A System Dynamic Model to Analyze the Freshwater Dependence of the Marcellus Shale in Bradford Country, Pennsylvania

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Abstract:

The hydraulic fracturing of shale gas depends heavily on adequate water resources. With the rapid development of shale gas, a significant amount of freshwater is used together with the generation of large quantities of production and flowback waters. Water issues have become increasingly important for shale gas development. To figure out the relationship between shale gas development and freshwater, here we define a freshwater dependence coefficient (FDC), which is ratio between the total freshwater usage (surface and underground freshwater) and the total water demand of shale gas development. In Pennsylvania, an increasing amount of flowback water is reused in shale gas fracturing, which can reduce freshwater dependence. In this paper, we develop a water carrying capacity model of shale gas development using system dynamics. Based on the empirical data from the Marcellus Shale in Bradford Country, Pennsylvania, we analyze the nonlinear relationships between water resources and water management, particularly the relationships between freshwater dependence, the flowback percentage, freshwater dependence and reused flowback under different developnet scenarios. This paper provides a basis for further study on the water carrying capacity for shale development.

Keywords:

Shale gas, Freshwater dependence, System dynamics, Marcellus Shale, Water carrying capacity.

1. Introduction

Global energy demands have led to the extensive and rapid development of natural gas from unconventional shale gas reservoirs [1]. Water is critical for hydraulic fracturing, the essential and extensively applied technology for shale gas development [2] [3]. Water is also heavily used in natural gas production to cool and lubricate drill heads and to clear drill cuttings [2]. Shale gas production also generates large quantities of waste water and flowback water. Due to the growing concerns of freshwater scarcity [4] and water demands in domestic, industrial, and agricultural use [5], it is urgent to analyze and quantify the usage of freshwater in shale gas development from a holistic perspective.

A number of states in the United States require shale gas developers to report the types and volumes of additives in water on FracFocus (www.FracFocus.com), a chemical disclosure registry managed by the Ground Water Protection Council and Interstate Oil and Gas Compact Commission [5]. It is also compulsory for shale gas developers to report water use and to handle the large volumes of wastewater containing high concentrations of total dissolved solids (TDS) [1]. However, different states have different laws and regulations regarding water issues. For example, in Texas, most produced water is injected into the local underground disposal wells [1]. In Pennsylvania, however, because of the restrictions on the underground injection, most shale gas developers choose to transport and inject their waters in Ohio [6].

Some recent studies have discussed different types of water use during shale gas development [7]. Other studies have discussed potential water pollution and environmental impacts, including drainage of steams [8] and surface and ground water [9]. Among works that analyze wastewater handling during shale gas development [2, 10-11], some papers have used a footprint assessment method to analyze the water flow quantitatively [6], which provides useful data for further study. However, few studies examined the freshwater dependence of shale gas development, particularly in a systematic and quantitative way.

Here we define the freshwater dependence coefficient (FDC) of shale gas development as the ratio of the total surface and underground freshwater usage divided by the total water quantity the shale gas development demand, an important measure of water carrying capacity. Water carrying capacity has been well researched in many other fields, including soil [12] and regional water carrying capacity [13-14]. Water carrying capacity quantifies the water resources that support different uses, including population, industry, and agriculture. Many different models and methods have been used to calculate resource carrying capacity, such as the areas of ecological footprint [15], energy [16], and system dynamics [17]. Water carrying capacity has been extensively studied primarily using system dynamics.

System dynamics employs a complex system structure that uses a nonlinear system to analyze its dynamic behavior [18]. Its unique capability to represent the nonlinearity and feedback loops inherent in social and physical systems has allowed for its rapid growth [19]. System dynamics is characterized as a “strategy and policy laboratory” and “socioeconomic system laboratory” because it provides a tool to test the effects of various strategies and policies [18]. It is extensively used in many different areas, such as supply chain management [20], market forecasting [21], and environmental problems [18, 22]. System dynamics also gained enormous popularity in the analysis and management of large scale water systems such as simulating problems in water use [23], globally modeling water resources [24], planning water resources [25], and managing water quality [26] and water levels [27], along with the public understanding of water management options [28]. As an important component, freshwater dependence can use the system dynamics model of carrying capacity to figure out how much water being used depends on freshwater instead of reused water.

