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Key Shale Gas Water Management Strategies: An Economic Assessment Tool

James Slutz, SPE, Global Energy Strategies; Jeffrey Anderson, SPE, Select Energy Services; Richard Broderick, Fountain Quail Water Management; Patrick Horner, SPE, Aqua-Pure Ventures

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Abstract

As a result of recent innovations in horizontal drilling and hydraulic fracturing, shale gas has become an important global energy supply. However, water consumption and disposal issues associated with shale gas development, coupled with industry growth, are creating a need for sophisticated water management strategies. Current shale gas water management strategies fall into three key categories: disposal, re-use, and recycling. Disposal strategies involve sourcing fresh water for hydraulic fracturing and transporting all frac flowback and produced water to an injection well for disposal. Re-use strategies involve primary treatment of frac flowback, so it can be blended with make-up water for re-use as frac fluid. Recycling strategies involve treating the flowback to fresh water quality, either for re-use in hydraulic fracturing or for environmental discharge. This paper will analyze the total life cycle water management costs per frac by comparing the options and costs of water supply; water transportation; cost and options for disposal, re-use, and recycling; impact of water quality on frac chemical costs; the impact of water quality on frac performance and long-term well performance. This paper will also identify other impacts, including safety, public perception, community impact, and environmental liability.

INTRODUCTION

“When the well is dry, we know the worth of water.” – Benjamin Franklin.

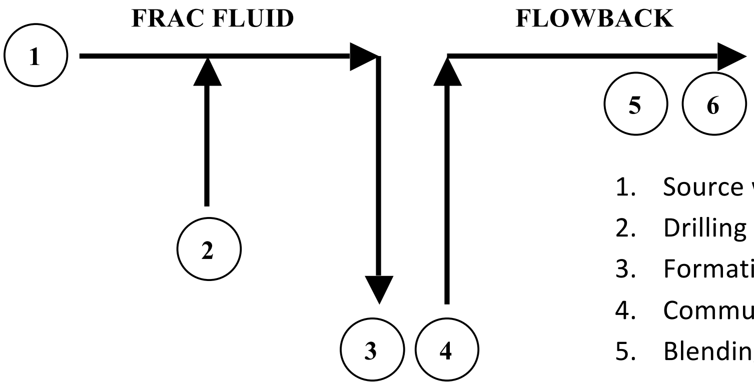
Water management typically make up between 5% and 15% of overall shale gas drilling and completion costs. When we understand the short and long term considerations that contribute to overall costs, we know the worth of shale gas water management. Understanding the variables that influence flowback quality and quantity are a key foundation to establishing an overall strategy. Cost components, such as fresh water, transportation, storage, treatment options, and disposal, are highly dependent on the nature of the flowback, and both regional geography and regulations. There are three basic shale gas water management strategies: disposal of flowback, re-use of flowback, and recycling of flowback. A simple economic model can be used to determine the most cost-effective strategy, depending on the specifics of a particular scenario. A proactive shale gas water management strategy can both reduce costs and enable long-term production by addressing and balancing the needs of industry, the regional regulators, the environment, and the community.

TECHNICAL CONTEXT

When developing a water management plan and assessing its economic viability, paying attention to the quality and quantity of frac flowback is of particular importance because of shale gas waters’ complex and variant chemistry. Understanding this chemistry is useful for evaluating a treatment system and/or the compatibility of flowback. Blending incompatible waters increase the potential of scaling. This section will examine six key variables – source water chemistry;

drilling and hydraulic fracturing program; formation geochemistry; communication with water bearing formations; flowback blending on surface with other waters; and flowback's time on surface – in order to foster an understanding of what contributes to the nature of flowback chemistry.

Flowback Chemistry



1. Source water chemistry.
2. Drilling and hydraulic fracturing program.
3. Formation geochemistry and rock mechanics.
4. Communication with water bearing formations.
5. Blending on surface with other waters.
6. Time on surface.

FIGURE 1.0: VARIABLES INFLUENCING FLOWBACK QUALITY AND QUANTITY

Source Water Chemistry

Water is the primary component of shale gas frac fluid, generally making up over 98% of the total composition. Frac fluid source water is obtained from groundwater, surface water (i.e., lakes, rivers, and streams), industrial effluent (i.e., flowback), and/or municipal effluent.

Source waters making up the frac fluid are often blended from different places to make up the total frac fluid volume. Evaluating the compatibility of the blended source waters will ensure the potential for scaling does not exist prior to hydraulic fracturing. Blending incompatible waters can increase the scaling index of components of concern and increase the probability of scaling. The primary compatibility issue for shale gas frac fluid is the potential for barium sulfate scale formation. For example, a surface water with a sulfate concentration of 125 mg/L $SO4$, blended with flowback with a barium concentration of 1500 mg/L Ba, could produce approximately 1750 kg of barium sulfate ($BaSO4$) from a single frac.[1] If barium sulfate scale formation is a concern, scaling index calculations should be conducted on blended surface waters and with interactions with formation geochemistry.

Frac Type and Chemical Program

There are three primary types of shale gas hydraulic fracturing:

Slick frac volumes are usually in the range of 80,000 to 120,000 bbl per frac. Slick frac fluid is primarily water with friction reducer (to reduce drag in tubing), biocides (to prevent microbial degradation), scale inhibitors (to reduce scaling potential), surfactants (to prevent water-wetting of formation), and propping agents (to maintain formation permeability after frac). Flowback volumes from slick fracs range from 10% to 40% of the original frac volume.

Gel frac volumes are typically less than slick frac volumes, but they contain more chemical. Primary gel frac additives include the use of water-based or cross-linked gel systems to increase the viscosity of the fluid, enabling it to carry more proppant. Gel breakers degrade thickeners or disable crosslinkers, which decreases viscosity and causes the fluid to deposit proppant into the newly created fractures.

Hybrid fracs involve using a combination of slick and gel fracs on different stages of the well.

Due to the recent expansion of shale gas development, there has been a significant advancement of hydraulic fracturing technology. It is expected that hydraulic fracturing chemical programs will become increasingly complex and diverse, which will add to the associated complications of water treatment.

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[1] When naturally occurring radioactive materials (NORM), such as radium 226, co-precipitate with barium sulfate, it increases the risk of accumulating NORM on tanks and equipment.

