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Bi-objective optimization of water management in shale gas exploration with uncertainty: A case study from Sichuan, China

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ABSTRACT

Shale gas exploration relies heavily on freshwater inputs while generating large amounts of wastewater. With the quick development of shale gas, water management during exploration has increasingly become a hotspot from both environmental and economic perspectives. This study investigated all the key water-consuming phases in exploration and optimized the freshwater use and flowback water control using a bi-objective programming model with the consideration of uncertainties in each phase, aiming at the optimal trade-offs between economic and environmental objectives. The model conducted a case study of shale gas projects in Sichuan, China. The results show that (a) Tolerance of the uncertainty in water demand for hydraulic fracturing can effectively reduce both economic and environment cost, thereby reducing total system cost. (b) System costs depends on risk preferences of decision-makers. (c) Direct reuse is the best strategy to treat wastewater at the early phase of hydraulic fracturing; while more constraints other than onsite treatment costs should be considered when treating produced water during the production phase. (d) There exists an “economics of scale” in the water management during shale gas exploration.

1. Introduction

Recent analysis of uncertainties related with future scenarios has highlighted the importance of unconventional petroleum – primarily from tight formations such as shales - as well as development of new technologies as key factors (Wachtmeister et al., 2018a). With the breakthrough of fracturing technology and horizontal drilling technology, the development potential of shale gas is becoming more and more evident (Loh and Loh, 2016). Since 2010, the rise of shale gas has been rapid with major impact on global energy supply (Melikoglu, 2014; Aruga, 2016).

Many countries such as the USA, Canada, China and others have undertaken commercial exploration of shale gas, while the development of shale gas in the United States is the most remarkable one (Li et al., 2016; Soeder, 2018; Wachtmeister et al., 2018b). By 2040, it is projected shale gas production in the United States could account for nearly two thirds of the total natural gas production (U.S. Energy Information Administration, 2017). After the USA, Canada ranks second in terms of booming commercial exploration. Other countries like Argentina are still in early phases of exploration. EU countries are not expected to mirror US developments due to constraints caused by public acceptance, governance issues, mineral rights, and environmental regulations (Kuchler, 2017; United Nations Conference on Trade and Development, 2018).

According to the U.S. Energy Information Administration (2015), China have the most abundant technically recoverable resources of shale gas in the world. The Chinese's commitment to reach a peak of carbon dioxide emissions in 2030 primarily focuses on decreasing the share of coal in primary energy supply. Development of natural gas – including shale gas – has become an important contribution to this goal (Yang et al., 2016; Dong et al., 2016; He, 2016). In the 13th Five-year plan in China, the development goal is to strive for achieving annual shale gas production of 30 billion cubic meters by 2020 (National Energy Administration, 2016).

Intensive water demand during exploration and water scarcity in shale areas can make water management a key problem that needs careful consideration. During shale gas exploration, both drilling and hydraulic fracturing require significant water inputs, while the latter is more water intensive (Jiang et al., 2014). As key step in shale development, the hydraulic fracturing process requires large amounts of
Fresh water while also producing significant volumes of wastewater, often with high salt content. Since majority of regions in China are water scarce areas, the impact of shale gas development on local water supply and water quality are highly concerned (Zou et al., 2016). The net water use is around 24500 m³/well in Sichuan Basin, China (Wang et al., 2018). The water intensity of shale gas development in Fuling China is about 50% higher than that in the USA (Guo et al., 2016). In the United States, 10–30 thousand cubic meters of water are demanded for each well during hydraulic fracturing process, while 20–30 thousand cubic meters of water are required for single well in Sichuan China (Yu et al., 2016). If drilling and other operations are included, the average water consumption per shale gas well in Sichuan and Chongqing is about 34 thousand cubic meters (Lu et al., 2016).

In this study, water management process includes fresh water transportation of shale gas exploration together with treatment and recycling of wastewater. The uncertainties during water management process of shale gas exploration have big impact to the water management, while this paper considers both water volume uncertainty and economic parameter uncertainty in details. Fuzzy numbers capture the water demand for hydraulic fracturing, while scenario analysis captures uncertainties in wastewater volumes. And a series of sensitive analysis for major economic parameters are carried to explore the impact to economic objective. We built a bi-objective programming model capable of considering uncertain economic cost and uncertain fresh water withdrawal volumes at the same time while also including fuzzy constraints. Moreover, this paper aims to study water management quantitatively by applying the model to a case study for Sichuan in China, and using the outcomes to contribute to the debate on sustainable development of shale gas in the future.

2. Literature review

Water management can result in multiple costs for different stakeholders during shale gas exploration (Shih et al., 2016). Consequently, water management is best understood from a system perspective. Decisions made by development operators and wastewater treatment operators often focus on economic objectives, like cost and benefit (Yang et al., 2014, 2015; Bartholomew and Mauter, 2016; Gao and You, 2015; Lira-Barragán et al., 2016, b). From the viewpoints of environmental regulators and social planners, negative outputs such as air pollution should be limited while scarce inputs such as fresh water should be conserved (Bartholomew and Mauter, 2016; Lira-Barragán et al., 2016a, b; Gao and You, 2015; He et al., 2018). Close to a water source used by cities, shale gas exploration could be banned to protect water supplies (Rahm et al., 2013). Public concerns over the environment has also changed wastewater management strategies (Eaton, 2013).

