MAKING WAVES: WATER RECYCLING INVESTMENT

Stakeholders face increasing complexity when considering investment in wastewater recycling operations.

ARTICLE BY KELLY JONES and CHRIS BRICKEY

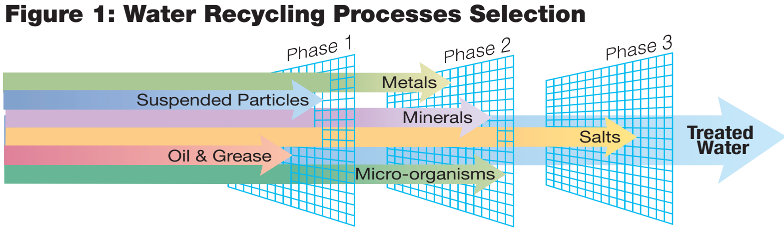
Hydraulic fracturing has been a boon to oil and gas production, transforming the U.S. energy landscape in just a few years. Yet the relatively large amount of water consumed and produced in these operations competes with growing populations for receding freshwater supplies and disposal options. Recycling of wastewater, both produced waters and flowback, can ease these pressures and reduce costs. In fact, some operators have aggressive plans to double and even triple the amount of wastewater they recycle in this year alone. But investing in such operations presents critical trade-offs for well operators and water-recycling service providers.

Opportunities lie in ensuring the economic feasibility of the more advanced stages of water recycling, specifically removal of total dissolved solids (TDS), commonly referred to as "salts." Stakeholders are at a crossroads: Can TDS be eliminated at a reasonable cost through technological innovation, or will operators accept higher TDS levels in fracturing fluid?

Ever-evolving technological improvements in TDS removal present uncertainty and opportunity. Investment decisions hinge on the upfront and operational costs of recycling wastewater and the market for the resulting products—both of which are evolving—in addition to local transportation costs and regional regulations.

Wastewater recycling processes fall into three major phases from which selections are made based on a number of site-specific variables.

Figure 1: Water Recycling Processes Selection



Phase 1	Phase 2	Phase 3
Remove Suspended Particles Flocculation, Micro/Sand filtration, Settling ponds, Sock/cartridge filtration	Deactivate Micro-organisms Chlorine disinfection, Chemical bactericides, UV radiation	Remove Salts Reverse osmosis, Evaporation, Forward osmosis, Membrane distillation
Remove Oil & Grease Walnut shell filtration, Acidification, Flotation	Remove Minerals & Metals Chemical precipitation, Nanofiltration, Ion exchange	
Multi-Phase Treatments		
Electrocoagulation, Chemical oxidation, Ultrafiltration, Ozonation		

Note: This is not a comprehensive list of wastewater components or treatment processes, but it provides a sense of how processes can be selected and combined to achieve a desired level of purification depending on the input and other variables.
Source: Wilson Perumal & Company, Inc.

Tailoring recycling processes

Recycling wastewater from hydraulic fracturing typically involves a tailored series of processes, chosen based on the contents of the wastewater (the input) and the desired purity of the treated water (the output). The extent to which the water is processed and the choice of technology used in each processing step significantly impact upfront costs and energy consumption per barrel processed.

Investment in water-recycling technology becomes more attractive when the availability of freshwater sources and disposal options decline. Growth in demand for recycling has spurred the development of more energy efficient, less expensive technologies. The resulting landscape is shifting with a myriad of equipment and process choices. Stakeholders facing this challenge should consider whether today's investment in equipment will be eclipsed by emergent technology.

Water recycling for hydraulic fracturing operations can be divided into three phases, illustrated in Figure 1. Phase 1 involves the removal of suspended particles, oil and grease. Deactivation of micro-organisms and removal of multivalent minerals and metals typically occurs subsequently, in Phase 2. If desalinated water is desired, Phase 3 entails the removal of salts, which are typically measured in milligrams per liter (mg/l) or parts per million (ppm) of TDS. While there have been recent developments in methods for the first two phases, it is in the third phase (TDS removal) that stakeholders find themselves bombarded by innovation, challenge, risk and opportunity.

Affordable pretreatment processes

Phases 1 and 2 of inland water recycling (removal of contaminants such as suspended solids, oil and grease, scaling minerals, metals and micro-organisms) are mandatory for most repurposing of fracturing wastewater and are often referred to as "pretreatment" when followed by TDS removal. Phases 1 and 2 include fairly established, proven processes with individual operating costs much less than $1 per barrel of water processed. Multiple technology and design options exist, from which recyclers

There are many official and unofficial terms used to indicate the TDS content of water.

Table 1: Water Categories (mg/l of TDS)	
Drinking water:	<500
Freshwater	<1,000
Brackish water	1,000–15,000
Seawater	~35,000
Brine	>30,000

Produced waters range from 1,000 to 400,000 mg/l.