Formation Geochemistry

Shales are sedimentary formations made up primarily of clay, calcite, and quartz. Pore spaces within the shale contain salt and organic material (such as natural gas). The salt within the pores is highly soluble and so are components within the shale itself. Time (how long the fluid has been underground), temperature, and pH level dictate the amount of material dissolved by the flowback. The geochemistry of the formation has a significant impact on how much dissolved material is absorbed by the frac fluid. Terrestrial shales (formed on land) tend to have significantly less salt, while marine shales (formed in ancient oceans) tend to have more. Formations with higher molecular weight hydrocarbons can also result in an increased level of dissolved organic material in the flowback. Swelling or expanding clays may also pose concerns during hydraulic fracturing. Producers should ensure that these clay minerals do not react adversely with frac fluids. For example, iIllite and smectite clay minerals are very reactive to fresh water, therefore a mild saline fluid, such as 2% KCL solution, or clay stabilizers should be added to freshwater-based hydraulic fracturing fluids when completing shale gas reservoirs that contain these minerals. Understanding the geochemistry of each formation can provide insight into the nature of the flowback.

Salt Water Bearing Formations

Shale formations often have an overlying or underlying water-bearing formation. These water-bearing formations tend to be highly saline (80,000 to 240,000 mg/L). If either natural or frac-induced communication between the producing zone and the water-bearing formation occurs, the quantity and salinity of the flowback can increase significantly. Note that these adjacent water-bearing formations are thousands of feet below the surface and are not in communication with shallow drinking water aquifers. Communication between the producing zone and a water-bearing formation can also result in larger produced water volumes after the well has been put into production. .In other words, when hydraulic fracturing into an adjacent salt water formation occurs, flowback and produced water volumes may greatly increase. This can significantly impact the economics of shale gas production, due to the larger volumes of water that need to be managed. Hydraulic fracturing strategies that minimize communication between producing zones and water-bearing formations can significantly reduce the volumes of flowback and produced water that return to the surface.

Blending on Surface

When flowback returns to the surface, it is usually stored and blended with other flowback waters, produced water, and potentially salt-based drilling fluids and other wastes (such as berm or wash water). This blending can lead to unexpected changes in the overall composition, causing complications with treatment, if the technology cannot adapt to the variability.

Time on Surface

When flowback returns to the surface, it contains organic material (both frac chemicals and naturally occurring material from the formation) and bacteria. The bacteria break down the organic material in the water sulfate-reducing bacteria has the potential to produce H2S. The resulting hydrogen sulfide creates safety concerns and increases the potential for corrosion.

Regional Flowback Compositions: Technical Overview

The salinity and/or total dissolved solids (TDS) in the flowback are key evaluation components for overall water management economics, as they impact how much of the flowback water can be blended with fresh water to make up the overall source water (as frac fluid for a new well). Areas with low flowback volumes and low TDS in the water will likely be able to meet frac-water chemistry requirements, enabling the entire load of flowback to be re-used with minimum treatment. Areas with high flowback volumes and high TDS in the water may result in a limited amount of flowback that can be blended for a new frac, or the waters may require higher levels of treatment to meet the frac chemistry water requirements.

The composition of flowback and produced water can vary significantly from region to region. Differences in composition that can impact overall management options include (but are not limited to) the treatability, disposal injectivity, and variability of early and late-stage flowback. The treatability of flowback is highly influenced by the composition of the water. The overall fouling and scaling potential of the water will also determine the effectiveness of treatment technology. In other words, the composition dictates the available options for treatment, the level of recovery to be expected, and the overall costs of the treatment.[2] Disposal injectivity is also impacted by the composition of the water. Waters with high levels of

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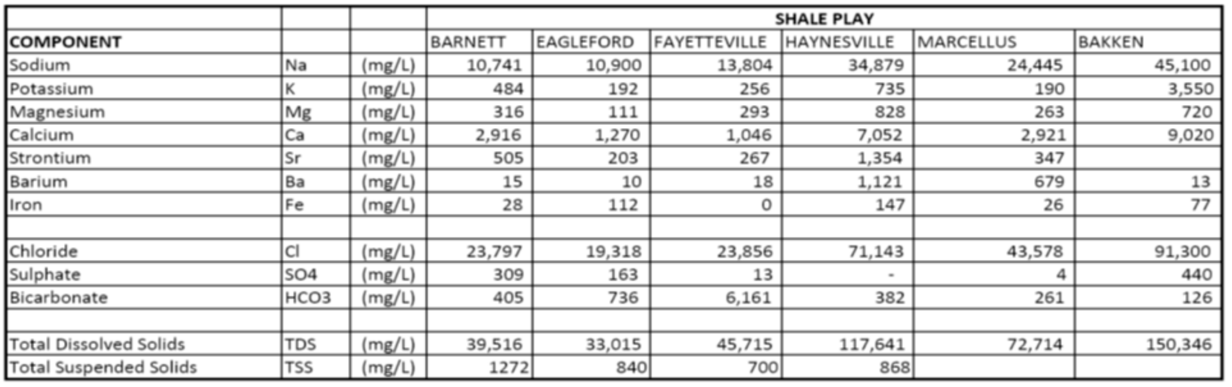
[2] For a more in-depth discussion, see Horner, Patrick, Brent Halldorson and James Slutz's "Shale Gas Water Treatment Value Chain –A Review of Technologies, Including Case Studies."

suspended solids, or other components that could reduce permeability of injection into formations, can limit both the rate at which the flowback can be disposed of and the overall volume a disposal well can take. Flowback that causes injectivity problems can significantly increase the cost of disposal. In order to estimate more accurate re-use blending mass balances or re-cycle recovery rates, the variability in early to late-stage flowback needs to be taken into account to determine the representative average for a given region. Flowback composition can vary significantly from early-stage flowback (day 1) to late-stage flowback (day 10 to 15). Early-state flowback has a higher flow rate but lower TDS. As time progresses, the flow rate decreases and the TDS in the water increases. To obtain an accurate estimate of the average flowback composition for a given area, one must conduct a mass balance that takes both daily volumes and composition into consideration. Taking into account the volume/flow profile is important because one has to consider TDS and volume jointly, in the function of time, to get a representative average of the overall total dissolved solids.



