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Water resource selection and optimisation for shale gas developments in Australia: A combinatorial approach

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ABSTRACT

Australia has significant quantities of technically recoverable shale gas and the potential to become a major producer of natural gas from these unconventional resources. However, the hydrocarbon extraction process from shale formations involves heavy drilling and hydraulic fracturing. Both these activities consume a considerable volume of water, which impacts local communities and the environment. This paper proposes a combinatorial methodology that incorporates multi-criteria decision-making and system dynamics to select the best water resources, and then investigate the regional impact of consuming those resources over the long-term. The methodology is described through a case study on the Beetaloo Basin, Northern Territory – a prospective shale gas resources deposit. The results show that the produced water and fresh groundwater are appropriate options for the basin, and appropriate scenarios can prevent the over-extraction of fresh groundwater, maximise the reuse of water, and minimise aquifer disturbance. The proposed methodology is designed to support petroleum companies when making decisions about which water resources to use in shale mining operations to balance various factors affecting the system.

1. Introduction

Australia has an estimated 11 Tcf[1] of contingent shale gas resources and 619 Tcf of prospective resources (Geoscience Australia, 2016). Developing these unconventional resources would contribute to growth in the country's energy market, but the shale gas industry in Australia is in its early stages, and additional exploratory activities are required to identify commercial reserves (Goldstein et al., 2012). In addition, regulatory, social, and environmental constraints are slowing the progress of these explorations (Cook et al., 2013). Overcoming these restrictions requires public acceptance, which could be achieved by maintaining a balance between the social, environmental, and economic aspects of the exploration and development phases of shale gas production (Rahm & Riha, 2012). A critical subject of public debate is the extraction and use of water to develop shale gas fields (Vidic, Brantley, Vandenbossche, Yoxtheimer, & Abad, 2013). Drilling and hydraulic fracturing activities demand a considerable volume of water over a relatively short period of time (Rahm & Riha, 2012; Yang, Grossmann, & Manno, 2014). Yet, consuming huge quantities of water disturbs the environment and affects communities, particularly in locations with seasonal droughts and low stream flows (Soeder & Kappel, 2009). This means petroleum companies must find reliable, inexpensive, and viable sources of water for their operations to minimise environmental impact and sustainably coexist with communities. By nature, these decisions are complicated as they involve various stakeholders, scientific studies, and subjective information (Linkov & Moberg, 2011).

This paper proposes a methodology for selecting water resources for drilling and hydraulic fracturing during shale gas development. The methodology also demonstrates the long-term impact of consuming chosen water resources on the community and environment. As a typical example of a prospective shale deposit, the Beetaloo Basin in the Northern Territory, Australia has been chosen to demonstrate the proposed methodology in case study form. The methodology relies on a multi-criteria decision-making technique to determine the best water source(s) given technical, economic, social, and environmental factors. Then, the impact of using those water resources is simulated and analysed through system dynamics modelling. The factors explored include: the generation, availability, and consumption of water; its relationships with drilling and hydraulic fracturing activities; and the community and environmental impacts.

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[1] Trillion Cubic Feet

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The methodology is intended to assist petroleum companies in evaluating a range of water resources for shale mining activities. The results provide valuable inputs for optimising water management plans to successfully develop these unconventional resources in a sustainable way and with public acceptance.

The rest of paper is organised as follows. Section 2 presents the literature review, followed by the proposed methodology in Section 3. Section 4 presents the case study and results. A discussion is provided in Section 5. Section 6 concludes the paper and suggests further research directions.

2. Literature review

2.1. Shale gas developments

The hydrocarbons in shale resources are found in source rocks with very low permeability. Therefore, the oil and gas cannot naturally flow to the surface, and effectively exploiting shale gas requires a lengthening of the wellbore and artificially creating fractures in the rock formation (Jenkins & Boyer, 2008). However, recent technological advancements in horizontal drilling and hydraulic fracturing have allowed the commercial development of shale resources. Horizontal drilling increases the contact area of the wellbore with the reservoir by laterally extending the length of the well. Hydraulic fracturing generates a network of conduits that increase permeability by injecting a high-pressure fracture fluid into the rock formation (DOE, 2009). Water is an essential component of typical fracture fluids and, together with a proppant (sand, treated sand, or ceramic material), it normally accounts for 98% of the fluid's composition. The rest is made up of chemical additives (Speight, 2013). To complete a well, hydraulic fracturing consumes approximately 90% of the total volume of water (Stark & Thompson, 2013; Yang et al., 2014). The commercial development and production of shale gas resources requires hundreds or thousands of wells to be drilled and hydraulically fractured across a region and, consequently, immense quantities of water (DOE, 2009). Therefore, appropriately implementing water management plans is fundamental to sustainably procuring water, disposing of wastewater, and reducing the environmental and social impacts of shale gas development (Rahm & Riha, 2012). Water management, in this context, incorporates four core components: selecting the water sources, preventing the over-extraction of fresh water, reusing and disposing of the water produced, and avoiding aquifer disturbance (Cook et al., 2013).

