Investment Optimization Model for Freshwater Acquisition and Wastewater Handling in Shale Gas Production

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Major challenges of water use in the drilling and fracturing process in shale gas production are large volumes required in a short-period of time and the nonsteady nature of wastewater treatment. A new mixed-integer linear programming (MILP) model for optimizing capital investment decisions for water use for shale gas production through a discrete-time representation of the State-Task Network is presented. The objective is to minimize the capital cost of impoundment, piping, and treatment facility, and operating cost including freshwater, pumping, and treatment. The goal is to determine the location and capacity of impoundment, the type of piping, treatment facility locations and removal capability, freshwater sources, as well as the frac schedule. In addition, the impact of several factors such as limiting truck hauling and increasing flowback volume on the solution is examined. A case study is optimized to illustrate the application of the proposed formulation. © 2015 American Institute of Chemical Engineers *AIChE J*, 61: 1770–1782, 2015
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Introduction

Efficient water management and wastewater treatment are important aspects in the completion stage of shale gas development. Stimulating, or fracturing, a single well requires approximately 20,000–40,000 m^3 (5–10 Mgal) of water. As each wellpad allows multiple wells to be drilled and each development area contains tens of wellpads, hundreds of millions of gallons of water must be sourced in a well field development area. Freshwater is acquired from conventional sources such as surface water and delivered to each wellpad site through truck hauling or pipelines. At the wellpad, freshwater can be stored in freshwater impoundment in preparation for hydraulic fracturing. During each stage of the fracturing process, water is mixed with sand and chemical additives and is pumped into the well. Subsequently, a portion of the frac fluid that was injected is recovered over the span of multiple weeks from the well containing various contaminants. Stimulation of the wells also results in a large volume of high-salinity wastewater stream, which is coproduced over the lifetime of the well (e.g., 20 years) with the gas, and is often disposed through injection wells. The integral role that water plays in shale gas development enabled by hydraulic fracturing, therefore, requires industry to face the challenge of managing water in both environmentally and economically sustainable ways. The decision, based on optimal economic performance, to effectively reuse produced water as a cost-effective asset, also effectively improves water management and helps to minimize environmental liability.

Shale formation characteristics can vary significantly from region to region.[1] The main differences that could impact water management strategies include variability of wastewater composition and flow rate, availability of disposal wells (e.g., 50,000 disposal wells in Texas vs. less than 10 in Pennsylvania due to geological differences), and freshwater supplies. The economics is further complicated by differences in state regulatory policies and the maturity of oil and gas industry in the region. Furthermore, there is a temporal shift in water management landscape as shale plays

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become saturated with wells. The wells that have been drilled over the past several years are now producing a large volume of wastewater that needs to be handled effectively.

Wastewater salinity level is a key component in evaluating water management economics as frac fluid criterion dictates the volume and quality of wastewater that can be reused through blending with freshwater. Several factors lead to a significant increase in the need for wastewater treatment. The performance of frac fluid has improved and become more tolerant of contaminants in the water, thereby encouraging more wastewater reuse.[2] Also, the disposal option of injecting wastewater in deep wells is not necessarily available in proximity to the wells, driving up the trucking cost. Although the cost of desalination has become more competitive over the past decades as a result of technological advances, it is not yet widely used in shale gas applications in the Marcellus and Utica plays. These restrictions in shale play development pose considerable logistic challenges that demand sophisticated management and logistical strategies. Because shale gas production has been a relatively recent development, there are very few publications related to its water management issues.

The need for infrastructure development arises due to the rapid growth rate in shale gas development. The optimization model proposed in this article builds on previous work by the authors, Yang et al.,[3] who developed a mixed-integer linear programming (MILP) model for the optimal water management given water sources and treatment facilities for a set of wellpads. An overview of shale gas operations is described in Ref. [3]. Whereas the previous work deals mainly with short-term operations, the model in this article is concerned with longer term decisions for investments in water treatment, pipelines, and impoundments. Buried water pipelines, for example, can be setup while the gas pipelines are buried to incur less environmental footprint in comparison to overland pipelines and trucks.[4] It should also be noted that Gao and You[5] have addressed a problem similar to this work except that in their case they assumed a fixed schedule for the fracturing, which is a significant limitation as the schedule has a major impact in the revenue.

In this work, we develop a generalized model that optimizes freshwater acquisition and wastewater handling in the life cycle of a given set of wellpads through a discrete-time MILP model. The objective is to maximize the gross profit by accounting for revenue of gas production and the capital cost of freshwater impoundment, piping and mobile treatment units, and operating cost including fracturing costs, freshwater-related costs, and wastewater-related costs. Freshwater costs include freshwater acquisition, transportation, and storage, whereas wastewater costs include treatment, storage, transportation, and disposal. Given are freshwater source locations and withdrawal data, potential freshwater impoundment locations, wellpad location and fracturing stages, flowback profiles, treatment locations, treatment capacity and removal capabilities, and potential freshwater piping connections. The goal is to determine the optimal freshwater sources to acquire freshwater for the given set of wellpads, treatment facility capacity and removal options that cater to the flowback and produced water characteristics of the region. In addition, the optimal frac schedule for the wellpads is also to be determined.

The article is organized as follows. First, we introduce the relevant background for desalination and assess practical options for wastewater treatment options. We next introduce the general problem statement, its assumptions, and the mathematical formulation. Finally, we provide an example to illustrate the application of the model and present several scenarios that evaluate the sensitivity of various aspects of the model.

Background

Flowback water refers to the wastewater generated in the first few weeks following well stimulation, although the quantity and quality vary from site to site and from play to play. The general trend of increased salt concentration and decreased flow is predominant. Long-term produced water, which could be up to 70% of the total wastewater generated during the lifetime of a well, has a salinity level that could be as high as 360,000 ppm.[6] It is estimated that while water acquisition cost will increase by 20% from 2013 to 2022, wastewater treatment cost will increase by 60%, a significant part of which will come from treating the streams to discharge standard to meet the current and anticipated challenges from these wastewater streams. There are several schemes that can be adopted for wastewater reuse or disposal.

The flowback water profile provides an opportunity for reusing the initial flowback and blending it with freshwater to be used at the next well. Depending on the presence of other constituents in the stream, the next period of flowback can go through primary treatment options including deoiling and straining for the removal of suspended solids, oil and grease, bacteria, and divalent ions to prepare the stream for reuse.[2] As contaminant concentration increases, intermediate strategies such as disinfection (to remove microbes), organics removal, and softening (to remove divalent metal cations which cause scaling) are adopted to treat the stream to reuse standard. This option can be done either onsite through a mobile treatment unit or at a centralized wastewater treatment facility (CWT). The high salinity streams require energy intensive operations and a level of high integrity in the equipment (added cost). In addition, a major concern is managing the large quantity of produced water once the gas field is saturated with producing wells and the wastewater cannot be internally reused by the operator. Thus, demineralization through more advanced options for additional reuse or discharge to surface water (<500 ppm total dissolved solids (TDS) in the state of Pennsylvania) is considered, although conventional thermal processes are unsuitable due to the prohibitive capital cost, large installation footprint, and significant energy requirement.[6]

Desalination technologies can be categorized as thermal and membrane processes. The primary challenge is the variability in TDS concentration over the lifetime of the well, which constrains the selection of appropriate treatment technologies. As produced water management is mainly an economic decision, installation cost, energy cost, and secondary waste management cost are of primary concern. We present several desalination technologies that are suitable for use under the incentive of treating produced water. The feed water TDS level criterion for each technology is specified in Table 1. As can be seen, reverse osmosis (RO) can typically operate with low salinity level, forward osmosis (FO) can be adopted for medium TDS range, and finally, membrane distillation (MD), with or without crystallizer for the concentrated stream, is required to handle waste streams with up to 300,000 ppm of TDS.[2]

Reverse osmosis

RO is a mature technology and has been widely used in seawater desalination. The membrane permeability in RO

Table 1. Specifications of Desalination Technologies

Technology	Max TDS Concentration (ppm)	Max Recovery (%)	Reference
Reverse osmosis	35,000	50	7
Forward osmosis	70,000	60	8
Membrane distillation	300,000	60–95	8
Mechanical vapor recompression	200,000	50	8

allows it to effectively reject monovalent ions and low molecular weight organic compounds.[6] In addition, the process is highly modular and scalable. However, it is used to a much lesser extent in shale gas wastewater treatment because RO units are only able to process low-salinity influent water not exceeding 35,000 ppm of TDS with about 50% recovery level. Further recovery is limited by the very high osmotic pressures of the saline produced water stream.[9]

Forward osmosis

An option for desalination of intermediate concentration brines is FO, which is a technology that can avoid some of the drawbacks of pressure-driven membrane processes. A semipermeable membrane is used to separate the feed from a concentrated draw solution. The osmotic pressure difference across the membrane allows water to diffuse from the feed to the more concentrated draw solution such as thermolytic salts, therefore rejecting TDS as well as suspended solids in the process. The main difference between FO and RO is the driving force for separation. Whereas RO applies hydraulic pressure to overcome osmotic pressure, FO relies on the osmotic pressure differential between the feed and the draw solution that has a higher osmotic pressure to drive the flux. As a result, an additional step is necessary to regenerate the draw solution. FO can be used as a standalone process, or as a pretreatment for RO or distillation. The advantage of FO is that it can operate at relatively low pressure and temperature, which reduces the energy consumption. Unlike RO, FO is not limited by the high-pressure tolerance and is suitable for treating wastewater with less than 70,000 ppm TDS.[10]

