. Energy Information Administration's report, the global shale gas resource base is considered to be significant on almost every continent (U.S. EPA, 2013; Figure 1). The initial estimate of technically recoverable resources of shale gas in the 41 countries is collectively 7,299 trillion cubic feet (U.S.EIA, 2013; Accenture, 2012). United States and Canada are in the midst of a remarkable natural gas boom due to the combination of the two technological advances: hydraulic fracturing and horizontal drilling. Because of its extremely low permeability, shale must be fractured for entrapped gas to flow for subsequent collection. The combination of hydraulic fracturing, or fracking, and horizontal drilling techniques is expected to increase world technically recoverable gas reserves by 47% according to the U.S. EIA's study (U.S.EIA, 2013).

**Figure1.** Global Shale Gas Resources

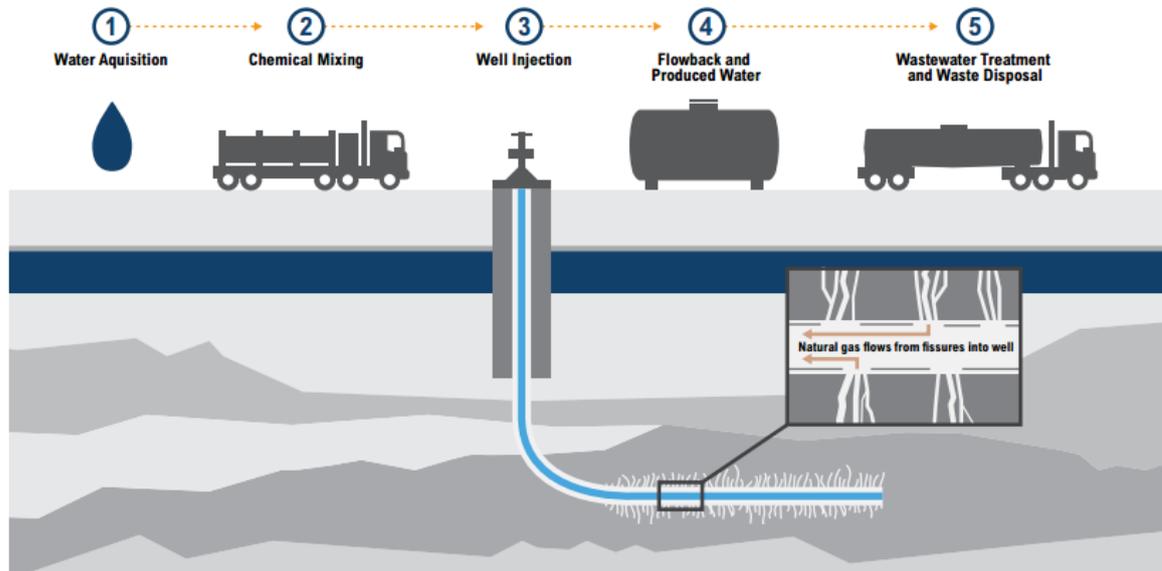


*Source: U.S Energy Information Administration*

Profitably viable gas production from shale is achieved by vertical and horizontal drilling followed by hydraulic fracturing. In contrast to conventional wells, a single horizontal well can greatly increase the extent of contact between the shale formation and the wellbore (Gregory, 2011). The hydraulic fracturing process uses a mixture of chemicals, sand (or proppant) and often large volume of water under high pressure to create interconnected fractures that increase the formation's permeability and significantly increase the flow rates of

gas into the well. One of the most widely concerned issues in shale gas production is water management including water use and wastewater disposal (Figure 2).

**Figure 2.** Hydraulic Fracturing Water Cycle



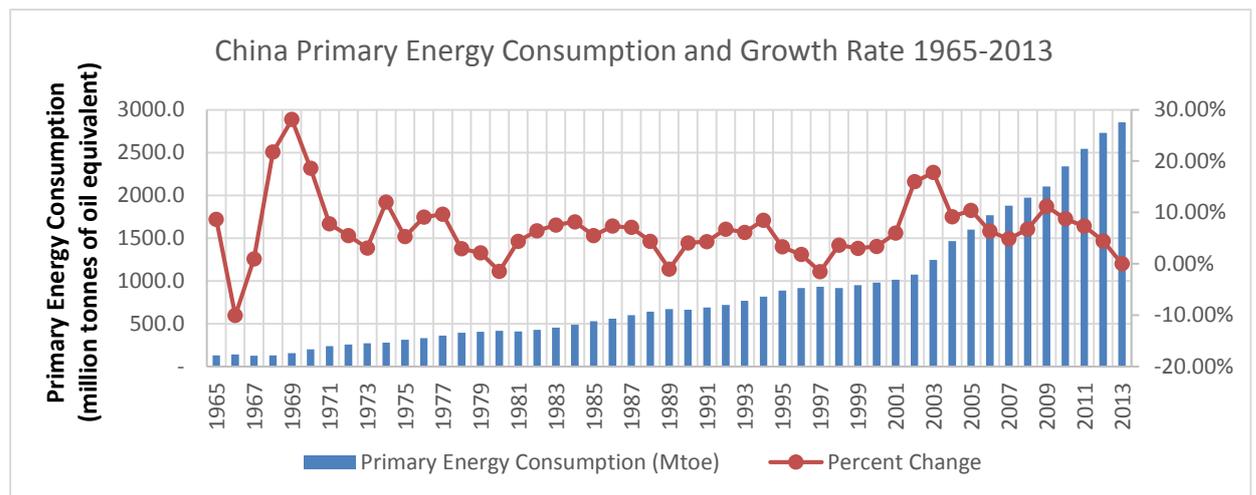
*Source: WRI's adapted version of the hydraulic fracturing water cycle from U.S. EPA*

As a water-intensive process, water uses for hydraulic fracturing per unconventional well requires a range of 8,000 to 100,000 cubic meter of water, depending on the geological features of the formation (Vengosh et al., 2014). Despite of increasing use of reused or recycled water, freshwater is still the first choice to be used for hydraulic fracturing processes. The need for freshwater is a growing concern, especially in areas of severe water scarcity and competition from different users. When fracking process is complete, the mixture of fracturing fluid and formation water will flow back to the surface over a few days to week time period. The chemical composition of the flowback water the mixing ratios between the injected water and the naturally occurring brines within the shale formation as well as the nature of the brines within formation (Vengosh et al., 2014). High concentrations of salts, metals, oils, and soluble organic compounds are present in the flowback and produced water. Therefore, flowback and produced water management associated with unconventional oil and gas extraction has become a growing environmental and health concern. Several treatment technologies and management options have been applied by shale gas operators throughout the U.S.. Some of the common wastewater management practices include disposal through underground injection wells or surface storage tanks as well as treatment through wastewater treatment plants. However, issues of induced seismicity from high volume of injected water,

contamination of streams and groundwater from spills and inadequate treatment and disposal have still resulted in a significant public concern.

China, a country with rapid economic growth, has generated a GDP with an average annual growth of 10.51% over the past ten years (World Bank, 2014). This rapid economic development has driven the country's higher energy demand. Over the last decade, the energy demand of China has continued to grow at different phase (Figure 3), and since 2009 China became the world's largest energy producer and consumer. Due to its abundant natural gas resources and strong reliance on coal consumption, the country is actively moving to developing natural gas in order to reduce the heavy use of coal and the related air and water pollution (ODI, 2015). Natural gas has unique advantages over other types of fossil fuel in terms of energy efficiency, clean combustion, and reduction of greenhouse gas emission. Since 2000 as China's energy demand has rapidly increased, natural gas consumption has grown six-fold in China (ODI, 2015).

Figure 3. China Historical Primary Energy Consumption and Growth Rate\*



Source: U.S. Energy Information Administration

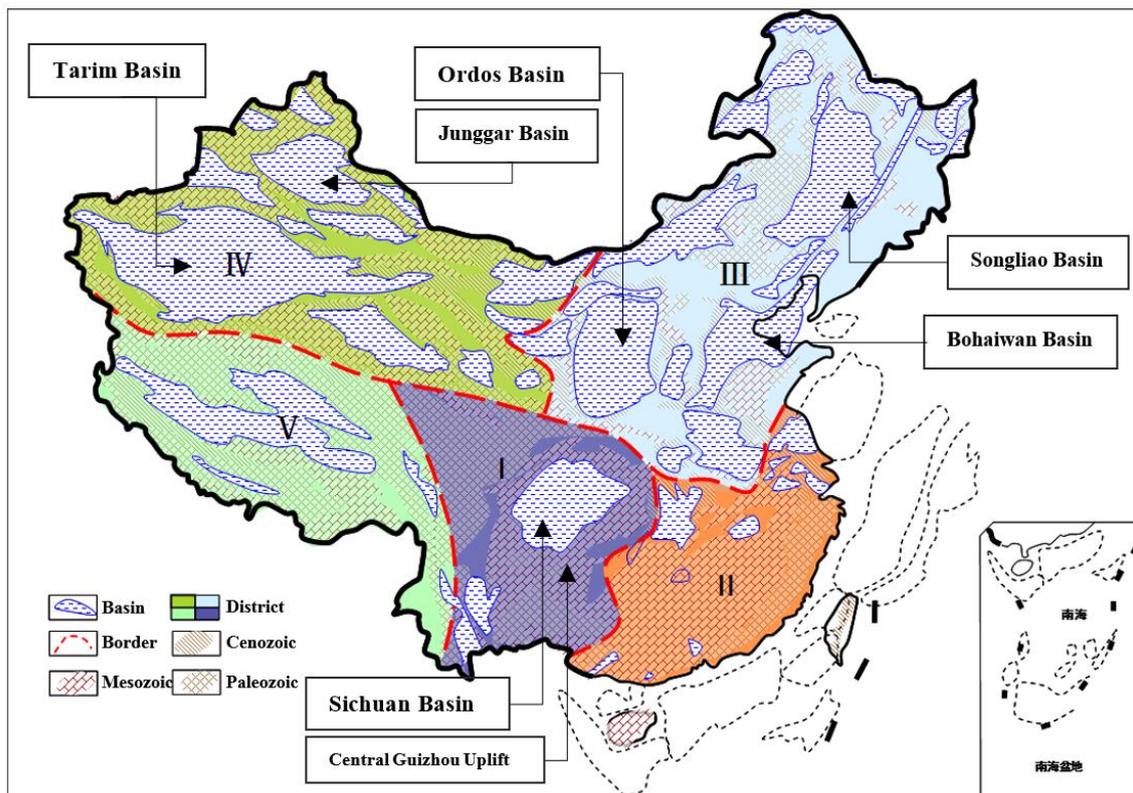
\*Growth Rate: the amount of increase in primary energy consumption in that particular year compared to previous year

The U.S. revolution of shale gas exploration and production has had a profound implication on the globe's unconventional resources development. According to U.S. EIA's estimates, China possesses the most abundant technically recoverable shale gas resources (1,115 trillion cubic feet) worldwide (U.S. EIA, 2013). China's 12th Five-Year Plan (2011-2015) places great emphasis on the exploration and production of unconventional energy sources.