Early modelling studies chiefly focused on optimization of economic objectives when building mathematical models for water management research. For example, Yang et al. (2014) and Yang et al. (2015) built two stage mixed integer stochastic linear programming model and set minimizing the economic cost as objective. More and more studies also include environment impacts, such as fresh water withdrawal and...
greenhouse gas emissions, together with economic objectives. Constructing bi-objective programming models is a direct way to optimize two objectives simultaneously, but such approaches have not been widely explored in literature. A noteworthy exception is Bartholomew et al. (2016) that consider both maximum economic benefit and minimum environmental impact in a bi-objectives optimization model.

Most studies use indirect approaches to optimize simultaneously two objectives, for example by constructing fractional single objective programming model or constructing single objective programming model while putting one of the objectives into constraints. Gao et al. (2015) use maximum profit of shale gas production per unit fresh water consumption as the objective function in a mixed integer linear programming model with the fractional form function. Lira-Barragán et al. (2016a) consider the variability of fresh water availability, establish a programming model with economic objective function, and determine the reuse network by using the total amount of water as the representative index of the environmental impact.

Constructing multi-level modeling framework is another way to achieve the balance between different objectives. Chen et al. (2018) consider both maximum economic benefit and minimum greenhouse gas emission at the same time to establish multi-criteria uncertain decision-making model. He et al. (2018) establish three level hierarchical framework considering water, energy, and air-emission during the life cycle of shale gas supply chains.

The main uncertainties during water management of shale gas exploration includes uncertain volume availability from water source, uncertainty in needed water volume for hydraulic fracturing, and uncertain volumes of generated wastewater. In published literature, typically estimate uncertain parameters using Monte Carlo simulations based on historical data, or fuzzy numbers, interval number or specific probability distribution to describe uncertain parameters based on historical data. Lira-Barragín et al. (2016a) studies uncertainty of water demand for single well hydraulic fracturing processes and wastewater generation of single well hydraulic fracture process by carrying out scenario analysis using Monte Carlo simulation. Zhang et al. (2016) use fuzzy membership functions and probability density functions to express uncertain information in an optimization model for wastewater treatment process of shale gas hydraulic fracture operation. Chen et al. (2018) use interval number to describe the uncertainty of environmental parameters and economic parameters.

From the literature review, one may conclude that the water management during shale gas development should consider both economic costs and environmental impacts, as well as uncertainty of water withdrawal for well completion and uncertainty of wastewater treatment after hydraulic fracturing. However, studies that establish multi-objective models only choose air emission as main environment impact index, but never use fresh water withdrawal volume as main environment impact index. Current studies that use economic objective as well as environment objective into consideration only focus on the wastewater treatment process, but hence lack consideration of fresh water transportation from water source and make it impossible to use fresh water withdrawal volume as main environmental impact index. Current papers mainly use sensitive analysis to treat uncertainty in multi-objective optimization model, but neglects direct consideration of uncertain parameters. Models that consider uncertainty well in literature unfortunately only use an economic objective function, but lack environmental considerations. Furthermore, most published studies focus on water management of shale gas operations in the USA, while studies in other countries relatively rare.

3. Methods and data

3.1. Problem statement for water management

A water management model may be constructed by considering the whole cycle of hydraulic fracturing during the shale gas exploration process. Multi-stage water fracturing is usually the primary choice during China’s shale gas exploration and typical lengths are usually more than several thousands of meters (Tang et al., 2011). The wastewater volumes generated after hydraulic fracturing may be large and initially display low total dissolved solids (TDS) concentration at first. However, after 5–14 days, the volume of flowback water decreases dramatically, and TDS concentration of wastewater increases at the same time (Slutz et al., 2012). The characteristics of flowback water from hydraulic fracturing of each individual well allows division of suitable study period into a flowback phase followed by a production phase period. This paper chooses the first two weeks after hydraulic fracturing as flowback period and the production process after that as production period according to the exist literature (Yang et al., 2015, 2015b).

The wastewater volume in relatively short flowback phase is large, while its corresponding TDS concentration is low. As the time that injected water is in contact with shale formation progresses, the TDS concentration in flowback water also increases (Estrada and Rao, 2016). For optimal handling, it is important that different water management strategies fit in alignment with the different wastewater characteristics of the flowback and production phases.

In this paper, water management strategies assumed applicable in the flowback phase are direct reuse, direct disposal, and indirect disposal. In contrast, the production phase allows reuse after onsite treatment, direct disposal, and indirect disposal. During the flowback phase, decision-makers should firstly determine wastewater volume that suitable for direct reuse or disposal and to the save former in a tank and send the latter for disposal. However, wastewater in the tank may not be reused for a couple of reasons at the end of a hydraulic fracturing process, so it could be sent for indirect disposal. During a production phase, decision-makers should determine wastewater volumes suitable for reuse after onsite treatment or direct disposal to collect the former to the tank and send the latter to a disposal well. The wastewater that are remained in the tank at the end of water usage process of hydraulic fracture should be transported for indirect disposal. The minimal time unit in this paper is one week.