Membrane distillation

MD is a thermally driven process that uses hydrophobic membranes to separate a warm aqueous feed with up to 300,000 ppm of TDS from a cool permeate. The temperature difference across the membrane serves as the driving force for the water transfer. As a result, the flux in MD is not very sensitive to the feed salinity. Another advantage of MD is that low-grade heat such as waste heat in power plant can be used as heat source. Compared to pressure-driven membrane processes, MD uses membranes with larger pores without an applied hydraulic pressure, leading to a lower propensity for fouling.[8] However, pretreatment is still important as contaminants such as organics and dissolved gas could still reduce the efficacy of the membranes by exerting partial pressures. To reduce secondary waste stream, an integration of MD with a crystallization unit could convert the raw brine to high quality water and salt crystals as products at a higher capital cost.[9]

Mechanical vapor recompression

The most widely demonstrated approach, in terms of reliability in demineralization of shale gas wastewater, is the mechanical vapor recompression (MVR) process, which uses electrical energy to supply thermal energy. The system includes heating the brine to evaporate the water, which is placed under partial vacuum by a compressor, allowing the water vapor to flow through a heat-exchanger, which recovers heat for the feed stream.[11] Using a compressor for evaporation instead of traditional heat source, energy savings can be achieved in this energy-intensive process. The unit is less susceptible to fouling and requires less pretreatment than membrane processes although scaling and corrosion are significant issues. The unit can also handle wastewater streams up to 200,000 ppm limited by salt solubility.[12] The recovered distillate is of high quality and can meet the surface water discharge standard in Pennsylvania, or reused as process water in other industrial applications. The concentrated brine can be crystallized and converted to salt cakes or disposed through Class II wells. While the operating and capital costs are lower compared to conventional thermal processes, the energy requirement is relatively high compared to membrane processes.[8] However, corrosion and scaling can occur and incur high operating and maintenance costs.[6] As the Marcellus play has relatively high TDS concentration in comparison with other shale plays, MVR is a feasible desalination option for the region.

Problem Statement

In the proposed model, the objective is to maximize profit by accounting for the revenue of gas sales and costs, including capital cost of impoundment, piping, and treatment facility, as well as operating costs including freshwater, pumping, treatment, and disposal. We assume that we are given the potential freshwater source locations and withdrawal data, potential impoundment locations, wellpad locations and total number of stages, and treatment units capability and locations. The goal is to determine the location and capacity of impoundment, the type of piping, treatment facility desalination technology, as well as the frac schedule, and the water sources to obtain freshwater.

The scheduling part of the problem is formulated through a discrete-time MILP model using as a basis the State-Task Network (STN) representation for batch scheduling.[13] The STN representation consists of three major elements: states, tasks, and equipment. Similar to STN-based batch processing models, the states correspond to the water sources and impoundments that feed into the wellpads. The processing tasks in the context of this work correspond to the fracturing of the wells on each wellpad. The investment decisions are superimposed on the scheduling model. The problem is optimized over a long planning horizon, which increases the computational difficulty for solving the MILP model since typically daily time period is considered.

The wellpads are divided into multiple areas. The potential water piping connections are highly dependent on the topography of the land. As the wellpads in each area are close in proximity, pipelines can be placed in between wellpads. Through the extensive use of pipelines, the advantage is that trucking freshwater can be greatly reduced or even avoided altogether, which improves the operations both economically and environmentally.

Frac fluid is blended using freshwater and wastewater. Because the various contaminants in the wastewater stream could interfere with frac fluid performance, operators fix the wastewater to freshwater ratio in the blending process to

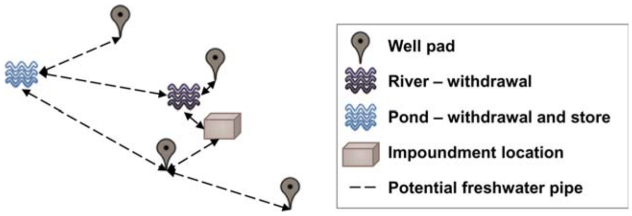

Figure 1. Main elements in water supply chain for shale gas production.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

maintain the efficacy of the fluid. As the purpose is to reuse the stream, this approach does not require wastewater streams to be treated to freshwater discharge standard, thereby avoiding extensive and costly treatment procedures. In this problem, we assume that the frac fluid criterion is specified by its TDS concentration level, which requires recycle and reuse of wastewater streams to meet the concentration target.

Freshwater can be obtained from rivers as well as ponds. The availability of water at the take point of the river affects the volume that the operator can withdraw from the river. In the problem formulation, we assume that all the freshwater sources are interruptible (i.e., small rivers or creeks close to the wellpads), which means that water can only be withdrawn from the sources if the flow rate in the source is above a threshold.[3] Alternatively, the ponds can serve either as a storage unit or a source. Freshwater sources supply water to the wellpads through either overland or buried pipelines. Overland pipelines can be rented and have a smaller environmental footprint. Buried pipelines, however, are mostly owned by the operator and are usually placed at the same time as burying the gas pipelines to minimize issues involving tree clearing and pipe freezing. Additional storage capacity can be met by impoundments.

After completion, streams of flowback can go through basic treatment onsite and then recycled to the next wellpad. It can also be trucked to CWT, where the streams are treated to discharge standard to be recycled at the next completion pad or discharged. As salinity level restricts the type of technology that can be used to treat the feed water, we consider several TDS removal options in the CWT. Depending on the desalination process, a concentrated wastewater stream is generated and trucked to disposal wells. The final option is that the flowback and produced stream can be trucked directly to disposal wells. The choice among these options is highly dependent on the flowback characteristics and handling costs. The locations and potential interconnections of the water sources, wellpads, and impoundments for the corresponding water supply chain are shown in Figure 1.

The assumptions made in the formulation of the model are as follows:

1. While the drilling schedule is fixed, the fracturing schedule is not. Wells can be fractured two weeks or later after the wells are drilled.
2. The wells in each wellpad are aggregated so that they are all stimulated before the frac crew is transferred to another wellpad. Each wellpad has a fixed number of stages that are available for completion during the modeled time period.
3. Freshwater sources connected to pipelines are seasonal, interruptible sources and their availability is given by the average historical flowrate data.[3]
4. Each pipeline segment has enough capacity to transfer freshwater used at the wellpads in each time period.
5. The sales price of gas is known as a function of time.
6. Flowback volumetric and compositional changes with time are known.
7. Frac tanks can only be placed on the completion pad.
8. Onsite treatment process provides adequate removal of most contaminants other than TDS for recycle.
9. CWT has pretreatment capability prior to desalination.
10. The treatment technologies considered can desalinate the water stream to discharge standard.
11. The cost of the desalination plant is annualized over the time horizon and is shared among a number of operators.

Problem Formulation

The problem can be formulated as a mixed-integer nonlinear programming (MINLP) model, which extends the MILP model Yang et al.[3] by considering investment in wastewater treatment, pipelines, and impoundments. The MINLP model involves the following constraint types: allocation constraints, material balances (some of which are bilinear), logic constraints, and an objective function. The main decision variables are 0–1 variables that are associated with various capital investment options. Additionally, y_{skt} is a binary variable that indicates the starting date t for wellpad s stimulation at rate k.

Constraints

Allocation Constraints. Constraint (1) specifies that each wellpad s has to be fractured exactly once at a given date t, and for a rate to frac per week k

$$\sum_k \sum_t y_{skt} = 1 \qquad \forall s \tag{1}$$

Constraint (2) represents a backward aggregation constraint from the STN model[14] that ensures there is no overlap between different wellpad operations

$$\sum_s \sum_k \sum_{t'=t-\mathrm{SFL}_{sk}-\mathrm{STC}+1}^{t} y_{skt'} \le 1 \qquad \forall t \tag{2}$$

where SFL_{sk} represents the duration of the hydraulic fracturing for the wellpad s stimulated at the rate of k stages per time period, STC represents the transition time required to move the frac crew from wellpad s to the next wellpad.

Water Use at Wellpads. Frac fluid at each wellpad can be supplied by a combination of freshwater and wastewater. The total weekly water requirement to frac a wellpad s is represented by constraint (3), where f_{st} is a continuous variable that defines the time profile of water use at each wellpad. SDW_s is the constant indicating water requirement for wellpad s during each time period of the fracturing. Water requirement for the remaining stages that are stimulated during the final time period is represented by the parameter SLW_s

$$f_{st} = \sum_k \left(\sum_{t'=t-\mathrm{SFL}_{sk}+2}^{t} \mathrm{SDW}_s y_{skt'} + \sum_{t'=t-\mathrm{SFL}_{sk}+1} \mathrm{SLW}_s y_{skt'} \right) \quad \forall s, \forall t \tag{3}$$

Both freshwater and wastewater can be used in frac fluid and is represented by constraint (4), where f_{st}^{FW} indicates the freshwater use and f_{st}^{WW} is the wastewater used at the wellpad

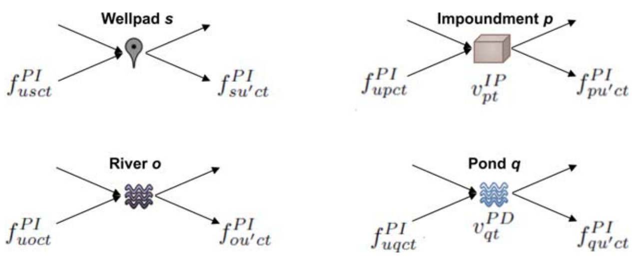

Figure 2. Flow directions for wellpads, impoundments, rivers, and ponds.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

$$f_{st}=f_{st}^{\mathrm{FW}}+f_{st}^{\mathrm{WW}} \qquad \forall s, \forall t \tag{4}$$