The freshwater dependence of shale gas development can fall into two basic categories, the water resource (freshwater) and the injected water management. This paper illustrates how to create a simple system dynamics model to present the relationship between water resources and water management and to determine the regional freshwater dependence of shale gas development. As noted above, different regions have different regulations and situations related to shale gas development. Here, we choose to study shale gas-related water usage in Bradford County, Pennsylvania, an area heavily involved in shale gas production in the Marcellus Shale gas field. A system dynamics model is developed to simulate the water use cycle. We assume different scenarios in the model to analyze changes in the dependence of shale gas development on freshwater, which provide a necessary basis for further studies on the water carrying capacity of shale development.

2. Methodology and model

2.1. Define the Problem

The Marcellus Shale is an organic-rich, sedimentary rock formation in the Appalachian Basin of the northeastern United States. It contains significant quantities of natural gas [29]. The Marcellus

Formation is now rapidly developing, with production focused on Pennsylvania [30]. The effects of shale gas extraction on water resources have raised significant societal concerns. Due to limited freshwater resources and the desire to balance the demand of different water uses, shale gas development cannot use as much water as needed. Flowback water, which is the large volumes of water with high concerns of dissolved solids return to the surface of the shale gas well [1], is often reused. In Pennsylvania, there were more than 16800 horizontal well permits issued from 2005 to 2014; each well uses 4.0-5.6 million gallons of water for fracturing [6]. The total usage of water volume is approximately 1% of total surface water in Pennsylvania [3, 5]. The main resource of the water includes surface water, groundwater, and flowback water. After being injected, 60%-96% of the injected water remains underground [1, 6]. Ways to handle the wastewater that returns to the surface include disposition into the underground using wastewater injection wells (UIC wells), wastewater treatment in brine/industrial waste or municipal sewage plants, and reused for shale gas development. In recent years, more than 90% of the wastewater has been reused in the fracturing operation in the local Marcellus Shale [5]. Different ways of waste water management affect the freshwater dependence of shale gas development and therefore the water carrying capacity.

There are many different tools for constructing the system dynamics model (SD model), in this paper, we used STELLA, a useful SD modeling tool, to construct our water carrying capacity model and freshwater dependence model for regional shale gas development. In STELLA, there are three basic factors, “stock”, “converter”, “flow” (see Fig 1). Usually, the “stock” is used to represent a changeable amount of a given variable, the value of it is determined by the value of inflow and outflow; the “flow” is used to connect two different “stock”, and the value of the stock depends on the functional relations between different “converter” and the the “stock”, the “converter” is a fix value or a graphical function which changes as time goes by. Meanwhile, there is also a red arrow named the “action connector”, which is use to connect different factors in the model to construct the functional relations between different facors.