3.2. Model formulation

3.2.1. Objective function

The objective function of the model includes both economic objective and environment objective. In term of economic objective, this paper considers economic cost as the economic objective. During the water management process, economic cost is made up of transportation cost, treatment cost, and disposal cost. Transportation cost occurs when transporting fresh water to well pad and transporting wastewater to disposal. Unit transport cost – transport load as well as transport distance affect the transportation cost – the specific relationship is as follow:

$$\text{Cost}_{\text{transport}} = C_{\text{transf}} \times \sum \sum \sum_\text{d} D_{\text{w}} \times f_{\text{trf},\text{ijt}} + C_{\text{truck}} \times \sum_\text{d} D_{\text{w}} \times \left( f_{\text{disposal}} + f_{\text{pro}} \right) + \sum \sum \sum_\text{d} f_{\text{disposal},\text{ijt}}$$

(1)

Onsite treatment cost is affected by unit treatment cost and volume, specific relationship is described as:

$$\text{Cost}_{\text{onsite}} = \sum \sum \sum_\text{d} \text{Cost}_{\text{onsite},\text{ijt}}$$

(2)

Disposal cost is affected by unit disposal cost and disposal volume, may be specifically expressed as follows:

$$\text{Cost}_{\text{disposal}} = \sum \sum \sum_\text{d} \text{Cost}_{\text{disposal},\text{ijt}}$$
\[
\text{Cost}_{\text{disposal}} = C_{\text{disposal}} \left( f_{\text{disposal}}^{\text{raw}} + f_{\text{disposal}}^{\text{direct}} + \sum_{i} \sum_{j} f_{i,j,t}^{\text{disposal}} \right)
\]  

(3)

According to Eqs. (1) – (3), the economic cost can be represented by the sum of three parts of the cost:

\[
F_1 = \text{Cost}_{\text{transport}} + \text{Cost}_{\text{ onsite}} + \text{Cost}_{\text{disposal}}
\]  

(4)

where, \(F_1\) is economic objective function, which is the total economic cost of water management during shale gas exploration.

This study uses fresh water volume as an index to reflect environmental impacts to study core characteristic of water management during shale gas exploration (Gao and You, 2015). The specific format of environment objective function is expressed as:

\[
F_2 = \sum_{i} \sum_{j} \sum_{t} f_{i,j,t}^{\text{fr}}
\]  

(5)

where, \(F_2\) denotes environment objective function.

The economic objective and environment objective are not only just different in form, but also cannot achieve optimal values at the same time. By improving environment objective, there should be less fresh water are needed to fracturing directly and more wastewater are needed to reuse and recycle for the fracturing. However, in order to recycle, more water management cost should be spent, which increase the economic cost and thus making the economic objective worse. On the other hand, since the transportation cost is cheaper than the wastewater treatment cost, it’s better to use more fresh water and less recycled water to reduce the economic cost. However, these will lead to the increase of environment impacts and making the environment objective worse. That means when the economic objective gets closer to optimum, there will be movement away from the optimal environment objective as a trade-off relationship exists between them. Therefore, it is necessary to obtain a pareto solution to the bi-objective optimization model to quantify this trade-off relationship.

3.2.2. Constraints

The constraints in this study mainly focus on two key factors that are volume of water needed for hydraulic fracturing and the volume of wastewater generated from hydraulic fracturing. Separate water strategies for flowback and production phases are studied. Wastewater is classified by TDS concentration, while wastewater generated during flowback phase are called level \(l_i\) wastewater and wastewater generated on production phase are called level \(l_i\) wastewater. Level \(l_i\) wastewater can be reused directly, while level \(l_i\) wastewater must be treated onsite before reuse and recycling. Water for hydraulic fracturing combines fresh water, level \(l_i\) wastewater and level \(l_i\) wastewater.

\[
f_{i,j,t}^{\text{fr}} + \sum_{i} f_{i,j,t}^{\text{raw}} = F_{i,j} \quad \forall \ i, j, t
\]  

(6)

However, Eq. (6) fails to reflect uncertainty of water required for hydraulic fracturing, so modifications need to account for uncertainty. Uncertain programming methods is the main approach that have been used to solve water management problems (Slutz et al., 2012; Zhou et al., 2013; Guo et al., 2010; Cai et al., 2016). The water volume for hydraulic fracturing assumes to have the form of triangle fuzzy parameter for uncertainty (Lira-Barragán et al., 2016a). For simplification, water requirements for individual wells assumed identical, while fracturing time is assumed to last for one week for all wells. \(F\) is the water needed for hydraulic fracture of single well, where, \(F = (F_1, F_2, F_3)\). Thus, (6) can be converted into (7) as follow:

\[
f_{i,j,t}^{\text{fr}} + \sum_{i} f_{i,j,t}^{\text{raw}} = \tilde{F} \quad \forall \ i, j, t
\]  

(7)

Since fuzzy parameter appears on the right side of equation, it is hard to compare with number on the left side of equation directly. In this sense, translating fuzzy parameter to a combination of expected interval endpoint can solve this problem (see supplementary information for details).