Source: Wilson Perumal & Co. Inc.

and operators select elements based on the contents of input and the desired output. There have been recent developments to improve efficiency in phases 1 and 2, but these are typically adaptations to or combinations of existing processes.

Together, a selection of pretreatment processes from Phases 1 and 2 can affordably purify wastewater to a relatively clean standard, but the resulting product may have a very high TDS content. At this juncture, the level of TDS in the treated water depends heavily on the wastewater's original TDS content, which varies greatly across plays and over the life of a single well. Table 1 displays commonly used terms and TDS content of different categories of water.

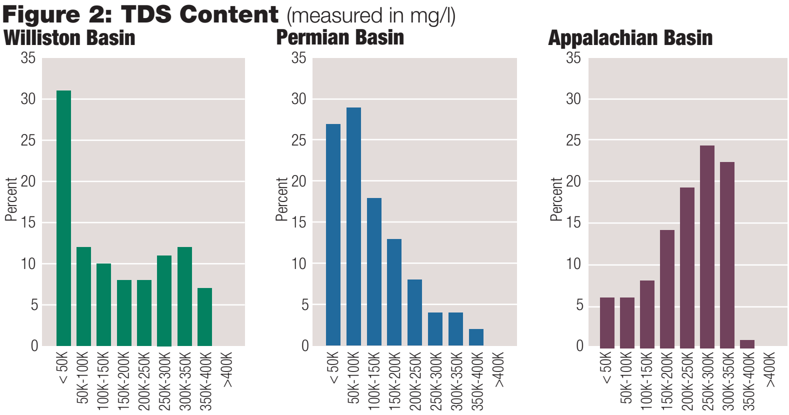
Produced water can vary from 1,000 to 400,000 mg/l TDS, according to a U.S. Geological Survey by the Department of the Interior. For example, the samples obtained in the Permian Basin contained an average of approximately 106,000 mg/l TDS though 45 samples registered with >350,000 mg/l TDS. Figure 2 illustrates the large variation in TDS content of produced waters even within the same geographic region. Thus, using Phase 1 and 2 processes exclusively often precludes the reuse of the treated water for drilling.

Rapid technological evolution

Phase 3 processes remove TDS from pretreated wastewater. This is challenging, because the TDS molecules separate into monovalent ions, dissolving into the water even at very high concentrations. Some of the technologies in Phase 3 can only process wastewater with less than 70,000 mg/l TDS; others can treat water with virtually no limit in TDS content.

The TDS content of produced waters varies greatly across plays and over the life of a well.

Figure 2: TDS Content (measured in mg/l)



Source: U.S. Dept. of Interior, U.S. Geological Survey, 2002

Processes in this last phase require significant upfront investments in equipment to remove TDS to a level appropriate for reuse in drilling. TDS removal is more energy-intensive than phase 1 and 2 processes, making these final processing stages much more expensive per barrel. We're unaware of any widely used TDS removal technologies that can purify average or high-salinity wastewater down to 500 mg/l TDS for less than $2 per barrel. Significant TDS removal currently costs more.

Recyclers use Phase 3 technologies in addition (not as an alternative) to pretreatment processes from Phases 1 and 2 because using TDS removal technology to perform the pretreatment is too costly or not possible. It would be prohibitively expensive, if not technically unfeasible, to place wastewater directly into an evaporator and boil off pure water from all of the contaminants.

Fortunately, rising demand for recycled water with low TDS levels is motivating companies to innovate more efficient Phase 3 processes. To make sense of the rapidly evolving landscape, TDS removal technologies for inland oil and gas water recycling applications can be segmented into three categories: established, adaptive and emergent technologies. Table 2 highlights differences among some well-known Phase 3 technologies.

Established TDS removal technology. Reverse osmosis (RO) and evaporation are established technologies that have been used to desalinate water for decades. RO filters TDS from pretreated wastewater by physically forcing the fluid across a membrane. It is generally less costly than evaporation, because it is less energy-intensive at the lower end of the TDS spectrum; however, RO is associated with membrane maintenance and replacement costs. RO is also limited by the wastewater's TDS level. If the wastewater contains greater than 70,000 mg/l TDS, some suggest an even lower limit, it cannot be run across the RO membrane without substantial dilution.

On the other hand, evaporators are almost unlimited in terms of the TDS concentration that they can handle. One of the most efficient types of evaporation for this kind of application is mechanical vapor recompression (MVR). MVR compresses the pure water vapor to provide additional heat to the boiling liquid. Boiling water still consumes a lot of energy, even when the water is pre-treated and condensed vapors utilized.

Depending on the input, evaporators can yield over 50% purified water (per barrel of wastewater processed) so clean that it has less TDS content than freshwater. Byproducts include condensed liquid brine that can be used to cap saltwater disposal wells. Crystallizers are used as an optional, subsequent step to produce commodity salts from the brine.