			SHALE PLAY					
COMPONENT			BARNETT	EAGLEFORD	FAYETTEVILLE	HAYNESVILLE	MARCELLUS	BAKKEN
Sodium	Na	(mg/L)	10,741	10,900	13,804	34,879	24,445	45,100
Potassium	K	(mg/L)	484	192	256	735	190	3,550
Magnesium	Mg	(mg/L)	316	111	293	828	263	720
Calcium	Ca	(mg/L)	2,916	1,270	1,046	7,052	2,921	9,020
Strontium	Sr	(mg/L)	505	203	267	1,354	347	
Barium	Ba	(mg/L)	15	10	18	1,121	679	13
Iron	Fe	(mg/L)	28	112	0	147	26	77
Chloride	Cl	(mg/L)	23,797	19,318	23,856	71,143	43,578	91,300
Sulphate	SO4	(mg/L)	309	163	13	-	4	440
Bicarbonate	HCO3	(mg/L)	405	736	6,161	382	261	126
Total Dissolved Solids	TDS	(mg/L)	39,516	33,015	45,715	117,641	72,714	150,346
Total Suspended Solids	TSS	(mg/L)	1272	840	700	868		

FIGURE 2.0: Example Flowback Analysis from various US Shale Plays

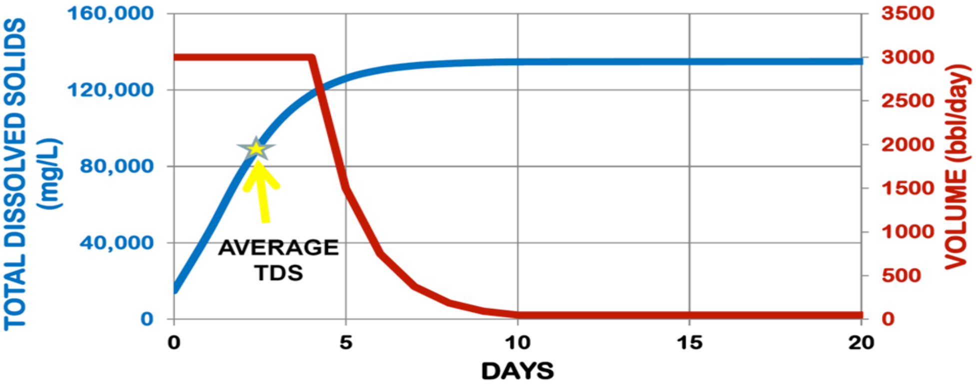


FIGURE 3.0: Example Flowback Volume vs. TDS Profile

ECONOMIC CRITERIA

The key economic criteria required to evaluate a shale gas water management plan are the cost and availability of source water; the types of water transport available and its associated costs; the types of disposal available and the associated costs; the type of overall management strategy used; and the available water treatment methods and their associated costs. Source water and disposal availability can both be highly impacted by regional geography and/or local regulations. The availability and cost of transportation is impacted by fuel prices, regional infrastructure, regional geography, as well as regional regulations. The cost and availability of treatment options is a function of the quality of water required for hydraulic fracturing, the flowback chemistry, and the state of the art of treatment technology. The level of industrial activity in a region can also impact cost criteria. Costs for early stage field development, when overall activity is low, can differ significantly from late stage field activity. Costs can either increase or decrease based on the level of infrastructure and/or availability of needed resources (source water, disposal, transportation, treatment, etc.). This paper provides high level estimates for economic criteria as an example of how to build an economic model. Any costs used for actual modeling should be double-checked as they will change with time, geography, and level of overall industrial activity. The overall water management costs (sourcing, transportation, storage, treatment, and disposal) make up approximately 5% to 15% of the overall well drilling and completion costs. Minimizing the costs associated with water management is an important part of maximizing short-term shale gas profitability. Other benefits of good water management programs that reduce community impact and the risk of environmental liability can increase long-term profitability by increased regulatory support and reduced environmental remediation costs.

Source Water

Different types of water may be sourced for hydraulic fracturing. As aforementioned, they include groundwater (i.e., alluvium or bedrock aquifers), surface water (i.e., lakes, rivers, or streams), industrial effluent (i.e., including recycled produced water), and treated municipal effluent.

Water costs vary based on transportation and regional availability. In water-rich regions, costs are typically lower, but drought conditions can quickly impact water costs. Water-rich regions in the United States include the northeast (Marcellus), east Texas/north Louisiana (Haynesville), and mid-continent (Woodford-Caney and Granite Wash/Anadarko and Arkoma Basins),. Costs of water are higher in arid regions due to inadequate supply and drought (or impending drought conditions). Arid regions in the United States include Eagle Ford, Denver-Julesburg Basin, Permian, and California.

Considering the costs of water supply, the typical cost of water at the source, without taking into account the cost of transportation, is \$0.01 to \$0.02/bbl, according to River Authorities in Marcellus. Water costs in Eagle Ford, Haynesville, and Barnett are \$0.25 – \$0.35/bbl, according to the records of private landowners with rights to surface water and groundwater. Reflective of 2012's water supply costs, water is between \$0.50 to \$1.00/bbl in the Bakken and Denver-Julesburg Basin, Colorado, due to dry conditions in the summer.

Transportation

Transportation of source and waste waters needs to be considered when evaluating the economic viability of water management strategies. Trucking and transfer pipelines are both viable transportation options. Trucking involves the use of water haulers, typically hauling anywhere from 100–160 barrel of water per load. Alternatively, three kinds of pipelines are available for transfer: the use of fast line or lock-ring irrigation pipe, high-density polyethylene (HDPE), and aluminum pipe with air-tight seals (Victaulic®).

Typical costs for the aforementioned options follow:

- Trucking \$0.02 to \$0.04/bbl/mile.
- Transfer costs vary according to elevation and/or weather conditions and so forth. Costs can range from \$0.02/bbl/mile for Louisiana transfer to \$0.40/bbl/mile for North Dakota during the winter. Costs also vary based on regional viability: it is in the highest of cost spectrum for HDPE in North Dakota, and the lowest for fast line in Louisiana.

That said, when transportation is concerned, different costs such as public perception and public safety also need to be taken into account in today's market. As this will be further elaborated in the "long-term considerations" section of this article, there is a significant bonus in getting trucks off the road and transferring water via pipeline. Moreover, trucking is logistically unfeasible in supporting continuous hydraulic fracturing of multiple horizontal wells, with 20+ stages per well, from the same pad. Many operators are currently using the multi-well pad drilling strategy; pipeline transfer at 50 to 100 BWPM is a feasible option.

Storage

Fresh water

Transported fresh water is stored in either pits (the standard practice is to line fresh water pits) or in portable above ground tanks. Portable above ground tanks can be classified as frac tanks, steel paneled tanks, or poly-walled tanks. The specifications for these tanks follow:

Frac tanks come in one standard 500 bbl size. Each one requires a winch truck to mob, set up, and demob from site.

Steel paneled tanks can be of various footprints and storage sizes (i.e., Poseidon, Goliath, Hercules, Fraction, and so forth). They are typically >40,000 bbl and are used for longer-term applications. They are round, tall, and usually 12 feet in height. They require large equipment (i.e., crane and several semi- trailers) and crew to set up.

Poly walled tanks are 5 feet to 6 feet long and in various heights (2 ft, 4 ft or 8 ft). They are constructed with interlocking LDPE sections that allow for accommodation for multiple drill location layouts. Numerous size and shape layouts are available to suit storage needs. They are also easy to set up with light equipment. That said, area limitations may restrict this option on certain locations.

