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pubs.acs.org/IECR

Two-Stage Fracturing Wastewater Management in Shale Gas Development

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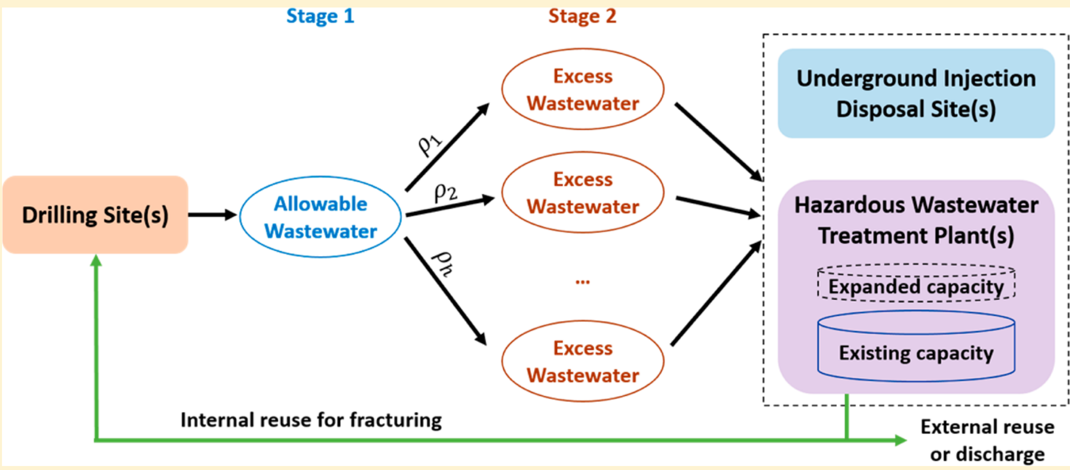
Supporting Information



ABSTRACT: Management of shale gas wastewater treatment, disposal, and reuse has become a significant environmental challenge, driven by an ongoing boom in development of U.S. shale gas reservoirs. Systems-analysis based decision support is helpful for effective management of wastewater, and provision of cost-effective decision alternatives from a whole-system perspective. Uncertainties are inherent in many modeling parameters, affecting the generated decisions. In order to effectively deal with the recourse issue in decision making, in this work a two-stage stochastic fracturing wastewater management model, named TSWM, is developed to provide decision support for wastewater management planning in shale plays. Using the TSWM model, probabilistic and nonprobabilistic uncertainties are effectively handled. The TSWM model provides flexibility in generating shale gas wastewater management strategies, in which the first-stage decision predefined by decision makers before uncertainties are unfolded is corrected in the second stage to achieve the whole-system's optimality. Application of the TSWM model to a comprehensive synthetic example demonstrates its practical applicability and feasibility. Optimal results are generated for allowable wastewater quantities, excess wastewater, and capacity expansions of hazardous wastewater treatment plants to achieve the minimized total system cost. The obtained interval solutions encompass both optimistic and conservative decisions. Trade-offs between economic and environmental objectives are made depending on decision makers' knowledge and judgment, as well as site-specific information. The proposed model is helpful in forming informed decisions for wastewater management associated with shale gas development.

1. INTRODUCTION

Shale gas development has boomed in the past few years as a result of advances in fracturing techniques and increasing energy demand. It is projected that shale gas production will account for about 55% of the total U.S. dry gas production by 2040.[1] The rapid increase of shale gas production may plausibly result in a number of environmental problems, among which wastewater management has received more concerns and public scrutiny. A large quantity of wastewater, including flowback and produced water (hereinafter FP water) is generated during hydraulic fracturing operations.[2−4] The FP water may be reused, treated onsite or offsite, and disposed in deep-well injection wells, depending on site-specific information, availability of treatment/disposal techniques, characteristics of the generated FP water, local geologic/hydrogeological/seismologic conditions, and regulatory and permitting allowances.[3,5−12] Managing FP water is a challenging environmental issue, complicating the shale gas operations and development in practice. Selection of the appropriate management strategies for shale gas wastewater has become a priority task in unconventional oil and gas industries. Planning and management of wastewater reuse,

Received: October 13, 2016
Revised: January 19, 2017
Accepted: January 19, 2017
Published: January 19, 2017

DOI: 10.1021/acs.iecr.6b03971
Ind. Eng. Chem. Res. 2017, 56, 1570−1579

treatment, and disposal requires sound and defensible decisions. For these purposes, the systems-analysis based decision support is helpful for effective management of shale gas wastewater and provision of cost-effective decision alternatives from a whole-system perspective.[13,14]

Previously, some optimization models have been proposed for dealing with wastewater management issues in shale gas development. For example, Karapataki[15] developed a mixed-integer linear programming model to techno-economically evaluate wastewater management options in the Marcellus shale play. Yang et al.[16] optimized fracturing schedule by incorporating water transportation, treatment and reuse using mixed-integer linear programming. Gao and You[17,18] proposed a mixed-integer linear fractional programming model for water supply chain network planning associated with shale gas production. Based on life cycle analysis, Gao and You[19] further analyzed water acquisition and wastewater management through a multiobjective nonconvex mixed-integer nonlinear programming model for shale gas supply chain planning. Guerra et al.[5] addressed water supply and wastewater management issues in an optimization model for shale gas supply chains management. However, these models are deterministic and cannot handle the uncertainties existing in the modeling parameters for shale gas wastewater management. More recently, attempts have been made to cope with the uncertainty issue in shale gas wastewater management. Lira-Barragán et al.[20] developed a mathematical programming model for planning water networks in shale gas operations, where water usage for fracturing and flowback water are modeled as uncertain modeling parameters based on scenarios analysis. Zhang et al.[2] proposed an uncertainty programming model based on the fuzzy-stochastic mixed-integer programming for shale gas wastewater management under uncertainties. However, the above-mentioned models are single-stage and cannot deal with the recourse issue when uncertainty in the future is known. Such a problem can be formulated as a two-stage stochastic programming (TSP) problem, in which the first-stage decision is made before uncertainties (i.e., values of random variables) are unfolded, and a corrective or recourse action named the second-stage decision is undertaken after realization of uncertain events.[21−27] TSP is effective in dealing with the recourse issue, which means the corrective actions can be taken to minimize the potential penalties due to decision infeasibility.[22,23] TSP has been actively developed and applied in a variety of research fields. In actual wastewater management for shale gas development, either some of the site information may not be available for being elicited as a probabilistic density distribution (PDF) or the available information is insufficient for generating a PDF and can only be expressed as intervals. For example, cost-related parameters related to transportation, treatment and disposal of wastewater, and capacity expansion of wastewater treatment facilities, as well as available capacity of wastewater treatment facilities frequently fall in these categories.