Adaptive TDS removal technology. Innovators and manufacturers are adapting RO and MVR to increase efficiency. For instance, VSEP (vibratory shear enhanced process) increases the effectiveness of RO by vibrating the membrane to deter scaling. In an effort to reduce the energy consumption of evaporation, at least one company has commercialized a solution that couples evaporation with nanofiltration, and there are other efforts to adapt evaporators for mobile solutions. These adaptations show promise, but may soon be eclipsed by emergent technologies.

Emergent TDS removal technology. Forward osmosis (FO) is a promising emerging candidate for the removal of TDS from wastewater. FO separates pure water from the pretreated wastewater using a membrane and the osmotic pressure differential to drive the separation (rather than the physical force used in RO). FO likely requires more pretreatment than evaporation due to membrane sensitivity, but it should recoup that cost in relative energy savings. Membrane distillation, another emergent technology, vaporizes the pretreated wastewater at a membrane over which only pure water vapor passes. Both of these newer technologies are expected to require less membrane maintenance than RO and handle wastewater with higher TDS levels.

The emergent technologies in Phase 3 are also expected to consume less energy per barrel than both RO and evaporation, in part because they have been developed to correspond with lower grade energy sources, such as natural gas and solar energy. Evaporators for inland applications were originally designed to run on grid electricity. Inefficiencies (i.e. costs) arise in converting them for use with lower grades of energy.

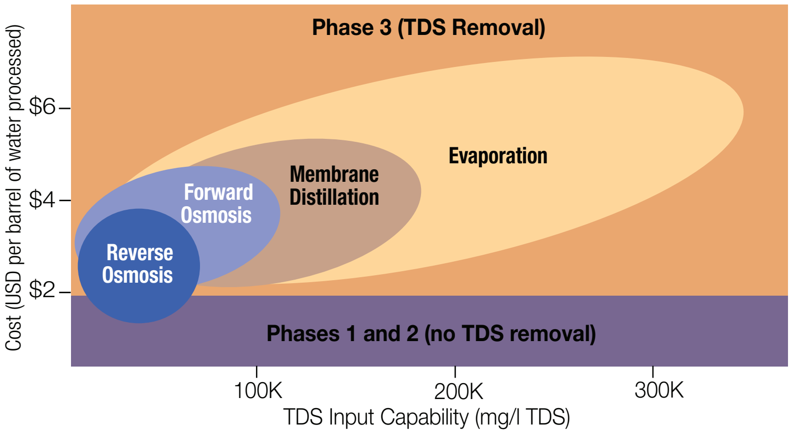
Although many of the emergent technologies have undergone substantial testing in real-world inland hydraulic fracturing scenarios, they have only recently been commercialized for broad use; therefore, the cost estimates associated with emergent technologies are theoretical. Stakeholders and investors in water-recycling operations must weigh the guarantees of established and adaptive technologies against the quick pace in development of more cost-effective options for TDS removal.

Demand trends

The economics of investing in water-recycling solutions depend heavily on local demand for the quality of treated water. Almost all water has some level of TDS, and it's an important specification when selecting water for drilling. The appetite of operators for drilling with freshwater, rather than with treated desalinated water or brackish water, is in flux and difficult to determine in many regions until a specific site for a water-recycling facility is chosen. Key variables impacting this demand include availability of freshwater, restrictions on waste disposal, fracturing fluid specifications and risk tolerance.

Primary and secondary research confirmed a large range in the types of water that operators use for drilling as well as uncertainty in how these preferences will change in the near term. Wastewater that has been treated extensively with all three phases (pretreatment and desalination) can be even cleaner than a drinking water standard (<500 mg/l TDS). Yet the economics in many areas do not currently support the cost-intensive processing required to purify wastewater to this level.

Figure 3: Costs And Technology



Note: These are generalized estimates. Costs and capabilities vary due to many factors including the content of input wastewater, the desired output, the facility setup, and local costs of supplies and transportation.
Source: Wilson Perumal & Co. Inc.

Operational costs and TDS removal capabilities of Phase 3 technologies vary based on many factors.

The preference for freshwater in drilling is driven strongly by the availability of freshwater and wastewater disposal at relatively low prices. Even when recycled water can be used at a cost savings relative to trucking or drilling down for fresh or brackish water, indications are that some operators may not switch to recycled water. Large operators may be more likely than smaller operators to embrace drilling with recycled water or water with higher TDS levels, since they possess the financial reserves required to fund this experimentation and are also more concerned about their reputations as environmental stewards. For minor operators, affordability of recycling solutions is the primary concern.