Produced water

Produced water is stored in lined pits with leak detection and monitoring, permanent steel tanks with secondary containment, or portable tanks (frac tanks, steel paneled tanks, or poly walled tanks as noted above) with secondary containment, and leak detection and monitoring.

Typical Costs associated with storing produced water follow:

- Pits: $1.00/bbl volume of storage (for construction).
- Frac tanks: $35 to $60/day/500 bbl tank ($ 0.07 to $0.12/bbl/day).
- Portable tanks: $0.04 to $0.09/bbl/day.

Mob, set up, and demob costs play significant roles in the choice of storage, and in many cases dictate the storage option selected. Similarly, regional regulations and requirements also delimit storage choices for produced water. For example, lined pits are not accepted in most states for produced water storage becauseof the potential for leaks.

Waste Water Management Options: Disposal

Frac fluid may be disposed of in three ways: Class II disposal well (disposal well), the use of evaporation ponds, and recycling and/or re-use of frac flowback (this will be discussed at length in the following section). One of the ways of managing frac flowback is to inject all of the flowback into a disposal well without reusing or recycling any of it. Evaporation ponds are only an option in areas with very dry climates. Furthermore, evaporations ponds have very high end-of-life remediation costs, due to the accumulation of waste material over time. Moreover, legislation surrounding the use of evaporation ponds have been tightening in recent years.

- Without taking regional availability into account, typical Class II disposal injection costs range between $0.75/bbl and $3.00/bbl at the well.
- Since Class II disposal well costs are greatly affected by regional geology, some examples follow:
- Barnett: disposal wells are plentiful and they are at the lower end of the cost spectrum.
- Haynesville: disposal wells are plentiful in east Texas, but injections rates are limited by pressure/plugging problems. They are at the middle of the cost spectrum. That said, wells are virtually non-existent in north Louisiana.
- Marcellus: disposal wells are virtually nonexistent in PA. Some are available in Ohio and West Virginia.
- Eagle Ford: disposal wells are plentiful along the coast and in the middle of the play. Gulf coast wells are at the lower end of the cost spectrum. Inland wells (in the central part of the play) are not as prolific and they are prone to plugging/mechanical plugging, they are at the higher end of the cost spectrum.
- Bakken: disposal well numbers vary according to specific regions in the Williston basin . Some areas are fine, but others are in dire need. All available disposal wells are at the high end of the cost spectrum due to capacity issues.

Waste Water Management Options: Re-use / Recycle

Re-use Process Description

Re-use technology provides primary treatment of flowback and produced water such that it can be blended with additional source water to meet the fracturing water chemistry requirements. The level of treatment provided by the re-use technology varies depending on the flowback chemistry and the fracturing water chemistry requirements. At times, no treatment is conducted on the flowback and it is blended with additional source water for re-use. Re-use treatment can include suspended solid removal, removal of residual frac chemicals, and/or removal of other components of concern, such as scale forming cations or anions. Re-use technology can range from $1.00/bbl for basic TSS removal to over $2.00/bbl, if removal of specific scale-forming components or particle-size polishing needs to be included.

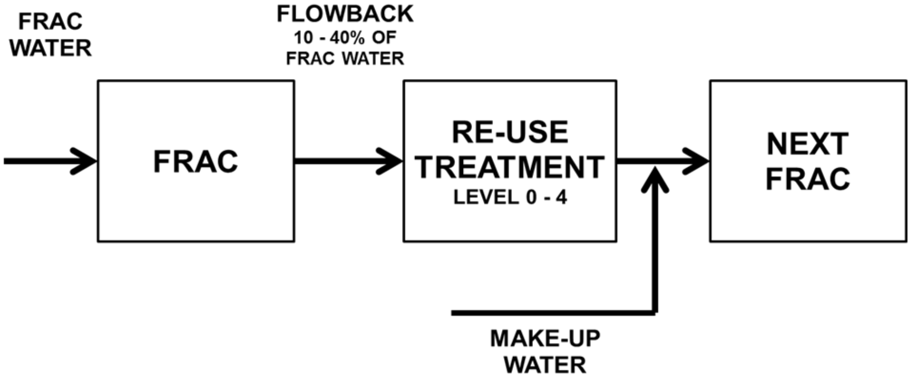


FIGURE 4.0: Overview of Re-use Strategy

In-field and/or near-source treatments reduce the need for water sourcing, storage, and transportation. Using technology that shortens the time and length of water transportation reduces both environmental impacts, as well as costs associated with water management. An example of re-use technology is Fountain Quail's ROVER Mobile Clarification System (ROVER). The ROVER system is a rugged self-contained in-field technology designed for primary treatment of shale gas flowback at, or near, the source. The system removes suspended solids and soluble organics from flowback and produced water, and returns clean brine that can be blended for re-use as frac fluid. ROVER is comprised of a low-profile clarification trailer and auxiliary support trailer. Flowback from the source (i.e., frac tank, pit) is pumped into ROVER via an adaptable location feed pump. Suspended solids and organics are then separated from the solution using an adjustable chemical system. The solids settle to the bottom where they are collected and de-watered. Clean brine is then pumped out of the system to a designated location specified by the customer (Horner et al, 2011).

FIGURE 5.0: Fountain Quail's ROVER Mobile Clarification System

Recycle Process Description

Recycling technology removes both suspended and dissolved material from the water, enabling high-quality water for re-use or discharge into the environment. Recycling wastewater to a high specification provides the best quality of water for re-use. Storage and transportation of the distilled water also negate the risk of environmental liability. It also allows the water for other industrial uses, discharge to the environment, or irrigation. Recycling facilities can take the place of disposal wells in areas where trucking distances to disposal wells are very long. The recycling facility reduces the volume of water required for disposal, which decreases water management costs, since disposal trucking and injection are charged volumetrically. Value-added products are also increasingly being developed from the concentrated brine. These products include kill fluid, salt-based drilling fluids, and commercial-grade dry salt, as demonstrated by Salt Water Solutions' LLC crystallization facility in New York. When both the distilled water and concentrate have value, there are significant environmental and cost benefits.