The freshwater mass balance at each wellpad is described by the mass balance in (5). The continuous variable $f_{uu'ct}^{\mathrm{PI}}$ represents the flow using pipeline of type c from location u to u'. The set u represents locations of all wellpads, river sources, pond sources, and impoundments, which are given by the indices s, o, q, and p, respectively. The nomenclature for flow directions at each location type is indicated in Figure 2

$$\sum_{u\in \mathrm{DP}_{us}}\sum_{c}f_{usct}^{\mathrm{PI}}=f_{st}^{\mathrm{FW}}+\sum_{u'\in \mathrm{DP}_{su'}}\sum_{c}f_{su'ct}^{\mathrm{PI}} \qquad \forall s, \forall t \tag{5}$$

Freshwater Source Constraints. Constraint (6) describes the mass balance for river take-points, where f_{ot}^{RI} is a continuous variable that represents the withdrawal rate from river source o. The utilization of source o is then restricted by the binary variable y_{o}^{FW} to a flow rate upper bound of $F_{ot}^{\mathrm{max,RI}}$ in constraint (7)

$$\sum_{u\in \mathrm{DP}_{uo}}\sum_{c}f_{uoct}^{\mathrm{PI}}+f_{ot}^{\mathrm{RI}}=\sum_{u'\in \mathrm{DP}_{ou'}}\sum_{c}f_{ou'ct}^{\mathrm{PI}} \qquad \forall o, \forall t \tag{6}$$

$$f_{ot}^{\mathrm{RI}}\leq y_{o}^{\mathrm{FW}}F_{ot}^{\mathrm{max,RI}} \qquad \forall o, \forall t \tag{7}$$

Similarly, freshwater can also be obtained from ponds. In addition to withdrawal of freshwater, ponds can serve as storage vessels. The volume of pond q on week t is given by the continuous variable v_{qt}^{PD}, and withdrawal of freshwater from the pond at time t is given by f_{qt}^{PD}. The weekly mass balance is described by constraint (8)

$$\sum_{u\in \mathrm{DP}_{uq}}\sum_{c}f_{uqct}^{\mathrm{PI}}+v_{qt-1}^{\mathrm{PD}}+f_{qt}^{\mathrm{PD}}=v_{qt}^{\mathrm{PD}}+\sum_{u'\in \mathrm{DP}_{qu'}}\sum_{c}f_{qu'ct}^{\mathrm{PI}} \qquad \forall q, \forall t \tag{8}$$

Constraint (9) establishes the use of pond q and withdrawal from the source is limited by water availability in the pond through constraint (10). Through the binary variable y_{q}^{PD}, the volume and withdrawal are zero if the pond is not used, otherwise, these variables are bounded by the maximum capacity $\mathrm{CP}^{\mathrm{PD}}$ and maximum withdrawal F_{qt}^{PD} from the pond, respectively

$$0\leq v_{qt}^{\mathrm{PD}}\leq y_{q}^{\mathrm{PD}}\mathrm{CP}^{\mathrm{PD}} \qquad \forall q, \forall t \tag{9}$$

$$f_{qt}^{\mathrm{PD}}\leq y_{q}^{\mathrm{PD}}F_{qt}^{\mathrm{PD}} \qquad \forall q, \forall t \tag{10}$$

Additional freshwater storage can be fulfilled by impoundments, which can be either constructed by the operator or rented. v_{pt}^{IP} is the continuous variable indicating the volume of water in impoundment p. The mass balances are given by the following constraint (11)

$$\sum_{u\in \mathrm{DP}_{up}}\sum_{c}f_{upct}^{\mathrm{PI}}+v_{pt-1}^{\mathrm{IP}}=v_{pt}^{\mathrm{IP}}+\sum_{u'\in \mathrm{DP}_{pu'}}\sum_{c}f_{pu'ct}^{\mathrm{PI}} \qquad \forall q, \forall t \tag{11}$$

Impoundment capacity l_{p}^{IP} and water volume v_{pt}^{IP} are bounded by the maximum $\mathrm{CP}_{p}^{\mathrm{max,IP}}$ and minimum $\mathrm{CP}_{p}^{\mathrm{min,IP}}$ capacity in constraints (12) and (13). y_{p}^{IP} and yI_{pt}^{IP} indicate the use of impoundment p

$$\mathrm{CP}_{p}^{\mathrm{min,IP}}y_{p}^{\mathrm{IP}}\leq l_{p}^{\mathrm{IP}}\leq \mathrm{CP}_{p}^{\mathrm{max,IP}}y_{p}^{\mathrm{IP}} \qquad \forall p \tag{12}$$

$$v_{pt}^{\mathrm{IP}}\leq \mathrm{CP}_{p}^{\mathrm{max,IP}}yI_{pt}^{\mathrm{IP}} \qquad \forall p, \forall t \tag{13}$$

The volume of water in the impoundment is restricted by the capacity of the impoundment as in constraint (14), and constraint (15) relates the two binary variables y_{p}^{IP} and yI_{pt}^{IP} to indicate the use of each impoundment

$$v_{pt}^{\mathrm{IP}}\leq l_{p}^{\mathrm{IP}} \qquad \forall p, \forall t \tag{14}$$

$$y_{p}^{\mathrm{IP}}\geq yI_{pt}^{\mathrm{IP}} \qquad \forall p, \forall t \tag{15}$$

Wastewater Handling and Investment Constraints. The superstructure for flowback handling is shown in Figure 3.

In constraints (16) and (17), f_{st}^{FB} and c_{st}^{FB} are continuous variables that indicate flowback flowrate and concentration of each wellpad during time t, which define the profiles over the horizon depending on the frac schedule. $\mathrm{SF}_{st}^{\mathrm{FB}}$ and $\mathrm{SC}_{st}^{\mathrm{FB}}$ are parameters that indicate flowback flow rate and TDS concentration

$$f_{st}^{\mathrm{FB}}=\sum_{k}\sum_{t''\in t-t'-\mathrm{SFL}_{sk}+1}\sum_{t'}\mathrm{SF}_{st''}^{\mathrm{FB}}y_{skt'} \qquad \forall s, \forall t \tag{16}$$

$$c_{st}^{\mathrm{FB}}=\sum_{k}\sum_{t''\in t-t'-\mathrm{SFL}_{sk}+1}\sum_{t'}\mathrm{SC}_{st''}^{\mathrm{FB}}y_{skt'} \qquad \forall s, \forall t \tag{17}$$

The flowback stream from wellpad, f_{st}^{FB}, can be treated onsite, trucked to CWT for desalination and discharge, or disposed directly as described in constraint (18), and their flow rates are denoted by $f_{st}^{\mathrm{FB,OT}}$, $f_{st}^{\mathrm{FB,CT}}$, and $f_{st}^{\mathrm{FB,DP}}$

$$f_{st}^{\mathrm{FB}}=f_{st}^{\mathrm{FB,OT}}+f_{st}^{\mathrm{FB,CT}}+f_{st}^{\mathrm{FB,DP}} \qquad \forall s, \forall t \tag{18}$$

f_{st}^{OT} is a continuous variable representing the combined flowback streams from producing wells that is being treated

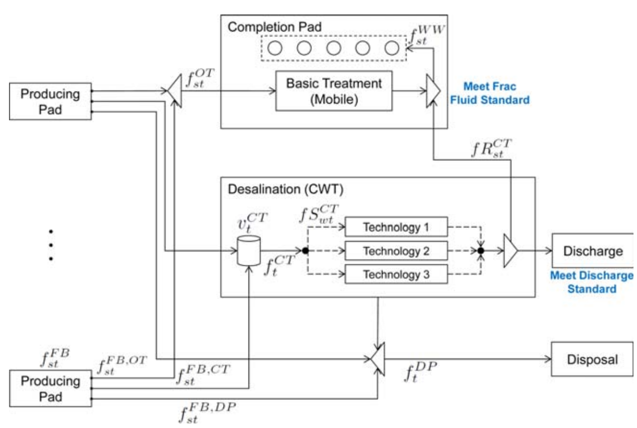

Figure 3. Wastewater flows.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

onsite and recycled to wellpad s. f_t^{CT} is the flow trucked to CWT for desalination. The desalination unit is assumed to have gone through pretreatment and the additional cost is incorporated. f_t^{DP} is the flow rate that is trucked to disposal wells.