Different combination of expect interval endpoint will lead to decision-maker’s different satisfaction degree to the fuzzy number. The certain degree that fuzzy equation is established is called satisfaction degree, and takes value between 0 and 1. It is supposed that decision-makers satisfaction degree to the Eq. (7) is \(\alpha\) \((0 \leq \alpha \leq 1)\). Then the (7) can be converted into two equivalent normal equation, as follow:

\[
f_{i,j,t}^{\text{fr}} + \sum_{i} f_{i,j,t}^{\text{raw}} \leq (0.5 - \alpha)E_1^F + (1 - 0.5 - \alpha)E_2^F
\]  

(8)

\[
f_{i,j,t}^{\text{fr}} + \sum_{i} f_{i,j,t}^{\text{raw}} \geq (0.5 - \alpha)E_2^F + (1 - 0.5 - \alpha)E_1^F
\]  

(9)

The satisfaction degree \(\alpha\) is a degree that decision maker satisfies the fuzzy number as well as a degree that decision maker satisfies the uncertain constraint established. For larger values of \(\alpha\), the corresponding decision process becomes more certain. This study uses different \(\alpha\) as the index to reflect uncertainty of volume of water needed for hydraulic fracture.

During the flowback phase, wastewater generated from well \(j\) of well pad \(i\) is affected by flowback rate and the total water needed for hydraulic fracture process, specific relationship is as follow:

\[
f_{i,j,t}^{\text{fr}} + f_{i,j,t}^{\text{disposal}} = F_{i,j,t} \quad \forall \ i, j, t
\]  

(10)

Decision-makers should firstly determine volume of flowback wastewater intended for direct reuse or direct disposal.

\[
f_{i,j,t}^{\text{fr}} + f_{i,j,t}^{\text{disposal}} \leq (0.5 - \alpha)E_1^{F_{i,j,t}} + (1 - 0.5 - \alpha)E_2^{F_{i,j,t}} \quad \forall \ i, j, t
\]  

(12)

\[
f_{i,j,t}^{\text{fr}} + f_{i,j,t}^{\text{disposal}} \geq (0.5 - \alpha)E_2^{F_{i,j,t}} + (1 - 0.5 - \alpha)E_1^{F_{i,j,t}} \quad \forall \ i, j, t
\]  

(13)

Volume of reuse water is equal to available flowback wastewater volume. Referring to state transition equation, the following equations are formed.

\[
f_{i,t}^{\text{fr}} - f_{i,t-1}^{\text{fr}} = \sum_{j} f_{i,j,t}^{\text{fr}} \quad \forall \ t
\]  

(14)

\[
\sum_{i} \sum_{j} f_{i,j,t}^{\text{fr}} = f_{i,t}^{\text{fr}} - f_{i,t-1}^{\text{fr}} \quad \forall \ t
\]  

(15)

Indirectly disposed flowback wastewater are the difference between flowback wastewater planned for direct reuse and flowback wastewater that were directly reused for hydraulic fracturing.

\[
f_{i,j,t}^{\text{disposal}} = \sum_{j} f_{i,j,t}^{\text{fr}} - F_{i,j,t} \quad \forall \ i, j
\]  

(16)

\[
f_{i,j,t}^{\text{fr}} + f_{i,j,t}^{\text{disposal}} = F_{i,j,t} \quad \forall \ i, j, t
\]  

(17)

During production phase, the volume of produced water is related to the flowback rate of production phase and the volume of water that is needed for hydraulic fracturing.

\[
F_{i,j}^{\text{pr}} = \eta_p F_{i,j} \quad \forall \ i, j
\]  

(18)

Decision-maker should firstly determine the volumes of produced wastewater intended for reuse after onsite treatment and direct disposal.

\[
f_{i,j,t}^{\text{fr}} + f_{i,j,t}^{\text{disposal}} \leq (0.5 - \alpha)E_1^{F_{i,j,t}} + (1 - 0.5 - \alpha)E_2^{F_{i,j,t}} \quad \forall \ i, j, t
\]  

(19)
Some parts of available wastewater after onsite treatment can be reused directly for following hydraulic fracturing processes and other parts will be sent to disposal wells (Henderson et al., 2011).

\[
p_{\text{red}} - p_{\text{pr}} - p_{\text{pr}} = \gamma \sum_{i} \sum_{j} f_{\text{env}}^{\text{mate}}, \forall \ t
\]

The produced wastewater that are indirectly disposed are the difference between produced wastewater planned for reuse after onsite treatment and the produced wastewater that reused to hydraulic fracturing.

\[
f_{\text{prodisposal}} = \sum_{i} \sum_{j} f_{\text{env}}^{\text{mate}} - \sum_{i} \sum_{j} f_{\text{env}}^{\text{disposal}}
\]

(23)

The wastewater that directly disposal combines wastewater generated in flowback and production phases.