"Brackish water," ranging from 1,000 to 15,000 mg/l TDS, can also be used for drilling. The Bureau of Economic Geology in Texas noted the use of brackish water, despite uncertain risks, due to its availability near the surface. Again, the availability of freshwater and disposal options plays into differences in demand. There is also some delineation in demand based on the fracturing fluid composition. Operators will tolerate or require different levels of TDS in the water they use for drilling depending on the desired viscosity and density of the fracturing fluid. For example, operators using gels (highly viscous fracturing fluid pumped at relatively low rates) will have different needs than those using slickwater (less viscous and pumped at higher rates).

There is no one-size-fits-all formula, and a recycled solution may not accommodate the specific needs of operators. The drilling demand for freshwater and different types of treated water varies even among operators in

The landscape of TDS removal technology is evolving rapidly.

Table 2: Removal Technology Trends

	Established ← TDS Removal Technologies			→ Emergent
	Reverse Osmosis	Evaporation	Forward osmosis	Membrane Distillation
What is it?	Physically pushes fluid against a membrane over which pure water passes	Boils pure water off as vapor and re-condenses it	Uses osmotic pressure differential to separate pure water at a membrane	Vaporizes fluid at a membrane over which pure water vapor passes
TDS Removal Capabilities*	• Input limitation: < 70K mg/l TDS • Output potential: > 500 mg/l TDS, depending on input	• Input limitation: N/A • Output potential: < 100 mg/l TDS	• Input limitation: < 125K mg/l TDS • Output potential: > 300 mg/l TDS, depending on input	• Input limitation: < 200K mg/l TDS • Output potential: < 100 mg/l TDS
Energy Consumption	Low relative to evaporation	Generally uses high-grade energy sources (i.e. grid electricity)	Can use low-grade energy sources (i.e. geothermal and solar)	Can use low-grade energy sources (i.e. geothermal and solar)
New Developments	Adaptation: Vibration of the membrane to reduce fouling	Adaptation: Coupling evaporation with nano filtration	Commercialization	Commercialization

*TDS removal capabilities are generalized estimates that vary due to many factors, including the content of input wastewater, the desired output, and the facility setup. Source: Wilson Perumal & Co. Inc.

the same geographic area. This creates challenges for stakeholders when selecting recycling equipment according to projected demand of the treated product.

Transportation and regional regulation

Transportation costs and local regulations also significantly impact the economics of water recycling for hydraulic fracturing, and can vary significantly by geographic location.

Transport costs can tip the economic feasibility of recycling ventures and have resulted in the proliferation of mobile or customized solutions located at the well. Many of the technologies discussed earlier have been adapted to modular components to eliminate the cost of transporting fluid to and from a recycling site. The mobile water-recycling market is highly fragmented for investors, but it's generally feasible for operators to procure small, temporary water-recycling operations for individual sites.

The processing technology chosen for mobile solutions can also be optimized based on the quality of the wastewater and specifications of drilling water at the site. On the other hand, mobile solutions are less able to adapt to the substantial changes in the quantity of wastewater. They are also limited in capacity and may not efficiently scale to accommodate the surges of water produced and consumed daily at a single site.

Centralized water-recycling facilities can mitigate changes in the quality and quantity of wastewater by pooling the batches of water received from multiple sites. The increased throughput also supports investment in more robust operations that can handle variation in specifications from multiple customers and generate more products for reuse. Energy-intensive evaporators are more commonly—if not almost exclusively—used in the design of permanent water-recycling facilities. Oil skimming and crystallization operations are also more likely in a centralized solution.

Although stand-alone wastewater recycling facilities don't eliminate transport costs, they do avoid disruption to the existing trucking infrastructure. Trucking costs can be mitigated by utilizing water lines, but the risk of leaks must be considered.

In addition to transportation issues, stakeholders must evaluate regulations in their particular locale. Certain jurisdictions may limit the use of freshwater, mandate waste-disposal methods, and require recycling solutions regardless of the cost. It's difficult to predict the fate of individual legislative initiatives or recommendations from government agencies, but, as a whole, regulations are likely to place ever growing pressure on freshwater supplies and disposal options as water is viewed increasingly as a critical, at-risk resource.

Weighing options

Stakeholders face increasing complexity when considering investment in wastewater recycling operations. Although innovation in "pretreatment" cleaning processes can help offset costs, the primary challenges lie in balancing the cost-efficiency of TDS ("salt") removal technology with evolving demand for different types of treated water.

Major operators with larger volumes, more substantial resources and significant reputational upside will likely shape the future. Local water and regulatory conditions will also play a strong role in recycling growth. One thing is undeniable: Stakeholders must consider the multitude of factors in tandem if they are to navigate the changing landscape and take advantage of upcoming opportunities.

Kelly Jones is managing partner of Wilson Perumal Capital, a private investment firm. Chris Brickey is a consultant at Wilson Perumal & Co., an international consulting firm helping oil and gas companies navigate challenges in strategy, operations, and managing complexity. They can be reached at kjones@wilsonperumal.com and cbrickey@wilsonperumal.com.