For the first option, basic onsite treatment, the total mass, and TDS balance are represented by constraints (19) and (20), where c_t^{OT} is the TDS concentration of the flowback water transported to basic treatment. Note that (20) involves bilinear terms on the summation of the right-hand side

$$\sum_s f_{st}^{\mathrm{OT}} = \sum_{s'} f_{s't}^{\mathrm{FB,OT}} \qquad \forall t \tag{19}$$

$$\sum_s f_{st}^{\mathrm{OT}} c_t^{\mathrm{OT}} = \sum_{s'} f_{s't}^{\mathrm{FB,OT}} c_{s't}^{\mathrm{FB}} \qquad \forall t \tag{20}$$

The second option is desalination at CWT. A wastewater tank (assuming constant mixing) with volume v_t^{CT} is used to temporarily store the flowback streams. The mass balance for the tank is expressed in constraint (21). The TDS concentration of the combined flowback stream is denoted by c_t^{CT} and the balance of TDS is represented by the bilinear constraint (22)

$$\sum_s f_{st}^{\mathrm{FB,CT}} + v_{t-1}^{\mathrm{CT}} = f_t^{\mathrm{CT}} + v_t^{\mathrm{CT}} \qquad \forall t \tag{21}$$

$$\sum_s f_{st}^{\mathrm{FB,CT}} c_{st}^{\mathrm{FB}} + v_{t-1}^{\mathrm{CT}} c_{t-1}^{\mathrm{CT}} = (f_t^{\mathrm{CT}} + v_t^{\mathrm{CT}}) c_t^{\mathrm{CT}} \qquad \forall t \tag{22}$$

Several treatment options can be used for TDS reduction in CWT such as RO and thermal distillation. The choice of each technology is represented by the binary variable y_w^{CT}, the throughput of each technology is indicated by the continuous variable fS_{wt}^{CT}. Constraint (23) allows the problem to choose at most one technology for TDS removal, and constraint (24) is the mass balance for flow through the desalination unit.

$$\sum_w y_w^{\mathrm{CT}} \le 1 \tag{23}$$

$$\sum_w fS_{wt}^{\mathrm{CT}} = f_t^{\mathrm{CT}} \qquad \forall t \tag{24}$$

The volumetric throughput each technology in CWT is bounded as in constraint (25), In addition, each technology is limited to treating feedwater with TDS concentrations given by parameter $\mathrm{CU}_w^{\mathrm{CT}}$, as is expressed in constraint (26)

$$fS_{wt}^{\mathrm{CT}} \le F_{wt}^{\max,\mathrm{CT}} y_w^{\mathrm{CT}} \qquad \forall w, \forall t \tag{25}$$

$$c_t^{\mathrm{CT}} \le \sum_w \mathrm{CU}_w^{\mathrm{CT}} y_w^{\mathrm{CT}} \qquad \forall t \tag{26}$$

A fraction of the desalinated water stream becomes a concentrated waste stream and needs to be disposed, thus the recycle stream from desalination depends on the parameter η_w, the recovery ratio

$$\sum_w \eta_w fS_{wt}^{\mathrm{CT}} \ge \sum_s fR_{st}^{\mathrm{CT}} \qquad \forall t \tag{27}$$

Disposal at an injection well is the final option being considered, where the cost of pretreatment is accounted for in the disposal cost

$$f_t^{\mathrm{DP}} = \sum_s f_{st}^{\mathrm{FB,DP}} \qquad \forall t \tag{28}$$

fR_{st}^{CT} represents the stream that is recycled to the wellpad s after desalination. Wastewater used at each site is through recycling of the treated water as follows

$$fR_{st}^{\mathrm{CT}} + f_{st}^{\mathrm{OT}} = f_{st}^{\mathrm{WW}} \qquad \forall s, \forall t \tag{29}$$

The TDS balance at wellpad s is represented by constraint (30), which involves bilinear terms. The stream that is treated onsite does not change in TDS concentration as we assume that the onsite treatment does not have desalination capability. The stream of frac fluid from blending recycled wastewater and freshwater on wellpad s has to meet the maximum frac fluid TDS standard concentration CF.

$$\mathrm{CD} fR_{st}^{\mathrm{CT}} + c_t^{\mathrm{OT}} f_{st}^{\mathrm{OT}} \le \mathrm{CF} f_{st} \qquad \forall s, \forall t \tag{30}$$

On the completion pad, the capacity of the frac tank at wellpad s is bounded by the maximum wastewater flow rate used at the wellpad as defined in constraint (31)

$$l_{st}^{\mathrm{ST}} \ge f_{st}^{\mathrm{WW}} \qquad \forall s, \forall t \tag{31}$$

fT_w^{CT} is a continuous variable indicating the throughput of the desalination plant

$$fT_w^{\mathrm{CT}} \ge fS_{wt}^{\mathrm{CT}} \qquad \forall w, \forall t \tag{32}$$

Pipeline Constraints. $y_{uu'c}^{\mathrm{PI}}$ are binary variables that indicate the existence of a pipeline of type c between u and u'. Constraint (33) ensures that both flow directions are allowed in any pipe in the structure

$$y_{uu'c}^{\mathrm{PI}} = y_{u'uc}^{\mathrm{PI}} \qquad \forall uu' \in \mathrm{DP}_{uu'}, \forall c \tag{33}$$

Constraint (34) indicates that at most one type of pipeline, buried or overland, can be chosen for each segment

$$\sum_c y_{uu'c}^{\mathrm{PI}} \le 1 \qquad \forall uu' \in \mathrm{DP}_{uu'} \tag{34}$$

In addition, pipeline flow capacities are bounded above by UF and below by LF

$$\mathrm{LF} y_{uu'c}^{\mathrm{PI}} \le f_{uu'ct}^{\mathrm{PI}} \le \mathrm{UF} y_{uu'c}^{\mathrm{PI}} \qquad \forall uu' \in \mathrm{DP}_{uu'}, \forall t \tag{35}$$

Objective

The objective of the problem, which is profit maximization, involves the sum of the following costs: (1) freshwater cost; (2) freshwater impoundment cost; (3) freshwater pipeline cost; (4) frac tank cost; (5) disposal cost; (6) wastewater disposal cost; (7) onsite treatment cost; and (8) CWT treatment cost.

Freshwater cost $\mathrm{COST}^{\mathrm{FW}}$ includes set-up cost and withdrawal cost from rivers and ponds. In constraint (36), $\mathrm{IC}_u^{\mathrm{FW}}$ is the set-up cost of source, and $\mathrm{OC}_u^{\mathrm{FW}}$ is the withdrawal cost coefficient

$$\begin{aligned}\mathrm{Cost}^{\mathrm{FW}} = &\sum_o \mathrm{IC}_o^{\mathrm{FW}} y_o^{\mathrm{RI}} + \sum_o \sum_t \mathrm{OC}_o^{\mathrm{FW}} f_{ot}^{\mathrm{RI}} \\ &+ \sum_q \mathrm{IC}_q^{\mathrm{FW}} y_q^{\mathrm{PD}} + \mathrm{OC}_q^{\mathrm{FW}} \sum_q \sum_t f_{qt}^{\mathrm{PD}}\end{aligned} \tag{36}$$

Impoundments can be either constructed by the operator or rented, and the cost term $\mathrm{Cost}^{\mathrm{IP}}$ includes both the construction and rental cost. $\mathrm{ICB}_p^{\mathrm{IP}}$ in constraint (37) is the base cost factor of the impoundment, whereas $\mathrm{ICI}_p^{\mathrm{IP}}$ is the incremental cost based on volume of the impoundment, and $\mathrm{OC}_p^{\mathrm{IP}}$ is the operating cost of the impoundment

$$\mathrm{Cost}^{\mathrm{IP}} = \sum_p (\mathrm{ICB}_p^{\mathrm{IP}} y_p^{\mathrm{IP}} + \mathrm{ICI}_p^{\mathrm{IP}} l_p^{\mathrm{IP}} + \mathrm{OC}_p^{\mathrm{IP}} \sum_t yI_{pt}^{\mathrm{IP}}) \tag{37}$$

Pipeline cost $\mathrm{Cost}^{\mathrm{PI}}$ is made up of installation cost and pumping cost as follows

$$\mathrm{Cost}^{\mathrm{PI}}=\sum_c \sum_u \sum_{u' \in \mathrm{DP}_{uu'}} \Big(\mathrm{IC}_c^{\mathrm{PI}}\mathrm{DI}_{uu'}y_{uu'c}^{\mathrm{PI}} + \sum_t \big(\mathrm{OC}_c^{\mathrm{PI}}\mathrm{DI}_{uu'}y_{uu'tc}^{\mathrm{PI}}+\mathrm{OCPU}f_{uu'ct}^{\mathrm{PI}}\big)\Big) \tag{38}$$

where $\mathrm{IC}_c^{\mathrm{PI}}$ is the pipeline installation cost, $\mathrm{OC}_c^{\mathrm{PI}}$ is the rental cost of the pipeline, and OCPU is the pumping cost.

As frac tanks are typically rented, the only coefficient associated with frac tank cost $\mathrm{Cost}^{\mathrm{WW,ST}}$ is the rental cost $\mathrm{OC}^{\mathrm{WW,ST}}$

$$\mathrm{Cost}^{\mathrm{WW,ST}}=\sum_s \sum_t \mathrm{OC}^{\mathrm{WW,ST}} l_{st}^{\mathrm{ST}} \tag{39}$$

Disposal cost $\mathrm{Cost}^{\mathrm{DS}}$ includes trucking cost from wellpad to disposal well and disposal cost. $\mathrm{OC}^{\mathrm{WW,TR}}$ is the coefficient of trucking cost, DW is the distance to disposal site, and $\mathrm{OCDS}^{\mathrm{WW}}$ is the disposal cost

$$\mathrm{Cost}^{\mathrm{DS}}=(\mathrm{OC}^{\mathrm{WW,TR}}\mathrm{DW}+\mathrm{OCDS}^{\mathrm{WW}})\sum_t f_t^{\mathrm{DP}} \tag{40}$$

Onsite treatment cost $\mathrm{Cost}^{\mathrm{OT}}$ including onsite treatment cost, $\mathrm{OC}^{\mathrm{WW,OT}}$ is the cost coefficient for treatment

$$\mathrm{Cost}^{\mathrm{OT}}=\mathrm{OC}^{\mathrm{WW,OT}}\sum_s \sum_t f_{st}^{\mathrm{OT}} \tag{41}$$