The objective of this study is to develop a two-stage stochastic fracturing wastewater management model, named TSWM, for supporting FP water management planning associated with shale gas development. The TSWM model incorporates interval analysis and TSP into a modeling-analysis framework, effectively reflecting the probabilistic and nonprobabilistic information. The proposed TSWM model is applied to a synthetic example problem in Zhang et al.[2] to demonstrate its feasibility, which is consistent with realistic site decision analyses in practices. The TSWM model enables decision makers to take corrective actions for their first-stage decisions on predefined wastewater allocation to various treatment and disposal facilities before uncertainties of wastewater generation rates are known. Through dynamic adjustment of the first-stage decisions, decision makers can make adaptive management strategies for shale gas wastewater treatment and disposal to minimize the penalties. The TSWM model provides flexibility in generating various decision alternatives for supporting FP water management in shale gas development under hybrid uncertainties.

2. MODEL DEVELOPMENT

2.1. TSWM Model for Shale Gas Wastewater Management. A two-stage fracturing wastewater management model, named TSWM, is formulated. With the stricter permitting and regulations, municipal wastewater treatment plants are banned for treatment of shale gas wastewater due to their insufficient capabilities for handling high concentrations of total dissolved solids (TDS).[8,9] Reuse is becoming prevalent in many shale plays since it can simultaneously reduce the amounts of water supply and wastewater; this is especially true in the Marcellus play with almost 90% of wastewater reuse rate in 2012.[2,11,12,28,29] To be consistent with the real-world situations, options for FP water management considered in the TSWM model include underground injection disposal, treatment in hazardous wastewater treatment plants (HWTPs), and reuse. The descriptions of the integrated FP water management system and assumptions are detailed in the work of Zhang et al.[2] The problem of concern is how to manage the allocation of FP water between different treatment/disposal options, as well as plan capacity expansions of treatment facilities.

From an integrated FP water management system perspective, the economic objective is preferably important. That means the decision maker prioritizes the decisions to achieve the minimized total system cost. As a result, the management objective of the TSWM model is to minimize the total system cost, including the costs for wastewater transportation, wastewater treatment and disposal, capacity expansion of the treatment facility, and revenues from reuse of wastewater after treatment in HWTPs. Decision variables include wastewater allocation from generation sources to various treatment and disposal facilities (continuous variables) and options for capacity expansions of treatment facilities (binary variables). The objective function of the TSWM model is thus formulated as follows:

$$\begin{aligned}\min f^{\pm} = {}& P_k\left(\sum_{i=1}^{5}\sum_{j=1}^{3}\sum_{k=1}^{3}(COP_{jk}^{\pm} + CTR_{ijk}^{\pm})T_{ijk}^{\pm}\right.\\ &\left.- \sum_{i=1}^{5}\sum_{j=2}^{3}\sum_{k=1}^{3}RE_{jk}^{\pm}RR_{jk}^{\pm}T_{ijk}^{\pm}\right)\\ &+ P_k\left(\sum_{i=1}^{5}\sum_{j=1}^{3}\sum_{k=1}^{3}\sum_{h=1}^{3}(XOP_{jk}^{\pm} + XTR_{ijk}^{\pm})\rho_h X_{ijkh}^{\pm}\right.\\ &\left.- \sum_{i=1}^{5}\sum_{j=2}^{3}\sum_{k=1}^{3}\sum_{h=1}^{3}RE_{jk}^{\pm}RR_{jk}^{\pm}\rho_h X_{ijkh}^{\pm}\right) + \sum_{j=2}^{3}\sum_{m=1}^{3}\sum_{k=1}^{3}CEX_{jmk}^{\pm}Y_{jmk}^{\pm}\end{aligned} \quad (1a)$$

where $R^{\pm}$ is a set of interval numbers, $R^{\pm} = [R^{-}, R^{+}]$, R^{-} and R^{+} are the lower and upper bounds of $R^{\pm}$, and R is a real number; i = an index for FP water generation sources (i = 1−5, representing five drilling sites); j = an index for FP water treatment and disposal facilities, including one underground injection disposal (UID) site (j = 1) and two specially designed and planned

HWTPs ($j = 2, 3$); k = an index for the planning periods ($k = 1$ to 3); m = an index for capacity-expansion options for HWTPs; $f^{\pm}$ = total system cost, which is the management objective to be minimized; P_k = duration of each planning period k (days); $COP_{jk}^{\pm}$ = treatment/disposal cost of allowable wastewater in facility j in period k (\$/bbl); $CTR_{ijk}^{\pm}$ = transportation cost of allowable wastewater from source i to facility j in period k (\$/bbl); $T_{ijk}^{\pm}$ = continuous decision variables, representing the allowable wastewater quantity in source i delivered to facility j in period k (bbl/day), which are called the first-stage decision variables; $X_{ijkh}^{\pm}$ = excess wastewater quantity in source i delivered to facility j in period k (bbl/day) when the wastewater generation rate is WWG_{ik} with a probability of ρ_h, which are called the second-stage decision variables, where excess wastewater is defined as surplus wastewater that exceeds the allowable wastewater quantity; $RE_{jk}^{\pm}$ = revenues from reusing wastewater in facility j in period k (\$/bbl); $RR_{jk}^{\pm}$ = wastewater reuse rate in facility j in period k (% of incoming wastewater quantity to the facility j); $XOP_{jk}^{\pm}$ = treatment and disposal cost for excess wastewater in facility j in period k (\$/bbl), $XOP_{jk}^{\pm} \geq COP_{jk}^{\pm}$; $XTR_{ijk}^{\pm}$ = transportation cost of excess wastewater from source i to facility j in period k (\$/bbl), $XTR_{ijk}^{\pm} \geq CTR_{ijk}^{\pm}$; ρ_h = probability level of the wastewater generation rate; $CEX_{jmk}^{\pm}$ = capital cost for capacity expansions with option m in facility j in period k (\$); and Y_{jmk} = binary decision variables, representing capacity-expansion option m in facility j at the beginning of the planning period k.

The constraints include:

(1) Capacity constraints of the underground injection disposal site: The amounts of wastewater delivered to the underground injection disposal site cannot exceed its available capacity over the planning horizon.

$$\sum_{i=1}^{5}\sum_{k=1}^{3} P_k(T_{i1k}^{\pm} + X_{i1kh}^{\pm}) \leq UIF^{\pm}, \quad \forall\, h \tag{1b}$$

where $UIF^{\pm}$ = available capacity of underground injection disposal site ($j = 1$) during the planning periods (bbl).