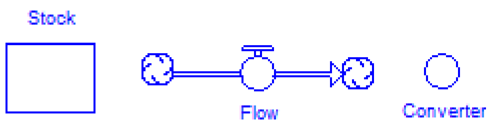

Fig. 1. Basic factors for System dynamics model in STELLA

2.2. The regional water carrying capacity model

To calculate the regional water carrying capacity, first we should know the “regional available freshwater”, which is the total volume of the regional water (both surface water and underground water), then we should know how much water can be used for the regional development, which is the “water distribution system” from “withdraw” (the max value of it is determined by “available percentage” and “regional available water”) . There are different types of water use, such as agricultural use and industrial use. Here we divide water use into two different types: “shale gas use” and “non-shale gas use”. For “non-shale gas use”, the “non-shale gas use freshwater demand” is determined by both the “per capita water demand” and the “population” (“population” is determined by the “moving in” people and “moving out” people, such as birth, death, immigration, and so on), and after being used for non-shale gas development, the water can be treated by water treatment plants and then return to surface water, which will increase the “regional available freshwater”, and some of the non-shale gas use water can not be renewed, we call it “wastage”. Meanwhile, for the max volume freshwater for “shale gas use”, it is determined by the water volume in “water distribution system” and “non-shale gas use freshwater demand”. Both freshwater for “shale gas use” and “reused water” for being “reused in shale gas development” are two main water source for “shale gas water injection”, the demand of water for shale gas development can be obtained by the regional average water demand per well and the number of active wells. For each well, after the water is injected, there are two different ways to handle the water: “remain underground”, or “return to the surface”. After being back to surface, it is called as “flowback water”, and some different ways are used to treat the “flowback water”, such as “reused for shale gas”, “treated by brine industrial and municipal sewage treatment plants”, “underground stored (UIC) and other”, and so on. All water management variables are determined by the percentage of each management treatment at different periods. For the “flowback water” “treated by brine industrial and municipal sewage treatment plants”, it will return to surface water, which will increase the “regional available freshwater” as well, Fig. 2 is a schematic figure of water carrying capacity model that shows the relationships (flow variables) between different stock variables on the basis of a water management system dynamic model [28].