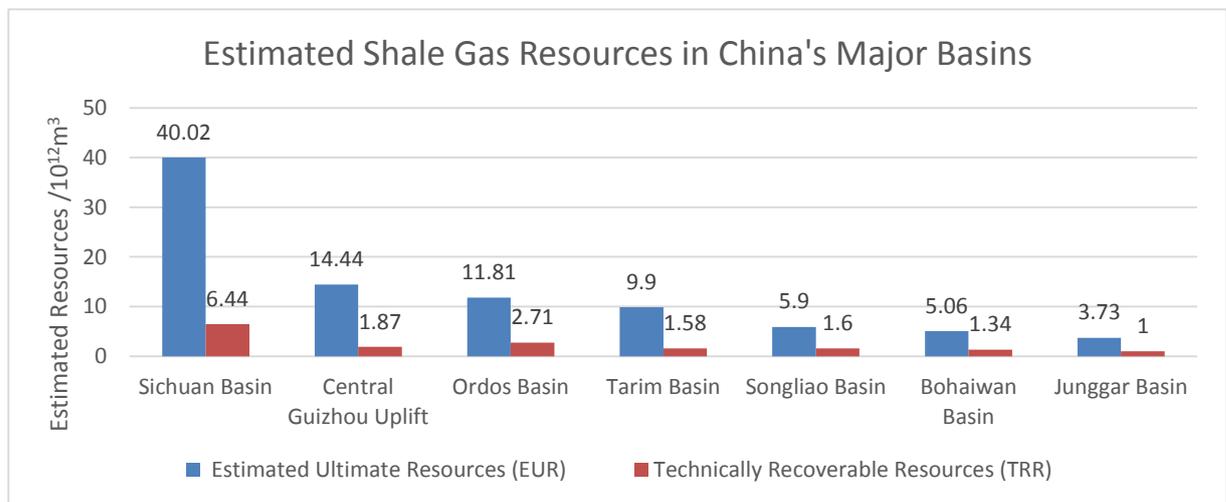
Following the 12<sup>th</sup> Five-Year Plan, the country has recently initiated the National Shale Gas Development Plan (2012), announcing its target to increase shale gas production to 6.5 billion cubic meters (bcm) per year by 2015 and 60-100 bcm by 2020 (Kolb, 2013). In the 13<sup>th</sup> Five-Year Plan (2016-2020), China's shale gas production goal is adjusted to 30 bcm by 2020. In

response to the nationwide development plan, the Ministry of Land and Resources of China has divided the territory into five shale resources districts and further assessed their exploration potential (Figure 4). According to the ministry's 2012 study, Sichuan Basin has the highest Estimated Ultimate Recovery (EUR) and Technically Recoverable Resources (TRR) of shale gas, followed by Central Guizhou Uplift, Ordos Basin and Tarim Basin (Figure 5). In addition, domestic natural gas companies have explored and drilled over 100 wells through strategic alliances with foreign operators during the past few years.

**Figure 4.** Major Shale Gas Exploration Districts and Basins in China



*Figure 5. (Data source: The Ministry of Land and Resources of China)*



As one of the notable cornerstones of shale gas development, the hydraulic fracturing technology is also related to various environmental issues among which is the limited freshwater resources. Although water required for shale gas production is relatively low as compared to coal combustion (Rogers, 2011), the nexus between shale gas development and water availability is particularly important for water-stressed countries like China. According to a recent report developed by World Resources Institute, over 60% of the country's shale gas resources are in areas associated with high to extremely high level of water stress (WRI, 2014). Sichuan Basin is one of the most promising areas of shale gas exploration in China. With an ambitious shale gas production goal, the area has actively undergone shale gas exploration and production activities. Although water is relatively abundant in the southern China, extensive agricultural and industrial activities in Sichuan Basin has resulted in high demand of water, and the spatial and seasonal variations in hydrological conditions have made it far more challenging to meet freshwater demand. Using data and information of regional shale gas development, water resources, water demand and supply, this thesis aims to evaluate the following critical topics:

- Estimate domestic and total water withdrawals in Sichuan Province and Chongqing Municipality and projected for the next 15 years;
- Quantify the current and projected baseline water stress situation in Sichuan Province and Chongqing Municipality for the next 15 years;
- Assess the expected water usage for shale gas development through projections of shale gas well development

In addition to examining water availability and shale resource development from a regional perspective, the result of this thesis is expected to inform energy and natural resources managers of potential risks associated with water availability, and identify the areas that are most at risk in the context of shale gas exploration.

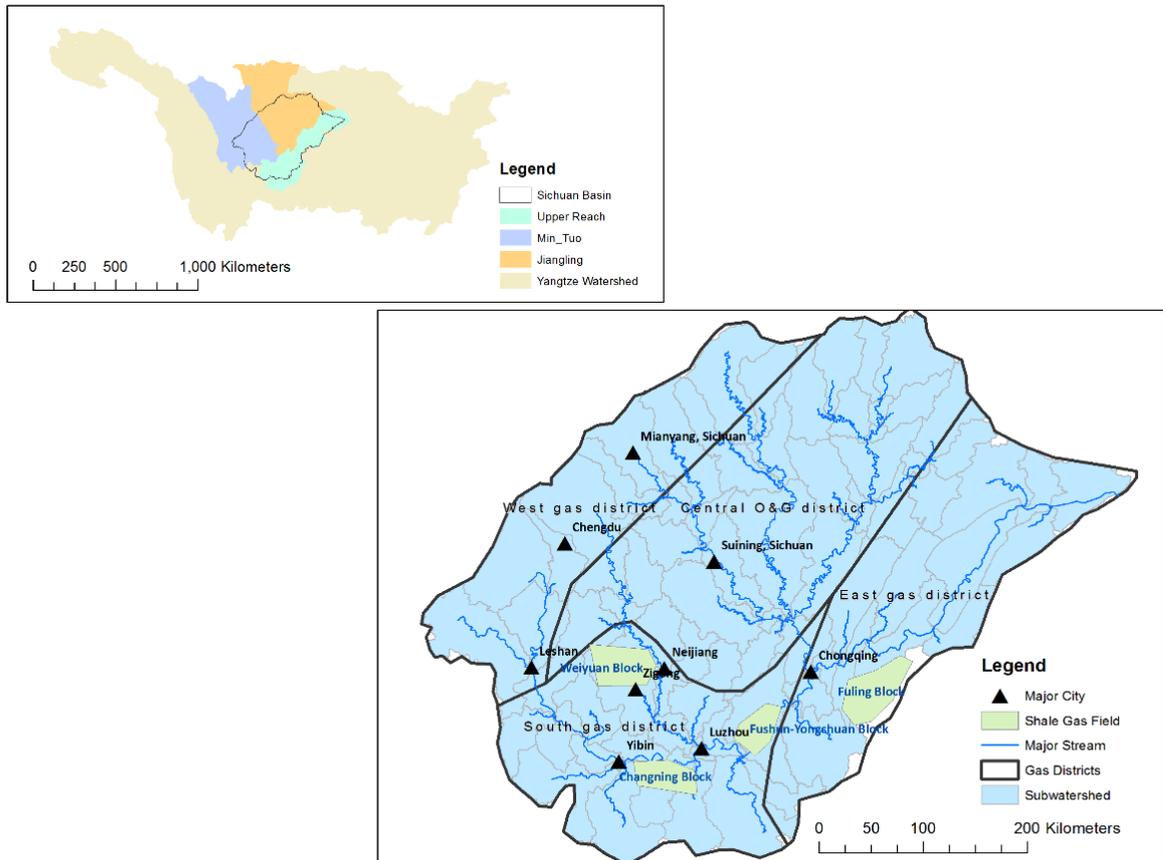
## **Methods and Materials**

### **Background of the Study Area**

Sichuan Basin is located in the southwest China, including east part of Sichuan Province and the entire Chongqing Municipality. With a total area of approximately 260,000 km<sup>2</sup>, Sichuan Basin is mainly framed by mountains ranges and hills (CNPC, 2012). Sichuan Basin's purple soil makes it one of the most fertile agricultural lands in China. In addition to agriculture, the Basin is one of the earliest bases for natural gas industry in China, with approximately 113 conventional gas fields being discovered and developed. Current production of conventional

natural gas from sandstone and carbonate rock occurs mainly in the Triassic Xujiahe and Feixiangguan formations (U.S. EIA, 2013). Recent estimates of shale gas resource have made Sichuan Basin a current focus of shale exploration in the country. As shown in Figure 6, the Weiyuan, Changning, Fushan-Yongchuan, and Fuling Shale Blocks are four key areas for current shale gas exploration in Sichuan Basin.