Improving water management through optimisation models in the shale gas industry has been studied in numerous papers. Many rely on mixed-integer linear programming to improve the water supply chain network and extend the water's lifecycle (Gao & You, 2014; Yang et al., 2014). Although these optimisation models provide valuable information for efficiently administering water resources, they do not consider the environmental and social aspects of shale mining, which are very important for the public's acceptance of shale developments (Zarghami & Szidarovszky, 2011). Therefore, when developing regionally appropriate solutions, it is critical to mitigate the impact of water consumption. This may include regulating water withdrawals, using brackish water instead of freshwater, and incorporating water recycling/reuse into policies (Jasmin, Laurence, & Adisa, 2016). In addition, the long-term regional impacts of these policies need to be investigated.

The extant literature lacks a method for identifying the main factors that will affect communities and the environment when making decisions about which water resources to select. Further, appropriate models for analysing the long-term and widespread impacts of these decisions about shale mining operations are scarce.

2.2. Multi-criteria decision making

Multi-criteria decision-making (MCDM) concerns decision making given multiple and conflicting criteria. It involves both quantitative and qualitative factors and numerous techniques for choosing the best, most feasible option. There are many forms of MCDM in the literature, e.g., multi-attribute utility theory (MAUT), techniques for ordering preferences by similarity according to ideal solutions (TOPSIS), the analytic hierarchy process (AHP), simple additive weighting (SAW), the simple multi-attribute rating technique (SMART), and so on. Our method relies on AHP, which derives ratio scales from paired comparisons in a multi-level hierarchy structure. The comparison values are either derived from actual measurements, or they are assigned from a fundamental scale that reflects relative preferences between a set of criteria and the available options. An AHP rating model comprises the following steps (Saaty, 2008):

Step 1: Develop a hierarchical structure for the research problem.
Step 2: Perform a pairwise comparison of the criteria and sub-criteria and generate comparison matrices using a fundamental scale of absolute numbers.
Step 3: Establish the rating categories for each criterion and sub-criterion and assign priorities to those categories from the pairwise comparisons. Generate comparison matrices for these categories also using a fundamental scale of absolute numbers. The ratings are expressed as idealised priorities in the ideal category with proportionate values allocated to the rest of the categories.
Step 4: Create a summary table for the prioritised rating categories of all criteria and sub-criteria.
Step 5: Evaluate the alternatives by applying their respective assigned ratings to each of the criterion or sub-criterion to obtain the overall priorities and determine the best option.

2.3. System dynamics

Systems dynamics (SD) is a methodology based on systems theory that studies the dynamic nature of complex feedback-driven systems (Cavana & Maani, 2000). First, a conceptual and qualitative model is created to describe the causal processes operating in the system. Then, a quantitative model is structured and built for a computer simulation to show the nature and direction of the relationships within the system, so as to observe and understand its behaviour and responses over time. These models also help to visualise and analyse the effects of different intervention strategies (Winz et al., 2009). Cavana and Maani (2000) point out the many advantages of SD modelling. First, such models reveal the nature of relationships using causal loop diagrams and stock flow diagrams. Second, these models include both linear and non-linear relationships. Third, policy issues can be measured to help decision making. Table 1 summarises the SD phases along with steps required in each phase; however, all steps are not necessary for every project.

3. Methodology

The methodology proposed in this section can be applied to any basin with prospective shale resources or during the development of an existing shale gas play. The main results are: the optimal sources of water, the key variables of the system, and the degree of adjustments needed to these variables to balance technical, economic, social, and environmental factors. The methodology consists of three phases as detailed in Fig. 1.

3.1. Phase 1: Data collection

In Phase 1, sufficient information from the basin of study about the shale gas development and its regional water characteristics is acquired to effectively apply the methodology. The main components of MCDM are the decision-makers, stakeholders, alternatives, and criteria, which are distinct to each region. Typically, petroleum companies are the decision-makers, and the community, the government, and other