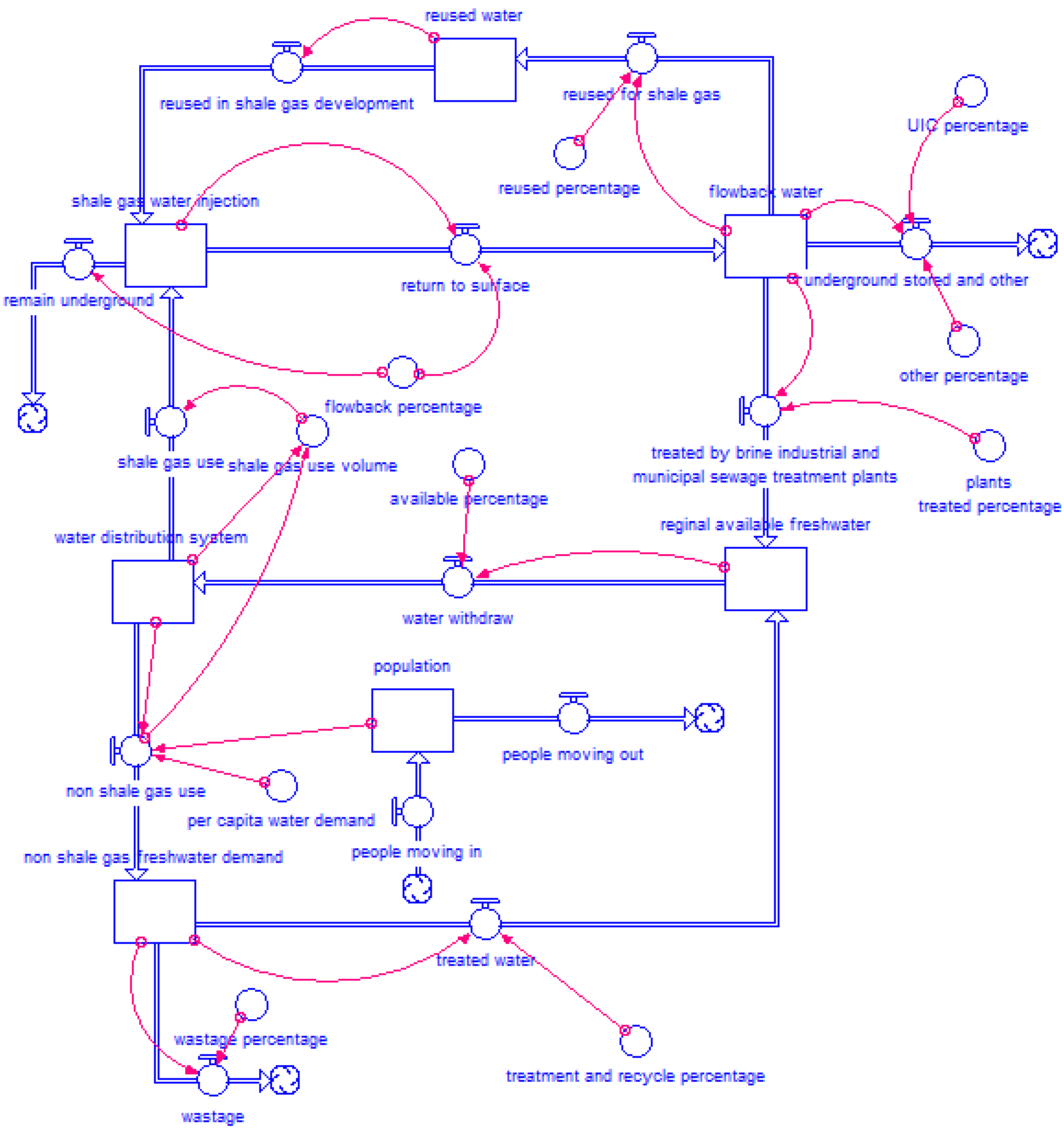

Fig. 2. System dynamics model of the water carrying capacity of Marcellus Shale in Bradford Country, Pennsylvania

2.3. The freshwater dependence model of shale gas development

In this paper, the freshwater dependence model (see Fig. 3) is constructed based on the water carrying capacity model of shale gas development (see Fig. 2). As mentioned above, we mainly study the freshwater dependence (FDC) by considering different scenarios of flowback water and flowback treatment. As we know, if the FDC=1, it means all the water used for “shale gas water injection” is from freshwater, and no flowback water reused or treated by plants, then:

“shale gas water injection”= “water demand per well”* “number of active wells” (1)

However, due to “reused for shale gas” and “treated by brine industrial and municipal sewage treatment plants” return to surface water, the FDC is less than 1, in order to calculate how much the FDC is, we assume the:

“max freshwater for shale gas”= “water demand per well”*“number of active wells” (2)

We assume the initial value of “available freshwater” equals to the “max freshwater for shale gas”. The “available freshwater” is reduced while being used by shale gas development (“shale gas development use”) for “shale gas water injection”, and then repeat the process mentioned in Fig. 2 for the wells one by one. After running the model:

FDC=1- “available freshwater”/ “max freshwater for shale gas”. (3)