(2) Capacity constraints of hazardous wastewater treatment plants: The quantity of wastewater allocated to each HWTP cannot be larger than the sum of its existing and increased treatment capacity in each planning period.

$$\sum_{i=1}^{5} (T_{ijk'}^{\pm} + X_{ijk'h}^{\pm}) \leq WTP_j^{\pm} + \sum_{m=1}^{3}\sum_{k=1}^{k'} EO_{jmk}^{\pm} Y_{jmk}^{\pm}, \quad \forall\, h, j = 2, 3;\ k' = 1, 2, 3 \tag{1c}$$

where $WTP_j^{\pm}$ = treatment capacity of hazardous wastewater treatment plant j (bbl/day) and $EO_{jmk}^{\pm}$ = increased treatment capacity with expansion option m for hazardous wastewater treatment plant j in period k (bbl/day).

(3) Wastewater treatment-demand constraints: The sum of allowable and excess wastewater quantity should not be less than wastewater generation rate under any probability level in each source in each planning period.

$$\sum_{j=1}^{3} (T_{ijk}^{\pm} + X_{ijkh}^{\pm}) \geq WWG_{ikh}^{\pm}, \quad \forall\, i, k, h \tag{1d}$$

where $WWG_{ikh}^{\pm}$ = random parameters, representing the wastewater generation rate in source i in period k with a probability of ρ_h (bbl/day).

(4) Technical constraints: All the decision variables are non-negative. Capacity expansion of each hazardous wastewater treatment plant can only occur once in any given planning period.

$$T_{ijk}^{\pm}, X_{ijkh}^{\pm} \geq 0, \quad \forall\, i, j, k, h \tag{1e}$$

$$Y_{jmk}^{\pm} = \{0, 1\}, \quad \forall\, j, m, k \tag{1f}$$

$$\sum_{m=1}^{3} Y_{jmk}^{\pm} \leq 1, \quad \forall\, j, k \tag{1g}$$

2.2. Solution Method. The TSWM model described in the previous section is an interval two-stage stochastic programming model, involving hybrid uncertainties expressed as interval and stochastic parameters. A two-step interactive algorithm is introduced to transform this model into two crisp submodels which can be more easily solved.[30−33] Since the management objective of the TSWM model is to minimize the total system cost, the first step is to formulate a submodel corresponding to f^- (the lower bound of the objective function value), and the second step is to formulate a submodel corresponding to f^+ (the upper bound of the objective function value) based on the first submodel, where $T_{ijk}^{\pm}$ are decision variables to be optimized. If $T_{ijk}^{\pm}$ are predetermined by decision makers, the TSWM model can be solved using the above two-step algorithm; when $T_{ijk}^{\pm}$ are unknown, conversions are first made as follows:[23]

$$T_{ijk}^{\pm} = T_{ijk}^{-} + \Delta T_{ijk} \cdot y_{ijk} \tag{2}$$

where $\Delta T_{ijk} = T_{ijk}^{+} - T_{ijk}^{-}$ and $0 \leq y_{ijk} \leq 1$.

The submodel corresponding to f^- is first formulated and solved as follows:

$$\begin{aligned}\min f^- = {} & P_k\left(\sum_{i=1}^{5}\sum_{j=1}^{3}\sum_{k=1}^{3} (COP_{jk}^{-} + CTR_{ijk}^{-})(T_{ijk}^{-} + \Delta T_{ijk} \cdot y_{ijk}) - \sum_{i=1}^{5}\sum_{j=2}^{3}\sum_{k=1}^{3} RE_{jk}^{+} RR_{jk}^{+} (T_{ijk}^{-} + \Delta T_{ijk} \cdot y_{ijk})\right) \\ & + P_k\left(\sum_{i=1}^{5}\sum_{j=1}^{3}\sum_{k=1}^{3}\sum_{h=1}^{3} (XOP_{jk}^{-} + XTR_{ijk}^{-})\rho_h X_{ijkh}^{-} - \sum_{i=1}^{5}\sum_{j=2}^{3}\sum_{k=1}^{3}\sum_{h=1}^{3} RE_{jk}^{+} RR_{jk}^{+} \rho_h X_{ijkh}^{-}\right) + \sum_{j=2}^{3}\sum_{m=1}^{3}\sum_{k=1}^{3} CEX_{jmk}^{-} Y_{jmk}^{-}\end{aligned} \tag{3a}$$

Subject to

$$\sum_{i=1}^{5}\sum_{k=1}^{3} P_k(T_{i1k}^{-} + \Delta T_{i1k} \cdot y_{i1k} + X_{i1kh}^{-}) \leq UIF^{+}, \quad \forall\, h \tag{3b}$$

$$\sum_{i=1}^{5} (T_{ijk'}^{-} + \Delta T_{ijk'} \cdot y_{ijk'} + X_{ijk'h}^{-}) \leq WTP_j^{+} + \sum_{m=1}^{3}\sum_{k=1}^{k'} EO_{jmk}^{+} Y_{jmk}^{-}, \quad \forall\, h, j = 2, 3;\ k' = 1, 2, 3 \tag{3c}$$

$$\sum_{j=1}^{3} (T_{ijk}^{-} + \Delta T_{ijk} \cdot y_{ijk} + X_{ijkh}^{-}) \geq WWG_{ikh}^{-}, \quad \forall\, i, k, h \tag{3d}$$

DOI: 10.1021/acs.iecr.6b03971
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$$T_{ijk}^{-} + \Delta T_{ijk} \cdot y_{ijk} \geq 0, \quad \forall\ i, j, k \tag{3e}$$

$$X_{ijkh}^{-} \geq 0, \quad \forall\ i, j, k, h \tag{3f}$$

$$Y_{jmk}^{-} = \{0, 1\}, \quad \forall\ j, m, k \tag{3g}$$

$$\sum_{m=1}^{3} Y_{jmk}^{-} \leq 1, \quad \forall\ j, k \tag{3h}$$

Based on the solutions of f_{opt}^{-}, $X_{ijkhopt}^{-}$, Y_{jmkopt}^{-} and y_{ijkopt} from the first submodel corresponding to f^{-}, the submodel corresponding to f^{+} is then formulated as follows:

