RPSEA

Feasibility Assessment of Early Flowback Water Recovery for Reuse in Subsequent Well Completions

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Feasibility Assessment of Early Shale Gas Flowback Water Recovery for Reuse in Subsequent Well Completions

Abstract

Fresh water is critical for natural gas production in the Barnett Shale, where in excess of 3 to 5 million gallons are required for the completion of each gas well. The financial costs, logistical challenges and public relations concerns over the use of fresh water supplies thus impel Barnett gas producers to use less fresh water and to use it more efficiently. The objectives of this work were to develop a simple, empirical modeling approach for characterizing and forecasting flowback water rates and total dissolved solids (TDS) and to use such models to characterize the efficacy of flowback water recycling based on predefined TDS reuse criteria.

Approximately one third of the fracwater used for a typical Barnett Shale well is recovered from the initiation of blowback until the time that the well produces salable volumes of natural gas. Flowback water production could be efficiently described and modeled using either an exponential or hyperbolic equation; (these are commonly used in forecasting petroleum and natural gas production). Both models were found to be particularly sensitive to the initial flowback rate, which unfortunately tends to be rather erratic during the first few days of flowback production. It is suggested, therefore, that the “initial” value used not necessarily be that of the first day of flowback, but may be averaged among the first three to five days or otherwise adjusted so that the resulting flowback rate and production curves follow a reasonable course.

Flowback chloride and TDS concentrations were efficiently described by a power function of cumulative flowback. The rate of change in flowback TDS concentration reflects the sum effect of exponential (or hyperbolic) decline in flowback rate and the increasing TDS concentration as flowback waters accumulate. Initially TDS rises rapidly because of high flowback rates and rising TDS concentrations. However, although TDS concentrations

continue to rise, the precipitous drop in flowback caused TDS accumulation to slow and its rate of change to then begin to drop. The net result is that TDS concentrations begin to level off more or less in parallel with flowback accumulation.

In analyzing flowback water production volumes and TDS concentration using these models for a hypothetical location, it was found that at the field scale that a substantial portion of recovered flowback could be recycled for subsequent well completions across a wide range of TDS reuse thresholds. This finding stems from the observations that: 1.) only a portion (roughly a third) of the fracwater used to complete a well is typically recovered as flowback during the first several weeks following well completion, and 2.) The volume –weighted TDS concentration is low enough so that the recovered flowback can be diluted for effective reuse. Thus, the substantial recovery of a useful fraction of flowback water for reuse is technically feasible and logistically achievable.

The primary benefits of recycling flowback water include a potentially substantial reduction in the volume of freshwater needed to complete future wells as well as a concomitant reduction in the volume of wastewater that must otherwise be disposed.

Introduction

The Barnett Shale of the Fort Worth Basin is presently the largest producing natural gas field in Texas and the second largest in the United States. The field covers 20+ counties in North Texas, including the Fort Worth metropolitan area. As of May, 2011 there were more than 15,000 wells in the field producing nearly 5.9 billion cubic feet (BCF) per day or roughly 10% of U.S. natural gas production (TXRRC, 2011; US EIA 2011). The Barnett Shale has produced more than 10 trillion cubic feet (TCF) of natural gas thus far with peak gas production likely to occur over an extended period of time due to increasingly efficient well drilling and completion technologies (TXRRC, 2011; Powell, 2011). The Barnett Shale is a major economic driver on the state and local levels generating billions of dollars a year in economic output, including expenditures for development activities, salaries, state and local taxes, lease bonus and royalty payments and related economic benefits.

Fresh water is critical for natural gas production in the Barnett Shale where in excess of 3 to 5 million gallons of “fracwater” are required for the completion of each gas well. The financial costs, logistical challenges and public relations concerns over the use of fresh water supplies impel Barnett gas producers to use fresh water efficiently. Approximately 90+% of the fresh water used in Barnett gas well completion is for the fracturing of the producing shale formation, to liberate natural gas so that it can be produced and sold. Approximately a third of the fracwater used to complete a new well is returned as “flowback”, at least some of which could potentially be recycled for use in subsequent well completions. If the amount of fresh water necessary for completing new wells can be reduced, the total fresh water demand required to develop the Barnett Shale will also be reduced. . The recycling of this “flow back” water for the completion of subsequent gas wells may ultimately provide a means to substantially decrease fresh water demands of gas operators, to reduce the volume of spent flowback that needs to be disposed and to concomitantly reduce the cost of drilling and completing new wells.

