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Research article

Shale gas wastewater management under uncertainty

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ABSTRACT

This work presents an optimization framework for evaluating different wastewater treatment/disposal options for water management during hydraulic fracturing (HF) operations. This framework takes into account both cost-effectiveness and system uncertainty. HF has enabled rapid development of shale gas resources. However, wastewater management has been one of the most contentious and widely publicized issues in shale gas production. The flowback and produced water (known as FP water) generated by HF may pose a serious risk to the surrounding environment and public health because this wastewater usually contains many toxic chemicals and high levels of total dissolved solids (TDS). Various treatment/disposal options are available for FP water management, such as underground injection, hazardous wastewater treatment plants, and/or reuse. In order to cost-effectively plan FP water management practices, including allocating FP water to different options and planning treatment facility capacity expansion, an optimization model named UO-FPW is developed in this study. The UO-FPW model can handle the uncertain information expressed in the form of fuzzy membership functions and probability density functions in the modeling parameters. The UO-FPW model is applied to a representative hypothetical case study to demonstrate its applicability in practice. The modeling results reflect the tradeoffs between economic objective (i.e., minimizing total-system cost) and system reliability (i.e., risk of violating fuzzy and/or random constraints, and meeting FP water treatment/disposal requirements). Using the developed optimization model, decision makers can make and adjust appropriate FP water management strategies through refining the values of feasibility degrees for fuzzy constraints and the probability levels for random constraints if the solutions are not satisfactory. The optimization model can be easily integrated into decision support systems for shale oil/gas lifecycle management.

1. Introduction

Shale gas has become one of the most critical energy resources in the world. Its production has been made possible by advances in drilling technologies and cost reductions (Gregory et al., 2011; Rahm, 2011; Karapataki, 2012; Slutz et al., 2012; USEIA, 2012; Nicot et al., 2014). The USEIA (2012) estimated that annual shale gas production in the United States will increase from 5.0 TCF (trillion cubic feet) (23% of total U.S. dry gas production) in 2010 to 13.6 TCF (49% of total U.S. dry gas production) in 2035. Hydraulic fracturing (HF) is the key technology that has enabled shale gas development. In HF operations, a large amount of fracturing fluid (water and proppants) is injected under high pressure into low-permeability shale formations to induce fracturing and improve the mobility of natural gas. Large-scale production of shale gas has become economic through application of HF technologies. A horizontal fracturing well consumes approximately 2–7 million gallons of water (Vidic et al., 2013). A large quantity of wastewater is generated, including flowback and produced water, together referred to as FP water (Nicot et al., 2014). Flowback is the fluid returned to the surface during the hydraulic fracturing process itself, while produced water is the fluid that returns to the surface once the well is in production (USEPA, 2011a; Ferrar et al., 2013). Volumes of FP water are large and vary from play to play, depending on the characteristics of the basins and formations (Veil and Clark, 2010; Clark et al., 2013; Murray, 2013; Yang et al., 2013). FP water generally contains high levels of total dissolved solids (TDS) and some naturally occurring toxic compounds, including, in some cases, naturally occurring radioactive material (NORM), dissolved from the formations. If FP water is discharged without any

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treatment or after inadequate treatment, it may pose a threat to the environment and public health due to its high salinity and dissolved chemicals (Kargbo et al., 2010; Rahm, 2011; Shaffer et al., 2013). Thus, FP water needs to be disposed of in permitted disposal wells or treated before it can be discharged to a body of water or else reused. There is growing pressure on industry from stakeholders to increase the reuse of FP water rather than using disposal wells.

In regional FP water management planning, multiple drilling sites (FP water sources) and various wastewater treatment/disposal facilities may be considered to comprise an integrated FP water management system (Hammer and VanBriesen, 2012; Penn State Cooperative Extension, 2012). The FP water generated from different sources will be delivered to various treatment and/or disposal facilities in multiple project periods. Because of differences in transportation distances (resulting in varied transportation costs) and variations of treatment and disposal costs, different management strategies for allocation of FP water to various treatment/disposal facilities can lead to significant variations of total treatment/disposal costs for large volumes of FP water. With the increased quantity of FP water, existing treatment facilities will experience pressure to expand their capacity in order to treat more wastewater. From the perspective of a total FP water management system, the best management decisions are those with the minimum overall costs including wastewater delivering, treatment/disposal, and treatment facility capacity expansion costs (Fig. 1). Achieving this goal of minimum cost control will require effective strategies for FP water management.