\[
f_{\text{disposal}} + f_{\text{prodisposal}} = f_{\text{disposal}}, \forall \ i, j, t
\]

(24)

3.2.3. Model

With two independent objectives and fuzzy constraints, bi-objective uncertain optimization water management model can be established as follow.

\[
\begin{aligned}
\min F_1 &= \text{Cost}^{\text{transport}} + \text{Cost}^{\text{mate}} + \text{Cost}^{\text{disposal}} \\
\min F_2 &= \sum_{i} \sum_{j} \sum_{t} f_{\text{env}}^{\text{w}}
\end{aligned}
\]

\[
\begin{aligned}
&f_{\text{w}}^{\text{w}} + \sum_{i} \sum_{j} f_{\text{env}}^{\text{env}} \leq (0.5 - \alpha) E_{1}^{F_{ij}} + (1 - 0.5 - \alpha) E_{2}^{F_{ij}}, \forall i, j, t \\
&f_{\text{w}}^{\text{w}} + \sum_{i} \sum_{j} f_{\text{env}}^{\text{mate}} \geq (0.5 - \alpha) E_{1}^{F_{ij}} + (1 - 0.5 - \alpha) E_{2}^{F_{ij}}, \forall i, j, t \\
&f_{\text{w}}^{\text{w}} + f_{\text{prodisposal}} \leq (0.5 - \alpha) E_{1}^{F_{ij}} + (1 - 0.5 - \alpha) - E_{2}^{F_{ij}}, \forall i, j, t \\
&f_{\text{w}}^{\text{w}} + f_{\text{prodisposal}} \geq (0.5 - \alpha) E_{1}^{F_{ij}} + (1 - 0.5 - \alpha) - E_{2}^{F_{ij}}, \forall i, j, t \\
&f_{\text{w}}^{\text{w}} + f_{\text{prodisposal}} = \sum_{i} \sum_{j} f_{\text{env}}^{\text{prdisposal}} - \sum_{i} \sum_{j} f_{\text{env}}^{\text{prdisposal}}, \forall t \\
&f_{\text{w}}^{\text{w}} + f_{\text{prodisposal}} \leq \sum_{i} \sum_{j} f_{\text{env}}^{\text{prdisposal}}, \forall t
\end{aligned}
\]

s.t. (25)

3.3. Solution approach

The satisfaction degree to uncertain constraint is set from 0.5 to 1 and the weights of economic cost and weights of environment cost are assigned values between 0 and 1, while the sum of two weights equals 1. After determining relative weights of two objectives, the economic and environment cost are solvable by using compromise-programming methods. Water management problems under different scenarios are then solved using GAMS software and equations in Section 3.2.

3.4. Data

This paper uses three shale gas well pads in Sichuan as a case study. The general input parameters are list in Table1. Except the onsite treatment cost and onsite treatment recovery rate, all other data is collected from oilfield interviews (Gao and You, 2015; Henderson et al., 2011). The volume of water for hydraulic fracturing used in this study can be found in supplementary information.

Weekly flowback rates of the first two weeks after hydraulic fracturing are relatively high and show major fluctuations, as seen in historical water statistics. The weekly flowback rates during production phase is less than 0.1%, which has much lower impact on wastewater generation. Consequently, weekly flowback rates during production phase may be set as constant and corresponding to the mean value of historical data. In this study, the mean value is 0.088%.

Three different scenarios are created to reflect the uncertainty of the flowback rate in the first two weeks after hydraulic fracturing. Average flowback rates of China’s shale gas exploration is 10–15% (Zou et al., 2016). Consequently, we choose 10% and 15% as flowback rate endpoints for and separate into three resulting intervals: smaller than 10%, greater than 10% but smaller than 15%, greater than 15%. The mean values in three intervals can be obtained from historical data. Values for the three intervals should be divided by 2 (i.e. length of flowback phase) in order to obtain weekly flowback rate. Then, three scenarios are as follows:

a) Low flowback scenario, which weekly flowback rate is 3%.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck transportation cost($/m^3/kilometers)</td>
<td>0.2</td>
</tr>
<tr>
<td>Pipeline transportation cost($/m^3/kilometers)</td>
<td>0.1</td>
</tr>
<tr>
<td>Onsite treatment cost($/m^3)</td>
<td>10.9</td>
</tr>
<tr>
<td>Distance between water source and well pad(kilometers)</td>
<td>10</td>
</tr>
<tr>
<td>Distance between well pad and disposal well(kilometers)</td>
<td>5</td>
</tr>
<tr>
<td>Disposal cost on disposal well($/kilometers)</td>
<td>2.2</td>
</tr>
<tr>
<td>Onsite recovery rate</td>
<td>75%</td>
</tr>
</tbody>
</table>
b) Baseline flowback scenario, which weekly flowback rate is 6.5%.

c) High flowback scenario, which weekly flowback rate is 9%.