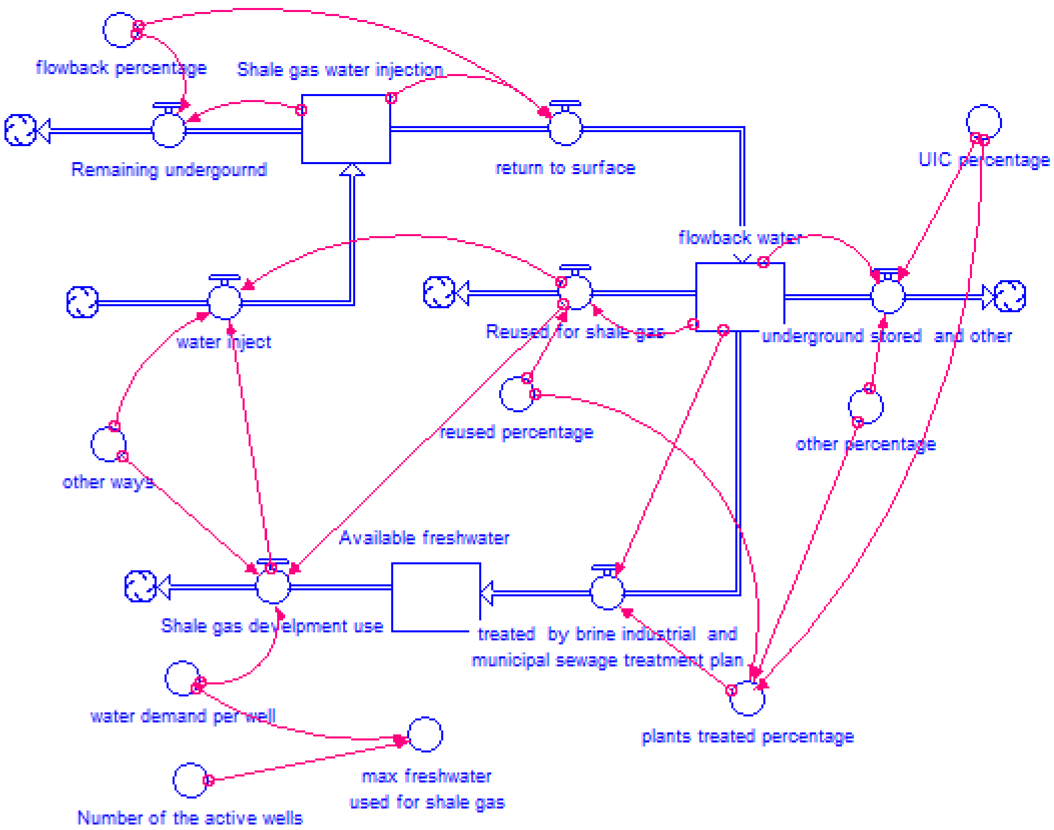

Fig. 3. Freshwater dependence model (sub-model) of shale gas development

Note: “reused_percentage”,“UIC percentage”,“plants treated percentage”,“other percentage” are the different percentages of flowback treatment. The sum of these values is 1. “other_ways” represents the water injected into the shale gas well, which is not from freshwater or regional reused flowback water, such as acid mine drainage (AMD), and reused flowback water from other regions.

3. Scenarios and results

3.1. Basic scenarios

According to Hansen E. et al. [6], the average injection fluid per well for Marcellus wells in the Susquehanna River Basin, Pennsylvania is 4.3 Mgal/ well, 86% of which comes from freshwater and the rest 14% comes from flowback water. The average flowback percentage is 6%, and 32% of the flowback water is reused on shale gas development. Five percent of flowback water is transported to Ohio to be injected underground, and 39% and 15% of flowback water is transported to brine/industrial water treatment plants and municipal sewage treatment plants, respectively, to be treated and returned to surface water (freshwater). Here we use these values from paper [6] as the basic scenario (Scenario 1 in Table 1) to verify the result of the model. Reported percentages of flow back water returning to the surface cover a wide range, with the lowest reported value being 4% [6], while 10%-40% is in the larger end [1]. Therefore, in Scenario 2, we assume the other variables are the same as in Scenario 1, however the flowback return percentage 4% to 40%. In addition, the percentage of the flowback water reuse is also an important variable. Hansen E. et al. [6] reported the lowest reuse percentage of 6%, whereas Arthur and Cole [5] reported more than 90% flowback water reuse. Therefore, we assume the flowback return percentage between 4% and 40%, and the reused percentage from 6% to 90%. The percentages of other treatments change accordingly to reveal the differences in freshwater dependence.

Table 1. Scenarios of key variables

Variables	Scenario 1	Scenario 2	Scenario 3
Water demand per well(Mgal)	4.3	4.3	4.3
Flowback water return percentage	0.06	0.04-0.40	0.04-0.40
Flowback reuse percentage	0.32	0.32	0.06-0.90
Underground injection	0.05	0.05	0.05-0
Brine/industrial water treatment Municipal sewage treatment	0.54	0.54	0.78-0.10
Other treatments	0.09	0.09	0.11-0

3.2. Results

3.2.1. Model verification

According to the shale gas database such as FracFocus and PA DEP Oil & Gas Reporting Website (https://www.paoilandgasreporting.state.pa.us/), we got the information of 1321 drilled shale gas wells in Bradford County since 2007 (Bradford County has more than 3000 shale gas wells permits from 2007 to 2014[1]). Therefore, we assume the time steps are 1321, each well only reuses the flowback water from one single local shale gas well, and the water from “other_ways” is 0. If all the water comes from freshwater, the number is 1321*4.3, which is 5680.3 Mgal. In Scenario 1, the reported leftover available water is 292.66 Mgal, so the used freshwater is 5387.64; thus, the freshwater dependence coefficient is 94.84%, which is larger than the 86% reported by Hansen E. et al. [6]. This indicates that there are other ways of getting water, which can be as high as 0.38 Mgal /well. We therefore update the value of “other_ways” to 0.38 Mgal.