Objectives and Scope

The objectives of this work were:

1. To develop a simple, empirical modeling approach for characterizing and forecasting flowback rates and volumes.
2. To characterize the relationship between flowback water recovery and total dissolved solids (TDS) concentration and from this develop a simple, empirical modeling approach for charactering and forecasting flowback TDS.
3. To develop a simple, empirical modeling approach for characterizing and estimating the efficacy of flowback water recycling based on pre-defined TDS reuse criteria.

The scope of this project encompassed an evaluation of flowback data from eleven producing wells believed to be generally representative of the Barnett Shale of Texas. This work may also be found to be more or less representative of other shale gas plays in North America.

Methods

Flowback water measurements and samples were taken from eleven producing natural gas wells in the Barnett Shale, made available by companies participating in the study. Flowback quantity data were measured in the field by gauging the daily accumulation of water in flowback tanks. Flowback quality parameters that were measured in the field included: chloride concentration (using a field site glass refractometer) and specific gravity (using a field hydrometer).

Water samples that were collected from each location were analyzed in a commercial laboratory for total dissolved solids (TDS), chlorides and specific conductance.

Results and Discussion

The sections to follow describe the characteristics of the flowback water with time following a hydraulic fracturing event in terms of volumes collected and salinity, factors that weigh most heavily on the logistics and economics of water management. Also described is the use of the flow and salt composition information base to develop models that describe the mass of water and salt that emerge from a completed well over the weeks following a frac job event. The model is then used to estimate the benefits and assess the general feasibility of early flowback water capture to provide a water stream that can be reused with minimal or no processing required for demineralization. Capture of early flowback water can be accomplished with an automated system consisting of in-line water flow and conductance measurements, real time data acquisition and analysis, and computer control of solenoid valves that allow the diversion of flowback water to separate storage for moderate and high concentration brines. A design concept for an automated system that captures early flowback water of low-moderate salt content separated from flowback and produced waters of high total dissolved solids is presented and discussed in a companion report submitted to RPSEA (Galusky, L.P. 2011. Report 08122-06). This report builds on the previous report and presents an engineering analysis of actual field data to assess the feasibility of early flowback water capture.

Flowback Rates and Volumes

A substantial fraction (25 to 40+ %) of the 100+ thousand bbls of water ("fracwater") that is used to create secondary porosity and to thus stimulate shale gas production returns to the surface under pressure during the first several weeks after well completion as "flowback" water. The rate of flowback is typically very high (greater than 1,000 bbls/d) during the first few days but drops off exponentially to very low levels (less than 100 +/- bbls/d) after several days. Flowback was measured at eleven locations in the Barnett Shale to determine general flowback trends and patterns and to determine if exponential and/or hyperbolic equations could be used to model flowback rate and cumulative production.

It was found that Barnett Shale flowback water generation follows a generally exponential (and in some cases, hyperbolic) pattern as shown for the average values of flowback from eleven sites (Figure 1). In this graph the average daily values of flowback rates and cumulative volumes are given along with exponential and hyperbolic curves whose parameters were adjusted to provide the best fit to the data. Given in Figure 2 are daily flowback rates and cumulative volumes as estimated by the hyperbolic function on which are overlaid the standard deviations (of the variation between sites) computed from the eleven locations. Graphs showing measured flowback rates and accumulation for each of the eleven sites are given in Appendix A, along with a compilation of the respective best-fit model parameters used for each location (Table A-1).