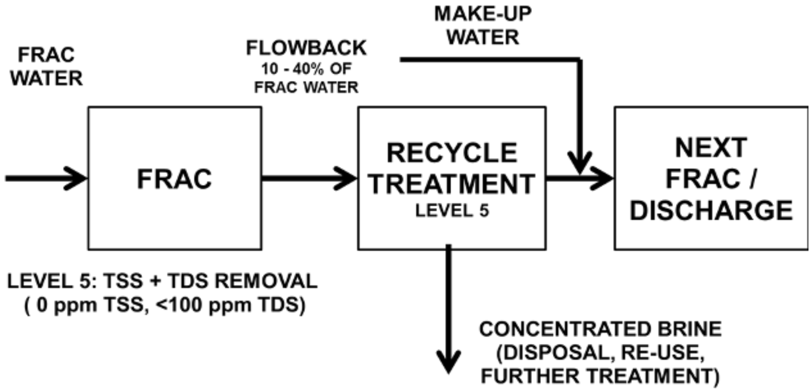


FIGURE 6.0: Overview of Recycling Strategy

A great example of shale gas water recycling technology would be Fountain Quail's NOMAD technology. NOMAD 2000 MVR Evaporator converts flowback waters with a high level of dissolved salt into distilled water (Hayes and Severin, 2012). Evaporative treatments work under the principle of condensing evaporated steam by boiling a solution in its liquid state. Unlike conventional evaporators, NOMAD 2000 MVR uses a compressor instead of a conventional heat source to input energy into the evaporation process.[3] Energy costs in hydraulic fracturing are usually about 10% of the overall operating costs; NOMAD aims to produce distilled water from waste water at the lowest energy cost possible. In order to reduce the possibility of fouling, all insoluble or sparingly soluble material, such as oil, suspended solids, or mineral compounds susceptible to forming high quantities of scale (that cannot be managed with inhibitors), must be removed prior to treatment with NOMAD (Horner et all, 2011). NOMAD is thus equipped with Aqua-Pure technology that harvests distilled evaporated steam from the evaporator end of the exchanger (Horner et al, 2011). The highly controlled vapor is then subjected to an additional localized concentration factor of less than 1.1, avoiding localized precipitation of scaling compounds (Horner et al, 2011). Aqua-Pure technology also employs a highly efficient specialized plate and frame heat exchanger. While providing a relatively high heat transfer coefficient, the plate type exchanger offers a low, fixed static head and very low pressure drop on the concentrate circulating fluid or the evaporating compartment. The heat flux can also be easily adjusted by adding more surface area or plates in a given frame. The highly effective heat transfer coefficient allows the surface temperature to be very near to both fluid stream temperatures, thus reducing the risk of fouling. There are no hot or cold spots and no dead flow zones, which subsequently reduces the risk of fouling or scaling (Horner et al, 2011).[4]

Modular recycling technology rates can vary from \$3.50/bbl to \$6.25/bbl depending on a number of factors:[5]

- Higher capacity facilities tend to have lower volumetric process rates due to the ratio of capacity to support workforce and infrastructure.
- The recovery percentage of distilled water as per feed water is a function of feed water salinity.
- The fouling potential of the feed water determines the type and cost of pretreatment required.

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[3] The high energy efficiency is achieved by utilizing the latent heat of the condensing steam as the primary energy source for boiling the wastewater. Conventional distillation requires 1,000 BTU/lb of steam, while MVR evaporation requires a theoretical 25 BTU/lb of steam produced. The energy input by the compressor for MVR evaporation is required to compensate for the difference in latent heat of vaporization between the boiling brine and condensing steam, heat losses in the pre-heat exchangers, and energy loss of the system to the environment (Horner et al, 2011).

[4] For more technical information regarding NOMAD, please see Horner, Patrick, Brent Halldorson and James Slutz's "Shale Gas Water Treatment Value Chain –A Review of Technologies, Including Case Studies."

[5] For an independent analysis of NOMAD technology, please see Hayes, Tom and Blaine F. Severin's article, "Evaluation of the Aqua Pure Mechanical Vapor Recompression System in the Treatment of Shale Gas Flowback Water: Barnett and Appalachian Shale Water Management and Reuse Technologies, Contract 08122-05."

FIGURE 7.0: Barnett Shale Recycling Facility with 2 NOMAD evaporators, with three hydraulic fracturing operations surrounding the facility.

LONG-TERM COSTS AND BENEFITS ANALYSIS

In addition to the tangible short-term costs, additional considerations – i.e., public safety, community relationships, regional regulatory concerns, environmental concerns, and long term well performance – can have significant impact on the economic outcome of shale gas developments. Instead of taking a minimizing-costs approach, this paper wishes to illustrate how a cost analysis that takes into account people, environment, assets, and production (P.E.A.P) can make win-win and viable long-term business plans. Factoring P.E.A.P into long-term cost analysis is important, and perhaps even more important than short-term increases in production and assets, because better environmental and people-focused practices build relationships that allow for long-term economic benefits that outweigh short-term gains. For example, a proactive shale gas water management system builds best-practice reputation for a producer, allowing the producer easier access to regulatory permits and more bargaining power when making land deals. This accelerates the producer's ability to expand, move in, and work. Spending more initial costs in recycling frac flowback into fresh-water quality prevents the exuberant costs associated with spill remediation. A producer that takes into account public safety and community relations by reducing truck traffic in shale gas developments may also further benefit from strong community support. This will furthermore decrease shale gas related injuries and fatalities. Taking care of the environment and people is thus not only a good thing, but also a viable long-term business plan –P.E.A.P. are not mutually exclusive. The following sub-sections tackle some of the considerations (Wilson and McCutcheon, 2003).

Public Safety

One of the most serious safety issues for industry, according to worker safety data, is vehicle accidents. According to the bureau of labor statistics, 20% of industrial fatal injuries are the result of vehicle accidents (US Department of Labor, 2012). More specifically, in the oil and gas industry, 40% of fatal occupational injuries are related to transportation events (US Department of Labor, Fact sheet, 2012). Therefore, a reduction of the total trucking miles will reduce the risk of vehicle accidents and injuries, which will be further discussed in the following section.

Community Relationships

The communities that experience unconventional gas development range from urban, rural, agricultural, to industrial. The community impacts of shale gas development in these areas include increased noise, traffic congestion, extensive infrastructure use and damage, and developmental competition for community resources.

Trucking associated with shale gas development greatly impacts communities. Shale gas development requires the movement of a large amount of equipment and materials, specifically the hauling of water. In addition, water is transported over a very short period of time, which increases the intensity of trucking activity. This is the reason why technologies, such as transfer pipelines, that substantially reduce truck traffic have a very real benefit on community relationships through the reduction of noise, traffic congestion, and road damage.

Many communities also deem water supplies (both its quantity and quality) as critical issues. Technology that reduces water demand, thus, has the long-term benefit of improving community relations and the shorter term benefit of reducing the cost of water acquisition. Water management strategies that reduce the use of water resources will be perceived as beneficial to communities. For example, in areas where water resources are constrained, communities will see these water management strategies as minimizing impact on existing water use (e.g., agriculture). In some areas, rapid water withdrawals create concerns over impact to surface and ground water quality.