The last term is CWT treatment cost $\mathrm{Cost}^{\mathrm{CT}}$, which has several components, desalination capital and operating cost, wastewater hauling cost, concentrated stream disposal cost, and desalinated water discharge cost. AR is the annualized factor, $\mathrm{IC}_w^{\mathrm{WW,CT}}$ and $\mathrm{OC}_w^{\mathrm{WW,CT}}$ are the capital and operating cost of desalination using treatment process w, $\mathrm{OCDC}^{\mathrm{WW}}$ is discharge cost for desalinated water, and DC is the distance to CWT.

$$\begin{aligned}\mathrm{Cost}^{\mathrm{CT}}=&\sum_w \mathrm{ARIC}_w^{\mathrm{WW,CT}} fT_w^{\mathrm{CT}}+\sum_w \sum_t \mathrm{OC}_w^{\mathrm{WW,CT}} fS_{wt}^{\mathrm{CT}}\\ &+\sum_t \mathrm{DC}f_t^{\mathrm{CT}}\\ &+\mathrm{OCDC}^{\mathrm{WW}}\sum_t\Big(\sum_w \eta_w fS_{wt}^{\mathrm{CT}}+\sum_s fR_{st}^{\mathrm{CT}}\Big)\\ &+\mathrm{OCDS}^{\mathrm{WW}}\sum_w\sum_t(1-\eta_w)fS_{wt}^{\mathrm{CT}}\\ &+\mathrm{OC}^{\mathrm{WW,TR}}\mathrm{DW}\sum_w\sum_t(1-\eta_w)fS_{wt}^{\mathrm{CT}}\end{aligned} \tag{42}$$

The profit from gas revenue can be represented by (43), where P_{st} is the parameter representing revenue from production for each wellpad during time period t, and SFL_{sk} is the length of time it takes to frac wellpad s at frac rate k

$$\mathrm{Revenue}=\sum_s \sum_t \sum_k P_{s,t+\mathrm{SFL}_{sk}} y_{skt} \tag{43}$$

Combining terms (36)–(43) we have the objective function (43), which defines the maximization of the total profit

$$\begin{aligned}&\max.\ \mathrm{Gross\ profit}=\mathrm{Revenue}\\ &-(\mathrm{Cost}^{\mathrm{FW}}+\mathrm{Cost}^{\mathrm{IP}}+\mathrm{Cost}^{\mathrm{PI}}+\mathrm{Cost}^{\mathrm{WW,ST}}\\ &+\mathrm{Cost}^{\mathrm{DS}}+\mathrm{Cost}^{\mathrm{OT}}+\mathrm{Cost}^{\mathrm{CT}})\end{aligned} \tag{44}$$

MILP approximation

The formulation with constraints (1)–(35) corresponds to an MINLP due to the bilinear terms of flowrate multiplied by concentration in constraints (20), (22), and (30). To eliminate nonlinearities, we discretize TDS concentration variables that are part of the bilinear terms into intervals accounting for the treatment units inlet criteria, frac fluid criterion, discharge standard, and minimum and maximum TDS concentration of the wastewater in the region. While this is an approximation, it still allows for enough resolution to distinguish the ability to recycle the stream and the selection of discrete desalination technology choice. Thus, we discretize the concentration terms c_{st}^{FB} and disaggregate the flow f_{st}^{FB} as follows

$$\left.\begin{aligned} c_{st}^{\mathrm{FB}}&=\sum_r \mathrm{CI}_r z_{str}^{\mathrm{FB}} && \forall s,\forall t\\ \sum_r z_{str}^{\mathrm{FB}}&=1 && \forall s,\forall t\\ f_{st}^{\mathrm{FB}}&=\sum_r \hat{f}_{str}^{\mathrm{FB}} && \forall s,\forall t\\ \hat{f}_{str}^{\mathrm{FB}}&\le F^{\max} z_{str}^{\mathrm{FB}} && \forall s,\forall t,\forall r\end{aligned}\right\} \tag{45}$$

where z_{str}^{FB} are the binary variables selecting the concentration value CI_r and $\hat{f}_{str}^{\mathrm{FB}}$ that are the disaggregated variables for f_{st}^{FB}. Similarly, the other bilinear terms are approximated in the same fashion. Note, we included zero for ensuring that the inequality in (26) is satisfied when the technology w is not chosen.

The objective in (44), along with the linearized constraints (45) and (1)–(35), form the MILP model for the water source location and treatment management problem.

Case Study

Optimization model

We consider a case study with 14 wellpads as shown in Figure 4 with production curve shown in Figure 5. Each wellpad becomes available at a different time as indicated in the figure and Table 2. Wellpads are geographically distributed in two clusters in a given region. There are five nearby interruptible river sources, four ponds, and two impoundments serving the wellpads in the two areas. The time horizon is 3 years and it is discretized into 156 weekly time steps. Three completion rates, 20, 30, and 40 stages per week, are considered for one frac crew. The slowest stimulation rate is usually selected during periods of low water availability. The flowback flowrate and TDS level profile are given in Figure 6. Choice of two types of pipelines, overland, and buried, are incorporated in the model. The buried pipelines are more expensive, whereas the overland pipelines are used less frequently in the winter due to the possibility of freezing pipelines. Furthermore, three desalination technologies are considered for TDS removal, including MD, thermal distillation (MVR), and thermal distillation with crystallizer. Finally, we selected six discretization points within 330,000 ppm for the concentrations to avoid the bilinear terms through the constraints in (45). Cost data is presented in Table 3.

The MILP model consists of 111,399 constraints, 104,188 continuous variables, and 19,954 binary variables. The model is solved using GAMS 24.2/CPLEX 12.6 on an Intel 2.93 GHz Core i7 CPU machine with 4 GB of memory to a 0.1% optimality gap in approximately 7 h.

The optimized frac schedule leads to a gross profit of \$1,034,110,429, with \$1,115,618,566 in natural gas

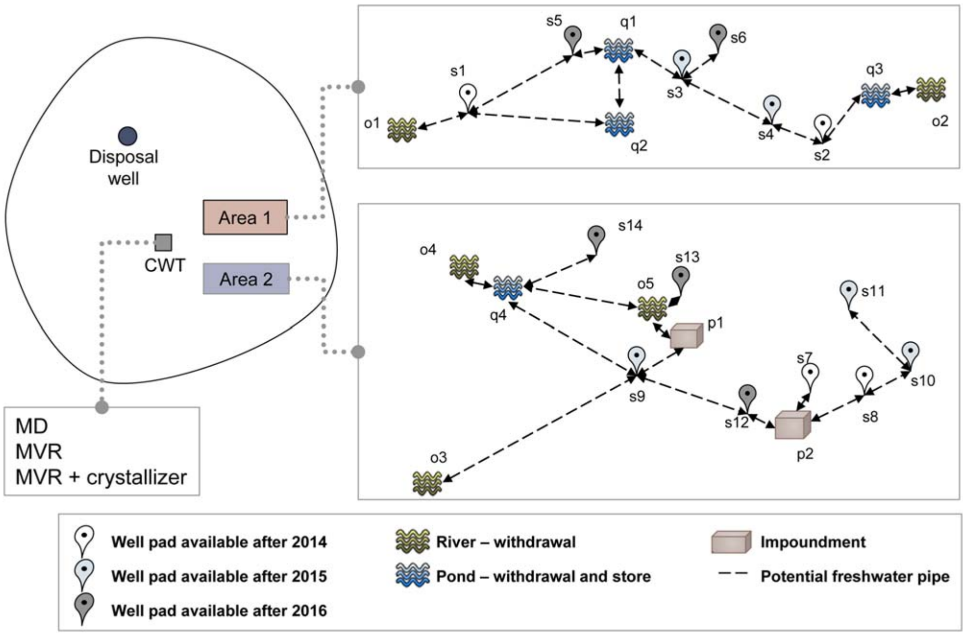

Figure 4. Layout of case study.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

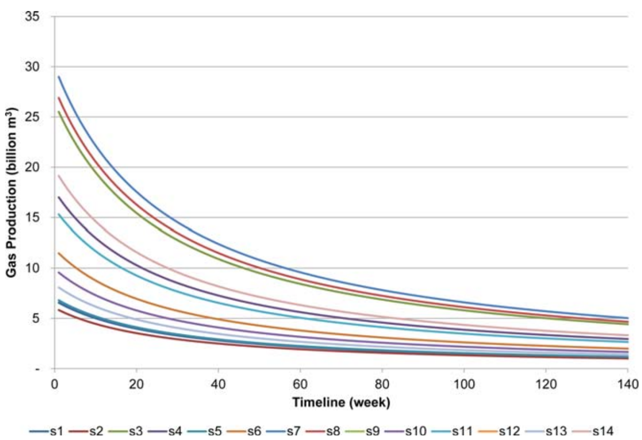

Figure 5. Total gas production curve of each wellpad.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

revenue (see Table 5). Water-related cost totals $81,508,137, which is around 7% of the total revenue. All river sources, all four ponds, and one impoundment are included in the configuration. All pipelines are buried as we specified in the problem that overland pipelines cannot be used between the months of December to February. In addition, thermal distillation is selected by the model as the optimal method for TDS removal in CWT.

We present several scenarios below that provide different solutions from the optimal solution in order to gain some insights into the nature of this problem when the assumptions are changed.

Scenario Description

Scenario 1: Heuristic schedule

First, the allocation constraints (1) and (2) greatly increase the size and complexity of the MINLP model. Therefore Scenario 1 optimizes the problem with a fixed heuristic schedule that is determined by intuition.