**Figure 6.** Geographic Location of Sichuan Basin and Four Key Shale Blocks



Located at the upper reach of the Yangtze River (Figure 6), Sichuan Basin has a southern sub-tropics warm and humid climate (Zhang et al., 2010). 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. Although water is generally more abundant in the southern China, Sichuan Basin has experienced multiple water stresses over the past few decades. A 50-year period of assessment showed a significant decrease in annual precipitation and stronger seasonal variations in the Sichuan Basin (Xu and Zhang, 2006). Another study also observed a significant decrease in precipitation during 1961-2000 in 7 weather stations located in Sichuan Basin, and further indicated the association with a serious drought during 2006 in the region (Xu et al., 2008). The same study also concluded that the changes in seasonal and monthly river discharges of tributaries in Sichuan Basin were deduced by human

activities such as irrigation and reservoir construction. A rainwater allocation study also revealed the significant seasonality of precipitation at the Daba village in Rongchang county of Chongqing Municipality (Zhang et al., 2010). In addition to the uncertainty in precipitation, uneven distribution of water resources and subsequent freshwater competition are also repeatedly reported in this region (Wang et al., 2012). As one of the most heavily populated and intensively industrialized areas in China, the Sichuan Basin has also faced serious pollution problems. Rapid economic and population growth have led to heavy waste discharge and severe air pollution. A study on groundwater quality showed that the acid depositions from industrial emission indirectly degrade the quality of groundwater and surface-water, worsening the region's freshwater resources (Li et al., 2005).

### **Domestic Water Demand Projection**

The data presented in this study is based on the following sources:

- Sichuan's population: 1991-2014 population of counties (Sichuan Statistical Yearbook 1991-2014)
- Chongqing's population: 2000-2014 population of districts (Chongqing Statistical Yearbook 2000-2014)
- Urban domestic water withdrawal (person<sup>-1</sup>): 2001-2013 watershed-wide data not including public water uses (Yangtze River Watershed & Southwest Rivers: Water Resources Bulletin, 2001-2013)
- Rural domestic water withdrawal (person<sup>-1</sup>): 2001-2013 watershed-wide data not including water demand for livestock (Yangtze River Watershed & Southwest Rivers: Water Resources Bulletin, 2001-2013)
- Domestic water withdrawal (10<sup>8</sup> m<sup>3</sup>): 2001-2013 Sichuan and Chongqing domestic water uses (Yangtze River Watershed & Southwest Rivers: Water Resources Bulletin, 2001-2013)

Domestic water demand includes all households water uses. This water use sector covers both within and immediately outside the confines of a residence, from urban to rural residential water uses (Liu et al., 2003). In our study region, domestic water use also covers use in government offices, public parks, and other withdrawals related to public supply uses (Zhang and Brown, 2005). Domestic water use is an important component of the total water consumption in Sichuan Province and Chongqing Municipality with a portion of 13.6% and 18.6% of their total water uses (CWRC, 2015), respectively. The current trends show that, between 1998 and 2013, water withdrawals from domestic sector has increased by 60% (CWRC, 2015), which is in part due to rapid urbanization and population growth.

Because domestic water use constitutes an important component of the total municipal withdrawals in many regions, multiple methods have been developed to accurately project

domestic water demand. Curve fitting and extrapolation were widely used for regional water managers to project variables such as total population, population served by public supply, and water demand. This mathematical methods are based on the fitting of a curve to historical population of water-demand data and then extending this curve to forecast at future values. In his 1990 book, Klostermann concluded that six of the most widely used curves of this type are: linear, geometric, parabolic, modified exponential, Gompertz, and logistic (Klostermann, 1990). This thesis, however, intends to estimate water demand based on urban and rural population growth at county level. Curves used to fit to the historical population data are various across counties (i.e. a logistic function fits to Chengdu's urban population growth; while a linear function fits to Mianyang's rural population trend). In addition, the fitting process can be easily affected by outliers and other variations in the measurements.

The multivariate model, such as IWR-MAIN (Institute for Water Resources – Municipal and Industrial Needs), is based on observed relationship between water use and causal factors of urban water demand. Despite its ability to accurately predict water use under a wide range of circumstances, models such as IWR-MAIN are input data-intensive and almost only suitable for application in the United States (Liu et al. 2003). New models such as WDF-ANN (Water Demand Forecast using Artificial Neural Network) adopt the technology of artificial neural network and the techniques of econometrics. Although the modeling approach appears promising and requires less input data, the ANN approach still requires high-resolution water consumption data and socio-economic data such as water prices and household income. Furthermore, the architecture of the ANN to capture the relationship is still in need of optimization.

For state-, county-, and municipal-level water resources planning purposes, population projections have been achieved by employing a Microsoft Excel FORECAST function, a least squares trending/regression function (PA DEP, 2008). In comparison to real data, the FORECAST function projection produced acceptable results (PA DEP, 2008). In this study, we applied the FORECAST function for domestic water use projection for the following considerations:

- (1) The FORECAST function only requires county or municipal population figures for respective years to perform projections; this allows us to perform basic projections when data needed for more sophisticated models are not readily available;
- (2) After a close inspection of population trends of our study area, approximately 90% of Sichuan's counties and Chongqing's districts have linear increase/decrease in the urban or rural population (with  $R^2 > 0.80$ ), and therefore the FORECAST function is expected to provide reasonable results;
- (3) The FORECAST function provides an efficient approach for estimating water demand; this study intends to introduce this projection approach to regional water manager.

A study (Brown et al., 2012) focused on U.S. freshwater withdrawal used water use data recorded by the U.S. Geological Survey (USGS) for the period 1960-1995 and projected withdrawals for the five categories of water use: (1) livestock, (2) domestic and public, (3) industrial and commercial, (4) thermoelectric power, and (5) irrigation (Brown, 2012). In this study, future domestic and public withdrawals were evaluated as:

$$\text{Domestic and public withdrawals} = \text{population} * (\text{domestic withdrawal person}^{-1})$$

This projection hinges on domestic water use per capita. The per capita domestic water withdrawal can effectively capture attributable changes such as the increase in the use of water-amenities (i.e. washing machines, swimming pool, and lawn sprinkler systems), adopting conservation measures, the decrease in average household size, and the completion of conversion of efficient plumbing system (Brown, 2000). By investigating the collection of our data, the average urban domestic withdrawal is 153 Liter/person/day, while rural residents consume on average 73 Liter/person/day of water. Therefore, we separated urban and rural population for total domestic withdrawals and modified the calculation method as follows:

$$\begin{aligned} \text{Domestic withdrawals} = & \text{urban population} * (\text{urban water withdrawal persons}^{-1}) \\ & + \text{rural population} * (\text{rural water withdrawal person}^{-1}) \end{aligned}$$

The projected urban/rural domestic withdrawal per capita is based on available watershed-scale data from 2001-2013 by applying Holt-Winters Exponential Smoothing Method using R. In general, exponential smoothing models deal with the level of a time series as well as its trend and seasonal variation (Billings, 2008). Holt-Winters method is a moving average exponential smoothing model with three parameters (Billings, 2008) – a level, a trend, and a seasonal component. This method has been widely used for domestic water demand extrapolations from the historical series due to its ability to capture multiple variables. To perform forecasting using simple exponential smoothing method in R, a simple exponential smoothing predictive model using “HoltWinters()” function in R can be performed to fit the historical data. The HoltWinters() function requires the input of parameters alpha (level), beta (trend), and gamma (seasonality). After fitting the historical data, “forecast.HoltWinters()” function in R forecast package can be used to perform extrapolation to the desired time period. A script example in R is shown below:

```
> seriesfit <- HoltWinters (series, alpha=x, beta =y, gamma=z)
> seriesforecast <- forecast.HoltWinters (seriesfit, h=18)
```

Where x,y,z are all numbers, h is the time period for projections (in this case, we need a 18-years projection from 2013 to 2030).

Since the per capita domestic water demand is on the annual basis, we left the  $\gamma = \text{FALSE}$  to exclude the seasonality consideration. The “forecast errors” or “residuals” are calculated for the time period covered by our original time series to compare across predictions of different selections of alpha and beta parameters. The prediction model that had the forecast errors normally distributed with mean zero with constant variance over time was identified as the best-forecasted model for our data.

### **Total Water Demand Projection**

The data presented in this study is based on the following sources:

- Domestic, agricultural, industrial and environmental water withdrawal ( $10^8 \text{ m}^3$ ): 2001-2013 Sichuan and Chongqing domestic water uses (Yangtze River Watershed & Southwest Rivers: Water Resources Bulletin, 2001-2013)

Total water use in regional water resources bulletin is documented as the following categories:

- Domestic and public
- Industrial and commercial
- Agricultural (livestock and irrigation)
- Environmental

Due to the insufficiency of relevant data of each category, the total water demand of Sichuan and Chongqing for the next 15 years was estimated based on the assumption that domestic water will continue to account for a fixed percentage of the total water uses. By investigating in historical data, we averaged the percentages of domestic water in total water demand, and further used these percentages to estimate total water demand for each county.

### **Water Stress Calculation and Visualization**

The data presented in this study is based on the following sources:

- Sichuan Water Resources ( $10^8 \text{ m}^3$ ) (Sichuan Province Water Resources Bulletin, 2005)
- Chongqing Water Resources ( $10^8 \text{ m}^3$ ) (Chongqing Province Water Resources Bulletin, 2001-2013)

In order to estimate water availability, the baseline water stress index was calculated to quantify the water stress across administrative regions:

$$\text{Water Stress Index (\%)} = \frac{\text{Total Water Demand (million cubic meters)}}{\text{Average Total Water Resources (million cubic meters)}} \times 100\%$$

The total water resources are obtained from regional water resources bulletins. Chongqing Municipality has continuous records of regional water resources available for public reviews, while Sichuan Province only publicized its 2005 Water Resources Bulletin. Although total water resources may vary due to climatic variability, the average total water resources can still reflect the total available water for Chongqing's regional development. For Sichuan Province, on the other hand, the use of a single-year (2005) water resources data can be less representative. However, it can still be used for our analyses because 2005 data can generally represent the normal climatic condition based on our review on historical dry and wet years.

Therefore, the water stress index was calculated by normalizing the total water withdrawals. In order to compare the water stress indices across sub-regions, we further visualized the water stress indices using ArcGIS as a tool.

### **Shale Gas Water Use Projection**

The data presented in this study is based on the following sources:

- National shale gas development goal: original and modified shale gas production goal in 2015 and 2020 (“Shale Gas 12<sup>th</sup> Five-Year Plan”, 2012; “13<sup>th</sup> Five-Year Plan”, 2015)
- Initial production and decline rates of shale gas wells: average shale gas well decline profile in Sichuan Basin (Liu et al., 2014)
- Water use per shale gas well: low, average, high water use per shale gas well based on data reported for water use for shale gas in the U.S. (Rahm and Riha, 2014; Vengosh et al., 2014)
- Water recycling scenario: water consumption under low, average, high impact scenarios based on the U.S. experience (JRC, 2013)

The projection of water use for shale gas production is based on the number of wells drilled per year (rate of exploitation) and water usage for hydraulic fracturing per well. The rate of exploitation depends on target production volumes, decline characteristics of shale gas well production, and the anticipated shale gas well lifespan.

