Optimal Design of Water Pipeline Networks for the Development of Shale Gas Resources

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Abstract

One of the major concerns in shale gas production is water management. Millions of gallons are required to fracture each well and a significant amount of the injected water returns to the surface as flowback. Operators are increasingly reusing flowback water to reduce freshwater consumption, while impaired water disposal can also be lowered. For that reason, the importance of effective design and operation of networks of water pipelines in US shales is growing. This work is aimed at addressing the optimal integrated planning of shale gas operations in multiple wellpads together with the design of water pipeline networks. We propose a multiperiod Mixed-Integer Linear Programming (MILP) optimization model to thoroughly solve the challenging stay-or-mobilize trade-off, yielding cost-efficient and well-balanced schedules, both for gas production and for water consumption. The proposed model, based on the concept of campaigns, permits to schedule shale gas operations at a very detailed level, accounting for the water distribution network required to maximize the reuse of impaired water coming from fractured wells. We address illustrative examples involving up to 20 pads, 4 fracturing crews, and about 100 wells developed over one year, showing that the design of water distribution networks can be effectively optimized.

Introduction

As shale gas production continues to grow rapidly in the US, other nations like Argentina seek to develop their own unconventional reserves to compensate for a sustained decline in conventional production. A point in common in both countries is that electricity generation relies heavily on natural gas. In fact, 37% of the electricity in the US is being currently generated by natural gas power plants, while the percentage in Argentina has increased to 56% (IEA, 2019). Moreover, the dominance of natural gas for electricity generation is expected to be sustained until 2050, when renewables (mainly driven by solar and wind) would finally reach the natural gas share (US EIA, 2020). In this context, the EIA projects that more than 90% of the natural gas in the US would come from unconventional formations (shale and tight) by 2050. Therefore, energy analysts (Weissman et al., 2016) suggest that shale gas is playing the role of a lower-carbon bridge fuel, reducing coal and oil consumption, while buying time to develop new technologies that will ultimately replace fossil fuels. Recent developments like flexible power plants show that natural gas is making way for renewables (Nunes, 2020). Flex-plants are built to ramp up and down quickly to compensate for highly variable power supplies from wind and solar. From this point of view, natural gas could be seen more as a destination fuel rather than a bridge. In any case, shale gas production is expected to intensify in the coming decades, and effective decision-making tools are essential to do it in a sustainable way.

One of the major concerns regarding shale gas development is water management. A single well typically requires 5 million gallons of water to be fractured, and up to 30% of the injected water may flow out of the well as flowback water in the first days of production, after the well is completed. Due to its high salinity, the impaired water poses difficult challenges for shale gas producers. One possibility is to treat the impaired water in centralized treatment plants (Yang et al., 2014), which so far has proved to be largely impractical. Recent studies indicate that the industry is focusing more on direct reuse or recycling rather than on water treatment, since it appears to be the more sustainable option (US EPA, 2018). Nowadays, salt is a common component in fracturing fluids, which employ a growing array of salt-tolerant chemicals (Rassenfoss, 2011). In fact, it is possible to successfully fracture a well using all recycled water (Blauch, 2010). Operators are increasingly reusing the flowback water to reduce the freshwater consumption for fracturing new wells (Drouven and Grossmann, 2017), while impaired water disposal expenses can also be lowered. There are two basic strategies: (a) recycling water on-site, feeding it back to impaired water storage tanks for future fracturing operations (intra-pad recycling), or (b) sending the impaired water to neighboring pads and reusing it in upcoming jobs (inter-pad recycling). Direct reuse of flowback water has been possible due to the development of salt-tolerant friction reducers, and is currently the most popular option due to the operational simplicity for contractors. In fact, roughly 90% of the flowback water is being recycled in the development of the Marcellus shale (Sun et al., 2019).

However, transportation costs are a major consideration in recycling. Companies tend to recycle water using a system of storage ponds. They are especially built for water from fracturing, with double liners and leak control alarms. The economics of water reuse is a major issue in many places since it is costly to haul millions of gallons of water using trucks. Recycling in Pennsylvania, for instance, is likely the lowest cost alternative where there are ponds built for storage and treatment near the drill sites (Rassenfoss, 2011). In other cases, it is often cheaper to use freshwater and onsite water purification to avoid a long haul. As a result, it is not surprising that, wherever possible, companies install water pipes to connect the wellpads among themselves. This appears to be the leading option in the development of shale gas resources in Argentina. The reason is that the main productive region, called Vaca Muerta (US EIA, 2019), is over a semi-desert landscape, yielding less expensive pipeline installation costs. In spite of their high upfront costs, pipelines are considered a worthwhile investment, which is proved by the fact that more than 36,000 miles of pipelines are either under construction or planned in North America (Awalt, 2019). Pipelines also require much less human capital than the other transportation modes, and are more efficient, reliable and safe. On average, transporting products by pipeline costs about $5 per barrel compared to $10-$15 a barrel for rail and $20 a barrel by truck (Congressional Research Service, 2014).

In US shales, the network of water pipelines connecting wellpads is growing quickly. But the main question is how to properly plan and operate these networks. Recent works address the water management problem together with the fracturing schedule (Yang et al., 2015; Drouven and Grossmann, 2017; Carrero-Parreño et al., 2018). However, these works are not aimed at determining an optimal design of water pipeline networks. When the number of fracturing crews, and/or the number of wellpads being considered is too small, the possibility to take advantage of pipelines moving water from one pad to the other is not obvious. For instance, in the works by Carrero-Parreño et al. (2018) and Yang et al. (2015) only one crew is available to develop 3 and 14 well pads, respectively. Moreover, in the latter case, it is not possible to return to the same pad to stimulate more wells, which makes the problem less attractive from the water flow planning perspective. In turn, Drouven and Grossmann (2017) address a problem with up to two fracturing crews over four candidate wellpads (a total of 29 wells), allowing for return-to-pad operations. However, all water hauling is assumed to be made by truck, and equipment mobilization costs are not included in the model. The mobilization issue is subsequently addressed in detail by Ondeck et al. (2019) in the multi-operational development planning of wellpads. Nevertheless, the model complexity is too high to be extended to more than a single pad, thus being unable to tackle inter-pad water transportation challenges.

The current work is aimed at addressing the optimal planning of shale gas operations in multiple wellpads together with the design of water pipeline networks to maximize water recycling. The optimization model permits to thoroughly solve the challenging stay-or-mobilize trade-off, yielding cost-efficient and well-balanced schedules, both for gas production and for water consumption. Compared to previous approaches, the main contributions of this work are the following:

(a) We propose a novel approach based on the concept of campaigns for scheduling shale gas development operations at a very detailed level. The model tightness enables us to solve large instances of the problem, involving a significantly larger number of resources (rigs, crews, equipment, etc.), pads and wells. A detailed discussion on the tightness of campaign-based, discrete-time scheduling formulations is addressed by Cafaro and Grossmann (2020).
(b) We integrate the multiwell pad development planning with the design of the water distribution network (comprising pipelines and storage facilities) required to maximize the reuse of impaired water coming from fractured wells.

The remaining of this paper is organized as follows: First, we formally state the problem in the Problem Definition section. We then describe the Model Assumptions and give some details about the model structure. We next introduce the proposed MILP Mathematical Formulation for solving the integrated problem. Two illustrative examples are addressed and solved, and the Computational Results are discussed, leading to the Conclusions presented in the last section of the manuscript.

Problem Definition

Given:

(a) A set of wellpads where multiple shale gas wells are to be developed. For every wellpad, the following information is assumed to be known:
    a. Geographic location
    b. Maximum number of wells to develop
    c. Lateral length of the wells and forecasted productivity curves
    d. Expected water consumption (for fracturing) and flowback (water production) after fracturing each well
    e. Land permits issuing dates
    f. Maximum flow of gas that can be delivered from each pad. This value is typically given by the size of the gas pipelines and compressor stations connecting the pad to the

midstream distribution network (Cafaro and Grossmann, 2014; Drouven and Grossmann, 2016).

(b) A set of operations to be performed on every single well to be developed. Similarly to Ondeck et al. (2019), four operations are performed on the wells: top-setting, horizontal drilling, fracturing and turning-in-line, in that order.

(c) A natural gas price forecast for every period of the planning horizon.

(d) A set of resources (rigs, crews, equipment, etc.) to perform each operation. The total number of available resources for each operation is assumed to be given.

(e) A set of freshwater sources from which pads can be supplied for fracturing.

(f) A set of disposal wells where impaired water coming from the shale gas wells can be injected.

(g) A superstructure of alternatives for installing water storage facilities and pipelines to move water between the nodes in the network, as illustrated in the example in Figure 1.

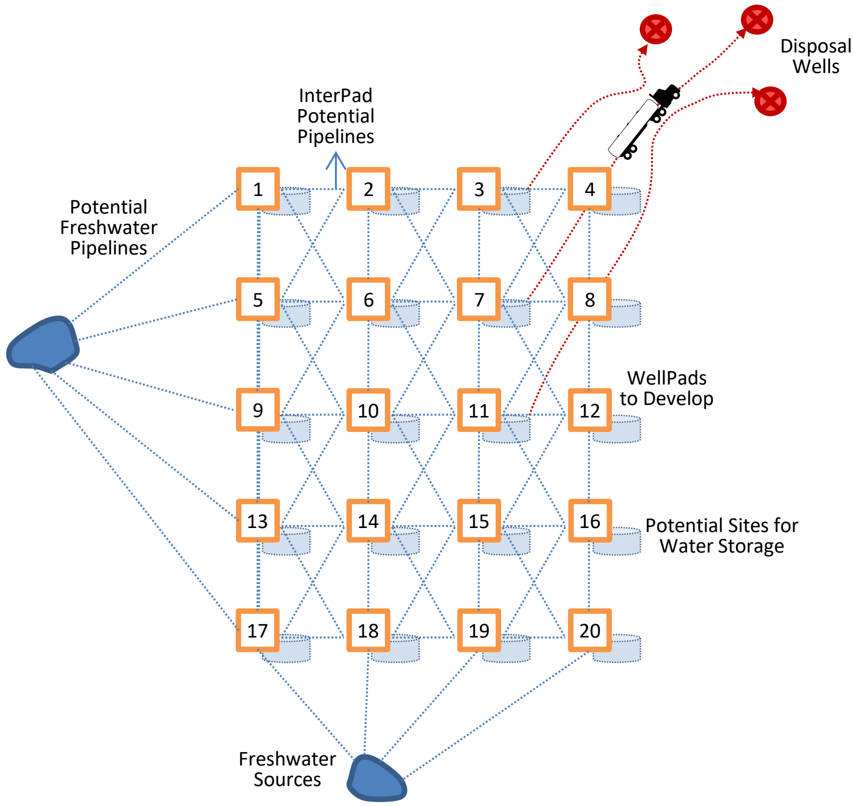


Figure 1. Superstructure of Alternatives for the Design of Water Pipeline Networks over a Shale Gas Development Region

The aim of the problem is to determine:

1. The size and location of inter-pad water pipelines, moving fresh or impaired water on either direction.
2. The size and location of water storage facilities where fresh and impaired water is temporarily stored before recycling and/or being sent to disposal wells.