Scenario 2: No desalination unit

Currently, most shale gas operators do not desalinate wastewater streams due to the high cost of mobile unit and the lack of centralized treatment facility. There are concerns associated with the disposal of large volumes of oil and gas wastewater by injection disposal, including risk of unwanted fluid migration and potentially induced seismicity.[15] Thus, in Scenario 2 we assume that a centralized desalination plant can be constructed to serve around 50 wellpads in the proximity (10 miles radius). This problem investigates the economic viability of constructing a desalination plant and the distribution of flowback water if desalination is not an option.

Scenario 3: Allow trucking

The model in this work considers only freshwater transported through pipelines as truck hauling has negative impact including road damages, traffic accidents, and environmental concerns. As a result, operators are encouraged to draw freshwater from nearby sources. We can modify the model to allow for trucking from an uninterruptible source (i.e., large water body with guaranteed water availability year-round) and examine its effect on the optimal solution.

Table 2. Case Study Wellpad Data

Wellpad	*s*1	*s*2	*s*3	*s*4	*s*5	*s*6	*s*7	*s*8	*s*9	*s*10	*s*11	*s*12	*s*13	*s*14
# of stages	120	120	210	140	140	210	434	492	280	175	280	175	70	350
Earliest frac time (week)	1	6	19	19	71	71	20	11	19	19	19	71	71	71

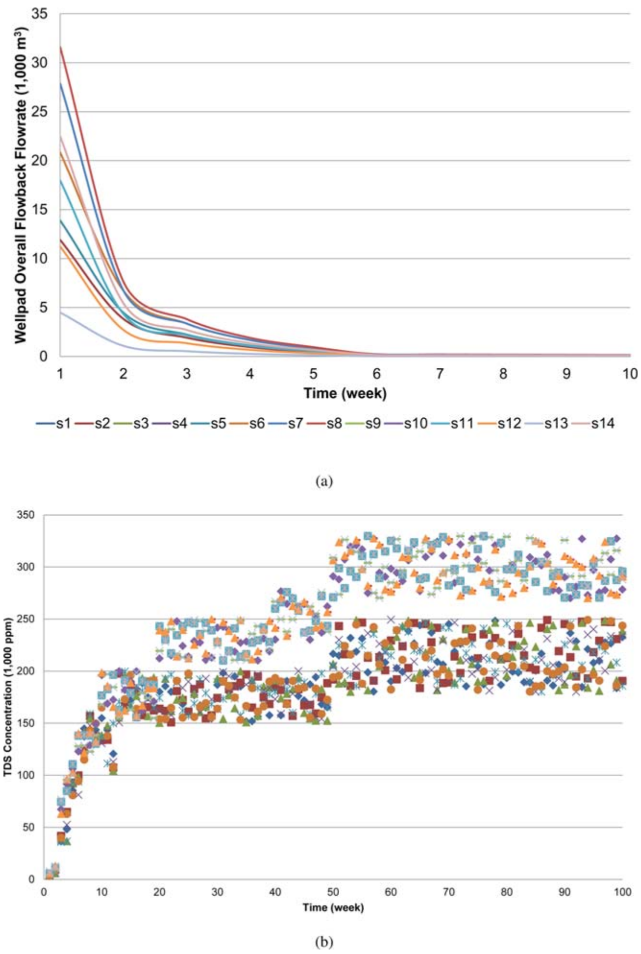

Figure 6. Flowback (a) flowrate profile and (b) TDS concentration.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

We introduce the continuous variable f_{st}^{TR} to represent the volume of freshwater trucked to each wellpad s during time period t, and modify the constraint (4) to obtain constraint (46)

$$f_{st}=f_{st}^{\mathrm{FW}}+f_{st}^{\mathrm{WW}}+f_{st}^{\mathrm{TR}} \qquad \forall s, \forall t \tag{46}$$

The following term is also added to the objective function indicating the trucking cost and the set-up cost for the uninterruptible freshwater source from where the truck hauls water

$$(\mathrm{OC}^{\mathrm{TR}}+\mathrm{OC}^{\mathrm{FW}})\sum_{st} f_{st}^{\mathrm{TR}}+\mathrm{IC}^{\mathrm{FW}}y^{\mathrm{TR}} \tag{47}$$

where $\mathrm{OC}^{\mathrm{TR}}$ is the trucking cost, y^{TR} is a binary variable indicating the use of trucking for freshwater acquisition, $\mathrm{OC}^{\mathrm{FW}}$ is the withdrawal cost, and $\mathrm{IC}^{\mathrm{FW}}$ is the perennial source set-up cost. In addition, we assume an additional 10% "bonding" cost for truck use which the operators have to account for to cover road damage.

Scenario 4: Higher flowback volume

In the Marcellus and Utica shale plays, flowback rate is relatively low compared to other shale plays, where the flowback rate may be as high as 25%. We double the flowback rate in the model (see Figure 6a) to analyze the distribution of wastewater as a result of higher flowback rate.

Results and Discussion

The computational statistics and objective value from all four scenarios are presented in Tables 4 and 5, respectively. Both revenue from natural gas sales and water-related costs are considered in optimizing the problem. Note from Table 5 that for these 14 wellpads, water-related cost makes up 7% (in the optimal case) to 11% (in Scenario 2 where desalination is not considered) of the revenue from gas production, which is quite significant. As can be seen, the heuristic schedule yields the lowest gross profit during the 3-year period.

Besides the scenario with heuristic schedule, all other cases obtained the same optimal frac schedule as the high revenue achieved from this schedule is an order of magnitude higher than the cost, thus it is unlikely that a different schedule with lower revenue will yield a low enough cost to compensate for the change in revenue. Both the optimal schedule and heuristic schedule are shown in Figure 7. In the optimal solution, all wellpads are stimulated under the fastest completion rate, whereas in the heuristic schedule, most wellpads are stimulated at a slower pace.

In the model, we assumed that the desalination facility could be shared by other operators that have around 200 wells to be completed during the same time period. It is interesting to note that the cost of Scenario 2 (no desalination) is 52% higher than that of the optimal case, considering that desalination is not a standard practice. Scenario 4 assumes that the flowback rate doubles in comparison to the flowback rate in the optimal case. The total water-related cost increases by 21%, which is expected since wastewater handling cost increases significantly. However, the pumping cost in Scenario 4 is actually lower compared to the optimal case, \$38.9 million to \$41.8 million, as Scenario 4 takes advantage of recycling the high flowback rate.

Freshwater-related costs for the various scenarios are summarized in Figure 8. The optimal solution, heuristic solution, and Scenario 2 solution have similar freshwater pumping costs at around \$42.8–\$44.7 million. In addition, Scenario 3 takes advantage of operational flexibility in truck use. Out of the 4.1 million m^3 (1073.8 Mgal) of water used to frac the 14

Table 3. Case Study Cost Coefficient Data*

Cost Coefficient	Unit	Value
$\mathrm{ICB}_p^{\mathrm{IP}}$	\$	360,000
$\mathrm{ICI}_p^{\mathrm{IP}}$	\$/m^3	7.40
$\mathrm{IC}_w^{\mathrm{WW,CT}}$	\$ million	9–15
$\mathrm{IC}_u^{\mathrm{FW}}$	\$	50,000–100,000
$\mathrm{IC}_c^{\mathrm{PI}}$	\$/km	202,000
$\mathrm{OC}_p^{\mathrm{IP}}$	\$/week	10,500
$\mathrm{OC}_u^{\mathrm{FW}}$	\$/m^3	0–1.98
$\mathrm{OC}^{\mathrm{WW,TR}}$	\$/m^3/km	0.28
$\mathrm{OC}^{\mathrm{WW,ST}}$	\$/m^3/week	4.70
$\mathrm{OC}^{\mathrm{WW,OT}}$	\$/m^3	25.16
$\mathrm{OC}_w^{\mathrm{WW,CT}}$	\$/m^3	42–84
$\mathrm{OCDC}^{\mathrm{WW}}$	\$/m^3	4.19
$\mathrm{OCDS}^{\mathrm{WW}}$	\$/m^3	101
$\mathrm{OC}_c^{\mathrm{PI}}$	\$/km/week	3438
OCPU	\$/week	35,000

*Coefficient based on reported industry average.

Table 4. Computational Statistics

	Optimal	1: Heuristic	2: No Desalination	3: Freshwater Trucking	4: Double Flowback Volume
# of binary var	19,954	16,831	16,830	16,831	16,830
# of continuous var	111,399	111,399	111,399	113,583	111,399
# of constraints	104,188	104,188	104,188	106,373	104,188

Table 5. Summary of Objective Values ($)

		Optimal	1: Heuristic	2: No Desalination	3: Freshwater Trucking	4: Double Flowback Volume
Revenue		1,115,618,566	985,551,244	1,115,618,566	1,115,618,566	1,115,618,566
Cost	Freshwater-related	57,942,917	58,502,626	60,538,657	52,988,194	53,813,066
	Capital	10,210,311	9,558,868	10,814,192	7,372,340	10,210,311
	Operating	47,732,606	48,943,758	49,724,466	45,615,853	43,602,755
	Wastewater-related	23,565,220	26,404,160	63,313,136	23,278,137	44,467,328
	Capital	3,912,326	3,600,535	0	3,598,665	5,109,462
	Operating	19,652,894	22,803,625	63,313,136	19,679,472	39,357,867
	Total cost	81,508,137	84,906,786	123,851,793	76,266,331	98,280,395
Gross profit		1,034,110,429	900,644,458	991,766,773	1,039,352,235	1,017,338,171

wellpads, 1.3 million m^3 (349.4 Mgal) is freshwater supplied through truck hauling. By allowing trucking, the uninterruptible water source for trucking is set up with four interruptible river sources, whereas the optimal scenario requires all five river sources to be setup. This allows for more robust freshwater supply during periods of low water availability in the interruptible sources, leading to the highest profit, $1039 million. As a result, whereas the optimal scenario requires the construction of a 38,000 m^3(10 Mgal) impoundment, Scenario 3 does not invest in this impoundment. Figure 9 shows the total water availability from the sources chosen in the optimized solution for each of the two areas as well as the cumulative trucking use in the two areas. As can be seen from the figure, there is a correlation between period of low water availability and increases in truck use. Overall, the cost for allowing freshwater truck hauling is lower than the optimal solution without the trucking option ($81.5 vs. $76.3 million). However, if freezing is not issue in a shale play region, overland pipeline can offer a less expensive option.