As of May 2014, 184 wells have been drilled for shale gas production in China, resulting in annual production of 1.4 bcm, according to China National Energy Administration (NEA). Most shale gas drilling has been conducted in Sichuan Basin, but there is only limited available information at present on existing well counts or the exact amount of shale gas production in the region. Therefore, we assumed that 50% of the country's shale gas wells (92 production wells) have been developed in Sichuan Basin. Target production volume of Sichuan Basin is key to the water usage projection. However, different levels of production goals have been set by local and central governments. Besides, divergent views about China's shale gas development are reflected in the published literature. The collection of production

goals and projections are summarized in Table 1. Although we found widely divergent views about the medium and long term prospects for shale gas production, we use the most recent target production volumes established by the central governments – 6.5 bcm by 2015 and 30 bcm by 2020 – to estimate the rate of exploitation and the subsequent water use.

**Table 1.** Summary of Target Production Volume and Projections from Multiple Sources

Stakeholder	Document	Level	Target production volume or projection
National Energy Administration (NEA)	Shale Gas Industry Policy (2013) <sup>1</sup> , National Shale Gas Development Plan, the 12th Five-Year Plan (2011-2015), the 13 <sup>th</sup> Five-Year Plan (2016-2020)	National	6.5 bcm (per year) by 2015 60-100 bcm by 2020 30 bcm by 2020 (most updated target)
Sichuan Development and Reform Commission, Sichuan Energy Administration	Sichuan Shale Gas E&P 2013 Work Plan	Provincial	1 bcm of production from Changning Block
Chongqing Fuling Government	Fuling Shale Gas Development and Usage Implementation Plan	Local	3.2 bcm by 2015
Standard Chartered	China Shale Gas: Potential Unearthed (Suttikulpanish et al., 2013)	National	60 bcm by 2020
MIT Researchers	Shale Gas in China: Can We Expect a Revolution? (Paltsev et al., 2013)	National	140-200 bcm/year in 2030 700-900 bcm/year in 2050
International Energy Agency	2014 Medium-Term Gas Market Report	Global	6.5 bcm by 2015 30 bcm by 2020
Harvard University's Belfer Center, Rice University's Baker Institute Center for Energy Studies	The Geopolitics of Natural Gas – Charting China's Natural Gas Future (Houser and Bao, 2013)	National	2015 and 2020 productions goals are both difficult to be met
Oxford Institute for Energy Studies	Will There be a Shale Gas Revolution? (Gao, 2012)	National	10 bcm/year in 2020
Research Institute of Petroleum Exploration & Development	Experience from Global Shale Gas Development and the Long-term Overview of Development in China (Dong et al., 2012)	National	10 bcm/year in 2020 60 bcm/year in 2030
BP	Energy Outlook 2035 (BP,2014)		60 bcm/year in 2030

<sup>1</sup> The Chinese Shale Gas Industry Policy is a collective effort by multiple ministries and agencies. The National Development and Reform Commission (NDRC) shapes overall policy and regulates natural gas prices; the National Energy Administration (NEA) establishes shale gas production targets; the Ministry of Land and Resources (MLR) controls mineral rights and operates the bid rounds; the Ministry of Finance (MOF) administers the shale gas production subsidy; the Ministry of Science and Technology (MOST) provides scientific funding for R&D in shale gas technologies; the Ministry of Environmental Protection (MEP) establishes environmental regulations to protect air and water quality.

Another key fundamental to our projection is determining average lifespan of Sichuan Basin shale gas wells. A study reported that the average well lifespan is 7.5 years in the Barnett Shale (Berman 2009). A study of water pollution risk associated with gas extraction from Marcellus Shale assumed a short 10-year well lifespan for assessing the well leak risk (Rozell and Reaven, 2011). Another study focused on shale gas development in Poland and Germany used an anticipated 10-year lifespan to assess land and water use scenarios (JRC, 2013). Therefore, we also developed an assumption that the longevity of extraction wells is 10-year in Sichuan Basin. In addition, the decline rate of production should also be considered in the process of production projection. Output for a typical shale gas well drops off sharply over the first three years of average well life. A study completed by Post Carbon Institute described the decline rates over the lifespan of shale gas production wells in major U.S. shale gas plays, illustrating a common sharp decline over the first three years of average well life (Hughes, 2014). Liu et al. compared fundamental geological parameters from Longmaxi and Qiongzhusi formations in Sichuan Basin, determining multiple development indices including initial production and decline profile for shale gas wells. These indices were then analyzed for our projection on shale gas well development in Sichuan Basin.

A review of multiple literature sources indicates considerable variability in water requirements for shale gas production (Rahm and Riha, 2014; DGIP, 2011; Vengosh et al., 2014). Wellbore depth, length of horizontal bore, and the geology of shale formation (i.e. substrate permeability) can lead to the variation in water usage. Table 2 summarized water withdrawal characteristic of prominent U.S. shale gas plays.

**Table 2.** Water Use Per Shale Gas Well in Different Shale Gas Basins in the U.S.

Basin	Water use per well (m <sup>3</sup> )	Source
Marcellus Shale	11,500 – 19,000	Lutz et al., 2013
	14,000 – 17,000	Tinto, 2013
Barnett Shale	10,000 (10,600) – 13,000	Nicot and Scanlon, 2012; Nicot et al., 2012
Haynesville Shale	21,500 (14,000 – 30,000)	Nicot and Scanlon, 2012; Nicot et al. 2012

Because of the wide variation in reported water requirements for fracturing, we assume water use of 11,000 m<sup>3</sup> of freshwater per hydraulic fracturing activity for our low-impact scenario, and 17,000 m<sup>3</sup> and 22,000 m<sup>3</sup> of water for our average case and high-impact scenarios.

Upon completion of the drilling process, shale gas wells may be repeatedly hydraulically fractured in order to maximize productivity. A study reported that shale gas wells are rarely refractured (Zoback et al. 2010), while other researchers claim that wells may be refractured for different frequency (Berman, 2009; SGEIS, 2011; Ineson, 2008). The Joint Research Centre of European Commission developed three scenarios for hydraulic fracturing frequency

over an anticipated 10-years lifespan (JRC, 2013), and we adopted these hypothetical scenarios for our analyses. After the completion of hydraulic fracturing, a portion of injected fluid will return to the surface (“flowback” water). In some shale plays, flowback water can potentially be recycled or reused, depending on its quality and available treatment technology (Acharya et al. 2011). Therefore, in order to assess the consumption of water as being the amount of water “used up” during hydraulic fracturing process, we further assigned three recycling scenarios (5%, 35%, and 70%) for our analyses. The assumptions with respect to water usage for each hypothetical scenario are summarized in Table 3.

**Table 3.** Water Impact Scenarios Used in this Study

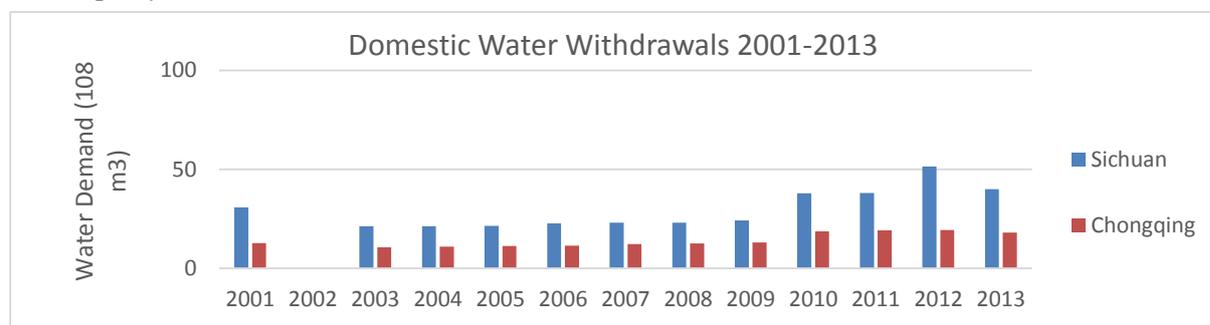
Scenario	Frequency of fracking per 10 years	Recycling scenario (%)	Water use per well (m <sup>3</sup> )
Low	1	70%	11,000
Average	2	35%	17,000
High	5	5%	22,000

## Results and Discussion

### Baseline Water Withdrawal: Review and Projection

During 2001 to 2013, a rise in domestic and public withdrawal was observed in both Sichuan Province and Chongqing Municipality (Figure 7). The domestic usage generally accounts for 10-20% of the total water withdrawals. The increasing water demand from domestic users was primarily caused by population growth and rapid expansion of the urban areas. Urbanization has led to significant lifestyle changes of local residents, resulting in increasing use of water-intensive amenities such as dishwashers and swimming pools.