$$\begin{aligned} \min f^{+} = {} & P_k\Bigg(\sum_{i=1}^{5}\sum_{j=1}^{3}\sum_{k=1}^{3}(COP_{jk}^{+} + CTR_{ijk}^{+})(T_{ijk}^{-} + \Delta T_{ijk} \cdot y_{ijkopt}) \\ & - \sum_{i=1}^{5}\sum_{j=2}^{3}\sum_{k=1}^{3} RE_{jk}^{-}RR_{jk}^{-}(T_{ijk}^{-} + \Delta T_{ijk} \cdot y_{ijkopt})\Bigg) \\ & + P_k\Bigg(\sum_{i=1}^{5}\sum_{j=1}^{3}\sum_{k=1}^{3}\sum_{h=1}^{3}(XOP_{jk}^{-} + XTR_{ijk}^{-})\rho_h X_{ijkh}^{+} \\ & - \sum_{i=1}^{5}\sum_{j=2}^{3}\sum_{k=1}^{3}\sum_{h=1}^{3} RE_{jk}^{-}RR_{jk}^{-}\rho_h X_{ijkh}^{+}\Bigg) + \sum_{j=2}^{3}\sum_{m=1}^{3}\sum_{k=1}^{3} CEX_{jmk}^{+}Y_{jmk}^{+} \end{aligned} \tag{4a}$$

$$\sum_{i=1}^{5}\sum_{k=1}^{3} P_k(T_{i1k}^{-} + \Delta T_{i1k} \cdot y_{i1kopt} + X_{i1kh}^{+}) \leq UIF^{-}, \quad \forall\ h \tag{4b}$$

$$\begin{aligned} \sum_{i=1}^{5}(T_{ijk'}^{-} + \Delta T_{ijk'} \cdot y_{ijk'opt} + X_{ijk'h}^{+}) \leq {} & WTP_j^{-} \\ & + \sum_{m=1}^{3}\sum_{k=1}^{k'} EO_{jmk}^{-}Y_{jmk}^{+}, \quad \forall\ h, j = 2, 3;\ k' = 1, 2, 3 \end{aligned} \tag{4c}$$

$$\sum_{j=1}^{3}(T_{ijk}^{-} + \Delta T_{ijk} \cdot y_{ijkopt} + X_{ijkh}^{+}) \geq WWG_{ikh}^{+}, \quad \forall\ i, k, h \tag{4d}$$

$$T_{ijk}^{-} + \Delta T_{ijk} \cdot y_{ijkopt} \geq 0, \quad \forall\ i, j, k \tag{4e}$$

$$X_{ijkh}^{+} \geq X_{ijkhopt}^{-}, \quad \forall\ i, j, k, h \tag{4f}$$

$$Y_{jmk}^{+} \geq Y_{jmk}^{-}, \quad \forall\ j, m, k \tag{4g}$$

$$Y_{jmk}^{+} = \{0, 1\}, \quad \forall\ j, m, k \tag{4h}$$

$$\sum_{m=1}^{3} Y_{jmk}^{+} \leq 1, \quad \forall\ j, k \tag{4i}$$

The solutions of f_{opt}^{+}, $X_{ijkhopt}^{+}$, and Y_{jmkopt}^{+} are obtained by solving the submodel corresponding to f^{+}. As a result, the optimal solutions of model 1 are obtained, which are $[f_{\text{opt}}^{-}, f_{\text{opt}}^{+}]$, $[X_{ijkhopt}^{-}, X_{ijkhopt}^{+}]$, $T_{ijkopt}^{\pm} = T_{ijk}^{-} + \Delta T_{ijk} \cdot y_{ijkopt}$, and $[Y_{jmkopt}^{-}, Y_{jmkopt}^{+}]$.

3. STATEMENT OF THE PROBLEM

The developed TSWM model is applied to the synthetic example case of a representative shale gas FP water management system in the work of Zhang et al.[2] to test its practical applicability. The detailed descriptions of the shale gas FP water management system and wastewater treatment/disposal options are found in the work of Zhang et al.[2] To extract natural gas at large scales, the system consists of five drilling sites, where water and proppants are injected into underground at high pressure to frack shale formations, and at the same time, wastewater including flowback and produced water is released.[2] In order to mitigate or reduce the impacts of wastewater to the environment and public health, wastewater has to be reused, treated, and/or disposed. Three wastewater treatment/disposal facilities exist, including one underground injection disposal site and two HWTPs. The wastewater generated at five drilling sites is delivered to these three facilities for further treatment and underground injection disposal. The 15-y planning horizon is divided into three equal planning periods (5 y each). Table 1 shows the allowable wastewater quantities from drilling sites to treatment and disposal facilities over the planning horizon. Table 2 presents the wastewater generation rates under various probabilities at five drilling sites. Table 3 shows the cost parameters for allowable wastewater, including transportation costs from drilling sites to treatment and disposal facilities during the three planning periods, and treatment or disposal costs in treatment/disposal facilities. The transportation costs and treatment or disposal costs for excess wastewater are listed in Table 4, which are assumed to be much higher than those for allowable wastewater; excess wastewater volume is defined by the exceedance of the allowable wastewater during each planning period (in Table 3). As a result, allocation of excess wastewater will lead to a

Table 1. Allowable Wastewater Quantities from Drilling Sites to Treatment/Disposal Facilities (bbl/day)

		period		
source	treatment/ disposal facility	$k = 1$	$k = 2$	$k = 3$
drilling site 1	UID site	[460, 610]	[480, 630]	[510, 670]
drilling site 1	HWTP 1	[2600, 3100]	[2800, 3400]	[3000, 3600]
drilling site 1	HWTP 2	[2500, 2680]	[2550, 2710]	[2590, 2730]
drilling site 2	UID site	[400, 550]	[440, 590]	[470, 620]
drilling site 2	HWTP 1	[1800, 2300]	[2000, 2600]	[2200, 2800]
drilling site 2	HWTP 2	[2200, 2380]	[2250, 2410]	[2290, 2430]
drilling site 3	UID site	[560, 710]	[580, 730]	[620, 770]
drilling site 3	HWTP 1	[2700, 3300]	[2900, 3500]	[3200, 3700]
drilling site 3	HWTP 2	[1700, 1880]	[1750, 1910]	[1790, 1930]
drilling site 4	UID site	[420, 560]	[450, 590]	[470, 640]
drilling site 4	HWTP 1	[1900, 2600]	[2300, 2900]	[2600, 3300]
drilling site 4	HWTP 2	[2920, 3110]	[2950, 3150]	[2990, 3160]
drilling site 5	UID site	[640, 790]	[660, 830]	[690, 850]
drilling site 5	HWTP 1	[2100, 2800]	[2400, 3200]	[2800, 3500]
drilling site 5	HWTP 2	[2000, 2180]	[2050, 2210]	[2090, 2240]