3. The time to perform the operations for the development of new wells at every pad.
4. The amount of water to move (i) from freshwater sources to pads, (ii) from pads to other pads, (iii) from pads to storage facilities, (iv) from storage facilities to pads, and (v) from storage facilities to disposal wells; at every period of the time horizon.

The goal is to make these decisions so as to maximize the Net Present Value (NPV) of the development project.

Model Assumptions

The multiperiod MILP formulation proposed in this work is based on the following assumptions:

1. The development of new wells is organized in campaigns, as explained in detail in the following sections. Each campaign comprises a set of wells of the same pad for which the operations are performed in the same "visit" or "trip" to the pad. Mobilization costs for moving and setting up equipment are paid every time a new operation starts on a pad, involving a set of wells grouped in a new campaign.

2. We assume that the four operations on the wells of the same campaign, namely Top Setting (TS), Horizontal Drilling (HZ), Fracturing (FRAC) and Turning-In-Line (TIL), are performed one after the other, with no interruptions or delays. In other words, given a number of wells in the same pad to develop over the same campaign, all of them are to be top-set one after the other, horizontally drilled one after the other, fractured one after the other, and turned-in-line one after the other, with no idle times between subsequent wells in the sequence, and no interruptions between subsequent operations, as illustrated in Figure 2. This assumption complies with the fact that, for safety reasons, no more than a single operation can be performed on a single pad at the same time. This also tends to minimize the overall time to develop all the wells in the campaign, as usually seen in practice. Although the length of each campaign is a decision variable, this assumption restricts the possibility of defining different campaign lengths for different operations on the same set of wells, which may significantly increase the model complexity. Future work will focus on relaxing this assumption.

3. All the wells in the same pad have the same lateral length and expected productivity curves. Furthermore, water production and consumption profiles for fracturing operations are also identical. From the industry perspective, this assumption is generally valid for new shale wells, since it is rather unlikely to propose different fracturing strategies for different wells of the same pad and predict different productivity curves for them.

4. Every available resource (rig, crew, pump, equipment, etc.) is able to perform just a single operation type (TS, HZ, FRAC or TIL). Besides, all the resources devoted to the same operation are identical.

5. We assume that the concentration of total dissolved solids (TDS) in the impaired water being recycled is reasonably low during the time horizon (typically one year). This assumption is based on the fact that the flowback water only accounts for a fraction of the water injected for fracturing (usually below 30%), and due to the fixed costs paid for resources (rigs, frac-pumps,

etc.) the rate of drilling and fracturing new wells is usually sustained over the time horizon. In fact, it is necessary to supply freshwater all along the time horizon, which will be mixed with the impaired water before being pumped for fracturing. Under these conditions, the use of salt-tolerant friction reducers (Drouven and Grossmann, 2017) makes it possible to use any mixture of fresh and impaired water, in any proportion. As a result, tracking water inventories for fracturing can be simplified to a single, aggregate fluid, with no need to trace TDS. In the results and discussion section we revisit the validity of this assumption.

6. Flow in water pipelines can be reversed. During a certain period water may flow from pad A to pad B, and in other period from B to A. This is a typical operation in pipeline transportation, particularly when covering short distances (Cafaro and Cerdá, 2014). The optimization of the pipeline network for water distribution is described in detail in the following sections.

7. We assume that pipelines are always filled with water, and that water is incompressible. Thus, any time a volume of water is injected in one of the ends of the pipeline, an equivalent amount is instantaneously received at the other extreme.

8. Besides water tanks for fracturing, larger water storage facilities or ponds may be installed at any wellpad location. These impoundments serve as buffers to compensate for the water flow (production/consumption) variations over the time horizon. The installation of new ponds implies considerable expenses in capital and operating costs.

9. All water pipelines and storage facilities determined by the model are assumed to be installed and ready to operate at the beginning of the planning horizon.

10. Unlike other water movements, transportation of impaired water from storage facilities to disposal wells is carried out by trucks due to the long distance from the shale development region to the disposal wells. Pipeline installation for this purpose is unlikely to be possible in practice.

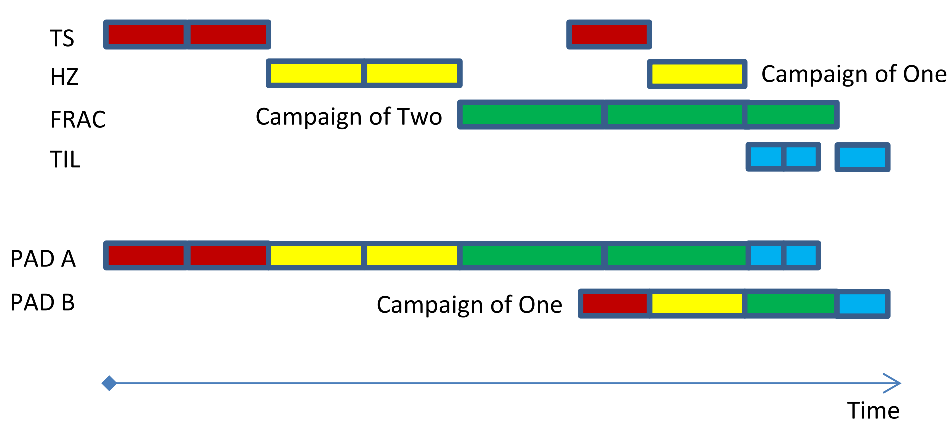


Figure 2. Gantt Chart showing the scheduling of the four operations related to a campaign of two wells and a campaign of one well in two different pads.

The Concept of Campaigns

As suggested by Ondeck et al. (2019), the development of shale gas wells usually involves a sequence of four operations, namely Top Setting (TS), Horizontal Drilling (HZ), Fracturing (FRAC) and Turning-In-Line (TIL). Because many wells are commonly drilled from a single site or "pad", shale gas companies usually plan their operations in campaigns, i.e. drilling, fracturing and/or turning-in-line several wells of the same pad in the same "visit" or "trip" to the pad (see Figure 2). The idea behind this is that longer stays, accomplishing more operations in longer campaigns, will certainly reduce the mobilization costs, which are known to be very expensive. However, the longer the equipment and crews stay at a certain pad, the later the company obtains revenues from gas production because of two main reasons: (a) wells do not produce gas until they are turned-in-line, and turn-in-line operations need to be postponed after long fracturing campaigns, and (b) due to safety reasons, wells must remain shut-in while other wells in the same pad are being fractured. If fracturing campaigns are too long, gas production from parent wells is substantially delayed.

In recent years, researchers have tackled the shale gas operations scheduling problem assuming different levels of complexity. One of the most detailed models was proposed by Ondeck et al (2019), focusing in the development of multiple operations on a single pad. The authors demonstrate that even assuming only one resource (crew) available to perform each type of operation, and ignoring the rest of the wellpads where such crews move after they finish each campaign of operations at the wellpad under study, the problem is still hard to solve. And it is particularly more challenging when mobilization costs are significant. However, by implementing the concept of campaigns into the optimization model, we are able to solve much larger problem instances, also making it possible to integrate the water network design problem to the scheduling of wellpad development operations.

Tracking Well Productivity, Water Consumption, Flowback and Water Production over Time

If we assume that a campaign of fracturing operations on r wells of the pad p starts at time period t ($y_{p,t,r}$ = 1) then for any period $t' \geq t$, we are able to estimate how much natural gas will be produced from those wells after turning them in line ($\gamma_{p,t',r}$), how much water will be consumed during fracturing operations ($\alpha_{p,t',r}$), and how much water will be produced from the same wells ($\beta_{p,t',r}$). The values of γ, α and β depend on the number of wells in the campaign, and are measured from the start time of fracturing operations, as illustrated in Figure 3. In the particular case of natural gas production, we assume that all the wells in the same pad have the same lateral length (l_p) and show similar productivity curves, typically following a hyperbolic decline (Drouven, Cafaro and Grossmann, 2017). By knowing this, we can infer a composite productivity curve from any set of r wells fractured over a single visit to pad p, as shown for a campaign of two wells at the right of Figure 3. The set of possible campaign lengths for pad p is called R_p. In the most general case, R_p = {1, 2, 3, …, nw_p}, where nw_p is the maximum number of wells to develop in pad p during the time horizon. The optimization model might decide on the one hand to develop all the wells in a single campaign of length nw_p, or on the other hand, develop the wells one by one, in nw_p different campaigns of length 1. The optimal solution usually suggests an intermediate strategy, comprising a sequence of campaigns with different lengths, even within the same wellpad.

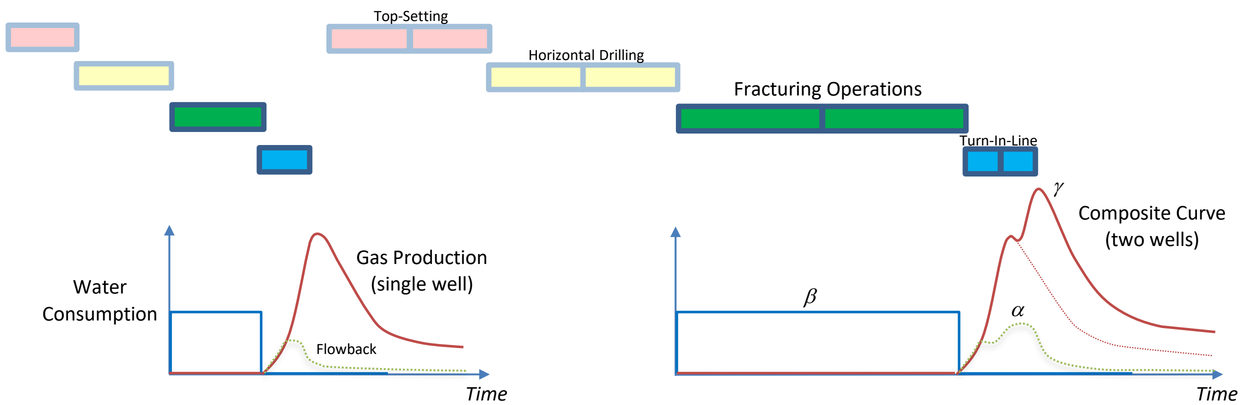


Figure 3. Typical gas productivity, frac water consumption, flowback and water production profiles for campaigns of operations of one and two wells.