**Figure 7.** 2001-2013 Domestic Water Withdrawals in Sichuan Province and Chongqing Municipality

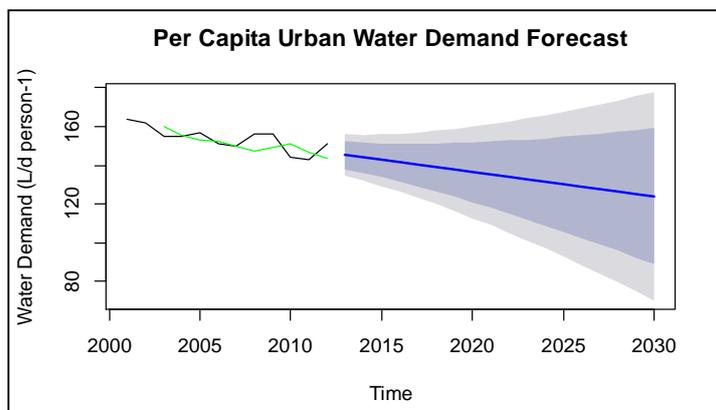


Source: Yangtze River Watershed & Southwest River Water Resources Bulletin 2001-2013

\*2002 data is not available

Domestic water use per capita has shown different trends between urban and rural communities over last decade. Between 2001 and 2013, the per capita urban water withdrawal slightly dropped from 164 liter/day to 151 liter/day in the Yangtze River watershed. This change may be the result of conservation measures and the completion of more efficient plumbing. However, a consistent growth in per capita rural water withdrawals was observed since 2001. Many factors can possibly contribute to the increase in water use per capita in rural communities, including the conversion of older or rural households, an increase in lawn and garden watering, and the use of water-using amenities. Although it includes our study area, Yangtze River watershed covers a much larger area, indicating that the domestic water withdrawal information might not perfectly reflect the water use efficiency of Sichuan and Chongqing regions. However, we still performed projections based on this data set because Yangtze River watershed has the most consistent and available records of water use efficiency across all water use sectors. As shown in Figure 8 and 9, Holt-Winters smoothing method was performed to fit historical data and generate future domestic withdrawals scenarios for urban and rural residential water uses. Based on our projections, the per capita urban water demand will continue to decrease, while per capita rural water demand will increase steadily, mainly due to the increasing use of water-intensive amenities.

**Figure 8.** Per Capita Urban Water Demand Forecast



**Figure 9.** Per Capita Rural Water Demand Forecast

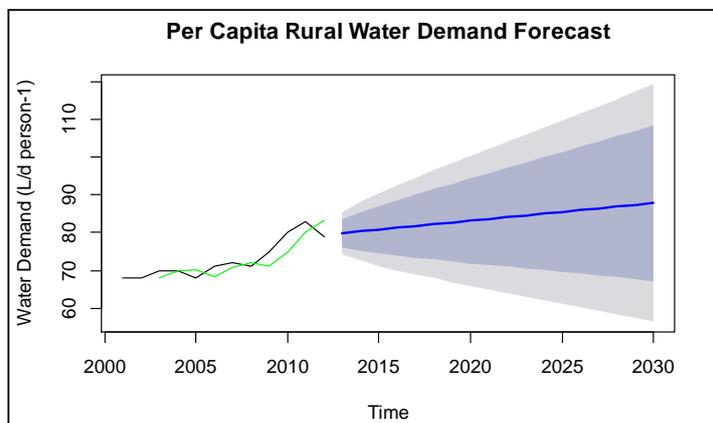
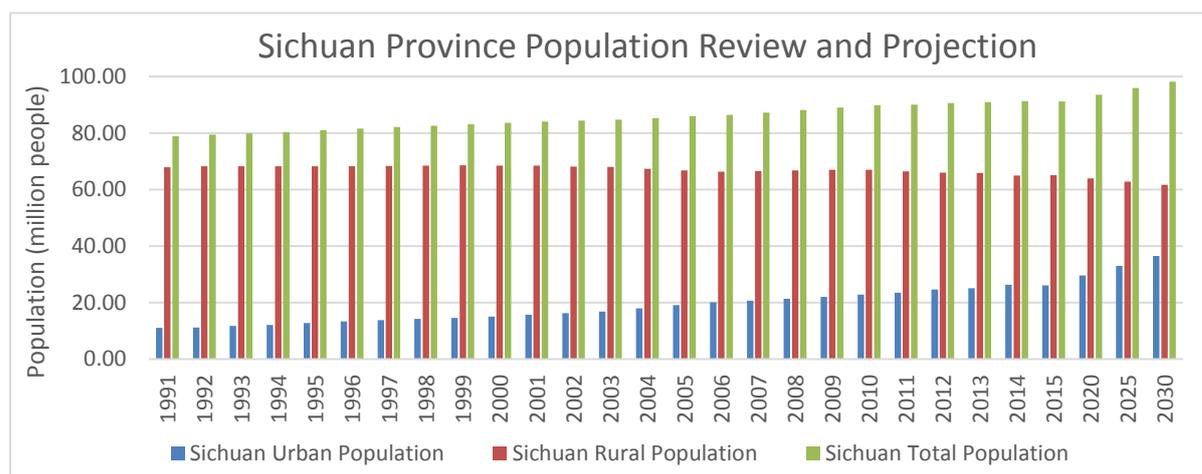


Figure 10 presents the historical records and estimates of urban, rural, and total population growth in Sichuan Province. Over the past 15 years, Sichuan’s urban population grew at an average rate of 3.87 percent, while rural population generally declined. For the combined population, Sichuan’s total population grew from 78.93 to 91.33 million between 1991 and 2014. This may in part due to generally improved access to health services. According to our projection, Sichuan’s total population will continue to grow for the next 15 years, reaching at 98.22 million in 2030. Figure 10 shows that Sichuan was and will continue to be a rural-dominant province until 2030. After a close inspection on county-level data, we found that rural population of areas such as Yibin and Panzhihua Cities continued to rise since early 90’. Although rural population will remain stable in the future, urbanization is anticipated to significantly contribute to the province’s total population. Specifically, we found that more developed and highly industrialized areas such as Chengdu City and Nanchong City had higher growth rate of urban population than less developed regions.

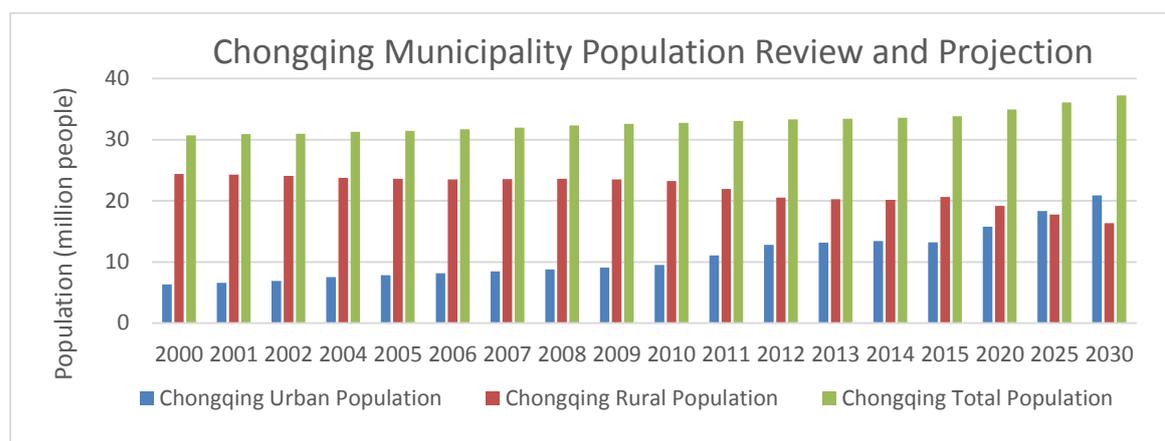
**Figure 10.** Sichuan Province Population Review and Projection



In contrast, Chongqing Municipality had a relatively stable total population between 2000 and 2014<sup>2</sup> (Figure 11). This, in part, may be caused by rural-to-urban migration in the regions (Qin, 2010). While rural population generally declined steadily over the last decade, urban population increased more than twofold from 2000 to 2014. Increased urban population in areas such as Yubei District and Jiangjin City had significantly contributed to the overall urban population growth. Our projection estimates show that Chongqing’s urban population will grow to nearly 20.9 million in 2030, continuing its urban conversion and surpassing rural population by 2025.

<sup>2</sup> Chongqing Statistical Yearbook did not separate urban population from rural population since 2000. Therefore, we did not include pre-2000 population data for urban and rural population projections.

**Figure 11.** Chongqing Municipality Population Review and Population



Based on the population projections, domestic water withdrawals from urban and rural sectors were calculated using Brown (2000) method. Table 4 summarizes the projected domestic water use of Sichuan Province and Chongqing Municipality from 2015 to 2030.

**Table 4.** Summary of Domestic Water Withdrawals Projection of Sichuan Province and Chongqing Municipality

		Population (million)		Domestic water use per capita (L/day)*		Domestic water withdrawals (bcm/year)		
		Urban	Rural	Urban	Rural	Urban**	Rural***	Total****
Sichuan	2015	26.14	65.10	142.66	80.83	1.36	1.92	<b>3.28</b>
	2020	29.59	63.98	136.43	83.17	1.47	1.94	<b>3.42</b>
	2025	33.03	62.86	130.20	85.50	1.57	1.96	<b>3.53</b>
	2030	36.48	61.74	123.97	87.83	1.65	1.98	<b>3.63</b>
Chongqing	2015	13.21	20.63	142.66	80.83	0.69	0.61	<b>1.30</b>
	2020	15.77	19.17	136.43	83.17	0.79	0.58	<b>1.37</b>
	2025	18.33	17.74	130.20	85.50	0.87	0.55	<b>1.42</b>
	2030	20.89	16.34	123.97	87.83	0.95	0.52	<b>1.47</b>

\*Projected values using data from Changjiang and Southwest Rivers: Water Resources Bulletin (2001-2013)

\*\*Urban domestic water withdrawals = Urban population \* Urban water use per capita

\*\*\* Rural domestic water withdrawals = Rural population \* Rural water use per capita

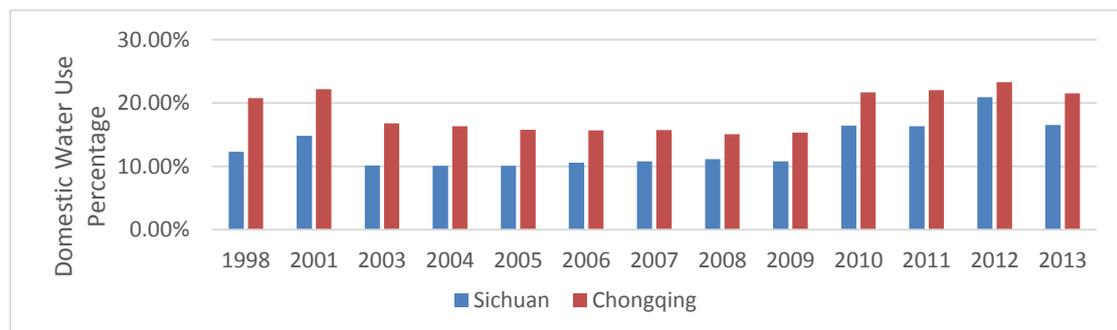
\*\*\*\* Total domestic water withdrawals = Urban water withdrawals + Rural water withdrawals

As presented in Table 4, even with the declined per capita water use, the overall urban water withdrawal is projected to increase in both study areas – from 1.36 to 1.65 bcm/year in Sichuan and from 0.69 to 0.95 bcm/year in Chongqing – due to rapid urban population growth. Although rural population is anticipated to decline for the next 15 years, rural domestic water withdrawal of Sichuan Province will still increase from 2015 to 2030. Rural water withdrawal in Chongqing, however, is projected to remain relatively stable since 2015. According to our projection, combined domestic water withdrawal in Sichuan and Chongqing will grow from 3.28 to 3.63 bcm/year and from 1.30 to 1.47 bcm/year, respectively. Our

projection also shows that during the next 15 years, urban domestic water withdrawals will become significant because of the increase in urban water users.