4. Results

4.1. Bi-objective optimization results

4.1.1. Baseline scenario with high uncertainty

Fig. 1 shows the variation of economic cost and environment cost as the economic objective weight have changed. With the changing weights, economic cost and environmental cost show nonlinear changes. The economic cost declines rapidly and the environment cost increases rapidly at the beginning. Increasing economic cost weight result in slight changes for economic cost and environment cost. From a system perspective, combinations of each set of economic cost and environment cost are indifferent, which is refer to pareto optimal. A decision-maker can use concrete strategies according to their own preferred priority between environment objective and economic objective. With increasing preference for economic objective, the proportion of fresh water usage has increased slightly, while the proportion of reused water usage has decreased slightly, which implies that a decision-maker is more willing to pay a certain environment cost for economic cost savings.

4.1.2. Baseline scenario with low uncertainty

Fig. 2 shows the pareto results when $\alpha = 0.5$ in baseline scenario. When $\alpha = 0.5$, the pareto optimal of economic cost is $465,977.8$ and the optimal environment cost is $368,160$ m$^3$ as the economic objective weight is 0. As the economic objective weight increases, economic objective was saved at the price of environment objective. The comparison between Figs. 1 and 2 indicates that when $\alpha$ increase from 0.5 to 1, both economic cost and environment cost increase as uncertainty of the system decreases. Growth of both economic and environment costs occur when the proportion of fresh water increases by 3% while proportion of reuse water decreases by 3%. This also confirms that a trade-off relationship exists between systematic uncertainty and overall system cost.

4.2. Wastewater reuse strategies

Fresh water usage ratio is calculated by the ratio of volume of fresh water that is used in hydraulic fracturing to total volume of water that is used for hydraulic fracturing. Similarly, reused water usage ratio is calculated by the ratio of volume of wastewater that is reused in hydraulic fracturing to total volume of water that is used in hydraulic fracturing.

### Table 2

<table>
<thead>
<tr>
<th>Economic objective weight</th>
<th>Environment objective weight</th>
<th>Flowback phase wastewater reuse proportion</th>
<th>Production phase wastewater onsite treat proportion</th>
<th>Wastewater reuse proportion</th>
<th>Direct disposal (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>90.6%</td>
<td>75.2%</td>
<td>56.3%</td>
<td>6080</td>
</tr>
<tr>
<td>0.1</td>
<td>0.9</td>
<td>90.6%</td>
<td>50.8%</td>
<td>38%</td>
<td>6463</td>
</tr>
<tr>
<td>0.2</td>
<td>0.8</td>
<td>90.6%</td>
<td>33%</td>
<td>24.7%</td>
<td>6808</td>
</tr>
<tr>
<td>0.3</td>
<td>0.7</td>
<td>90.6%</td>
<td>22.7%</td>
<td>17%</td>
<td>7006</td>
</tr>
<tr>
<td>0.4</td>
<td>0.6</td>
<td>90.6%</td>
<td>16.1%</td>
<td>12%</td>
<td>7136</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>90.6%</td>
<td>11.4%</td>
<td>8.5%</td>
<td>7226</td>
</tr>
<tr>
<td>0.6</td>
<td>0.4</td>
<td>90.6%</td>
<td>7.9%</td>
<td>5.9%</td>
<td>7293</td>
</tr>
<tr>
<td>0.7</td>
<td>0.3</td>
<td>90.6%</td>
<td>5.3%</td>
<td>3.9%</td>
<td>7345</td>
</tr>
<tr>
<td>0.8</td>
<td>0.2</td>
<td>90.6%</td>
<td>3.1%</td>
<td>2.3%</td>
<td>7386</td>
</tr>
<tr>
<td>0.9</td>
<td>0.1</td>
<td>90.6%</td>
<td>1.4%</td>
<td>1%</td>
<td>7420</td>
</tr>
<tr>
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<td>0%</td>
<td>7448</td>
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</tbody>
</table>

### Table 3

<table>
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<tr>
<th>Economic objective weight</th>
<th>Environment objective weight</th>
<th>Flowback phase wastewater reuse proportion</th>
<th>Production phase wastewater onsite treat proportion</th>
<th>Wastewater reuse proportion</th>
<th>Direct disposal (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>88.5%</td>
<td>70.5%</td>
<td>52.9%</td>
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<td>30%</td>
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<td>88.5%</td>
<td>26%</td>
<td>19.5%</td>
<td>7865</td>
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<td>0.7</td>
<td>88.5%</td>
<td>17.9%</td>
<td>13.4%</td>
<td>8042</td>
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<tr>
<td>0.4</td>
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<td>12.7%</td>
<td>9.5%</td>
<td>8158</td>
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<td>9%</td>
<td>6.7%</td>
<td>8239</td>
</tr>
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<tr>
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<td>3.1%</td>
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<td>88.5%</td>
<td>0%</td>
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<td>8436</td>
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</tbody>
</table>

Fig. 3 shows the results of water management strategies with different economic weight when $\alpha = 0.5$ in baseline scenario.

b) Baseline flowback scenario, which weekly flowback rate is 6.5%.

c) High flowback scenario, which weekly flowback rate is 9%.
increases by 0.1 when \( \alpha \) increases from 0.5 to 1. Conversely, the average increase of proportion of economic cost is 16.7% while the average increase of proportion of environment cost is 17.3%. This indicates significant impact of uncertainty for both economic and environment objectives.