All these elements constitute one part of the main structure of the proposed mathematical formulation, accounting for the scheduling of wellpad development operations. Another important part of the model is focused on the design of the water distribution network, as explained in the next section.

Design and Operation of the Water Distribution Network

The design of a water pipeline network can be formulated as an optimization problem, in which the pipeline investment cost, given by the selected pipeline diameters and their lengths, is to be minimized (Caballero and Ravagnani, 2019). However, the optimization problem addressed in this work exhibits more complexities. Although we know a priori the location and elevation of each node, the demand and production of water at each pad over time is unknown beforehand. The shale gas well development plan is a decision to be determined by the model, while the water pipeline network should be optimally designed according to that plan. In most water distribution network design problems (Bragalli, D'Ambrosio, Lee, Lodi and Toth, 2011; Araya, Lucay, Cisternas and Gálvez, 2018; Caballero and Ravagnani, 2019) the selected pipeline diameters must belong to a set of available commercial diameters with specific costs per unit length, which we also assume in this paper. However, to limit the scope of our model, we do not use detailed hydraulic and pressure calculations. We simply assume that a maximum head loss per length of pipe ($S = h_f/L$) is imposed for the water transportation, thus leading to a maximum flow rate for every inter-pad connection *i-j* that grows with the pipeline diameter ($D_{i,j}$). Based on the Hazen-Williams correlation for water networks, we state the following inequality,

$$Q_{i,j} \leq k_{i,j}\, {D_{i,j}}^{\omega} \tag{1}$$

where $Q_{i,j}$ is the water flow rate, $k_{i,j}$ is a constant obtained from the Hazen-Williams equation according to the pipeline rugosity, the selected head loss per length of pipe (S), and the unit system being used; while ω has been empirically determined from Hazen-Williams at the value of 2.63. Typical values for the hydraulic loss S are in the order of 10 Pa/m.

Another interesting feature in our model is that, similar to Caballero and Ravagnani (2019), water flow directions are decision variables. However, in contrast to that work, we assume that the flow direction can be reversed at any time during the time horizon, according to the production and demand volumes from the pads over the development plan.

On the other hand, it is usually considered that gravity is not enough to ensure water flow, which implies that pumps need to be installed along the pipelines. Note that if the pipeline flow is reversed, it is possible that more pumps and valves are required to operate in the reverse flow mode. Nonetheless, due to its relatively minor importance when compared to pipeline investment, the location and size of pumps and valves are out of the scope of our model. An important point to account for is the elevation difference between the wellpads. From that, the cost for moving water between two pads on one or the other direction would be different, leading to different operating costs. Such pumping costs per unit volume can be inferred from the friction head loss and elevation difference between the pads ($\Delta z_{i,j}$), as follows:

$$wtc_{i,j} \leq g\ \rho\ \left(S\ L_{i,j} + \Delta z_{i,j}\right)\ \eta\ Ec \tag{2}$$

where g is the gravitational constant, ρ is the water density, S is the head loss per length of pipe, $L_{i,j}$ is the length of the pipeline connecting i to j, η is the pump efficiency, and Ec is the unit energy cost. Note that $\Delta z_{i,j}$ = -$\Delta z_{j,I}$, thus yielding different unit transportation costs for direct and reverse flows. For simplicity, an average density for the water being transported between the nodes is adopted. Note that by fixing the head loss per unit length S, the water transportation cost is independent of the pipeline diameter.

Mathematical Formulation

From the modeling strategy and assumptions already explained, we develop a multiperiod MILP formulation given in terms of continuous and discrete decision variables, which are related through a set of constraints to be satisfied, and an objective function to be maximized.

Pad development constraints

Total number of wells to develop in a pad

Every single pad may have a different number of wells to be developed. In practice, multi-well pads may comprise 2, 4, 8, 20 or even more wells. If nw_p is the total number of wells that can be developed in pad p during the current planning horizon, then the following constraint must hold:

$$\sum_{r=1}^{R_p} \sum_{t=rt_p+t_{p,r}^{TS}-t_{p,r}^{HZ}}^{T-t_{p,r}^{FRAC}-t_{p,r}^{TIL}} r \cdot y_{p,t,r} \leq nw_p \qquad \forall p \in P \tag{3}$$

By definition, the condition $y_{p,t,r}$ = 1 implies that a total of r wells will be fractured one after the other starting at period t. Notice that classic discrete-time models (Ondeck et al., 2019; Carrero-Parreño et al., 2018, Yang et al., 2015) would simply impose $\sum_t y_{p,t} \leq nw_p$. Compared to the latter inequality, Eq. (3) is an extended form also including the terms and variables for which $r > 1$. Aimed at the minimization of the number of campaigns (to reduce the mobilization costs), the proposed formulation will show a smaller number of variables with nonzero values at the optimum, yielding a tighter relaxation. The impact of including the campaign-length index r in discrete-time scheduling formulations is addressed by Cafaro & Grossmann (2020).

Notice that a campaign of r wells on a pad p can only be fractured after τ periods from the beginning of the time horizon, accounting for pad ready times (after issuing land permits), top setting and horizontal drilling operations (previous operations required on the same set of wells). This is so because, for safety reasons, only one operation at a time can be performed on a single pad. Thus, $\tau = rt_p + t_{p,r}^{TS} + t_{p,r}^{HZ}$.

Resource limitation: Total number of fracturing crews

In practice, having a finite number of fracturing crews is one of the most critical limitations to obtain larger amounts of gas from the shale formations. If n^{FRAC} is the total number of available crews, we can impose a limit on the total number of fracturing crews being used at the same time, as follows:

$$\sum_{p \in P} \sum_{r \in R_p} \sum_{t'=t-t_{p,r}^{FRAC}+1}^{t} y_{p,t',r} \leq n^{FRAC} \qquad \forall t \in T \tag{4}$$

The latter formulation is based on the discrete-time State-Task-Network (STN) scheduling model proposed by Kondili et al. (1993). By assuming that fracturing crews have the same capabilities, the index of resources can be omitted in the binary variable $y_{p,t,r}$.

Limit on the number of resources for other operations

Based on assumptions 1 and 2, we can readily impose similar constraints derived from the maximum number of available resources to complete other operations. If n^{TS}, n^{HZ} and n^{TIL} (given data) are the total number of available resources for top-setting, horizontal drilling and turning-in-line, respectively, we simply state:

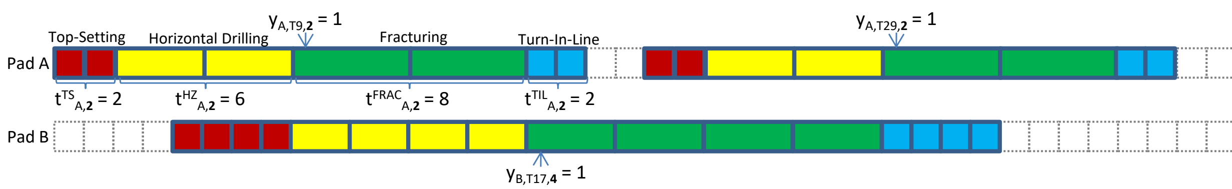
$$\sum_{p \in P} \sum_{r \in R_p} \sum_{t'=t-t_{p,r}^{TS}+1}^{t} y_{p,t'+t_{p,r}^{TS}+t_{p,r}^{HZ},r} \leq n^{TS} \qquad \forall t \in T \tag{5}$$

$$\sum_{p \in P} \sum_{r \in R_p} \sum_{t'=t-t_{p,r}^{HZ}+1}^{t} y_{p,t'+t_{p,r}^{HZ},r} \leq n^{HZ} \qquad \forall t \in T \tag{6}$$

$$\sum_{p \in P} \sum_{r \in R_p} \sum_{t'=t-t_{p,r}^{TIL}+1}^{t} y_{p,t'-t_{p,r}^{TIL},r} \leq n^{TIL} \qquad \forall t \in T \tag{7}$$

Notice that constraints (5), (6) and (7) rely on the assumption that all the operations on the same set of wells are performed in a non-interrupted sequence. In other words, if different binary variables were introduced to account for the starting times of the different operations, from the definition of the variable $y_{p,t,r}$ one could state: $y_{p,t,r}^{FRAC} = y_{p,t,r}$; $y_{p,t,r}^{TS} = y_{p,t+t_{p,r}^{TS}+t_{p,r}^{HZ},r}$; $y_{p,t,r}^{HZ} = y_{p,t+t_{p,r}^{HZ},r}$; $y_{p,t,r}^{TIL} =$

$y_{p,t-t_{p,r}^{TIL},r}$; which lead to the inequalities given above. Figure 4 illustrates a simple plan for the development of two pads (A and B) with nw_p = 4 wells in each pad. Pad A is developed in two campaigns of two wells each (this implies a return to the pad after developing the first two wells), while Pad B is developed in a single campaign. The total number of crews involved in every operation is tracked over time as in Eqs. (4), (5), (6) and (7) for operations FRAC (green), TS (red), HZ (yellow) and TIL (blue), respectively. The binary variables $y_{p,t,r}$ taking value one in the depicted solution and some of the parameters $t^{o}_{p,r}$ accounting for the length of the operations, are also indicated in Figure 4.



Time	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20
#TS	1	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
#HZ	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
#FRAC	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
#TIL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0

Time	T21	T22	T23	T24	T25	T26	T27	T28	T29	T30	T31	T32	T33	T34	T35	T36	T37	T38	T39	T40
#TS	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
#HZ	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
#FRAC	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
#TIL	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	1	1	0	0

Figure 4. Illustrative example showing the meaning of binary variables $y_{p,t,r}$, the operations length at every pad, and the number of crews being involved over the time horizon.

No overlapping constraints at every individual pad

As already stated, no more than a single operation can be performed at a time on each wellpad. Therefore, the following condition must hold for every single pad *p*, at every period *t*.

$$\sum_{r \in R_p} \sum_{t'=t-t_{p,r}^{FRAC}-t_{p,r}^{TIL}+1}^{t+t_{p,r}^{TS}+t_{p,r}^{HZ}} y_{p,t',r} \leq 1 \qquad \forall p \in P, t \geq rt_p \tag{8}$$

Constraint (8) is derived from the backward aggregation inequality of the discrete-time STN scheduling model (Kondili et al., 1993). From the first row of Figure 4 it follows that the two campaigns on Pad A do not overlap, meaning that constraint (8) is satisfied at every time period *t*.