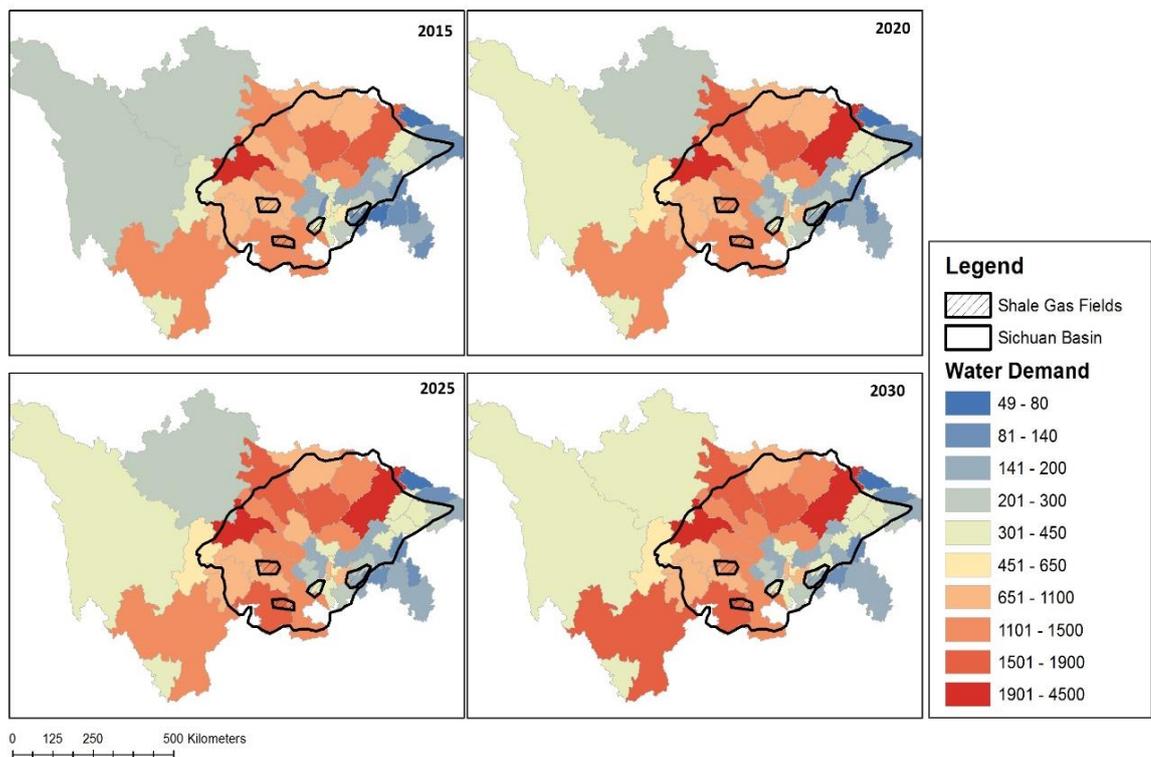
In order to estimate the total water demand from our projected domestic water demand, we further investigated the historical water use profiles for both regions. Figure 12 shows the percentages of domestic water use in total water demand from 1998 to 2013 in Sichuan and Chongqing, respectively. Historically, Sichuan used 13.16% of its total water demand for domestic and public purposes, while Chongqing used 18.64%. Therefore, we further calculated the total water demand for the next 15 years by applying the historical percentages. Figure 13 visualizes the total water demand for both regions from 2015 to 2030.

**Figure 12.** Domestic Water Use Profile in Sichuan Province and Chongqing Municipality



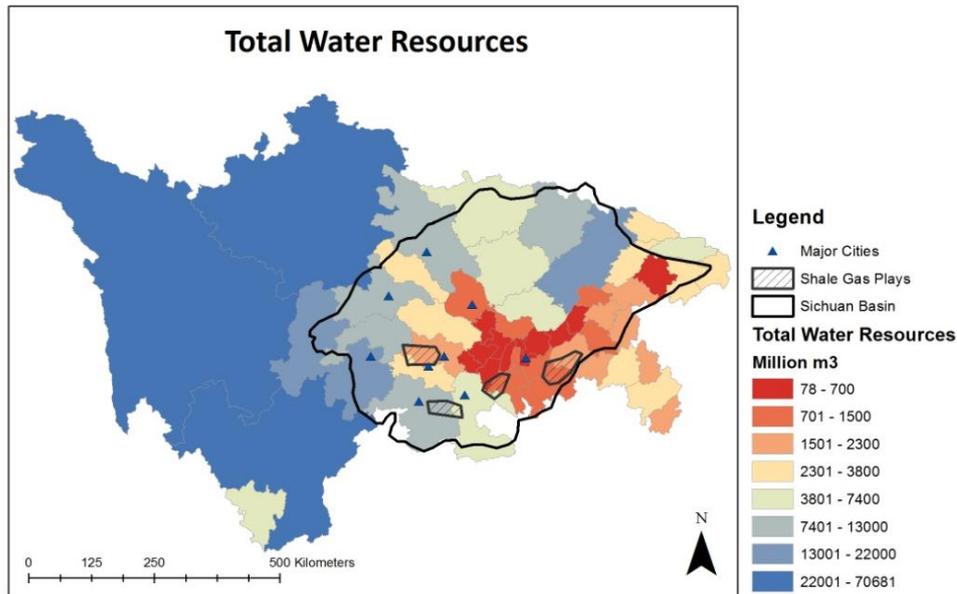
Source: Yangtze River Basin and Southwest Rivers Water Resources Bulletin 2001-2013

**Figure 13.** Total Water Demand Projection Visualization

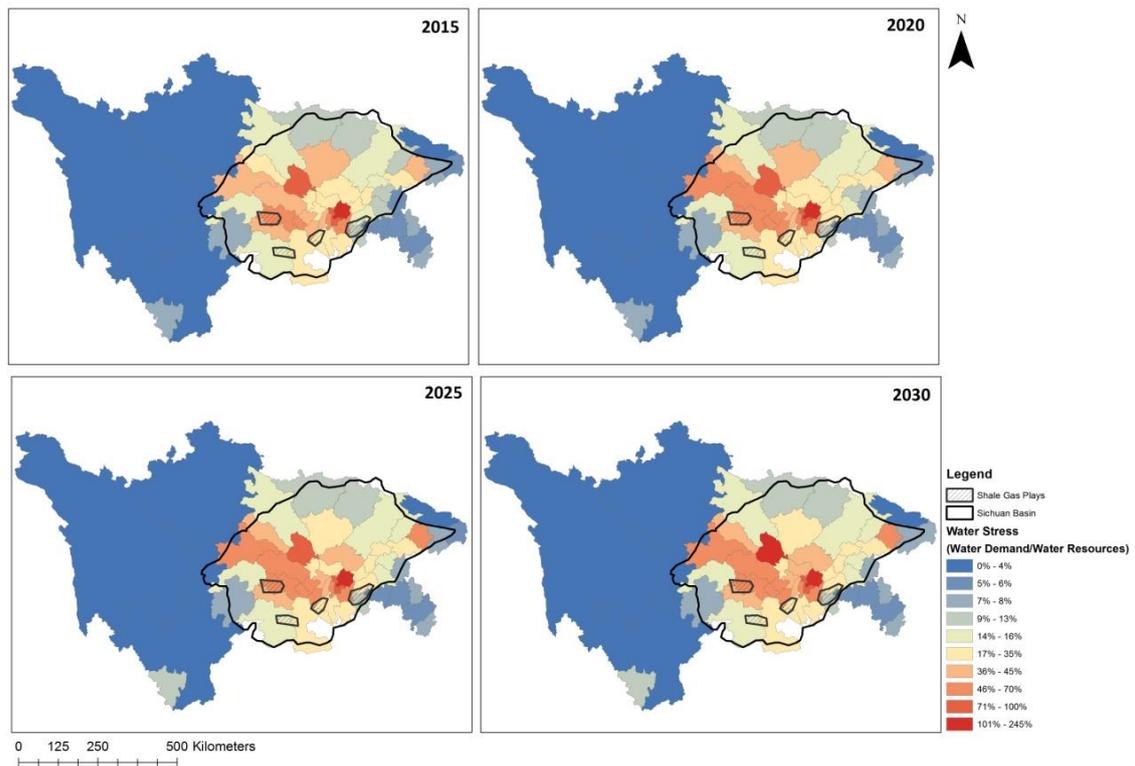


In order to quantify the water stress for each county, the water stress index was calculated by dividing the total water demand by the regional water resources (Figure 14). Figure 15 shows the visualization of water stress indices for each sub-region of Sichuan Province and Chongqing Municipality over 5-year intervals from 2015 to 2030.

**Figure 14.** Average Total Water Resources Visualization



**Figure 15.** Water Stress Projection Visualization



As shown in Figure 15, the regions colored in orange and red are expected to use 40% to up to 100% of its total water resources, indicating the potential of high to extremely high water stresses. In general, the areas identified as of high water stresses will shift towards and will concentrate in the center and southern part of the Sichuan Basin for the next 15 years. These are the areas where the urban centers and industrialized regions are located. Based on our analyses, dark red areas have the water stress indices greater than 1 (i.e., over 100% of water use relative to total water availability), indicating that in the future, these areas may require external water sources for regional development. The areas where shale gas extraction activities are currently occurring, shown as black-bordered blocks in the map, are also located in the areas of high water stresses. Although it is unknown to what extent shale gas exploration and extraction 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 regions of high water stresses.