Wastewater management cost allocation for the four scenarios is presented in Figure 10. For the optimal solution, the total cost for desalination (annualized capital cost, operating cost, sludge disposal, discharge cost, and trucking cost from desalination plant to disposal well) is $20.8 million for 250,000 m^3 (66.1 Mgal) of flowback water, whereas onsite treatment costs $2.5 million for a total throughput of 133,000 m^3 (35.2 Mgal). All the scenarios (other than Scenario 2) select thermal distillation as the choice for desalination. Note that other than Scenario 2 where desalination is not an option, none of the other scenarios use direct disposal through Class II injection well. This is mainly due to the relative distance between the centralized desalination plant and the disposal well with respect to the wellpads (21 km vs. 48 km) for this specific example.

In the problem formulation, we determine the volume of flowback water to recycle for frac fluid using a concentration upper bound of 50,000 ppm of TDS of the blended frac fluid, whereas operators use a percentage value of 15% of

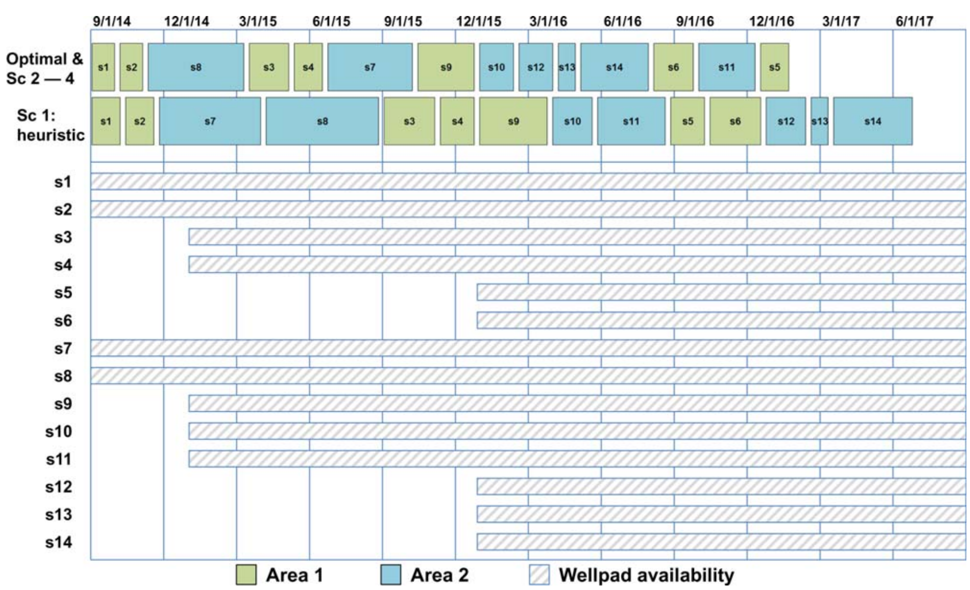

Figure 7. Comparison between the optimal and heuristic schedule.

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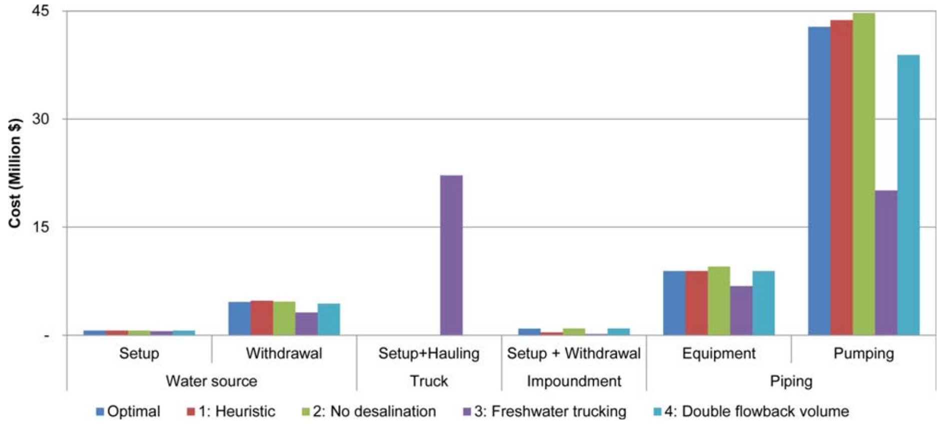

Figure 8. Freshwater cost comparison for all scenarios.

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flowback water to limit recycle. The percentage limit provides the industry with a convenient parameter to control system flows. However, the physical limitation of TDS concentration in frac fluid is a more technically meaningful operational constraint. The advantage of the current approach can be seen in the result from the optimal scenario as shown in Figure 11. The figure on the left indicates the overall frac fluid composition for each wellpad. Wellpad 1 uses only freshwater as it is the first one to be stimulated. All the wellpads use less than 15% of recycled water. However, if we examine the second figure, which represents the composition over time for wellpad 3, we can see that both in week 1 and week 7, the recycled water flowrate makes up about 20% of frac fluid. The first week of recycled water comes mainly from the initial flowback of wellpad 8, which has low TDS concentration. The last week of recycled water comes from desalinated wastewater, as the later period of flowback has high TDS concentration.

Note that the total freshwater-related cost is significantly higher than wastewater handling cost for cases that allow desalination. One reason for this is that only less than 3 years (time horizon of the example) of produced water is considered in this example. However, operators in the Marcellus expect around 10 bbl of produced water per month for each well for the lifetime of the well. This small stream of high salinity produced water requires proper handling and can incur a high cost.

Conclusion

An MILP model has been proposed for capital investment decisions related to freshwater sources, storage, and flowback treatment facility for managing water in shale gas development. The proposed model assumes given potential freshwater source locations and withdrawal data, potential impoundment locations, wellpad locations and total number of stages, and treatment units capability and locations. The

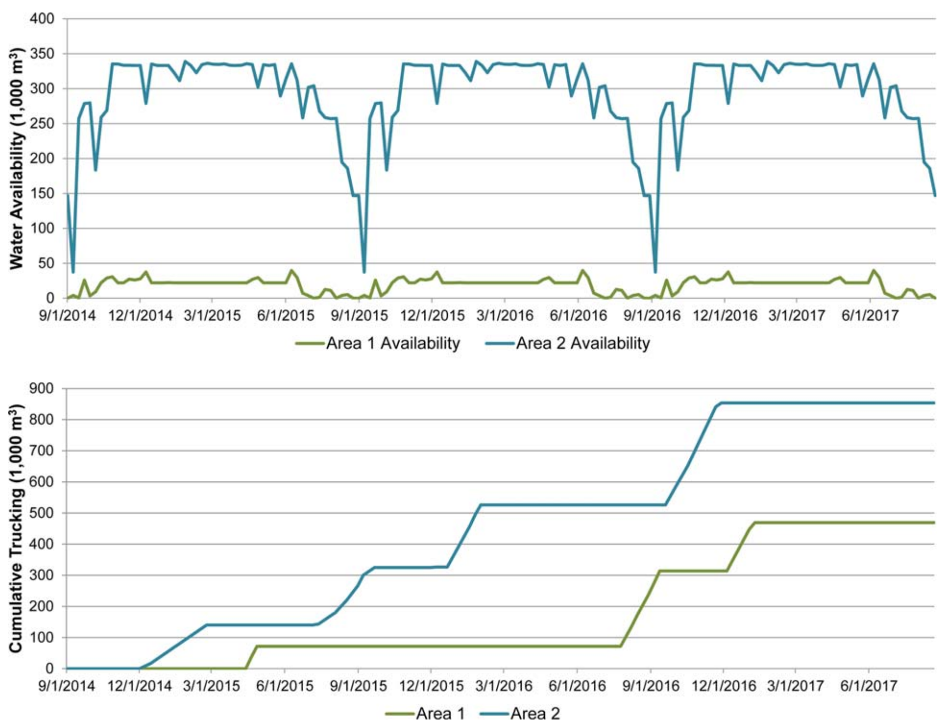

Figure 9. Result for Scenario 3: freshwater availability and trucking use.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

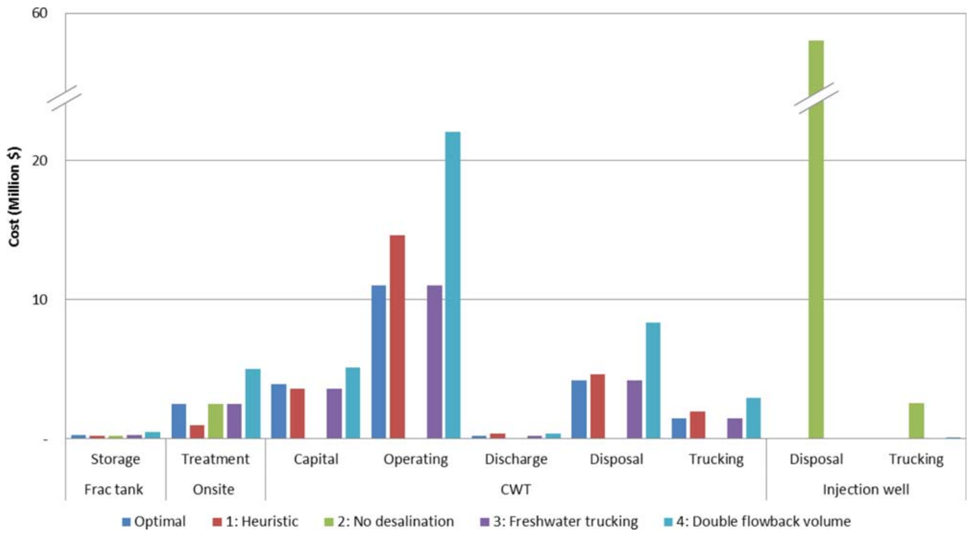

Figure 10. Wastewater cost comparison for all scenarios.