DOI: 10.1021/acs.iecr.6b03971
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Table 2. Wastewater Generation Rates under Various Probabilities (bbl/day)

source	wastewater generation level	probability level	period $k = 1$	$k = 2$	$k = 3$
drilling site 1	low	20%	[5450, 5650]	[5600, 5770]	[5750, 5900]
	medium	60%	[5750, 5900]	[5850, 5950]	[5900, 6000]
	high	20%	[6000, 6150]	[6100, 6250]	[6200, 6350]
drilling site 2	low	20%	[4220, 4410]	[4340, 4460]	[4470, 4550]
	medium	60%	[4480, 4620]	[4520, 4680]	[4630, 4700]
	high	20%	[4690, 4810]	[4760, 4850]	[4900, 5030]
drilling site 3	low	20%	[5080, 5220]	[5160, 5270]	[5210, 5340]
	medium	60%	[5300, 5410]	[5380, 5510]	[5460, 5530]
	high	20%	[5490, 5570]	[5560, 5690]	[5620, 5750]
drilling site 4	low	20%	[5840, 5940]	[5900, 6000]	[5980, 6070]
	medium	60%	[6050, 6130]	[6060, 6170]	[6110, 6190]
	high	20%	[6200, 6300]	[6240, 6350]	[6260, 6380]
drilling site 5	low	20%	[4970, 5070]	[5060, 5150]	[5110, 5220]
	medium	60%	[5100, 5210]	[5200, 5270]	[5250, 5300]
	high	20%	[5240, 5330]	[5320, 5400]	[5340, 5410]

Table 3. Cost Parameters for Allowable Wastewater Transportation and Treatment/Disposal ($/bbl)

source	treatment and disposal facility	period $k = 1$	$k = 2$	$k = 3$
	transportation costs			
drilling site 1	UID site	[2.1, 2.8]	[2.7, 3.5]	[3.3, 3.9]
drilling site 1	HWTP 1	[3.0, 3.6]	[3.2, 4.0]	[3.6, 4.5]
drilling site 1	HWTP 2	[5.2, 6.0]	[5.8, 6.8]	[6.2, 7.2]
drilling site 2	UID site	[6.2, 6.8]	[6.6, 7.2]	[7.1, 7.7]
drilling site 2	HWTP 1	[2.6, 3.7]	[3.3, 3.8]	[4.0, 4.9]
drilling site 2	HWTP 2	[3.2, 3.6]	[3.5, 4.1]	[3.7, 4.4]
drilling site 3	UID site	[3.9, 4.5]	[4.6, 5.0]	[5.3, 5.7]
drilling site 3	HWTP 1	[4.5, 5.1]	[5.1, 5.5]	[5.7, 6.1]
drilling site 3	HWTP 2	[4.9, 5.3]	[5.3, 5.7]	[6.1, 6.5]
drilling site 4	UID site	[2.5, 3.0]	[3.0, 3.5]	[3.6, 4.1]
drilling site 4	HWTP 1	[5.8, 6.3]	[6.5, 7.0]	[7.0, 7.5]
drilling site 4	HWTP 2	[3.4, 3.9]	[4.1, 4.5]	[4.6, 5.1]
drilling site 5	UID site	[6.8, 7.3]	[7.2, 7.7]	[7.6, 8.1]
drilling site 5	HWTP 1	[2.9, 3.5]	[3.3, 3.8]	[3.6, 4.1]
drilling site 5	HWTP 2	[2.8, 3.4]	[3.5, 4.0]	[4.0, 4.5]
	operational costs of treatment/disposal facility			
	UID site	[1.2, 1.9]	[1.8, 2.6]	[2.4, 2.9]
	HWTP 1	[3.5, 4.3]	[4.2, 4.7]	[5.0, 5.5]
	HWTP 2	[2.9, 3.7]	[3.4, 4.2]	[3.9, 4.9]

significant increase of the total system cost. Table 5 presents the wastewater reuse rates in two HWTPs and revenues from wastewater reuse; the parameters listed in Table 5 indicate that the wastewater reuse is becoming prevalent in shale gas wastewater management. The available capacity of the underground injection disposal site is [18.9, 20.0] × 10^6 bbl over the planning horizon. The treatment capacities of two HWTPs are [12000, 13700] and [11400, 12500] bbl/day, respectively. As the amounts of wastewater increase, existing capacities of two HWTPs will not be able to meet the treatment requirements; capacity expansions of two HWTPs are considered. Table 6 lists the capacity expansion options and capital costs for various options in two HWTPs, which are representative of real-world conditions in major U.S. shale plays.

If the allowable wastewater quantities, predetermined by decision makers before uncertainties are known, are sufficient for meeting the wastewater treatment/disposal requirements, no additional expenses will occur, leading to a minimized total system cost. However, if the allowable wastewater quantities are not sufficient, excess wastewater will be delivered, resulting in penalties (i.e., higher transportation and treatment/disposal

Table 4. Cost Parameters for Excess Wastewater Transportation and Treatment/Disposal ($/bbl)

source	treatment and disposal facility	period $k = 1$	$k = 2$	$k = 3$
	transportation costs			
drilling site 1	UID site	[4.2, 4.9]	[4.8, 5.6]	[5.6, 6.1]
drilling site 1	HWTP 1	[5.1, 5.7]	[5.3, 6.1]	[5.7, 6.6]
drilling site 1	HWTP 2	[7.3, 8.1]	[7.9, 8.9]	[8.3, 9.3]
drilling site 2	UID site	[9.0, 9.6]	[9.4, 10.0]	[9.8, 10.5]
drilling site 2	HWTP 1	[5.4, 6.5]	[6.1, 6.6]	[6.8, 7.7]
drilling site 2	HWTP 2	[5.0, 6.4]	[6.3, 6.9]	[6.5, 7.2]
drilling site 3	UID site	[7.1, 7.7]	[7.8, 8.2]	[8.5, 8.9]
drilling site 3	HWTP 1	[7.7, 8.3]	[8.3, 8.7]	[8.9, 9.3]
drilling site 3	HWTP 2	[8.1, 8.4]	[8.5, 8.8]	[9.3, 9.7]
drilling site 4	UID site	[4.9, 5.4]	[5.4, 5.9]	[6.0, 6.5]
drilling site 4	HWTP 1	[8.2, 8.7]	[8.9, 9.4]	[9.4, 9.9]
drilling site 4	HWTP 2	[5.8, 6.3]	[6.5, 6.9]	[7.0, 7.5]
drilling site 5	UID site	[9.7, 10.1]	[10.0, 10.5]	[10.4, 10.8]
drilling site 5	HWTP 1	[5.6, 6.3]	[6.1, 6.5]	[6.4, 6.9]
drilling site 5	HWTP 2	[5.5, 6.1]	[6.2, 6.8]	[6.7, 7.2]
	operational costs of treatment/disposal facility			
	UID site	[3.8, 4.5]	[4.4, 5.2]	[5.0, 5.5]
	HWTP 1	[5.8, 6.6]	[6.5, 7.0]	[7.3, 7.8]
	HWTP 2	[5.4, 6.2]	[5.9, 6.7]	[6.4, 7.3]