Resource mobilization

A major advantage of the proposed formulation is the simplicity to manage equipment mobilization. Mobilization constraints have been highlighted by previous authors as one of the most complicating inequalities in their MILP models (Ondeck et al., 2019). In our model, they are accounted for in a straightforward way, given the definition of campaigns. More precisely, every single campaign pays for the mobilization of the resource required to accomplish the corresponding operation. If we focus on fracturing crews, whenever $y_{p,t,r}$ equals 1 a crew has to mobilize to pad *p* at time period *t*, since a campaign of *r* fracturing operations will start at that time period. We obtain the present value of mobilization costs *MC* accounting for all the operations (TS, HZ, FRAC, TIL) as follows:

$$MC = \sum_{p \in P} \sum_{r \in R_p} \sum_{t = rt_p + t_{p,r}^{TS} - t_{p,r}^{HZ}}^{T - t_{p,r}^{FRAC} - t_{p,r}^{TIL}} y_{p,t,r} \left[\varphi_t \, mp_{FRAC} + \varphi_{t - t_{p,r}^{HZ}} \, mp_{HZ} + \varphi_{t - t_{p,r}^{HZ} - t_{p,r}^{TS}} \, mp_{TS} + \varphi_{t + t_{p,r}^{FRAC}} \, mp_{TIL} \right] \tag{9}$$

where φ_t is the discount factor for any cashflow in time period t and mp_o is the mobilization cost associated to operation o.

Natural gas production constraints

Well productivity

Production from a campaign of r wells can be delivered after the fracturing tasks on all the wells have been completed and they are turned-in-line. By assumption 2, all the wells in the same campaign are turned in line right after fracturing. Based on that assumption, the wells' productivity from a single pad at every time period can be readily obtained, as first proposed by Cafaro and Grossmann (2014).

$$F_{p,t} = \sum_{r \in R_p} \sum_{t' = rt_p + t_{p,r}^{TS} + t_{p,r}^{HZ}}^{t} (\gamma_{p,t-t',r} \cdot y_{p,t',r}) \qquad \forall p \in P, t \in T \tag{10}$$

In Eq. (10), the parameter $\gamma_{p,\tau,r}$ represents the total volume of gas obtained from a set of r wells that have been fractured over a single campaign, τ periods after fracturing operations started.

Well shut-ins

As discussed in previous works (Ondeck et al., 2019) some production wells may need to be shut in to prevent damage when performing fracturing operations on new wells. The aim is to prevent frac-hits, meaning that a producing parent well may become charged with pressure from a child well that is being fractured next to it. In this model, we assume that every production well in a pad needs to be shut-in if a new well in the same pad (or occasionally in other interfering pads) is being fractured. If not, production wells may become vulnerable to an intersection from a nearby propagating fracture, leading to severe production losses. From the geological characterization of the shale formation, operators usually predict the pairs of pads *p-p'* that may interfere among themselves, from which the binary parameter $i_{p,p'}$ is derived. In logic terms, this condition can be written as in (11), yielding the equivalent algebraic constraint (11').

$$\bigvee_{r \in R_p} \bigvee_{\substack{t' \geq t - t_{p,r}^{FRAC} + 1 \\ t' \leq t}} y_{p,t',r} = 1 \Rightarrow y_{p',t}^{SHUT} = 1 \qquad \forall t \in T, (p,p') \colon i_{p,p'} = 1 \tag{11}$$

$$\sum_{r \in R_p} \sum_{t' = t - t_{p,r}^{FRAC} + 1}^{t} y_{p,t',r} \leq y_{p',t}^{SHUT} \qquad \forall t \in T, (p,p') \colon i_{p,p'} = 1 \tag{11'}$$

Natural gas production

Production from a wellpad is mostly determined by the productivity of its wells ($F_{p,t}$). However, during shut-in periods, wells can recover pressure and accumulate gas that will be later released when the fracture of nearby wells is completed. Similar to previous models, we keep track of the amount of gas retained ($S^{IN}{}_{p,t}$) and released ($S^{OUT}{}_{p,t}$) from the wells of the pad at every time period. As a result, the gas production from a single pad at every time period is given by:

$$GP_{p,t} = F_{p,t} - S_{p,t}^{IN} + S_{p,t}^{OUT} \qquad \forall p \in P, t \in T \tag{12}$$

The total amount of accumulated gas retained in the wells of a pad at the end of every time period can be tracked as follows:

$$L_{p,t} = L_{p,t-1} + S_{p,t}^{IN} - S_{p,t}^{OUT} \qquad \forall p \in P, t \in T \tag{13}$$

Finally, gas production is set to zero during shut-in periods, as imposed by the upper bound constraint:

$$GP_{p,t} \leq GP_{p}^{max}(1 - y_{p,t}^{SHUT}) \qquad \forall p \in P, t \in T \tag{14}$$

The maximum gas production rate from a single pad ($GP^{max}{}_{p}$) is assumed to be known, and is typically inferred from the capacity of the pipelines and compressors connecting the pad to the natural gas network. Moreover, total gas accumulation ($L_{p,t}$) and gas release rates ($S^{OUT}{}_{p,t}$) are subject to maximum values usually given by the shale gas operator depending on the number of wells in the pad and the characteristics of the shale formation.

Water management constraints

From assumption 5, either freshwater, impaired (produced) water, or a mixture of them can be used to fracture new wells. In other words, the total dissolved solid (TDS) concentration of the water used for fracturing operations is unrestricted. As suggested by Drouven and Grossmann (2017), operators are using impaired water for stimulation due to technological advances in the development of friction reducers. A survey conducted by Mauter and Palmer (2014) in the Marcellus shale (US) reveals that impaired water reuse is not inhibited by high concentrations of TDS since high-salinity tolerant friction reducers are able to remain effective at TDS concentrations as high as 150,000 ppm. One of the major goals of the optimization model is to aid companies to reduce freshwater consumption and impaired water disposal. Shale gas operators do not find water quality as a barrier to reusing water, but they are challenged to design efficient distribution networks to manage water flows among wellpads when the fracturing schedule is unknown. The current mathematical model is aimed at solving the wellpad development planning, the water pipeline network design and the water management problems in a single step, as captured by the following constraints.

Water production

Similar to gas production, water flows coming out from the wells of a single pad can be determined from the fracturing schedule as follows (see Figure 3).

$$WP_{p,t} = \sum_{r \in R_p} \sum_{t'=rt_p+t_{p,r}^{TS}+t_{p,r}^{HZ}}^{t} (\alpha_{p,t-t',r} \cdot y_{p,t',r}) \qquad \forall p \in P, t \in T \tag{15}$$

Water consumption

By knowing the volume of water required during every period of a fracturing campaign, we can also state:

$$WC_{p,t} = \sum_{r \in R_p} \sum_{t'=t-t_{p,r}^{TS}-t_{p,r}^{HZ}}^{t} (\beta_{p,t-t'+1,r} \cdot y_{p,t',r}) \qquad \forall p \in P, t \geq rt_p \tag{16}$$

where $\beta_{p,t,r}$ is the amount of water required during the *t*-th period of fracturing operations over a campaign of *r* wells in pad *p*, as also depicted in Figure 3.

Water balance

The overall inventory of water at a certain pad can be followed over time by adding impaired water flows coming from the wells, subtracting the amount of water consumed for fracturing new wells, summing water flows coming from other pads ($WT_{p',p,t}$), deducting water flows derived to other pads ($WT_{p,p',t}$) and/or sent to disposal wells ($WJ_{p,k,t}$), and finally adding the amount of freshwater that may be supplied to pad *p* from any source *c* during the same time period ($FW_{c,p,t}$).

$$\begin{aligned} WS_{p,t} = WS_{p,t-1} + WP_{p,t} - WC_{p,t} + \sum_{p' \neq p} \left(WT_{p',p,t} - WT_{p,p',t} \right) - \sum_{k \in K} WJ_{p,k,t} \\ + \sum_{c \in C} FW_{c,p,t} \qquad \forall p \in P, t \in T \end{aligned} \tag{17}$$

Designing the water distribution network

To design the pipeline network and storage infrastructure for water management, we assume we are given a set of alternative pipeline diameters (*d*) and water impoundment sizes (*s*). The new binary variables $wf_{c,p,d}$ and $wp_{p,p',d}$ account for the selection of a pipeline of diameter *d* to connect the freshwater source *c* with the pad *p*, or the pad *p* with the pad *p'*, respectively. In turn, $ws_{p,s}$ equals one if an impoundment of size *s* is installed at pad *p*. Based on these variables, we can model the following upper-bounding constraints.

$$FW_{c,p,t} \leq \sum_{d \in D} fp_d \; wf_{c,p,d} \qquad \forall c \in C, p \in P, t \in T \tag{18}$$

Constraint (18) imposes an upper bound on the amount of freshwater that can be supplied from source *c* to wellpad *p*, given by the diameter *d* of the pipeline selected by the model to connect both nodes. Maximum flow rates fp_d for different pipeline diameters are determined from the Hazen-Williams correlation for freshwater networks, as explained in the model assumptions. If no pipeline is installed between *c* and *p* ($wf_{c,p,d}$ = 0 for all *d*), the freshwater flow should be equal to zero at any time. Similarly, constraints (19) impose limits on the inter-pad flows on either direction, according to the diameter of the pipelines connecting every pair of nodes. The maximum flowrate ip_d is also determined from the Hazen-Williams correlation, now accounting for the fact that the pipelines move impaired water.

$$WT_{p',p,t} \leq \sum_{d\in D} ip_d \ wp_{p,p',d} \quad ; \quad WT_{p,p',t} \leq \sum_{d\in D} ip_d \ wp_{p,p',d} \qquad \forall p < p', t \in T \tag{19}$$

Finally, the maximum amount of water that may be stored in a pad depends on the size of the storage facility installed at that node, as imposed by constraint (20). Note that minimum amounts of water typically managed in frac tanks at every well pad are not considered part of the water storage. In other words, if $\sum_{s\in S} ws_{p,s} = 0$, there are only frac tanks in pad p, and no significant volumes of water can be stored for later periods ($WS_{p,t} = 0$).

$$WS_{p,t} \leq \sum_{s\in S} is_s \ ws_{p,s} \qquad \forall p \in P, t \in T \tag{20}$$

Objective Function

The objective function seeks to maximize the net present value of the shale gas development project, while accounting for the water management costs. More precisely, the objective function comprises positive terms from the gas production and commercialization, and negative terms related to investment and operating costs.