[1]http://www.depreportingservices.state.pa.us/ReportServer/Pages/ReportViewer.aspx?/Oil_Gas/Permits_Issued_Detail

3.2.2. The relationship between freshwater dependence and flowback return percentage

As we know, as the flow back return percentage increases, more flowback water can be available for reuse . Here, we use the freshwater dependence model of shale gas development to test the relationship between freshwater dependence and different flowback return percentage using Scenario 2 with different flowback return percentage. Fig. 4 shows that with all other variables being the same as those used in Scenario 1, the FDC is inversely related to the flowback return percentage, and the correlation coefficient is "-0.0163". As the flowback percentage increases from 0.04 to 0.40, which is mentioned in different papers [1, 6], the FDC decreases from 0.877 to 0.568, and amount of the freshwater used decreases from 4983.21 Mgal to 3227.26 Mgal, which will be a significant contribution for improving the local water carrying capacity. In order to increase the "flowback return percentage", and decrease the FDC, there are several ways, such as enhancing the "flowback" technology to make sure more injected water return to surface, making more regulations to ensure the developers get more flowback water to surface other than remain underground, and so on.

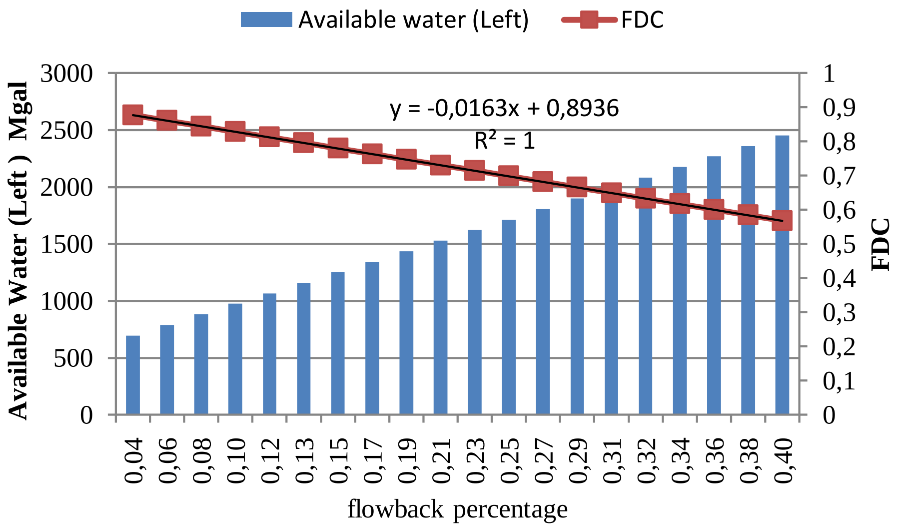

Fig. 4. Relationship between flowback percentage and FDCr

3.2.3. The relationship between freshwater dependence and reused flowback

As mentioned above, in Pennsylvania, there are restrictions on the underground injection, so most shale gas developers choose to transport and inject their waters in Ohio [6], but as the development of share gas and the potential risk of underground injection, Ohio also has more and more restrictions on it, so we assume the "UIC percentage" will decrease to 0 gradually. And according to Hansen E. et al. [6] and Arthur and Cole [5], the "Flowback reuse percentage" are 0.06 and 0.09 respectively in different year, so we assume the "Flowback reuse percentage" increases from 0.06 to 0.09 gradually for the 1321 shale gas wells in Bradford county. Then we assume left flowback is treated by Brine/industrial water treatment. Here we examine the role of flowback water reuse in affecting FDC in Scenario 3. As flowback becomes reused more, FDC will decrease. However, according to Stave K.A. [28], most of the waste water treated by brine industrial waste treatment and municipal sewage treatment plants returns to the surface water system, which increases the amount of the available water. If the reused percentage of flowback water increases, the flowback treated by brine industrial waste treatment and municipal sewage treatment plants will decrease, and the water returns to the surface water will decrease correspondingly. With different values of the flowback percentage, the affection degree will be different. Here, we use Scenario 3 to test the relationships between freshwater dependence and reused flowback with a different flowback percentage. We assume that as the reused percentage of flowback increases, the underground injection (UIC) and other treatments will reduce to 0 gradually. The FDC is affected by both the flowback percentage and the reused percentage of flowback. Therefore, here we test the relationship between the FDC and the flowback return percentage *reused percentage (actual flowback reuse percentage for short) by inputting the values of variables in the freshwater dependence model of shale gas development according to Scenario 2. Fig. 5 shows that the relationship between the FDC and actual flowback percentage are non-linear, and as the actual flowback percentage increases, the FDC decreases more slowly. This pattern indicates that for shale gas developers, there are one or some conditions to balance both the FDC and the cost of getting flowback water and reusing it.