Table 5. Parameters Related to Wastewater Reuse

	period $k = 1$	$k = 2$	$k = 3$
	wastewater reuse rate (%)		
HWTP 1	[0.75, 0.81]	[0.83, 0.88]	[0.90, 0.95]
HWTP 2	[0.70, 0.76]	[0.78, 0.84]	[0.86, 0.92]
	revenues from wastewater reuse ($/bbl)		
HWTP 1	[1.1, 1.6]	[1.2, 1.7]	[1.3, 1.8]
HWTP 2	[0.9, 1.3]	[1.1, 1.5]	[1.2, 1.6]

DOI: 10.1021/acs.iecr.6b03971
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Table 6. Treatment Capacity Expansion Options and Capital Costs of Two HWTPs

facility	capacity expansion option m	period $k = 1$	$k = 2$	$k = 3$
capital costs of capacity expansion (10^6 present value)				
HWTP 1	1	[15.5, 16.6]	[14.0, 16.2]	[10.6, 12.3]
HWTP 1	2	[18.2, 19.4]	[15.8, 17.3]	[13.9, 15.7]
HWTP 1	3	[20.9, 22.1]	[17.5, 19.4]	[14.7, 16.2]
HWTP 2	1	[11.2, 13.5]	[9.6, 11.5]	[7.6, 9.9]
HWTP 2	2	[13.1, 14.8]	[11.0, 13.3]	[9.7, 11.6]
HWTP 2	3	[15.8, 17.3]	[13.6, 15.2]	[11.8, 13.4]
increased treatment capacity (bbl/day)				
HWTP 1	1	[590, 630]	[590, 630]	[590, 630]
HWTP 1	2	[740, 780]	[740, 780]	[740, 780]
HWTP 1	3	[820, 860]	[820, 860]	[820, 860]
HWTP 2	1	[530, 560]	[530, 560]	[530, 560]
HWTP 2	2	[620, 660]	[620, 660]	[620, 660]
HWTP 2	3	[790, 830]	[790, 830]	[790, 830]

costs for excess wastewater) and, therefore, a higher total system cost. The problem under consideration is how to plan the wastewater allocation patterns from a variety of drilling sites to various treatment and disposal facilities under hybrid probabilistic and nonprobabilistic uncertainties. The proposed TSWM model is employed to deal with such a planning problem, where the first-stage predefined decision for wastewater allocation is corrected by the second-stage decision to achieve the optimality of the whole system after uncertainties are known. The developed model is solved by Lingo, a programming modeling software, with less than one second of computational time for each submodel on a computer equipped with an Intel Core i5-5200U 2.20 GHz CPU and 8 GB RAM.

4. RESULTS

The solutions obtained from the TSWM model are shown in Table S1 in the Supporting Information. Partial solutions are intervals, reflecting the impacts of uncertain input model parameters such as wastewater transportation costs, operational costs for treatment and disposal, revenues of wastewater reuse, capacity of wastewater treatment and disposal facility, facility capacity expansions, and wastewater generation. Decision variables of wastewater allocation may vary within their interval solutions, offering flexibility in forming informed decisions for wastewater management. For example, the lower value, the upper value, or any value within the interval for each decision variable can be determined by decision makers, leading to a number of combinations of decision variables and, consequently, solutions for wastewater management decisions. Solutions of $T_{ijk}^{\pm}$ in Table S1 in the Supporting Information are optimized values for allowable wastewater quantities, which are within their own intervals of allowable wastewater quantities (shown in Table 1). Solutions of $X_{ijkh}^{\pm}$ are excess wastewater quantities under low, medium and high wastewater generation rates with a probability of ρ_h. As a result, optimized wastewater allocation is a sum of $T_{ijk}^{\pm}$ and $X_{ijkh}^{\pm}$.

The detailed analyses of the solutions in Period 1 are presented in this paper (solutions in Periods 2 and 3 can be analyzed similarly). For wastewater allocation from drilling site 1 to UID site in period 1, solution of the optimized allowable wastewater quantity ($T_{111}^{\pm}$) is 610 bbl/day, which reaches its upper bound (Table 1). Solutions of $X_{1111}^{\pm}$, $X_{1112}^{\pm}$, and $X_{1113}^{\pm}$ are 0, [0, 150], and 250 bbl/day, respectively; therefore, there would be no excess wastewater from drilling site 1 to UID site in Period 1 when the wastewater generation rate is low; the quantity of excess wastewater would be up to 150 bbl/day when the wastewater generation rate is medium with a 60% probability of occurrence; there would be 250 bbl/day of excess wastewater when the wastewater generation rate is high with a probability of 20%. Thus, optimized wastewater shipped from drilling site 1 to UID site in Period 1 would be 610 (610 + 0), [610, 760] (610 + [0, 150]), and 860 (610 + 250) bbl/day, under low, medium and high wastewater generation rates, respectively. Allocation of excess wastewater is a corrective action (or recourse) to deal with the deficiency of the first-stage decisions, where the predefined policies for the allowable wastewater quantities have been made before wastewater generation occurs. This is an advantage of the proposed model compared to the conventional single-stage model. The optimal decisions obtained from the TSWM model consist of the first-stage predefined decisions and the second-stage recourse decisions. Using TSWM, the predefined policies for the allowable wastewater quantities in the first stage are compensated by the recourse decisions in the second stage after realization of random events. For wastewater allocation from drilling sites 2 and 5 to UID site, there would be no excess wastewater regardless of wastewater generation rates. Wastewater allocation from drilling sites 2 and 5 to UID site would be 400 and 640 bbl/day, respectively. Wastewater allocation from drilling site 3 to UID site under low, medium, and high wastewater generation rates would be 710, [710, 820], and 900 bbl/day, respectively, which includes 710 bbl/day of allowable wastewater quantity and 0, [0, 110], and 190 bbl/day of excess wastewater, respectively. Wastewater allocation from drilling site 4 to UID site under low, medium, and high wastewater generation rates would be [560, 660], [770, 850], and 920 bbl/day, including [0, 100], [210, 290], and 360 bbl/day of excess wastewater, respectively.