Regional Environmental Regulatory Concerns

Water-related concerns are one, if not the highest, area of concern among regulatory agencies. The most important way to minimize regulatory risk is to ensure compliance with rules and regulations that govern water management. Companies need to not just follow the regulations, but also understand where regulators see best practices evolving. For instance, regional environmental authorities permit injection and other approved means of disposal for frac flowback management. Most regional environmental authorities also encourage operators to use a waste management hierarchy to manage oil and gas wastes. This hierarchy encourages operators to manage wastes in the preferred order of reduce, recycle, and then dispose. Reducing water use and recycling flowback are seen by regulators as a preferred alternative to disposal. Using best practices that exceed minimum regulatory requirements builds good will with regulators. A reputation for exceeding minimum standards also benefits perceptions in community relations as noted above.

Another benefit of new technology for water treatment is the opportunity that it offers for allowing the regulatory system to evolve to better support state regulatory goals. An example of this effect is a change made in the Commonwealth of Pennsylvania on their water handling requirements. Because of newer technology that produces distilled water from frac flowback water, Pennsylvania now allows operators to transport the recycled water without a waste designation. This makes it easier for the producer to store and transport recycled water, thus reducing costs and logistical complications.

Environmental Concerns

The primary environmental liability in water management involves surface water handling, which includes transportation and storage. Transporting and storing fresh water has a much lower risk than transporting waste water (e.g., frac flowback water). Flowback water treatment, whether limited treatment for re-use of waste water or full treatment to distilled water, can reduce environmental liability and risk.

A re-use or recycle strategy reduces the distance for water hauling and the risk of loss-of-containment incidents. Recycling on, or in the vicinity of, the well pad can provide the greatest risk reduction.

Complete recycling of the flowback water by creating distilled water with a heat-based system provides the greatest reduction of environmental liability. In a complete recycling system, fresh water is used for frac treatment. All fluid storage and water transportation in advance of the frac treatment is fresh water, so environmental liability of a spill is almost completely mitigated during this phase of the operations. If you consider that frac flowback is typically 10% to 40% of the water used, the risk of a spill causing an adverse incident is reduced to less than 30% of the water handling system.

Long-Term Well Performance

The issue of long-term well performance and frac water quality is an issue for producing companies and frac service companies to determine. Different operators have varying perspectives, as well as different operational requirements in different basins. The role of water treatment providers is to provide the water specifications requested by the operator. The technologies are available to treat flowback water for total suspended solid (TSS) or removal of both TSS and total dissolved solid (TDS). Water treatment and recycling can be effectively cost-managed to provide the most desirable water quality. Achieving the desired water quality specification and reusing/recycling frac flowback water are not mutually exclusive.

COST MODELS: TWO CASE STUDIES

The following case studies will explore the impacts of key criteria on overall water management costs. The first case study (Case A) will discuss water management costs at the Barnett shale. It will look at a play where the TDS of flowback is relatively low (average of approximately 50,000 mg/L), and with overall low disposal costs (transportation plus disposal), due to the close proximity of abundant disposal wells. The second case study (Case B) will discuss the Marcellus shale. It will examine how things change as flowback TDS increases and the availability of disposal decreases. All data used in these models are general estimates. Any and all of these numbers can change significantly with time, geography, fuel prices, level of field activity, regulations, and advances in treatment technology. The models provide a general understanding of how the various criteria impact overall economics.

Case A: The Barnett Shale

Disposal wells for frac flowback are relatively abundant in the Barnett shale. This means that transportation to disposal locations and unloading wait-times will also be low. That said, as disposal demand approaches disposal capacity, unloading wait-time can increase significantly or trucks may have to drive a longer distance to alternate disposal wells. While the Barnett shale's disposal capacity is high, high drilling density also allows for re-use and recycling facilities to be located at, or near, a large number of fracs without the need for frequent relocation. This also helps to maintain utilization of the re-use or recycling facilities: the higher the facility is utilized, the lower the overall volumetric treatment cost becomes (they have an inverse relationship). Based on this case study, a re-use strategy could reduce overall water management costs by 30%, and reduce total trucking miles by 69%.

The frac flowback re-use strategy provides the greatest impact on trucking, which affects public safety, traffic, road infrastructure damage, and vehicle emissions. A recycling strategy would increase overall water management costs by 76%, but reduce trucking miles by 48%. The recycling strategy does not reduce overall costs due to the abundant availability of disposal wells. That said, recycling does help to reduce environmental liability by reducing the need for transportation and storage of salt water, as well as reducing the associated risks of either truck-spill or loss of pipe or storage containment.

Recycling becomes increasingly favorable from an economic perspective when the average distance and/or unloading times at disposal wells increase. Recycling also becomes favorable if the logistics warrant the use of high–capacity, centralized facilities that bring down the overall volumetric treatment costs. If the concentrated brine from recycling facilities can be used as a secondary product, such as kill fluid or salt based drilling fluid, the economics become increasingly favorable due to the reduction of transportation and disposal costs associated with the concentrated brine. In the event that the concentrated brine can be converted into a marketable product, it would transform the waste product from a liability to an asset.

Case B: The Marcellus Shale

Disposal wells in the Marcellus are nonexistent due to the regional geology. This means that wastewaters must be transported for long distances to out-of-state disposal wells. This significantly increases the cost of disposal due to high transportation costs associated with long trucking routes. A re-use strategy would reduce overall water management costs by an estimated 89%, and reduce total trucking miles by 93%. Note that a re-use strategy is dependent on the producer's ability to re-use high percentages of the treated flowback.

A recycling strategy would reduce overall water management costs by 41% and reduce total trucking miles by 53%. As in Case A, recycling becomes increasing favorable if concentrated brine can be used as valuable secondary products, instead of needing to be trucked for disposal. Regions, such as the Marcellus, where disposal costs are very high, warrant the evaluation of crystallization technology (not part of evaluation for this article) that provides greater than 95% of the flowback as fresh water, which also enables greater options for the re-use of the associated salt products.