### Shale Gas Water Use Projection

Although China's one of the most promising shale gas deposits lies in Sichuan, shale gas production in Sichuan Basin is at very early stage. A limited number of studies have reported the current state of shale gas development in the Sichuan Basin. To date, PetroChina and Sinopec are two biggest players in Sichuan's shale gas development (Table 5). On this basis, we assumed that 143 (23 of PetroChina and 120 of Sinopec) shale gas wells have been drilled before 2015.

**Table 5.** Summary of Current State of Shale Gas Development in Sichuan Basin

Major company	Current state of shale gas development
Petro China	<ul style="list-style-type: none"> <li>As of October 2014, PetroChina drilled 23 shale gas wells in Sichuan Basin, with a cumulative production of 0.2 bcm; the company's production goal is 2.6 bcm in 2015, 5 bcm in 2017, 12 bcm in 2020</li> </ul>
Sinopec	<ul style="list-style-type: none"> <li>As of December 2014, 120 wells were drilled including 49 fractured wells in Fuling shale play; to date, the cumulative shale gas production in Fuling play is 1.14 bcm; the target output is 5bcm/year in 2015</li> </ul>

Source: Yang and Wang, 2014; Zeng and Luo, 2014

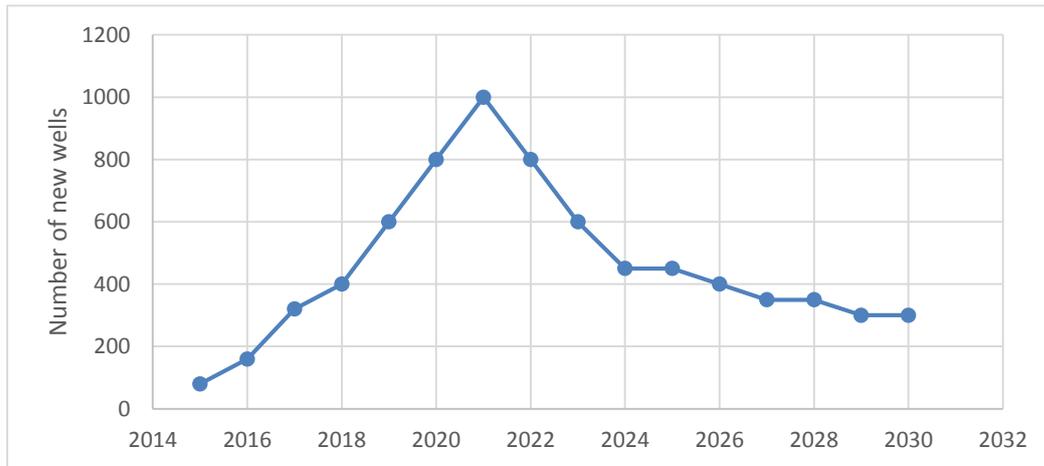
The first key fundamental in determining the water withdrawal of shale gas production in Sichuan Basin is the well development projection, as water usage is explicitly linked to the rate of exploitation. Shale plays currently being developed do not constitute a homogenous resource and development rate. Each shale play has its own set of geological and geographical characteristics, and variability in factors including development policy, land surface, and infrastructure availability. Historical drilling rates have varied significantly, depending on the

shale play's characteristics. Barnett play, for instance, has the drilling rates peaked in 2008 at 2,707 wells per year and currently stabilized at less than 400 wells per year. In the Marcellus of Pennsylvania, horizontal drilling rate peaked in 2013 at approximately 1,350 wells per year and have fallen to current levels of 1,200 wells per year. Although annual drilling rates varied across plays, some general development patterns can be observed. Depending on the play's geological properties, a peak drilling rate seems to occur in the 5<sup>th</sup> to 7<sup>th</sup> year of a play's gas production. In addition, the well development is expected to slow down one or two years after the peak drilling rate, and further fall to a relatively stable drilling rate. Therefore, by comparing Sichuan shale play with the U.S. major shale plays (i.e. areas of shale plays, technically recoverable shale gas resources), we developed a hypothetical scenario for well development in Sichuan Basin (Table 6; Figure 16) largely based on U.S. Haynesville Shale Play experience. For the first three years, the number of well being drilled will increase by twofold per year. The number of new wells will reach at 400 in 2018 and increase by 200 wells per year until the drilling rate peaks at 1,000 wells per year in 2021. As discussed above, the rate of exploitation will decline by 200 wells per year and remain stable at around 400 wells per year in the following years. This projection also reveals two stages of shale gas development (Tian et al., 2014): 1) the innovation stage when industry needs to invest in technology innovations, resulting in lower rates of drilling, and 2) the scaling-up stage during which production of shale gas is rapidly increased and has a rate of exploitation to plays of similar geology.

**Table 6.** Summary of Well Development and Projected Shale Gas Production from 2015 to 2030

	Annual production (m <sup>3</sup> )	Well drilled	Total wells	Annual production (bcm/year)	Cumulative production (bcm)	National Target (bcm/year)	Sichuan Target (bcm/year)
2015	16,500,000	80	223	2.74	4.74	6.5	2.6
2016	9,900,000	160	383	4.38	9.12		
2017	6,633,000	320	703	8.15	17.27		
2018	5,306,400	400	1,103	11.94	29.21		
2019	4,775,760	600	1,703	17.84	47.05		
2020	4,393,699	800	2,503	25.19	72.24	30	12
2021	4,086,140	1,000	3,503	33.63	105.87		
2022	3,840,972	800	4,303	36.39	142.26		
2023	3,648,923	600	4,903	36.03	178.29		
2024	3,466,477	450	5,353	34.16	212.45		
2025	3,293,153	450	5,803	34.37	246.82		
2026	3,128,496	400	6,203	34.11	280.93		
2027	2,972,071	350	6,553	33.28	314.20		
2028	2,823,467	350	6,903	32.49	346.69		
2029	2,682,294	300	7,203	30.91	377.60		
2030	2,548,179	300	7,503	26.52	404.12		

**Figure 16.** Projected Well Development in Sichuan Basin for the Next 15 Years



On the basis of the hypothetical scenario for well development in Sichuan Basin, we further calculate the annual production and cumulative production to assess whether the target production volume of shale gas can be achieved based on the hypothetical drilling rate. 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 (Table 7). Noted that the initial production (IP) rate per well has been increasing in part due to increased horizontal well lengths and more effective fracturing technology. All the shale plays in active production have qualitatively similar decline characteristics over the well’s lifespan. The production rate of a well in the Marcellus shale gas play, for example, will decrease by 80 percent in the first five years and by 92% by 10 years (JRC, 2013).

**Table 7.** Comparison of Initial Production and Decline Rate of U.S. Major Shale Plays

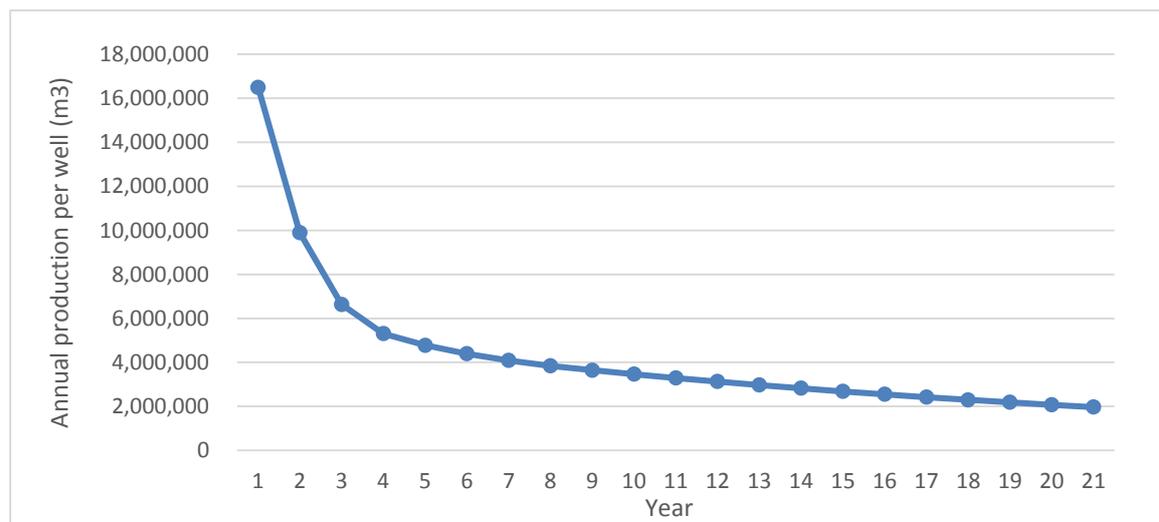
Shale Play	Barnett	Fayetteville	Woodford	Marcellus	Haynesville
Initial Production (1*10 <sup>3</sup> m <sup>3</sup> /d)	60.6 (2010) 70 (2014)	65.7 (2010) 78 (2014)	108.1 (2010) 143 (2014)	90 (2010) 98 (2014)	261.5 (2010) 400 (2014)
1st Year Decline Rate	65%	68%	59%	75%	82%
2nd Year Decline Rate	34%	33%	43%	34%	45%
3rd Year Decline Rate	19%	22%	32%	22%	30%
Final Decline Rate	6%	7%	5%	6%	9%

Source: O’Sullivan and Paltsev, 2012; Liu et al., 2014

Data on shale gas well initial production and decline characteristics is still sparse in Sichuan Basin due to the limited time existing wells have been producing. However, a recent study conducted by Liu et al.(2014) investigated and compared key geological parameters from Sichuan Basin with historical data from the major U.S. shale plays, and further determined the initial production and decline rates for shale gas development in Sichuan. In this report, we

performed the calculation of annual production and cumulative production based on their resulting initial production of 50,000 m<sup>3</sup>/d and the unique decline rate curve for Sichuan Basin (Figure 17). As shown in Figure 17, the Sichuan Basin shale play has a similar decline characteristic to the US cases; a significant production decline during the first five year of production followed by moderate rates of decline in subsequent years. With the consideration of well performance, the estimated overall production of Sichuan shale gas were calculated based on our previous projection on well development (Table 6).