For wastewater delivery to HWTP 1 in Period 1, there would be no excess of wastewater from drilling site 4 in Period 1 regardless of wastewater generation rates, due to its high transportation and treatment costs; for drilling sites 1, 2, 3, and 5, excess wastewater would be delivered only under high wastewater generation rates. In the case of wastewater delivery to HWTP 2 in Period 1, no excess wastewater would be shipped from drilling sites 1 and 3 due to their relatively high transportation costs. Drilling sites 2 and 5 would accept excess wastewater only under medium and high wastewater generation rates with the probabilities of 20−60%. Excess wastewater would be diverted to drilling site 4 only under high wastewater generation rate. The results indicate that transportation and treatment costs have significant impacts on excess wastewater allocation. When wastewater generation rate is low, the allowable wastewater quantities can meet the demands for wastewater treatment and disposal and thus no excess allocation is desired. With the increases of wastewater generation rates, excess wastewater would be preferably shipped to treatment and disposal facilities with low transportation and treatment costs.

The wastewater treatment/disposal patterns under medium wastewater generation rates over the planning horizon are also shown in Figure 1. Most of wastewater from five drilling sites would be shipped to two HWTPs due to limited capacity of UID site over the planning horizon (same under low and high wastewater generation rates). UID site will receive [11.73, 12.72]% of the total wastewater generated from five drilling sites

DOI: 10.1021/acs.iecr.6b03971
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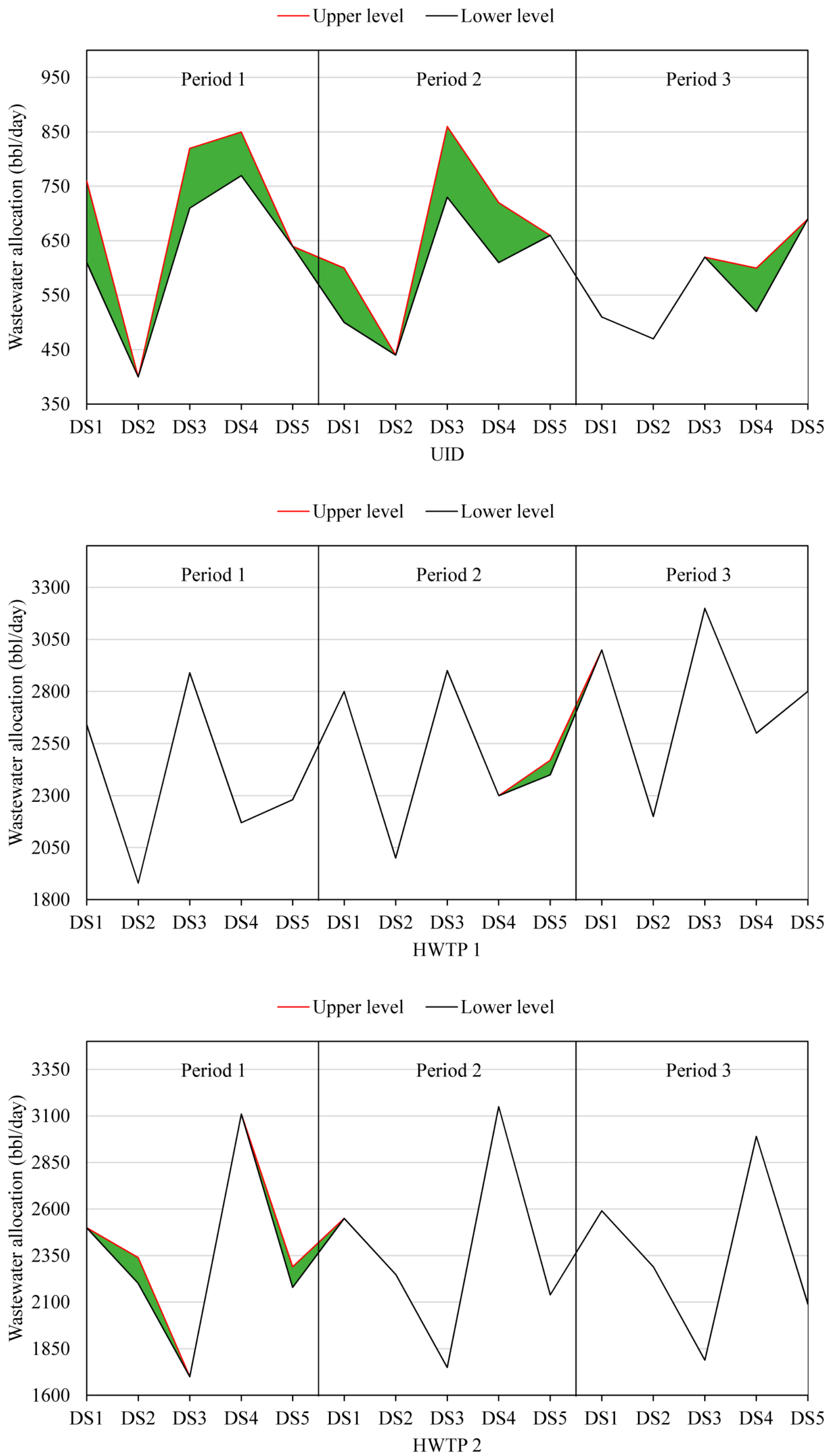

Figure 1. Wastewater allocation patterns under medium wastewater generation rates (DS1 drilling site 1; DS2 drilling site 2; DS3 drilling site 3; DS4 drilling site 4; DS5 drilling site 5).

in Period 1; the ratio will decrease to [10.82, 11.89]% and [9.91, 10.16]% in Periods 2 and 3, respectively, due to limited capacity of UID site and expanded capacities of two HWTPs. UID site will be preferably used to dispose excess wastewater due to its lowest penalty (i.e., the lowest operational costs of excess wastewater disposal) over the planning horizon. In Period 1, excess wastewater will be shipped to UID site and HWTP 2, due to their relatively low operational costs for treatment and disposal. In Period 2, most excess wastewater will be delivered to UID site except for a small portion to HWTP 1. This is because the

DOI: 10.1021/acs.iecr.6b03971
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capacity of HWTP 1 will continue to be expanded and there will be no capacity expansion of HWTP 2. In Period 3, excess wastewater will only be shipped to UID site, with a quantity of up to 80 bbl/day.