Table 3 shows results for wastewater reuse during flowback and production phases when \( \alpha = 1 \) in baseline scenario. It indicates that, the wastewater reuse proportion is 90.6% in flowback phase when \( \alpha = 1 \), regardless of changes in economic objective and environment objective weights. The comparison between Tables 2 and 3 shows that the proportion of wastewater reuse and the proportion of wastewater that are treated onsite decrease by as much as 10% and 8% separately in production phase when \( \alpha \) increase from 0.5 to 1. Conversely, the volume of wastewater that are treated onsite decrease by as much as 10% and 8% separately in production phase when \( \alpha \) increase from 0.5 to 1. Conversely, the volume of wastewater that directly disposal increase about 1000 m\(^3\) by average. This is because less uncertainty requires more fresh water usage and less wastewater reuse for hydraulic fracturing. It demonstrates that improving tolerance to uncertainty can improve the efficiency of fresh water usage as well as wastewater reuse.

### 5. Discussion

#### 5.1. The impact of uncertainty to economic cost and environment cost

Economic cost and environment cost increases as the \( \alpha \) increases, as shown in the chapter 4. The average increase of environment cost and economic cost is shown in Table 4 when \( \alpha \) increases from 0.5 to 1. The average increase of economic cost is 16.7% while the average increase of environment cost is 17.3%. This indicates significant impact of uncertainty for both economic and environment objectives.

Fig. 4 shows change of economic cost and environment cost as the increase of \( \alpha \) when economic weight is 0.1 in baseline scenario. Both economic and environment costs increase linearly with decreasing of uncertainty after selecting economic weight and environment weight. The economic cost increases by $13,385 and environment cost increases by 10,887 m\(^3\) as \( \alpha \) increases by 0.1 when \( w_1 = 0.1 \) in baseline scenario. The variation range of environment cost and economic cost decrease with increasing value of \( \alpha \). For example, variation range of economic cost decrease from $12,968 when \( \alpha = 0.5 \) to $10,100.8 when \( \alpha = 1 \). The flexibility of change in economic cost and environmental cost decrease as the uncertainty of water needed for hydraulic fracturing decrease.

Star points represent series of pareto solution given a fixed \( \alpha \) and gather around another decreasing curve with changes in \( \alpha \). Choosing a proper uncertainty level has significant impacts than changing the economic or environmental weights for balancing the two objectives.

#### 5.2. The impact of uncertainty to wastewater reuse strategies

The variation of wastewater reuse is shown by keeping relative weights unchanged and increasing the \( \alpha \) in each subfigures of Fig. 6. Following Section 2.3, \( w_1 \) represents economic cost weight as \( w_1 \) stands for environment cost. While \( \alpha \) has significant impact to wastewater reuse strategies in the first two row of Fig. 6, the impact can be neglected in the last row for economic objective priority dominates over environment objective. Thus, the volume of wastewater intended for treatment and reuse draws closer to zero.

As shown in Fig. 7, the proportion of wastewater reuse in flowback fracturing.

#### 4.2.1. Baseline scenario with high uncertainty

Resulting wastewater reuse is displayed separately for flowback and production phases. During production phase, the volume of wastewater reuse is typically smaller or equal to the volume of wastewater that are treated onsite.

Table 2 shows that the wastewater reuse proportion is 90.6% in flowback phase when \( \alpha = 0.5 \) whatever underlying changes for economic objective weight and environment objective weight. Therefore, reusing flowback wastewater as much as possible is the best overall strategy regardless of economics or environmental perspectives. In contrast, the proportion of wastewater reuse and the proportion of wastewater that are treated onsite is highest when environment objective weight equals 1 and the specific values are 56.3% and 75.2% respectively.

As shown in Fig. 3, the proportion of wastewater treated onsite and the proportion of wastewater reuse in production phase exhibits nonlinear decreases, while the volume of wastewater that disposal show nonlinear increases with growth of the economic objective weight.

#### 4.2.2. Baseline scenario with low uncertainty

Table 3 shows results for wastewater reuse during flowback and production phases when \( \alpha = 1 \) in baseline scenario. It indicates that, the wastewater reuse proportion is 90.6% in flowback phase when \( \alpha = 1 \), regardless of changes in economic objective and environment objective weights. The comparison between Tables 2 and 3 shows that the proportion of wastewater reuse and the proportion of wastewater that are treated onsite decrease by as much as 10% and 8% separately in production phase when \( \alpha \) increase from 0.5 to 1. Conversely, the volume of wastewater that are directly disposal increase about 1000 m\(^3\) by average. This is because less uncertainty requires more fresh water usage and less wastewater reuse for hydraulic fracturing. It demonstrates that improving tolerance to uncertainty can improve the efficiency of fresh water usage as well as wastewater reuse.

#### 5. Discussion

#### 5.1. The impact of uncertainty to economic cost and environment cost

Economic cost and environment cost increases as the \( \alpha \) increases, as shown in the chapter 4. The average increase of environment cost and economic cost is shown in Table 4 when \( \alpha \) increases from 0.5 to 1. The average increase of economic cost is 16.7% while the average increase of environment cost is 17.3%. This indicates significant impact of uncertainty for both economic and environment objectives.