Over the past decade, a number of research efforts have been conducted regarding FP water issues in shale gas plays. Most of these studies focused on possible impacts of shale gas development on water quality (Osborn et al., 2011; Warner et al., 2012; Barbot et al., 2013), water use for shale gas production (Nicot and Scanlon, 2012), policy analysis for wastewater management (Rahm and Riha, 2012), and review of desalination technologies (Shaffer et al., 2013). There has been a lack of integrated FP water management planning from a total-system perspective, which could provide decision makers with strategies for allocating FP water and expanding treatment facility capacity in an optimal and cost-effective way. An optimization model on the basis of systems-analysis techniques may help address this gap. Development of such a techno-economic optimization management model will benefit a variety of decision makers and managers in the government and private industry. Recently, Karapataki (2012) developed a mixed-integer linear programming model for wastewater management in the Marcellus Shale. Due to limitations of knowledge and data, many model parameters inevitably contain uncertainty, including capacities of underground injection disposal facilities, cost and capacity of wastewater treatment plants, and the costs to transport FP water. The uncertainties may affect the accuracy (and, therefore, usefulness) of generated FP water management strategies. Most previously published studies have been unsuccessful in addressing and quantifying these uncertainties.

Therefore, the objective of this study is to develop an uncertain optimization model for FP water management (UO-FPW), where both FP water allocation to various treatment/disposal options and treatment facility capacity expansion are optimized. The UO-FPW model is based on the fuzzy-stochastic mixed-integer programming method, which can effectively deal with uncertain information expressed as fuzzy membership functions and probability density functions. The model is then applied to a representative hypothetical case study for supporting FP water treatment/disposal-option management, as well as treatment capacity expansion planning, under uncertainty. Optimal management strategies with a minimized total-system cost are generated to help decision makers select appropriate and cost-effective FP water treatment/disposal options in shale gas plays. Uncertainties in the model parameters expressed as stochastic and non-stochastic forms are effectively reflected. Tradeoffs between economic objective and system reliability are analyzed.

2. Uncertainty optimization model for shale gas wastewater management

An FP water management system involves a number of components with unique features. Consider an FP water management system consisting of multiple wastewater sources (drilling sites with one or more hydraulic fracturing wells) and various wastewater treatment/disposal options. The FP water is first collected and stored in on-site open pits and/or storage tanks, and then delivered to on-site/off-site facilities for treatment, disposal, and/or reuse (Gregory et al., 2011; USEPA, 2011a; Hammer and VanBriesen, 2012). Transport of wastewater to treatment and disposal facilities is mainly by truck.

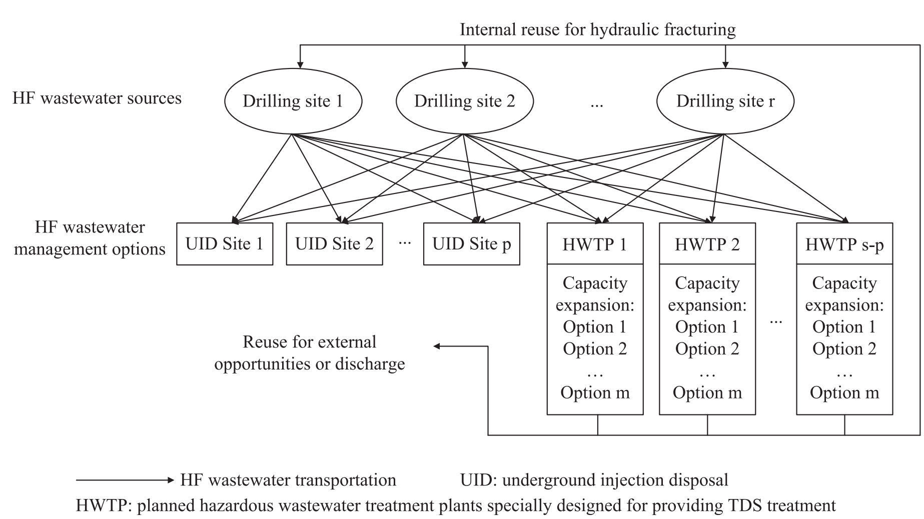

Fig. 1. An integrated FP water management system considering wastewater flow allocation and treatment facility capacity expansion.