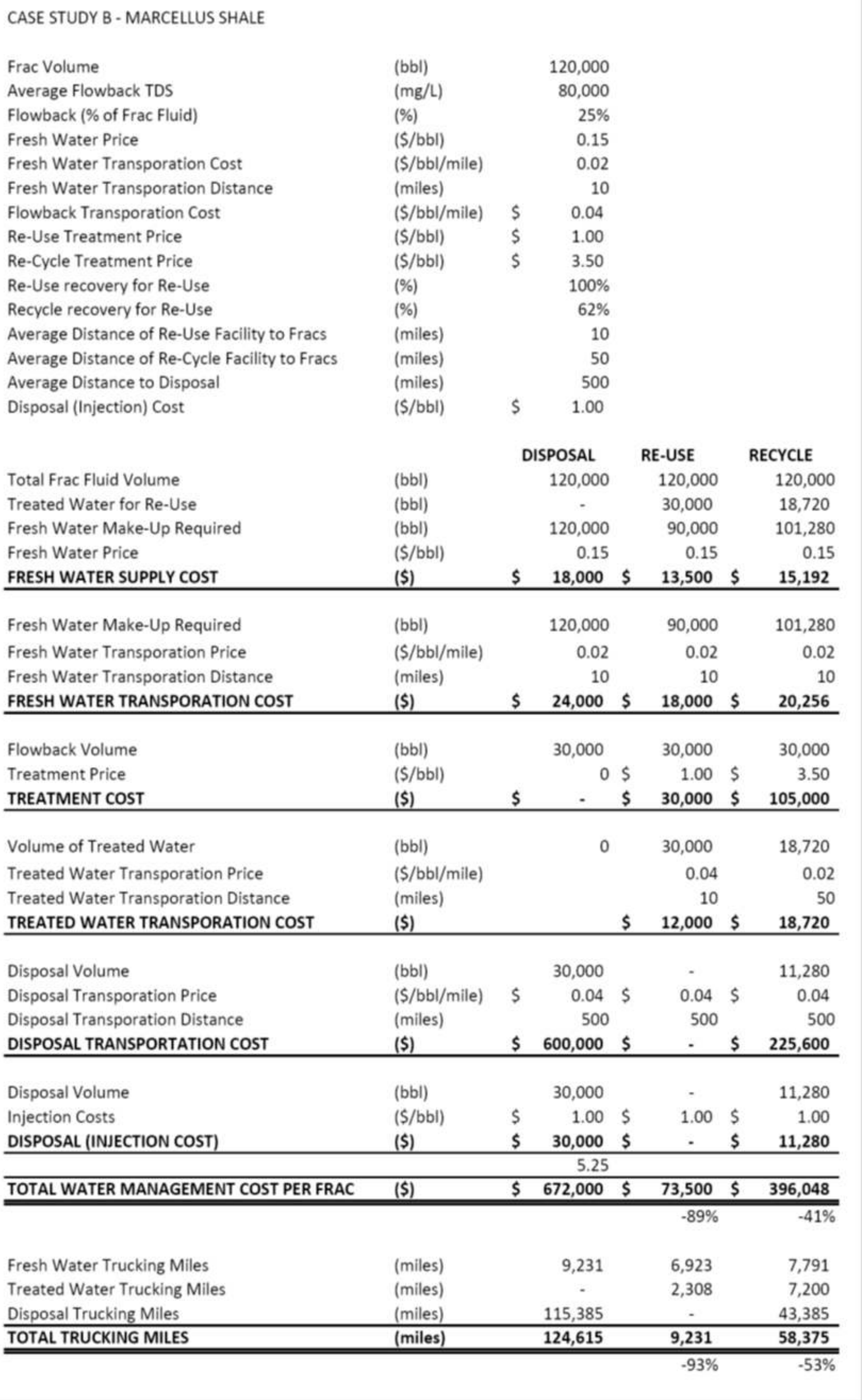
In an area like the Marcellus, re-use strategies are favorable when hydraulic fracturing programs are both continuous and close in proximity. This enables the transportation of the treated flowback to travel only short distances for immediate re-use. As hydraulic fracturing programs become staggered in both time and distance, the attractiveness of recycling strategies increase, since distilled water from recycling facilities can be discharged into the environment or easily stored, if not needed right away.

CASE STUDY A - BARNETT SHALE

		INPUT VARIABLES
Frac Volume	(bbl)	100,000
Average Flowback TDS	(mg/L)	49,500
Flowback (% of Frac Fluid)	(%)	40%
Fresh Water Price	($/bbl)	0.25
Fresh Water Transporation Cost	($/bbl/mile)	0.02
Fresh Water Transporation Distance	(miles)	15
Flowback Transporation Cost	($/bbl/mile)	$ 0.02
Re-Use Treatment Price	($/bbl)	$ 1.25
Re-Cycle Treatment Price	($/bbl)	$ 4.00
Re-Use recovery for Re-Use	(%)	100%
Recycle recovery for Re-Use	(%)	77%
Average Distance of Re-Use Facility to Fracs	(miles)	5
Average Distance of Re-Cycle Facility to Fracs	(miles)	10
Average Distance to Disposal	(miles)	50
Disposal (Injection) Cost	($/bbl)	$ 0.75

		DISPOSAL	**RE-USE**	**RECYCLE**
Total Frac Fluid Volume	(bbl)	100,000	100,000	100,000
Treated Water for Re-Use	(bbl)	-	40,000	30,694
Fresh Water Make-Up Required	(bbl)	100,000	60,000	69,306
Fresh Water Price	($/bbl)	0.25	0.25	0.25
FRESH WATER SUPPLY COST	**($)**	**$ 25,000**	**$ 15,000**	**$ 17,327**
Fresh Water Make-Up Required	(bbl)	100,000	60,000	69,306
Fresh Water Transporation Price	($/bbl/mile)	0.02	0.02	0.02
Fresh Water Transporation Distance	(miles)	15	15	15
FRESH WATER TRANSPORATION COST	**($)**	**$ 30,000**	**$ 18,000**	**$ 20,792**
Flowback Volume	(bbl)	40,000	40,000	40,000
Treatment Price	($/bbl)	0	$ 1.25	$ 4.00
TREATMENT COST	**($)**	**$ -**	**$ 50,000**	**$ 160,000**
Volume of Treated Water	(bbl)	0	40,000	30,694
Treated Water Transporation Price	($/bbl/mile)		0.02	0.02
Treated Water Transporation Distance	(miles)		5	10
TREATED WATER TRANSPORATION COST	**($)**		**$ 4,000**	**$ 6,139**
Disposal Volume	(bbl)	40,000	-	9,306
Disposal Transporation Price	($/bbl/mile)	$ 0.02	$ 0.02	$ 0.02
Disposal Transporation Distance	(miles)	50	50	50
DISPOSAL TRANSPORTATION COST	**($)**	**$ 40,000**	**$ -**	**$ 9,306**
Disposal Volume	(bbl)	40,000	-	9,306
Injection Costs	($/bbl)	$ 0.75	$ 0.75	$ 0.75
DISPOSAL (INJECTION COST)	**($)**	**$ 30,000**	**$ -**	**$ 6,980**
TOTAL WATER MANAGEMENT COST PER FRAC	**($)**	**$ 125,000**	**$ 87,000**	**$ 220,543**
			-30%	76%
Fresh Water Trucking Miles	(miles)	11,538	6,923	7,997
Treated Water Trucking Miles	(miles)	-	1,538	2,361
Disposal Trucking Miles	(miles)	15,385	-	3,579
TOTAL TRUCKING MILES	**(miles)**	**26,923**	**8,462**	**13,937**
			-69%	-48%