Table 7 lists the solutions for capacity expansions of two HWTPs, where zero solutions (representing no expansions) are not presented. With the increase of wastewater generation over time, the existing capacities of two HWTPs will not be able to meet the treatment requirements and should be expanded. Capacity expansion patterns of two HWTPs are different. HWTP 1 should be expanded at the beginning of each of the three planning periods, with an incremental capacity of [590, 630], [740, 780], and [590, 630] bbl/day, respectively, while the capacity of HWTP 2 should be expanded once with an increment of [790, 830] bbl/day at the beginning of Period 1. That is because HWTP 1 has relatively high reuse rates and revenues from wastewater reuse; in addition, it has relatively low transportation costs from most of the drilling sites.

Table 7. Solutions for Treatment Capacity Expansions of Two HWTPs

$Y_{jmk}^{\pm}$	value	incremental capacity (bbl/day)
$Y_{211}^{\pm}$	1	[590, 630]
$Y_{222}^{\pm}$	1	[740, 780]
$Y_{213}^{\pm}$	1	[590, 630]
$Y_{331}^{\pm}$	1	[790, 830]

The total system cost would be $\$[1.04, 1.37] \times 10^9$. It is also an interval due to interval input parameters, representing that the total system cost may vary within it depending on variations of decision variables. The two extremes of the interval solutions represent the optimiztic (lower bound) and conservative (upper bound) decisions for FP water treatment and disposal. Achieving the lower bound of the objective function value will reduce the probability of meeting the requirements for wastewater treatment and disposal due to lower allowable wastewater quantities; as a result, the risk of violating the allowable wastewater quantities will increase, consequently leading to high penalties due to transportation and treatment/disposal of excess wastewater. Willingness to accept the upper bound of the objective function value will lead to a low risk of violating the allowable wastewater quantities, and guarantee to meet the wastewater treatment and disposal requirements. Decision makers need to make trade-offs between economic and environmental (wastewater treatment/disposal) objectives to generate informed decisions depending on their expert knowledge and site-specific information.

5. DISCUSSION

The solutions derived from the TSWM model may provide flexibility in generating practical FP water management strategies. Through adjustment of the values of decision variables and objective function within their intervals, various FP water management strategies can be generated, reflecting the preferences and judgment of decision makers. If the allowable wastewater quantity ($T_{ijk}^{\pm}$) is predetermined by decision makers instead of being optimized in the TSWM model, the original two-stage decision making problem will become a single-stage problem (an interval-parameter linear programming). Decision makers may change the values of $T_{ijk}^{\pm}$ based on their preferences to generate a variety of scenarios for addressing varying policy issues for wastewater treatment and disposal.

This study has implications for real-world FP water management associated with shale gas development, where treatment and disposal of a large quantity of wastewater is a challenging issue in many shale plays in USA and across the world. Although the modeling results indicate HWTPs are major treatment facilities for FP water, UID will be a preferred option when applicable due to its relatively low disposal costs. However, applicability of UID for wastewater disposal needs to be evaluated specifically for each site. For example, UID is not considered a preferable option for FP water disposal in Pennsylvania since there are a limited number of UID wells available, while in Texas existence of a large number of wells enable UID as a viable option for large-scale wastewater disposal.[3] In alternative analyses, transportation costs may have significant impacts on the total system cost. This is especially true in some states where FP water needs to be shipped to HWTPs with long distances from the sources. In addition, the two-stage stochastic analyses based on the TSWM model may help decision makers make adaptation plans for FP water management since it may take corrective actions for the first-stage decisions when they are inappropriate.

The proposed model may be improved in the future by (1) taking into account of more wastewater treatment and disposal options, (2) incorporating site-specific information, and (3) coupling with water supply planning decision analysis to formulate an integrated shale gas and water management framework. At many sites, reuse of FP water is becoming a viable and dominant option, which may reduce not only the amounts of FP water, but also the total system cost. Assessing the impacts of variations of wastewater reuse patterns in the TSWM model will be crucial to address practical management issues.

6. CONCLUSIONS

A two-stage stochastic fracturing wastewater management model, called TSWM, has been proposed to support flowback and produced (FP) water management planning in shale plays. The TSWM model is capable of effectively addressing probabilistic and nonprobabilistic model uncertainties through integration of interval analysis and two-stage stochastic programming into a general model analysis framework for decision support. The proposed TSWM model is flexible in generating various optimal management strategies for shale gas FP water treatment and disposal. The first-stage decision predefined by decision makers before uncertainties are known (i.e., before random events occur) can be corrected in the second stage in order to achieve the whole-system's optimality. This is an advantage of the proposed model compared to single-stage model. Optimal decisions obtained from the TSWM model include the first-stage predefined decisions and the second-stage recourse decisions. Application of the TSWM model to a comprehensive synthetic example demonstrates its practical applicability and feasibility. The TSWM model provides effective decision support for FP water allocation and capacity expansion of treatment/disposal facilities. The interval solutions obtained indicate the lower and upper bounds of the objective function and decision variables, representing the optimiztic and conservative decisions, respectively. Achieving the lower bound of the objective function value will lead to an increased risk of violating the allowable wastewater quantities, while willing to accept the upper bound of the objective function value will guarantee to meet the wastewater treatment and disposal requirements. Trade-offs between economic and environmental objectives are analyzed to help decision makers select the most

DOI: 10.1021/acs.iecr.6b03971
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appropriate management strategies, based on their expert knowledge and judgment, as well as site-specific information. The developed TSWM model is coded in Lingo with high computational efficiency, enabling it applicable to large-scale real-world problem solving. The TSWM model provides flexibility in providing informed decisions for wastewater management in shale plays.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.iecr.6b03971.

Table S1, solutions obtained from the TSWM model (PDF)

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■ ACKNOWLEDGMENTS

X.Z. was supported by the Director's Postdoctoral Fellowship at Los Alamos National Laboratory. V.V.V. was supported by the DiaMonD project (An Integrated Multifaceted Approach to Mathematics at the Interfaces of Data, Models, and Decisions, U.S. Department of Energy Office of Science, Grant no. 11145687). I.J.D. was supported by a grant from the Cynthia and George Mitchell Foundation. The authors are thankful to the Editor-in-Chief, Associate Editor, and anonymous reviewers for their insightful comments, which have significantly contributed to improving the manuscript.

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