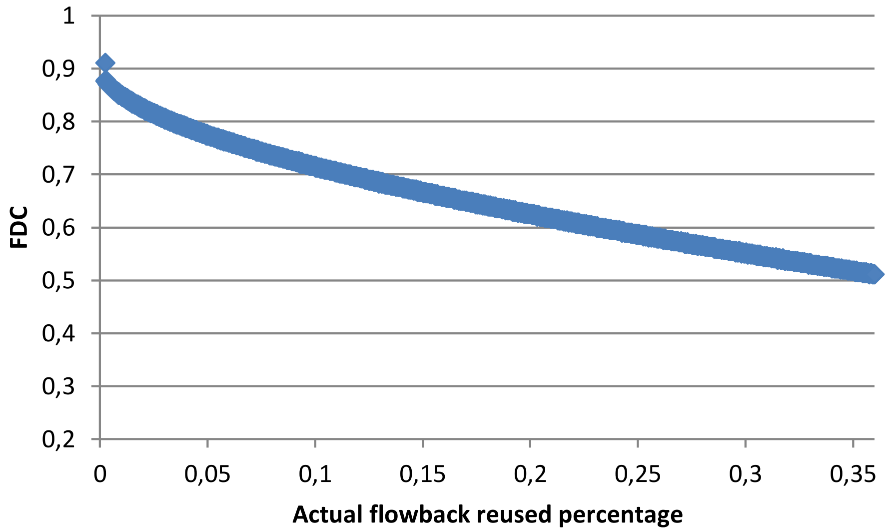

Fig. 5. Relationship between actual flowback reused percentage and FDC

4. Discussion and conclusion

In this paper, we primarily analyze the issues related to water use and management during the shale gas development. To study how much shale gas development relies on surface and underground water resources (freshwater for short), we defined the freshwater dependence coefficient (FDC), and then constructed both the water carrying capacity model of shale gas development and the sub-model, called the freshwater dependence model of shale gas development. We used the empirical data of Marcellus Shale Development in Bradford Country, Pennsylvania to test the sub-model and understand the relationships between FDC and flowback percentage and between FDC and reused flowback under different scenarios reported in literature.

We found that in Bradford county, to meet the water demands of the 1321 shale gas wells, in addition to the freshwater and the flowback water from local shale gas wells, there are approximately 501.98 Mgal (1321*0.38 Mgal) of water obtained from, e.g., the flowback of other regions or from acid mine drainage (AMD) and so on. As the flowback return percentage increases, the FDCdecreases. The FDC is inversely related to the flowback return percentage with a linear correlation coefficient of -0.0163. Meanwhile, if we increase the actual reused flowback percentage, the FDC decreases. The relationship between the flowback percentage and FDC is a non-linear correlation; as the actual reused flowback percentage increases, the decrease percentage of FDC declines gradually. For developers, as the flowback percentage increases, the cost will increase for both getting and treating the flowback water. Therefore, it will help us to find the balance between FDC and costs in future studies.

This study also provides the basis for further research into the regional water carrying capacity of shale gas development. However, there are still some problems left to be solved. For example, in the next step, we need to update the assumption of the quantity of inflow flowback water to brine/industrial water treatment and municipal sewage treatment plants and the outflow freshwater being returned to surface water to a non-linear one that depends on both the technology of the treatment and the capacity of the treatment plants. In this paper, we assumed the wells developed one by one; in a next step, we need to make a more accurate assumption using the empirical data of development dates. Meanwhile, we also need to consider the technically and economically feasible of different percentages in next step.

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