FIGURE 8.0: Cost breakdowns at the Barnett shale



CASE STUDY B - MARCELLUS SHALE

Frac Volume	(bbl)	120,000
Average Flowback TDS	(mg/L)	80,000
Flowback (% of Frac Fluid)	(%)	25%
Fresh Water Price	($/bbl)	0.15
Fresh Water Transporation Cost	($/bbl/mile)	0.02
Fresh Water Transporation Distance	(miles)	10
Flowback Transporation Cost	($/bbl/mile)	$ 0.04
Re-Use Treatment Price	($/bbl)	$ 1.00
Re-Cycle Treatment Price	($/bbl)	$ 3.50
Re-Use recovery for Re-Use	(%)	100%
Recycle recovery for Re-Use	(%)	62%
Average Distance of Re-Use Facility to Fracs	(miles)	10
Average Distance of Re-Cycle Facility to Fracs	(miles)	50
Average Distance to Disposal	(miles)	500
Disposal (Injection) Cost	($/bbl)	$ 1.00

		DISPOSAL	RE-USE	RECYCLE
Total Frac Fluid Volume	(bbl)	120,000	120,000	120,000
Treated Water for Re-Use	(bbl)	-	30,000	18,720
Fresh Water Make-Up Required	(bbl)	120,000	90,000	101,280
Fresh Water Price	($/bbl)	0.15	0.15	0.15
FRESH WATER SUPPLY COST	**($)**	**$ 18,000**	**$ 13,500**	**$ 15,192**
Fresh Water Make-Up Required	(bbl)	120,000	90,000	101,280
Fresh Water Transporation Price	($/bbl/mile)	0.02	0.02	0.02
Fresh Water Transporation Distance	(miles)	10	10	10
FRESH WATER TRANSPORATION COST	**($)**	**$ 24,000**	**$ 18,000**	**$ 20,256**
Flowback Volume	(bbl)	30,000	30,000	30,000
Treatment Price	($/bbl)	0	$ 1.00	$ 3.50
TREATMENT COST	**($)**	**$ -**	**$ 30,000**	**$ 105,000**
Volume of Treated Water	(bbl)	0	30,000	18,720
Treated Water Transporation Price	($/bbl/mile)		0.04	0.02
Treated Water Transporation Distance	(miles)		10	50
TREATED WATER TRANSPORATION COST	**($)**		**$ 12,000**	**$ 18,720**
Disposal Volume	(bbl)	30,000	-	11,280
Disposal Transporation Price	($/bbl/mile)	$ 0.04	$ 0.04	$ 0.04
Disposal Transporation Distance	(miles)	500	500	500
DISPOSAL TRANSPORTATION COST	**($)**	**$ 600,000**	**$ -**	**$ 225,600**
Disposal Volume	(bbl)	30,000	-	11,280
Injection Costs	($/bbl)	$ 1.00	$ 1.00	$ 1.00
DISPOSAL (INJECTION COST)	**($)**	**$ 30,000**	**$ -**	**$ 11,280**
		5.25		
TOTAL WATER MANAGEMENT COST PER FRAC	**($)**	**$ 672,000**	**$ 73,500**	**$ 396,048**
			-89%	-41%
Fresh Water Trucking Miles	(miles)	9,231	6,923	7,791
Treated Water Trucking Miles	(miles)	-	2,308	7,200
Disposal Trucking Miles	(miles)	115,385	-	43,385
TOTAL TRUCKING MILES	**(miles)**	**124,615**	**9,231**	**58,375**
			-93%	-53%

FIGURE 9.0: Cost breakdowns at the Marcellus shale

CONCLUSION

Due to the vast differences amongst the shale plays – drilling and completion strategy, flowback water chemistry, availability of disposal, availability of source water, regional regulations, level of activity, and existing infrastructure – no single water management strategy will be dominant. A combination of disposal, re-use, and recycle strategies would likely be used by a producer throughout the development of a shale play.

Disposal strategies often make the most sense in early development of a play when the level of infrastructure is low and the hydraulic fracturing programs are not continuous or localized in close proximity. However, disposal strategies create the highest level of truck traffic and the highest demand for fresh water. The highest economic impacts on disposal strategies are the availability of disposal wells and overall costs of disposal (transportation plus injection costs). Increases in fuel prices and tightening of regulations regarding disposal via injection can also have significant negative impacts on the costs of disposal. Disposal will also become less favorable as the level of field activity increases and the volumes of flowback begin to exceed the capacity for injection. Disposal wells are, however, favorable when disposal wells are closer in proximity than the re-use/recycling facilities.

Re-use strategies offer the greatest opportunity to reduce overall water management costs and total trucking miles. Cost reductions can range from 30% to 80%, and reductions in total trucking miles can range from 20% to 90%. Effective re-use strategies rely on continuous hydraulic fracturing schedules and the infrastructure to properly transport treated flowback from frac to frac. Re-use strategies can eliminate the need for disposal via injection entirely, provided that hydraulic fracturing schedules and infrastructure are adequately developed. This is especially true when the re-use facilities are tied into a number of sites through either pipeline or well-established road infrastructure. The greatest impacts on volumetric re-use costs are the overall size of the re-use facility and its utilization. Large facilities (in excess of 10,000 bbl/day with > 90% utilization) can cost less than $1.00/bbl. Smaller facilities (< 10,000 bbl/day with <75% utilization, or sophisticated effluent specifications), can cost in excess of $1.75/bbl.

Recycling strategies are most applicable when overall disposal costs are high and a re-use strategy is not effective due to lags in the hydraulic fracturing schedule, re-use facility's proximity to the sites, or lack of necessary infrastructure. Recycling technology can be a feasible option when it is difficult to continuously re-use treated flowback, or when the total volume of produced water in a region exceeds the capacity for disposal. As with re-use technology, the costs of recycling technology are impacted by the size of the facility and its utilization. Small facilities (2000 bbl/day with <80% utilization) can cost upwards to $6.50/bbl treated. Larger facilities (>10,000 bbl/day with >80% utilization) can cost around $3.50/bbl of flowback treated.

Most plays will likely adopt a combination of disposal, re-use, and recycling strategies throughout the various stages of development. The economic evaluation of a shale gas water management strategy has to take both short-term and long-term considerations into account. Short-term considerations include total costs of water supply, transportation, disposal, and treatment. Long-term considerations include overall environmental liability, public relations, impact to the community, and adaptability to changes in regional regulations. Cost-benefit analysis that takes into account people, environment, assets, and production (P.E.A.P) can make win-win and viable long-term water management and business plans for operators. An effective water management strategy has the potential to reduce overall costs and to enable shale gas development by addressing community concerns, and adapting to the specific regulatory and geographical considerations.

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