Net present value (NPV) of incomes from gas selling during the current time horizon

From the total flow of natural gas produced and delivered from pad p at every period t ($GP_{p,t}$), the present value of sale incomes CI can be obtained as in Eq. (21). Note that the price may vary with the pad depending on the natural gas composition. The presence of hydrocarbons like ethane, propane, and butane usually increases the price per unit volume. φ_t is the discount factor for cashflows within week t, usually given by $\varphi_t = (1+dr)^{-(t-1)/52}$, where dr is the annual discount rate.

$$CI = \sum_{t\in T} \sum_{p\in P} \varphi_t \ gprice_{p,t} \ GP_{p,t} \tag{21}$$

NPV of gas selling incomes, beyond the current time horizon

Since the length of the planning horizon is usually restricted to one or two years while the wells drilled and fractured in that period may produce shale gas for more than 20 years, projections of future incomes should also be included in the objective function to obtain a better estimation of the NPV of the project (Ondeck et al., 2019). If we know: (a) the time t when a campaign of r wells is fractured and then turned in line, (b) the gas composition at pad p, (c) future gas prices, and (d) the annual discount rate, the NPV of the total incomes from gas sales beyond the current time horizon can be roughly estimated beforehand with the parameter $finc_{p,t,r}$. In this calculation, shut-in periods beyond the current time horizon are simply ignored by assuming that they will be not required. Therefore, the NPV of the overall future production FI, beyond the horizon end, is obtained by Eq. (22).

$$FI = \sum_{t \in T} \sum_{p \in P} \sum_{r \in R_p} finc_{p,t,r}\ y_{p,t,r} \tag{22}$$

Operating costs

Similarly to mobilization costs (see Eq. 7), the NPV of operating costs *OC* can also be determined from the time at which every well at every pad is developed, as stated by Eq. (23),

$$\begin{aligned} OC = \sum_{p \in P} \sum_{r \in R_p} \sum_{t = rt_p + t_{p,r}^{TS} - t_{p,r}^{HZ}}^{T - t_{p,r}^{FRAC} - t_{p,r}^{TIL}} y_{p,t,r}\ \Big[& \varphi_t\ op_{r,FRAC} + \varphi_{t - t_{p,r}^{HZ}}\ op_{r,HZ} + \varphi_{t - t_{p,r}^{HZ} - t_{p,r}^{TS}}\ op_{r,TS} \\ & + \varphi_{t + t_{p,r}^{FRAC}}\ op_{r,TIL} \Big] \end{aligned} \tag{23}$$

Notice that operating costs $op_{r,o}$ depend on the length of the campaign (*r*). Longer campaigns imply a larger number of wells being developed in the same visit to the pad, thus resulting in larger operation costs for that single campaign.

Water acquisition and disposal costs

If $fwcost_c$ is the unit cost paid for the freshwater withdrawn from source *c*, the NPV of water acquisition costs *AC* can be calculated as in Eq. (24). Similarly, water disposal costs *DC* are given by Eq. (25).

$$AC = \sum_{t \in T} \sum_{c \in C} \sum_{p \in P} \varphi_t\ \ fwcost_c\ FW_{c,p,t} \tag{24}$$

$$DC = \sum_{t \in T} \sum_{p \in P} \sum_{d \in D} \varphi_t\ \ dwcost_d\ WD_{p,d,t} \tag{25}$$

Water transportation costs

Assuming that pumping a unit volume of water from source *c* to pad *p* implies a given cost $ftc_{p,c}$, regardless of the diameter of the pipeline connecting both nodes, then the NPV of freshwater transportation costs is given by the first term in the right-hand side of Eq. (26). This assumption is based on the fact that the head loss per length of pipe is fixed, and the corresponding parameter can be obtained as explained in the model assumptions. A similar calculation is made in the second term to obtain the pumping costs to move water from pad *p* to another pad *p'*, and vice-versa. Finally, impaired water transportation costs *TC* from pads to disposal wells are included in the last term of Eq. (26). Note that by assumption 10, impaired water transportation to final disposal is made by truck.

$$\begin{aligned} TC = & \sum_{t \in T} \sum_{c \in C} \sum_{p \in P} \varphi_t\ \ ftc_{c,p}\ FW_{c,p,t} + \sum_{t \in T} \sum_{p \in P} \sum_{p' \neq p} \varphi_t\ \ \left[wtc_{p,p'}\ WT_{p,p',t} + wtc_{p',p}\ WT_{p',p,t} \right] \\ & + \sum_{t \in T} \sum_{p \in p} \sum_{k \in K} \varphi_t\ \ dtc_{p,k}\ WJ_{p,k,t} \end{aligned} \tag{26}$$

Installation of pipelines and storage facilities

By assumption 9, water pipelines and impoundments selected by the optimization model will be ready for operation at the initial time of the planning horizon. From that, investment costs *PC* and *SC* can be calculated as in Eqs. (27) and (28), according to the diameter of the pipelines and the size of the storage facilities being installed, respectively.

$$PC = \sum_{c \in C} \sum_{p \in P} \sum_{d \in D} fwpc_{c,p,d} \;\; wf_{c,p,d} \; - \sum_{p \in P} \sum_{p' > p} \sum_{d \in D} iwpc_{p,p',d} \;\; wp_{p,p',d} \tag{27}$$

$$SC = \sum_{p \in P} \sum_{s \in S} wsc_{p,s} \;\; ws_{p,s} \tag{28}$$

Finally, the objective function for the proposed MILP model is given by Eq (29).

$$Max\ NPV = \ CI + FI - OC - MC - AC - DC - TC - PC - SC \tag{29}$$

Computational Results

The proposed MILP model formulation is applied to two examples and several instances for each with increasing complexity. The first example involves 12 wellpads (52 potential wells), while the second one involves 20 wellpads (126 potential wells). In all cases, the time horizon is divided into 52 weekly periods, over one year of operation. The maximum number of wells to develop at every pad, land permits issuing dates, wells lateral lengths, duration, and operations costs per week at every location are all given in Table 1. For reference, we also present the production peak expected per unit of lateral length of a well in each pad, during the first week of production. Complete productivity curves per unit of lateral length over time are given in the Supporting Information.

Crew mobilization costs amount to $100,000, 450,000, 350,000 and 20,000 for TS, HZ, FRAC and TIL operations, respectively. Well development campaigns may comprise 1, 2, 4 or 6 successive wells. For the economic evaluation, natural gas price is assumed to be fixed at $2.50 /MMBTU for the whole planning horizon. The net revenue percentage that the company owns from the production of each pad ranges from 84% to 90% (see Supporting Information), while the annual discount rate for project evaluation is set at 10%. All the computational experiments are solved on an Intel Core i7 CPU, using GAMS-CPLEX 29.1 with 4 parallel threads under deterministic mode. Unless specified, the problem instances are solved to 0% optimality GAP.

Example 1

This example deals with the first 12 wellpads presented in Table 1. The geographical location of the pads, potential sources of freshwater and disposal wells are depicted in Figure 5. The superstructure of alternatives for the design of the water distribution network is also shown in Figure 5. We solve several instances of this illustrative example to show the impact of the water management decisions in the wellpad development plan, as next explained.

Table 1. Land permit issuing dates, number of wells and lateral lengths, duration and time unit cost for development operations, and initial production peak for the wellpads in all the examples.

Well-pad	Land Permit Issuing (week)	Max. No. of Wells	Lateral Length (10^3 ft)	Duration (weeks) x Weekly Operation Cost (10^6 \$)				Initial Peak (10^3 scf/ ft.week)
				TS	HZ	FRAC	TIL	
1	1	2	6	1 x 1.5	1 x 2.0	1 x 5.0	1 x 0.10	16.20
2	1	2	7	1 x 1.5	1 x 2.4	1 x 6.0	1 x 0.10	12.96
3	1	4	12	1 x 1.2	2 x 1.4	2 x 3.5	1 x 0.12	10.37
4	1	4	16	1 x 1.2	2 x 1.6	3 x 2.6	1 x 0.16	18.00
5	1	4	6	1 x 1.5	1 x 2.0	1 x 5.0	1 x 0.10	14.58
6	1	6	7	1 x 1.5	1 x 2.4	1 x 6.0	1 x 0.10	11.66
7	12	6	12	1 x 1.2	2 x 1.4	2 x 3.5	1 x 0.12	9.33
8	12	6	16	1 x 1.2	2 x 1.6	3 x 2.6	1 x 0.16	16.20
9	12	6	6	1 x 1.5	1 x 2.0	1 x 5.0	1 x 0.10	12.96
10	12	6	7	1 x 1.5	1 x 2.4	1 x 6.0	1 x 0.10	10.37
11	20	8	12	1 x 1.2	2 x 1.4	2 x 3.5	1 x 0.12	8.29
12	20	8	16	1 x 1.2	2 x 1.6	3 x 2.6	1 x 0.16	14.40
13	20	8	6	1 x 1.5	1 x 2.0	1 x 5.0	1 x 0.10	17.01
14	20	8	7	1 x 1.5	1 x 2.4	1 x 6.0	1 x 0.10	13.61
15	20	8	12	1 x 1.2	2 x 1.4	2 x 3.5	1 x 0.12	10.89
16	28	8	16	1 x 1.2	2 x 1.6	3 x 2.6	1 x 0.16	18.90
17	28	8	6	1 x 1.5	1 x 2.0	1 x 5.0	1 x 0.10	17.01
18	28	8	7	1 x 1.5	1 x 2.4	1 x 6.0	1 x 0.10	13.61
19	36	8	12	1 x 1.2	2 x 1.4	2 x 3.5	1 x 0.12	10.89
20	36	8	16	1 x 1.2	2 x 1.6	3 x 2.6	1 x 0.16	18.90

The first computational instance (1.1) consists on determining the operations development plan that maximizes the net present value (NPV) of the gas production, not taking into account water pipeline and storage costs, as usually seen in practice. We assume that a total of 20 crews are available, 4 for TS, 4 for HZ, 4 for FRAC and 8 for TIL. In a second step, we fix the wellpad development plan and solve the proposed optimization model to find the best water distribution network (WDN) that permits to supply every wellpad, as required by the optimal development plan. Alternative pipeline diameters, sizes for water storage facilities, transportation capacities and associate costs are given as Supporting Information.