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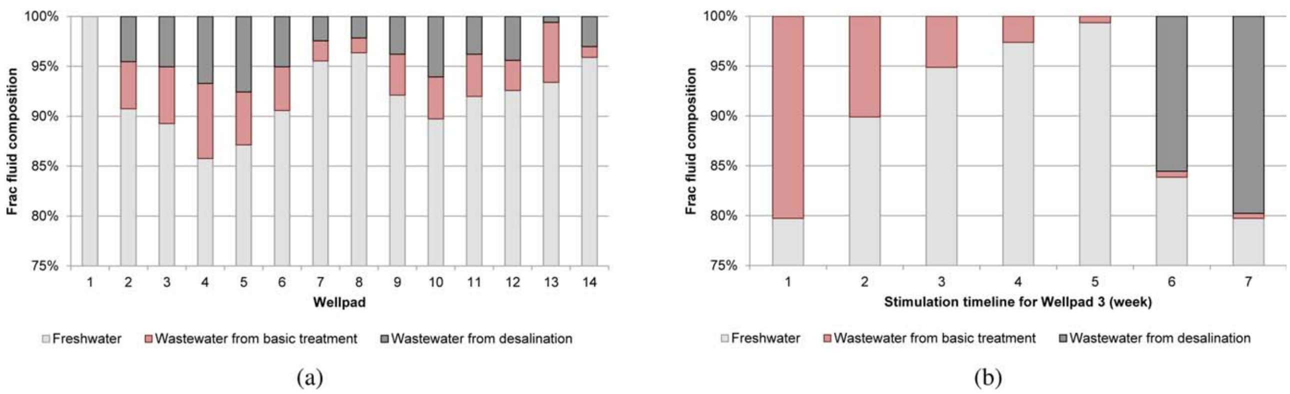

Figure 11. Frac fluid composition in the optimal scenario for (a) all wellpads averaged over time and (b) wellpad 3.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

objective was to maximize profit by determining the location and capacity of impoundment, the type of piping, treatment facility desalination technology, as well as the frac schedule, and the water sources to obtain freshwater.

We have presented a case study with 14 wellpads, 9 freshwater sources, and 3 desalination technologies analyzing water-related costs under a number of scenarios. From the results, the importance of simultaneously optimizing completion schedule with water acquisition, transportation, storage, and treatment has been demonstrated. Also, it has been shown that desalination can be cost-effective for operators if collaboration could be established. Although transporting freshwater by truck is relatively expensive and incurs a high environmental impact, allowing truck hauling, in addition to pipeline transportation, can still provide enough flexibility to guarantee freshwater supply so that fewer freshwater sources need to be accessed for pipeline transportation and less capital investment is required for impoundment construction. Finally, we have shown that for regions with high flowback rate, the wastewater handling cost does increase as expected. However, with proper recycling schemes, the flowback water can be blended for frac fluid use and reduce freshwater supply cost. Some of the future work will address the bicriterion optimization in which both the gross profit and the minimization of environmental impact are considered to derive the set of Pareto-optimal solutions.

Acknowledgment

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Notation

Indices and sets

c = pipeline type
$\mathrm{DP}_{u,u'}$ = potential pipeline
k = stages per day fractured scenarios
o_u = freshwater source river
p_u = impoundment
q_u = freshwater source pond
r = concentration discretization intervals
s_u, s'_u = wellpads
t, t', t'' = time interval
u, u' = all locations

Superscripts

CT = CWT
DP = disposal
FB = flowback water
FW = freshwater
IP = impoundment
max = upper bound
min = lower bound
OT = onsite treatment

PD = pond
PI = pipeline
RI = river
ST = frac tank storage
TR = truck
WW = wastewater

Parameters

η_w = desalination recovery, %
AR = annualized factor for investment on treatment units
CD = TDS discharge concentration tolerance, ppm
CF = concentration upper bound in frac fluid, ppm
$CP_p^{IP,max}$ = upper bound capacity of impoundment, m^3
$CP_p^{IP,min}$ = lower bound capacity of impoundment, m^3
CP^{PD} = upper bound capacity of pond, m^3
CU_w^{CT} = concentration upper bound in desalination unit inlet, ppm
DC = distance to desalination facility, km
$DI_{uu'}$ = distance between u and u', km
DW = distance to disposal, km
$F_{wt}^{max,CT}$ = maximum CWT capacity, m^3
$F_{ot}^{max,RI}$ = maximum withdrawal rate from river, m
F_{qt}^{PD} = water flow rate available for withdrawal
IC_u^{FW} = freshwater source set-up cost, \$
IC_c^{PI} = capital cost of pipelines, \$/km
$IC_w^{WW,CT}$ = investment cost for desalination technology, \$
ICB_p^{IP} = base investment cost for impoundment, \$
ICI_p^{IP} = incremental investment cost for impoundment, \$/m^3
LF = minimum pipe capacity, m^3
OC_u^{FW} = freshwater cost from source u, \$/m^3
OC_p^{IP} = operating cost for impoundment, \$/week
OC_c^{PI} = operating cost of pipelines, \$/km/week
$OC_w^{WW,CT}$ = CWT treatment cost, \$/m^3
$OC^{WW,OT}$ = wastewater onsite treatment cost, \$/m^3
$OC^{WW,ST}$ = wastewater frac tank storage cost, \$/m^3/week
$OC^{WW,TR}$ = wastewater trucking cost, \$/m^3/km
$OCDC^{WW}$ = desalinated water discharge cost, \$/m^3
$OCDS^{WW}$ = disposal cost, \$/m^3
OCPU = pumping cost, \$/week
P_{st} = price of gas production at each wellpad, \$
SC_{st}^{FB} = flowback/produced water concentration in time period t, ppm
SDW_s = freshwater use at each wellpad in each period, m^3
SF_{st}^{FB} = flowback/produced water flow rate per time period t, m^3
SFL_{sk} = frac weeks of each wellpad
SFT_{st} = remaining flowback/produced water in the next 20 years, m^3
SLW_s = freshwater use at each wellpad in the last period, m^3
STC = crew transition period, week
STF_k = frac rate, stage/week
UF = maximum pipe capacity, m^3

Binary variables

y_w^{CT} = indicates the technology for desalination
y_p^{IP} = impoundment p is set up
y_q^{PD} = pond o is set up
$y_{uu'c}^{PI}$ = defines existence of piping connections
y_o^{RI} = river o is set up
y_{skt} = defines the beginning of stimulating each wellpad
yI_{pt}^{IP} = impoundment p is used

Continuous variables

c_t^{CT} = TDS concentration of the feedwater stream to desalination, ppm
c_{st}^{FB} = wellpad flowback TDS concentration, ppm
c_t^{OT} = TDS concentration of the flowback water transported to basic treatment, ppm
f_t^{CT} = total wastewater processed through desalination, m^3
f_t^{DP} = wastewater disposed, m^3
$f_{st}^{FB,CT}$ = flowback water to be desalinated, m^3
$f_{st}^{FB,DP}$ = flowback water to be disposed at an injection well, m^3
$f_{st}^{FB,OT}$ = flowback water to be transported to basic treatment, m^3
f_{st}^{FB} = wastewater flowback at each wellpad, m^3
f_{st}^{FW} = freshwater supplied through pipe and used at each wellpad, m^3
f_{st}^{OT} = onsite treatment throughput, m^3
f_{qt}^{PD} = pond withdrawal from precipitation, m^3
$f_{uu'ct}^{PI}$ = freshwater flow from one location to the next, m^3
f_{ot}^{RI} = river allowed withdrawal, m^3
f_{st}^{TR} = freshwater transported to each wellpad through trucking, m^3
f_{st}^{WW} = wastewater use at each wellpad, m^3
f_{st} = total water use at each wellpad per time period, m^3
fR_{st}^{CT} = desalinated wastewater recycled to the completion pad, m^3
fS_{wt}^{CT} = wastewater processed through desalination unit w, m^3
fT_w^{CT} = desalination plant throughput, m^3
l_p^{IP} = capacity of impoundment, m^3
l_{st}^{ST} = capacity of wastewater tanks, m^3
v_t^{CT} = CWT wastewater storage tank, m^3
v_{pt}^{IP} = volume of impoundment, m^3
v_{qt}^{PD} = volume of pond, m^3

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