Fig. 4 shows change of economic cost and environment cost as the increase of \( \alpha \) when economic weight is 0.1 in baseline scenario. Both economic and environment costs increase linearly with decreasing of uncertainty after selecting economic weight and environment weight. The economic cost increases by $13,385 and environment cost increases by 10,887 m\(^3\) as \( \alpha \) increases by 0.1 when \( w_1 = 0.1 \) in baseline scenario. The variation range of environment cost and economic cost decrease with increasing value of \( \alpha \). For example, variation range of economic cost decrease from $12,968 when \( \alpha = 0.5 \) to $10,100.8 when \( \alpha = 1 \). The flexibility of change in economic cost and environmental cost decrease as the uncertainty of water needed for hydraulic fracturing decrease.

Star points represent series of pareto solution given a fixed \( \alpha \) and gather around another decreasing curve with changes in \( \alpha \). Choosing a proper uncertainty level has significant impacts than changing the economic or environmental weights for balancing the two objectives.

#### 5.2. The impact of uncertainty to wastewater reuse strategies

The variation of wastewater reuse is shown by keeping relative weights unchanged and increasing the \( \alpha \) in each subfigures of Fig. 6. Following Section 2.3, \( w_1 \) represents economic cost weight as \( w_1 \) stands for environment cost. While \( \alpha \) has significant impact to wastewater reuse strategies in the first two row of Fig. 6, the impact can be neglected in the last row for economic objective priority dominates over environment objective. Thus, the volume of wastewater intended for treatment and reuse draws closer to zero.

As shown in Fig. 7, the proportion of wastewater reuse in flowback
5.3. The comparison of bi-objective optimization in different scenarios

Fig. 8 presents comparisons of bi-objective optimization solutions among three scenarios. The low flowback scenario has the highest economic cost and environment cost among all scenarios. Low flowback rates during the first two week causes more fresh water demand for hydraulic fracturing and this enhanced the greater environment impact. At the same time, more fresh water implies that more transportation fees are acquired, which generates higher economic costs. In contrast, the high flowback scenario has the lowest economic and environment costs. Direct reuse of wastewater from the flowback phase and reuse of wastewater after onsite treatment have greater water saving effects in the high flowback case than in other scenarios. This indicates that to centrally treated wastewater can reduce both economic cost and environmental cost effectively and that “economics of scale” exists.

5.4. Sensitivity analysis

This section conducts a sensitivity analysis to explore how different economic parameters influence the economic objective. Unit cost of pipeline transportation has the largest impact among four studied
economic parameters. This is understandable from the significant volumes of fresh water are transported by pipeline from a water source to a well pad. In contrast, variations of other economic parameters don't have any significant impact on the economic objective. Onsite treatment cost of wastewater is much larger than the other cost parameters in line with findings of Grecu et al. (2018), but we find that corresponding variations do not generate any noteworthy changes in the economic objective. This point to the conclusion that just decreasing costs of onsite treatment fails efficiently improve water management, without assistance from further improvements in wastewater technology and water recycling. Fig. 9 displays the resulting sensitivities.

6. Conclusions and future studies

This study constructs a bi-objective programming model for water management in shale gas exploration that considers uncertainty of volume of water needed for hydraulic fracturing as well as uncertainties in flowback wastewater volumes. Bi-objective optimization results and corresponding wastewater strategies derive from solving the model based on data from real exploration activities in Sichuan. The main conclusions are as follows:

(1) Reasonable acceptance of uncertainty can effectively save both economic and environment costs and flexibly adjust them according to decision-maker preferences. Furthermore, it helps to enhance the enthusiasm for onsite treatment and reuse of wastewater during production phase. In contrast, both economic and environment costs increase and more wastewater is directly disposed during the production phase as uncertainty decreases. The proportion of fresh water usage increases, along with environment cost increases and the economic cost decreases when decision maker increases the weight of economic objective and fixes the satisfaction degree for uncertain constraints.

(2) The impacts of different water management strategies can be distinctive throughout the production phase. Regardless of the value of weight, the best water strategy is to reuse the wastewater as much as possible during the flowback phase. Relatively high onsite treatment cost is one of several reasons that make wastewater management strategies to remain at low levels of ambition. The “economics of scale” of wastewater handling during shale gas exploration suggests that centralized treatment has higher efficiency.

(3) In addition to the management strategies addressed in this study, improvement of onsite technologies for wastewater treatment and establishment of gradual treatment system with well-formulated treatment standards can promote the increased efficiency in water management during shale gas exploration. High onsite treatment cost and low technical treatment level still restrict efficient use of water during developments of shale gas. Thus, technical and economic uncertainty remains for water management in shale gas exploration and additional research is required to illuminate such remaining issues.

In future studies, a more detailed comparative analysis of system boundaries, multiple uncertain factors and data set of different case studies should be provided. Also, to better recognize the influence of technology progress to the water management of shale gas exploration may help us make the water management process more efficiency.

Acknowledgments

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2019.01.003.

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