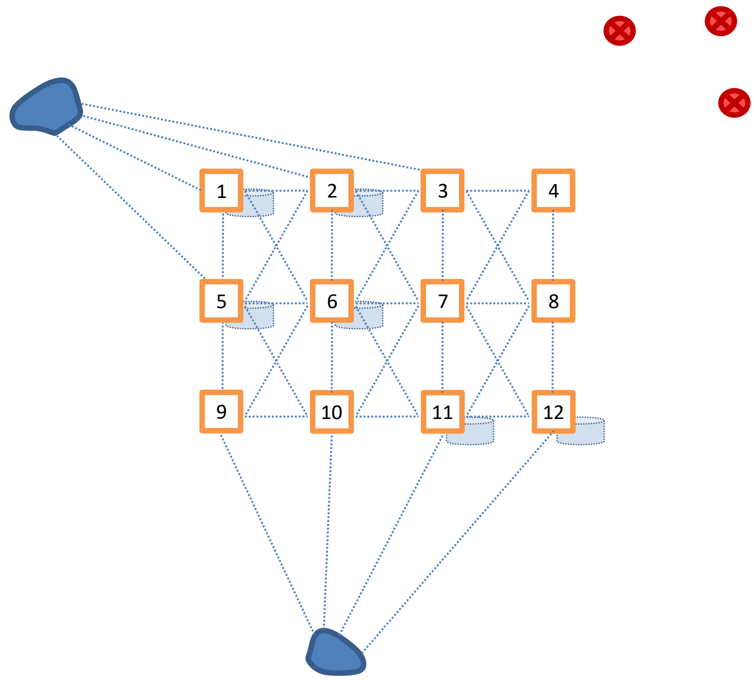


Figure 5. Wellpads and superstructure of alternatives for the design of the water distribution network in Example 1.

The solution found by the MILP model is depicted in Figure 6. As can be readily seen from this picture, after seeking for the maximization of the natural gas production revenues the operator may need to establish a complex water network design, with many connections and storage facilities. In fact, all the potential sites for storing water (locations 1, 2, 5, 6, 11 and 12) need to be used to recycle flowback water. Figure 6 also shows the bidirectional movement of water at segments 2-3 and 5-9, together with the evolution of the total volume of water stored at node 11 over time.

The MILP model involves 13,567 constraints and 13,837 variables, of which 3,251 are 0-1. Model sizes and computational results are summarized in Table 2. Perhaps not surprisingly, the optimization model without the water management cost terms in the objective function (first step) is solved very quickly in only 1.9 CPU seconds. The NPV of natural gas revenues amounts to MM$ 137.16. After fixing the development plan and adding the water cost terms to the objective function (second step), the required WDN design is found in 143.4 CPU s, even though the number of discrete variables is reduced to only 79 after pre-processing. The total NPV of the project, now accounting for the WDN costs, reduces to MM$ 101.28.

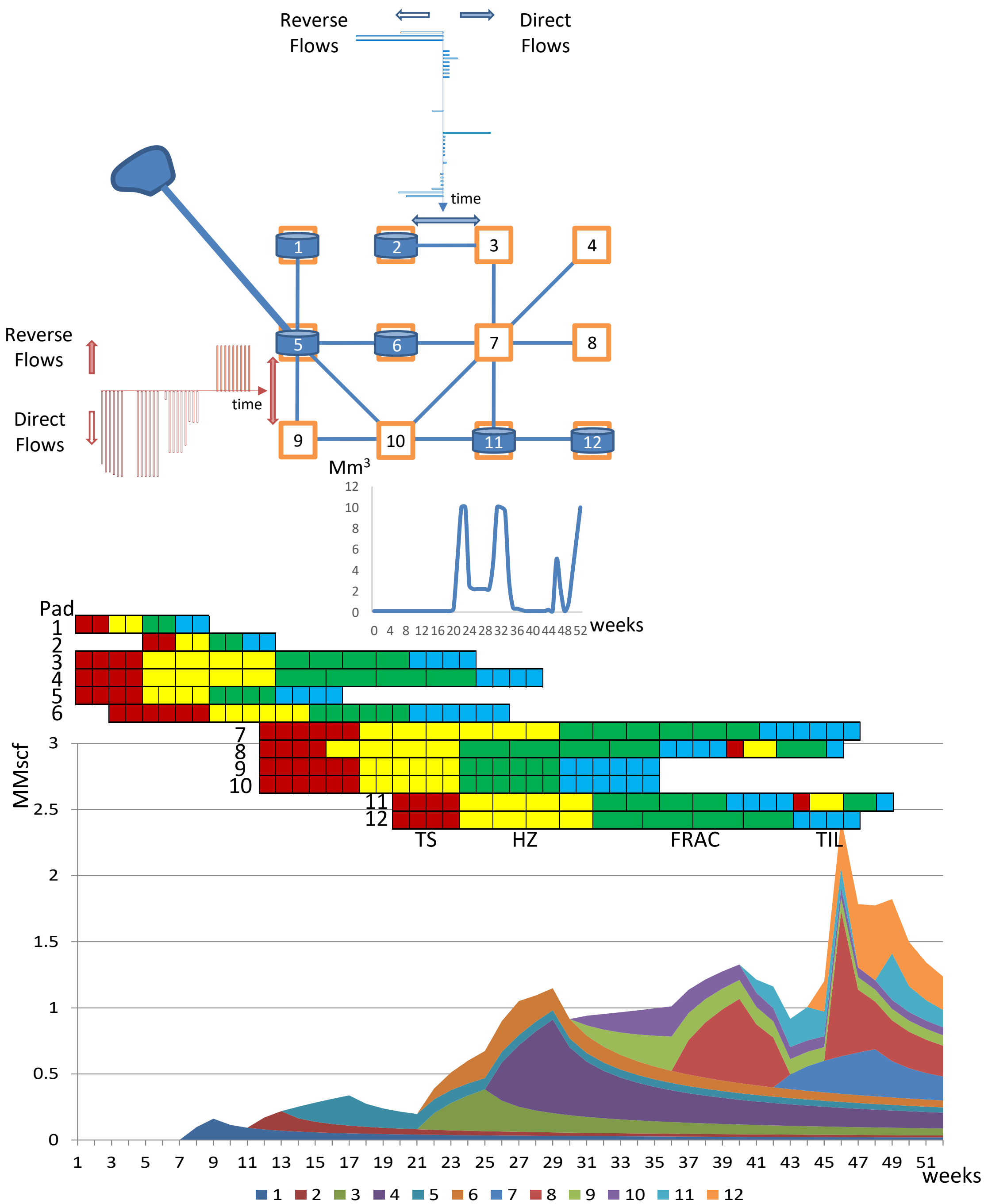


Figure 6. Optimal solution for the maximization of gas production revenues, and the most economical water distribution network required for complying with this development plan.

Table 2. Model Dimensions and computational results for all the problem instances.

Problem Instance	Step	Cont. Vars.	Binary Vars.	Const.	Best Solution Found [10^6 $]	CPU Time [s]
1.1	1	10,586	3,251	13,567	137.16	1.9
	2	10,586	1,889	13,567	101.28	143.4
1.2	-*	10,586	3,251	13,567	107.23	100,000*1
1.3	-*	10,586	3,251	13,567	107.21	100,000*2
1.4	-*	10,586	3,251	13,567	117.21	100,000*3
2.1	1	15,704	4,087	25,271	236.21	51.6
	2	15,704	2,551	25,271	188.81	7789.2
	3	15,704	4,041	25,271	189.27	5802.1
	4	15,704	2,551	25,271	189.28	705.0
	5	15,704	4,087	25,271	189.28	3705.5
	-*	15,704	2,551	25,271	189.28	100,000*4

* Full model   *1 Opt. GAP = 0.4%   *2 Opt. GAP = 1.1%   *3 Opt. GAP = 0.2%   *4 Opt. GAP = 5.3%

The second computational instance (1.2) consists on determining the well development plan together with the WDN in a single step. After 100,000 CPU s, the optimality gap can be reduced to 0.4%. The best solution found amounts to MM$ 107.23 of NPV (a 5.9% improvement with regards to instance 1.1), and is presented in Figure 7. Although the WDN is significantly simpler, all the flowback water can still be recycled, reducing freshwater consumption by 189 $10^3 m^3$ (a 25% reduction), and impaired water disposal by 206 $10^3 m^3$ (avoiding more than 10,000 truckloads) (Smith, 2012). The WDN shows less interpad connections (120.0 km of pipelines instead of 152.5 km) and half of the water storage facilities required by the previous instance (at nodes 5, 11 and 12). Moreover, pipelines are used more steadily, most of the time in a single flow direction. Interestingly, the total revenues from gas sales, not accounting for water management costs, are still high: MM$ 136.32. This yields a remarkable finding: by just conceding MM$ 0.8 due to a less intensive and smoother development plan, water management costs can be reduced by MM$ 6.8.

From the development plan suggested by the optimal solution of the integrated problem, one can see that the number of resources required, particularly the most expensive ones (for horizontal drilling and fracturing operations), hardly ever hit their maximum values. This is easily explained by the relative smoothness of the drilling plan, which seeks for a more sustainable use of the water resource. In fact, the solution depicted in Figure 7 shows that the 4 horizontal drilling resources are simultaneously used during 4 of the 52 weeks, while the 4 fracturing crews are all busy during just one week of the planning horizon. This suggests that the number of available resources for HZ and FRAC operations may be cut off. Indeed, by reducing the number of HZ and FRAC crews from 4 to 3 (experiment 1.3), the optimal solution deteriorates by merely MM$ 0.02 (0.01%), yielding exactly the same water distribution network as in Figure 7.