**Figure 17.** Production Profile of Shale Gas Wells in Sichuan Basin



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

The Chinese central government strongly incentivizes shale gas production with a number of national policies. The principle guideline Chinese shale gas policies are set forth in the Shale Gas Five-Year-Plan. The central government provided a series of supporting policies to support shale gas production including a subsidy program, listing of shale gas as an independent mineral resources, and production targets. According to the National Energy Administration (NEA), the government’s shale gas production targets are 6.5 bcm by 2015 and 30 bcm (recently updated) by 2020. Although the government does not specify in the original document, multiple studies indicate that the production goal should be annual production target volume (Sandalow et al., 2014; Gunningham, 2013; Kolb, 2013). Sichuan basin has the estimated shale gas resource of 40.02 tcm, accounting for approximately 30% of the national total. According to Sichuan Development and Reform Commission (DRC), the shale gas production in the Sichuan Basin should contribute 40% of the national target (i.e. in 2015, 2.6 bcm/year out of 6.5 bcm and 12 bcm/year in 2020) (Wilson, 2013). Therefore,

based on our analyses, the projected shale gas production in Sichuan shale plays is able to achieve the 2015 goal and greatly surpass the 2020 goal.

As discussed in the previous hypothetical scenarios of water use in shale gas industry, we assumed a range of water use per shale gas well of 11,000 m<sup>3</sup> and 22,000 m<sup>3</sup> for the hypothetical low and high impact scenarios, respectively. Additionally, the low impact scenario assumed a single frack during the anticipated 10-year lifetime of the well, with a flowback fluid recycling ratio of 70%, and high impact scenario assumed that each well is fracked 5 times in its first year of production with a recycling ratio of only 5%. The recycling ratio is an important index to evaluate how much water is recovered and recycled, meaning that the balance is “consumed”. The consumed water includes water that remains underground as well as grey and black water (JRC, 2013), indicating that the water is either at unrecoverable depth, converted into a product, or polluted to an extent that it can no longer be used for other purposes. The amount of water used/consumed for shale gas extraction, as calculated for each hypothetical scenario, is given in Table 8.

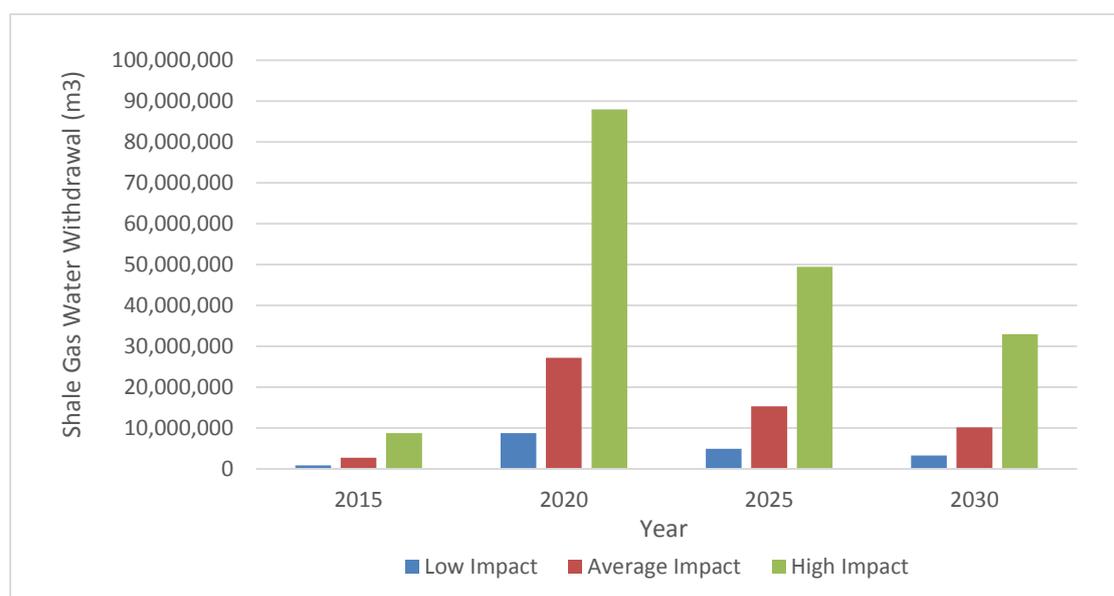
**Table 8.** Projected Water Withdrawals for Shale Gas Development in Sichuan Basin under Three Water Impact Scenarios from 2015 to 2030

Year	Well Drilled	Withdrawal (m <sup>3</sup> )			Consumption (m <sup>3</sup> )		
		Low	Mean	High	Low	Mean	High
2015	80	880,000	2,720,000	8,800,000	264,000	1,768,000	8,360,000
2016	160	1,760,000	5,440,000	17,600,000	528,000	3,536,000	16,720,000
2017	320	3,520,000	10,880,000	35,200,000	1,056,000	7,072,000	33,440,000
2018	400	4,400,000	13,600,000	44,000,000	1,320,000	8,840,000	41,800,000
2019	600	6,600,000	20,400,000	66,000,000	1,980,000	13,260,000	62,700,000
2020	800	8,800,000	27,200,000	88,000,000	2,640,000	17,680,000	83,600,000
2021	1000	11,000,000	34,000,000	110,000,000	3,300,000	22,100,000	104,500,000
2022	800	8,800,000	27,200,000	88,000,000	2,640,000	17,680,000	83,600,000
2023	600	6,600,000	20,400,000	66,000,000	1,980,000	13,260,000	62,700,000
2024	450	4,950,000	15,300,000	49,500,000	1,485,000	9,945,000	47,025,000
2025	450	4,950,000	15,300,000	49,500,000	1,485,000	9,945,000	47,025,000
2026	400	4,400,000	13,600,000	44,000,000	1,320,000	8,840,000	41,800,000
2027	350	3,850,000	11,900,000	38,500,000	1,155,000	7,735,000	36,575,000
2028	350	3,850,000	11,900,000	38,500,000	1,155,000	7,735,000	36,575,000
2029	300	3,300,000	10,200,000	33,000,000	990,000	6,630,000	31,350,000
2030	300	3,300,000	10,200,000	33,000,000	990,000	6,630,000	31,350,000

Figure 18 shows a comparison of shale gas water withdrawals from 2015 to 2030 under different water impact hypothetical scenarios. As shown in the figure, during early development stage, the water withdrawal is relatively insignificant. In the year of 2015, for instance, the total water uses for shale gas extraction will be less than 10 million cubic meters

even under the high water impact scenarios. However, with the anticipated rapid expansion of shale gas exploration and extraction activities, the water withdrawals will increase significantly and peak in the year when shale gas production is projected to be most active. In 2020, the water usage for shale development can peak to 88 million cubic meters under high water impact scenario, while withdrawal is still less than 10 million cubic meters under the development of our low impact scenario. Over the subsequent years, the water withdrawals will generally decrease with the lower rate of drilling activities.

**Figure 18.** Comparison of Water Withdrawals for Shale Gas Development in Sichuan Basin under Three Water Impact Scenarios from 2015 to 2030



## Discussion

In this study we projected the urban and rural population and domestic water demand for each sub-region of Sichuan Province and Chongqing Municipality. By assuming that domestic water demand will continue to account for a fixed percentage of the total water utilization, total water demand was estimated using historical water use profiles. Furthermore, water stress indices were calculated and visualized for a spatial distribution.

Shale gas production in Sichuan Basin is still at the very early stage of the development. Therefore, we developed a well development profile based on the U.S. experience and further justified our estimation by comparing the projected shale gas production with regional production goals. Specifically, a declining shale gas production profile was used to calculate the projected shale gas production in Sichuan Basin. Based on the shale gas well development, I evaluated the water use for hydraulic fracturing based on the water use per well reported in the U.S. major shale gas plays (Vengosh et al. 2014). Specifically I used low,

average and high water impact scenarios to estimate the water withdrawals for shale gas development in the region for the next 15 years. On the basis of these projections, I draw the following conclusions:

1. The areas of high to extremely high water stress are expected to concentrate in the center and southern part of Sichuan Basin for the next 15 years, which overlay with the major urban centers and industrial activities in the Basin. Shale gas development will also occur largely in the southern part of the Basin, indicating that shale development in the area may pose potential risk on regional water resources.
2. According to our calculation of water usage for shale gas development under different water impact scenarios, water withdrawal for shale development in Sichuan Basin is relatively insignificant compared to the total water resources in the Sichuan Province and Chongqing Municipality. Even under the high water impact scenario in 2021, when the shale gas production activity is projected to be the most active, the water withdrawal for shale development will account only 0.0324% of the total water resources of Sichuan and Chongqing.
3. The complex and mountainous terrain of Sichuan Basin makes water transfer largely difficult and practically impossible. Therefore, if water withdrawal localized in areas of high water stress, water requirement for shale development will pose potential risk on local water resources especially under the average or high water impact scenarios. The result of this study can also be useful for the identification of areas that are most at risk; in these areas, there is a need to identify alternative water sources for shale gas development, such as industrial wastewater or brine water in addition to the option of recycling wastewater from oil and gas industries.

Due to insufficient data availability and several uncertainties, we developed the projections and scenarios based on several assumptions, including:

1. The projection of the total water demand was calculated by assuming that domestic water demand will account for a fixed portion of total water usage. However, this portion likely to change over time, especially with higher efficiency in water use in different sectors as well as the shift of regional development focus. Therefore, separate projections on agricultural and industrial water utilization and the development of multiple water demand scenarios can minimize these uncertainties.
2. In this study, stressors such as water quality and climatic variability were not included in our analyses of water availability. However, water stress is closely related to the availability of water resources, and therefore water quality degradation and variations in hydrologic

conditions, which are not included in our evaluation, could significantly increase the impact of water stress. These components should therefore be included in future studies.

3. Future investigation should also include the actual water sources for shale gas extraction. Sourcing water for shale gas extraction from regional river waters, groundwater, or water transferred from other regions can alter our estimates on the water availability for shale gas development in Sichuan Basin. This is also important to further quantify the regional impacts of shale gas development on local and more detailed water resources evaluation.

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