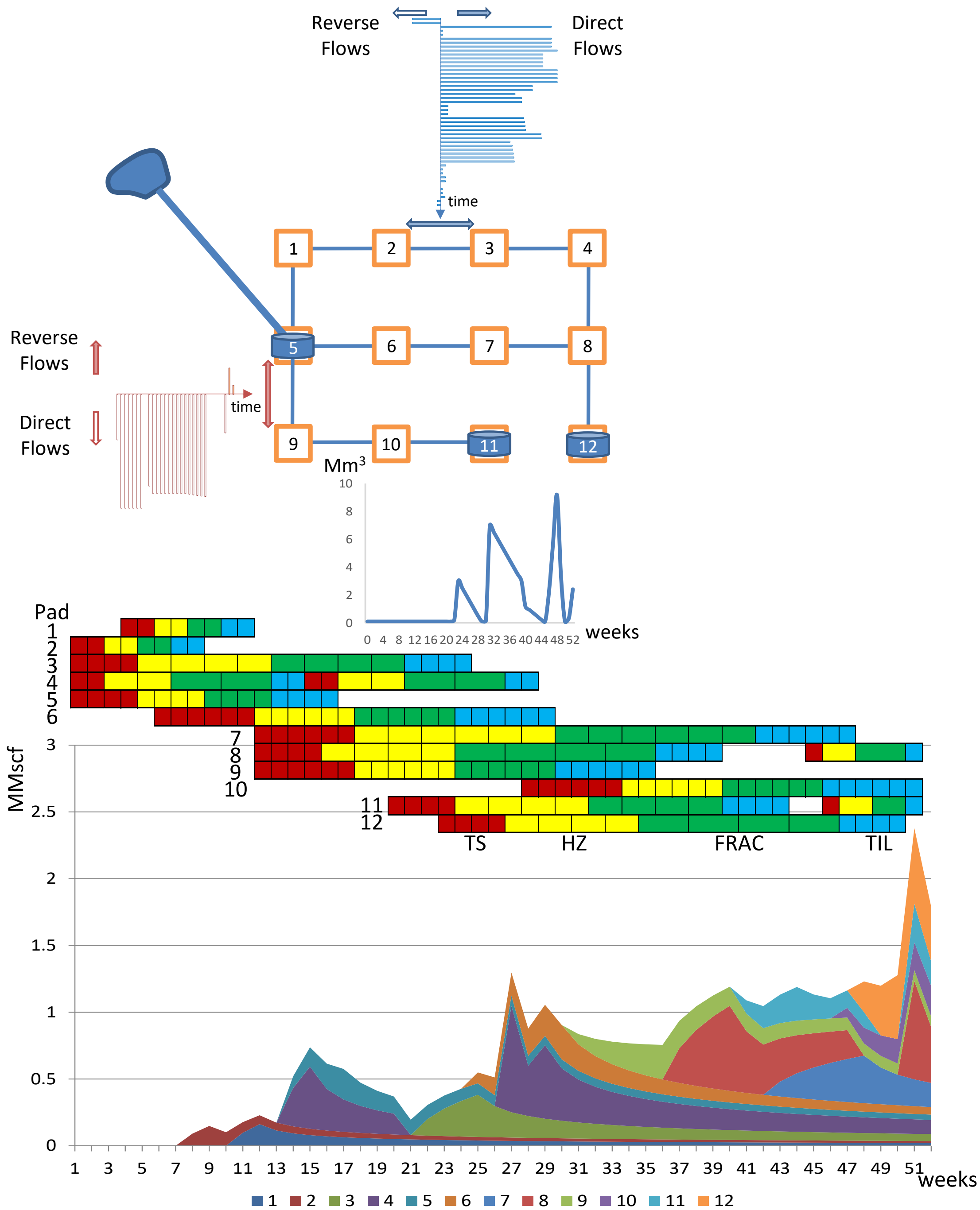


Figure 7. Best solution found for the simultaneous optimization of the wellpad development plan and the water distribution network design and operation.

On the robustness of the water distribution network

The last instance related to Example 1 is motivated by the need to quantify the impacts of modifying land permit issuing dates. Shale gas operators are usually concerned about the actual dates when they will finally be able to start their operations on every pad. Even though estimated dates are usually given, these values are highly uncertain. All previous instances of this problem show an "ordered" sequence of pad availability dates: pads 1 to 6 are available at the initial time, pads 7 to 10 are ready at week 12, while pads 11 and 12 could be developed starting at week 20 (see Table 1). In the current experiment (1.4), the initial times for wellpad development suffer significant changes. Although pads 1 and 2 are ready at the initial time, pads 3 and 4 are postponed more than 4 months (to week 18), while pads 5 to 8 could now be developed starting at week 4. Pads 9 and 10 are delayed until week 18, but drilling on pads 11 and 12 may start earlier, on week 12. As expected, the resulting development plan shows significant changes. More productive wells from pads 7, 8, 11 and 12 can be turned in line earlier, thus yielding an NPV increase amounting to MM$ 10. But the most interesting result comes from the fact that the optimized water distribution network remains the same. This result may be just a consequence of the geographical distribution of the wellpads over the region, or the fact that at the optimal solution all the wellpads are at least partially developed (meaning that at least one well of every pad is drilled and fractured). Further research is still required to conclude on the actual robustness of the water network design yielded by deterministic models like the one proposed in this paper. In fact, a two-stage stochastic programming model is currently under development to address this point.

Iterative procedure to find better integer solutions

From the previous computational results one can infer that the search for good feasible solutions to the integrated problem is rather challenging. In fact, if the task is left on the MILP solver, CPLEX returns, after 100,000 CPUs, a feasible solution whose NPV is more than MM$ 1 worse than the best solution reported in Figure 7. With the aim of searching for better integer solutions in much shorter computational times, we propose the algorithm described in this section. The algorithm is based on the fact that intensive, yet myopic well development strategies as the one depicted in Figure 6 are rapidly obtained (more precisely, in less than 2 CPU seconds). This fact relies on the tightness of the scheduling model based on the concept of campaigns, as discussed by Cafaro and Grossmann (2020). However, such an "optimal" solution from the gas production perspective yields rather expensive water distribution networks and operations, which are usually oversized (involving more pipelines and storage facilities than required). From this fact, one can give the model the option to improve the integrated solution (i.e., accounting for both shale gas revenues and water management costs), but just taking into account the subset of connections and storage facility locations suggested by more intensive strategies. Although this subset is relatively large when compared with the optimal design, it excludes many of the connections in the overall superstructure of alternatives, thus significantly reducing the model size.

Moreover, after solving the reduced problem, the improved well development plan can be fixed and the water network design problem can be solved again, now accounting for all the superstructure of alternatives. This step may yield new potential interconnections to be included in the reduced problem. The procedure can be repeated until the model solution shows no improvement, which usually occurs after 3 to 5 iterations. The proposed algorithm can be summarized as follows:

1. *Solve the well development MILP problem assuming no water management costs.*
2. *Fix the development plan and solve the water distribution network design and operation problem.*
3. *Solve the full MILP optimization problem (well development + water network design and operation) just accounting for the pipelines and storage facilities suggested by the optimal solution to Step 2.*

4. *If there is no significant improvement, then stop. Else, go to step 5.*
5. *Restore all possible pipelines and storage facilities and return to Step 2.*

Example 2

The second example is a larger case study, involving the 20 wellpads presented in Table 1. The aim of this example is two-fold: First, to assess the ability of the proposed model to cope with larger case studies, involving more complex development plans and water distribution networks. Second, we want to elaborate on the importance of return-to-pad operations, accounting for their impact on both gas production and water supplies. The best solution found for this example is depicted on Figure 8, presenting both the water distribution network and the wellpad development plan. This solution is found through the iterative procedure presented in previous sections, which takes 17,375 CPUs and 5 iterations to converge. The first solution (not accounting for water management costs) is found in less than one minute of CPU, but the following four MILPs take more than one hour on average each. In every step, MILPs are solved to optimality (0% GAP). On the other hand, the upper bound of the overall NPV maximization problem is still 5.25% above the best solution found, after 100,000 CPUs of computation. Although the optimality GAP is still high, the best solution found shows a simple but effective water distribution network that permits to recycle more than 285 $10^3 m^3$ of flowback water, avoids impaired water disposal, and reduces freshwater consumption by 25%.

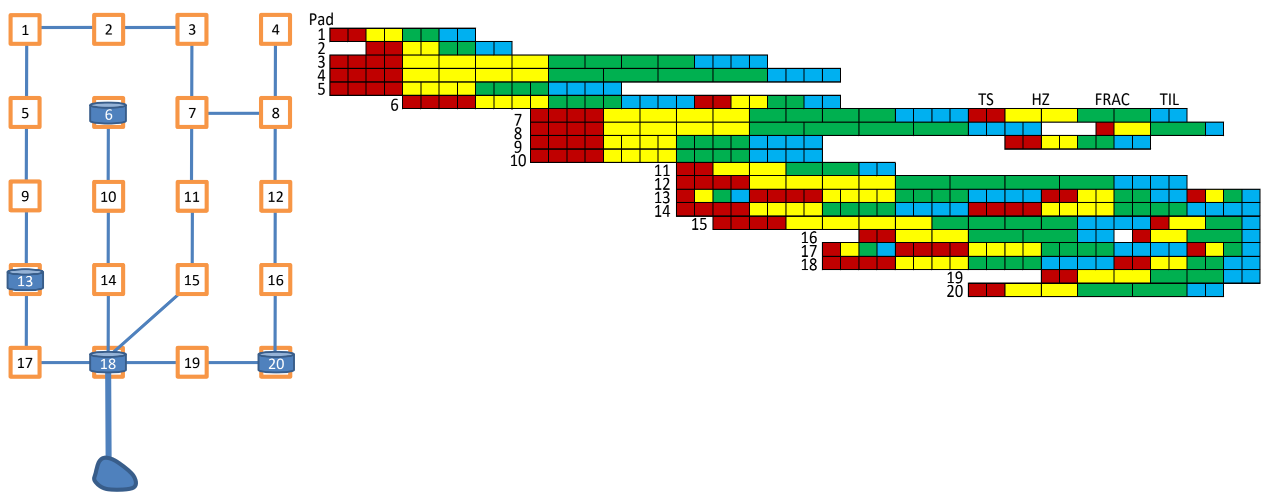


Figure 8. Best solution found for the water distribution network and wellpad development plan of Example 2.

All the projected wells of pads 1 to 5 are developed during a single campaign. In turn, wells in pads 6 to 9 are developed during two different visits to each location. On the other hand, many wellpads are not fully developed during the current time horizon, with up to 6 wells left for future interventions, as in pads 11, 19 and 20. The wellpad with more return-to-pad operations is 13, featuring a total of 4 campaigns: the first one starting at week 20 to develop a single well; the second starting at week 25, involving 4 new wells; the third starting at week 41, drilling 2 wells; and the last single well developed at week 48. Interestingly, the optimal water distribution network suggests placing a water storage facility at that location, what is closely related with the number of times that the flowback water is recycled within the same pad, as shown in Figure 9. Note that water consumption increases during fracturing campaigns, when the previously developed wells in the pad are shut-in, banning natural gas delivery.

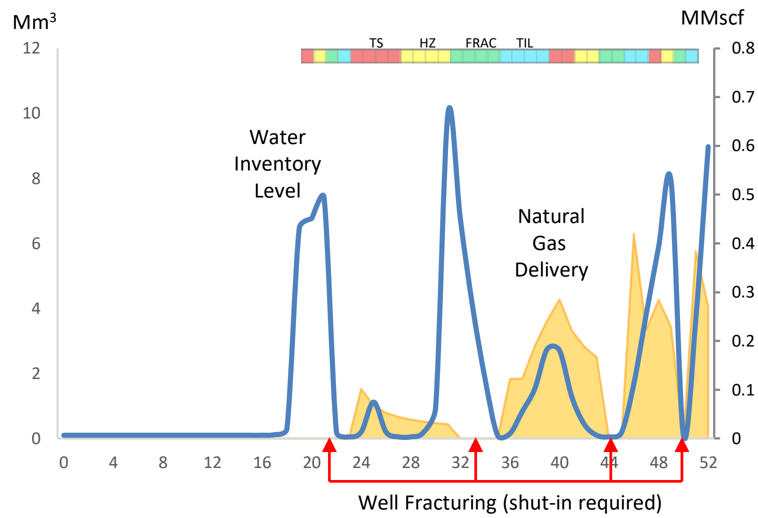


Figure 9. Evolution of water inventory levels and natural gas production flows from wellpad 13 in Example 2

On the quality of the recycled water

One of the critical assumptions in our model is that the concentration of total dissolved solids (TDS) in the impaired water being recycled is reasonably low during the time horizon. That is the main reason why the best solutions found for all instances of both examples avoid sending any water to disposal wells, which would imply long truck hauling. Instead, all impaired water is recycled and finally kept into the storage tanks at the end of the time horizon. To validate the water quality assumption, we implement a simple calculation as follows. We aim at tracking the average TDS concentration of the water being stored and used for fracturing over time, according to the well development plan that has been found. By assuming that TDS concentration of freshwater is about 300 ppm, and every flowback brings to the surface additional 100,000 ppm with regards to the injected water, we can calculate the overall concentration of TDS in the system over time. Eqs. (30) to (35) given in the Supporting Information account for these calculations through a recursive procedure. Note that these equations provide an estimation of the average concentration of TDS in the overall water being used for fracturing, and do not make part of the optimization model but they are solved afterwards.

In Figure 10 we show the evolution of the average concentration of TDS in the water being used for fracturing, according to the best solutions found for Examples 1 and 2. Note that the average TDS concentration is reasonably low during the entire time horizon, reaching a maximum concentration of 127,000 and 130,000 ppm, respectively, at the end of the year. Results show that most of the wells are fractured with water blends containing up to 50,000 ppm of TDS, while the last wells are fractured using roughly pure flowback water. Shale gas operators are reportedly considering the reuse of waters with salinity as high as 120,000 ppm (with low hardness and scale-causing contaminants) (Carrero-Parreño et al., 2018). Hence, on average, the impaired water being reused for fracturing shows reasonable TDS concentrations after one year of development. However, it is important to note that managing flowback water will be more challenging if the number of new wells to be fractured in the next planning horizon is reduced. In fact, the best solution found for Example 1 suggests that the storage facility at node 5 will be full of impaired water at the end of the first year, and the same is true for nodes 18 and 20 in Example 2.

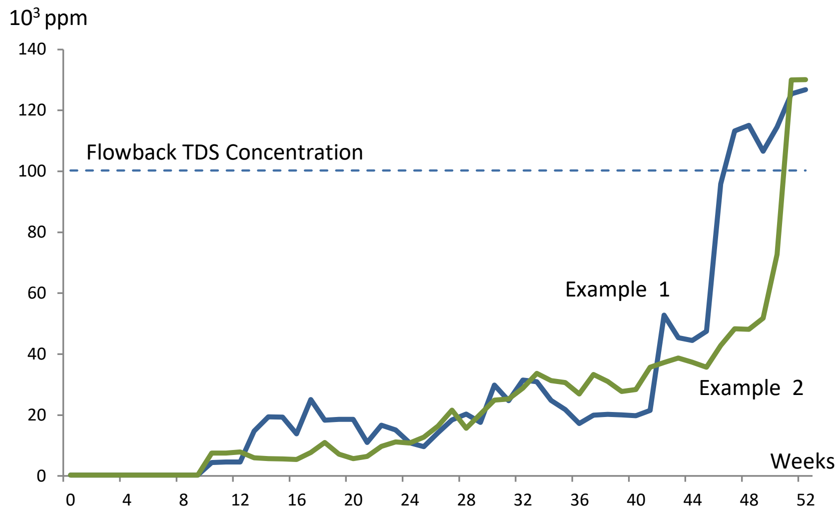


Figure 10. Average concentration of TDS in the water used for fracturing in Examples 1 and 2

Conclusions

We have developed a novel multiperiod MILP model for the scheduling of shale gas operations by introducing the notion of campaigns. Through this tighter formulation, the complexity of the scheduling problem is greatly reduced, yielding optimal solutions for real-sized problems with many crews, a large number of pads and multiple wells per pad, in reasonable computational times. Based on the model effectiveness, we are able to integrate the optimal design of water pipeline networks supporting the well development plan. The main model decisions are the size and location of inter-pad pipeline segments (moving fresh or impaired water on either direction) and the size and location of water storage facilities, where impaired water is temporarily stored before recycling. Besides that, the optimal solution determines the time to perform the operations for the development of new wells at every pad, and the amount of water to move from freshwater sources to pads, from pads to other pads, from pads to storage facilities, from storage facilities to pads, and eventually from storage facilities to disposal wells; at every period of the time horizon. To the best of our knowledge, this model represents the first approach in the literature addressing the optimal design of extensive water distribution networks for fracturing, reducing freshwater consumption and flowback water disposal during well development plans. In this way, water recycling is maximized, yielding substantial savings both from water acquisition and disposal costs, and most important, reducing the environmental impacts of shale gas operations.

We have successfully solved several case studies involving up to 20 wellpads and about 100 wells developed by 4 horizontal drilling rigs and 4 fracturing crews over one year of operation. However, since the computational burden grows quickly with the number of pads, we are not able to reduce the optimality gap of the MILP below 5% for the largest instances after 100,000 s of CPU. An interesting finding is that the so-called myopic development strategy, neglecting water management costs, is found very fast, in less than one minute of CPU even for the largest cases. Such a feasible solution usually yields oversized water distribution networks, from which we propose an iterative algorithm to find better solutions to the integrated problem. When compared to the myopic development strategy, we demonstrate that by conceding only 1% of the NPV of the incomes from natural gas selling, water management costs can be reduced by more than 25% due to a less intensive and smoother development plan. This implies more than $6 million savings in the total costs.

Overall, the optimal pipeline infrastructure for water recycling reduces more than 25% the freshwater consumption, saves on transportation costs, reduces the risk of leaks and environmental impacts, increases water supply reliability, and avoids the need for water disposal after one year of operation. With regards to water quality, the results show that the concentration of total dissolved solids (TDS) in the injected water keeps reasonably low during the time horizon, even though all impaired water is being recycled. Some studies are still lacking to determine for how long the full-recycling strategy is sustainable, and how to manage water blends at every single wellpad. That may require the detailed, nonlinear monitoring of TDS concentration on every single pipeline and storage tank, posing further challenges from the modeling perspective. Another interesting research direction is to solve the problem under uncertain conditions, making it possible to build a robust water pipeline network that performs relatively well under any scenario.

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Nomenclature

Sets

C Set of freshwater sources

D Set of alternative pipeline diameters

S Set of alternative pond sizes

K Set of deep wells for impaired water final disposal

O Set of operations (TS, HZ, FRAC, TIL)

P Set of wellpads

R_p Set of possible campaign lengths in pad p. In the most general case, $R_p = \{1, 2, 3, \ldots, nw_p\}$, where nw_p is the maximum number of wells to develop in pad p during the time horizon. The optimization model might decide to develop all the wells in a single campaign of length nw_p, or, in the opposite extreme, develop the wells one by one, in nw_p different campaigns of length 1.

The optimal solution usually suggests an intermediate strategy, comprising a sequence of campaigns with different lengths.

T Set of time periods (weeks)

Parameters

rt_p ready time for pad *p*, after issuing land permits

$t^o_{p,r}$ total number of periods to perform operation *o* on a campaign of *r* wells

n^o number of available resources to perform operation *o*

nw_p total number of wells that can be developed in pad *p* during the current planning horizon

$\gamma_{p,t,r}$ gas productivity from a campaign of *r* wells in pad *p*, *t* periods after fracturing starts

$\alpha_{p,t,r}$ flowback (water production) from a campaign of *r* wells in pad *p*, *t* periods after fracturing starts

$\beta_{p,t,r}$ water consumption rate during a campaign of *r* wells in pad *p*, *t* periods after fracturing starts

φ_t discount factor for time period *t*

fp_d maximum flowrate for a pipeline of diameter *d* carrying freshwater from a water source to a pad

ip_d maximum flowrate for a pipeline of diameter *d* moving water among pads

is_s overall water storage capacity of a facility of size *s*

Nonnegative Variables

$F_{p,t}$ productivity of pad *p* during time period *t*

$GP_{p,t}$ gas production delivered from pad *p* to midstream distribution during time period *t*

$L_{p,t}$ total gas retained (accumulated) on wells of pad *p* at the end of time period *t*

$WP_{p,t}$ flowback (water production) from pad *p* during time period *t*

$WC_{p,t}$ water consumption for fracturing wells in pad *p* during time period *t*

$WJ_{p,k,t}$ water volume sent from pad *p* to disposal well *k* during time period *t*

$WS_{p,t}$ water stock in pad *p* at the end of time period *t*

$FW_{c,p,t}$ freshwater supply from source *c* to pad *p* during time period *t*

$WT_{p,p',t}$ water moved from pad *p* to pad *p'* during time period *t*

Binary variables

$y_{p,t,r}$ = 1 if a campaign of *r* wells on pad *p* starts to be fractured during time period *t*

$y^{SHUT}_{p,t}$ = 1 if the producing wells in pad *p* should be shut-in during time period *t* due to interference with new fracturing operations

$wf_{c,p,s}$ = 1 if a pipeline of size *s* is built to supply pad *p* with freshwater coming from source *c*

$wp_{p,p',s}$ = 1 if a pipeline of size *s* carrying fresh and/or impaired water is built between pads *p* and *p'* ($p < p'$)

$ws_{p,s}$ = 1 if an impoundment (water storage facility) of size *s* is installed in pad *p* to store fresh and/or impaired water

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