Both equations do a good job of fitting to the data and can thus presumably be used for projecting flowback rates and volumes provided that accurate values are used for their respective input parameters. Exponential and hyperbolic equations and their respective input parameters are given below:

Exponential Functions

This equation estimates daily flowback production (bbls/d):

$q = q_i e^{-Dt}$

This equation estimates cumulative daily flowback production (bbls):

$V = (q_i - q) / D$

Where:

q = daily flowback rate (bbls/d)
qi = initial flowback rate (bbls/d)
D = exponential decline exponent (day^{-1})
t = flowback day
V = cumulative flowback volume (bbls)

Hyperbolic Functions

This equation estimates daily flowback production (bbls/d).

q = q(1+bDit)-(1/b)

This equation estimates cumulative daily flowback production (bbls):

$V = (q_i b/(D(1-b)))*(q_i^{(1-b)} - q^{(1-b)})$

Where (these parameters being the same as for the exponential function):

q = daily flowback rate (bbls/d)

q_i = initial flowback rate (bbls/d)

D = exponential decline exponent (day^{-1})

t = flowback day

V = cumulative flowback volume (bbls)

And (this parameter being unique to the hyperbolic functions):

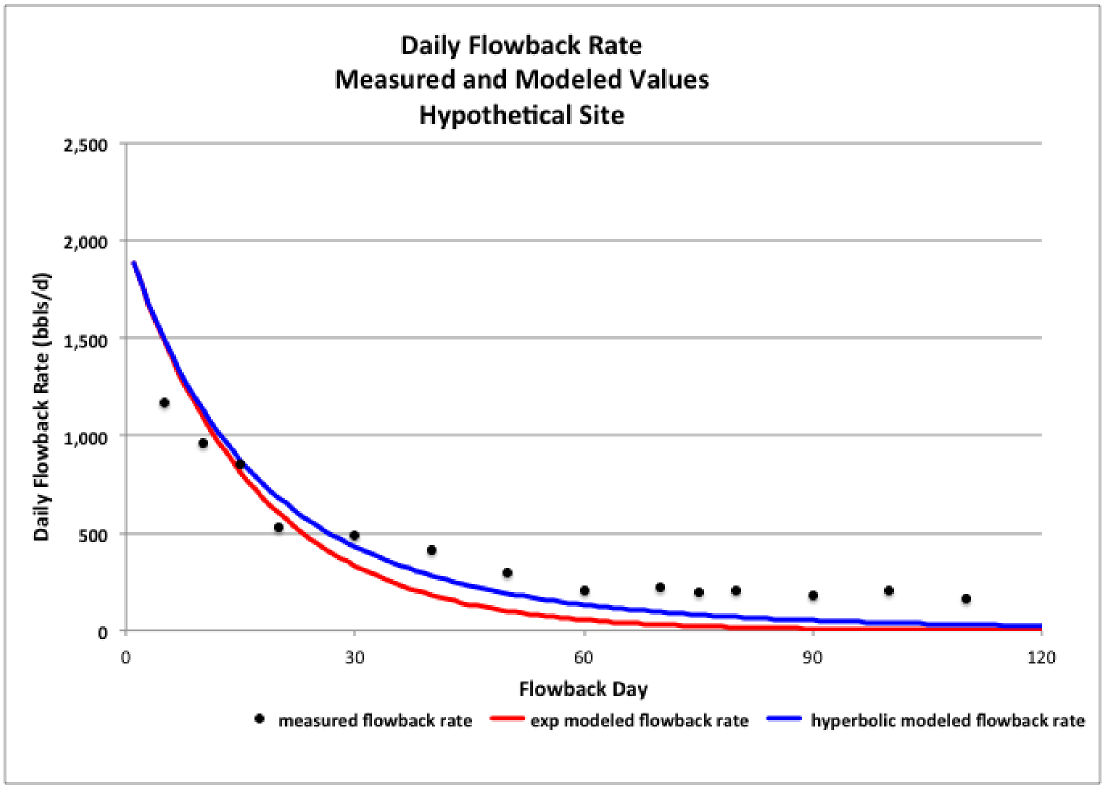
b = hyperbolic function exponent (fraction <= 1)

The potential advantage of the hyperbolic equation is that it allows for an increasingly more gradual rate of flowback decline over time, and this model appears to be a better fit for many of the Barnett Shale analyzed sites in this study.

It is easy enough to fit one of these equations to accumulated data once the general pattern is apparent. It is another matter to use them to forecast future flowback when the input parameters are unknown but must be estimated. However, as with using mathematical models for projecting any unknown future quantity, parameter values can be estimated using surrogate data from representative locations and adjusted early on by modifying their values based on real-time flowback performance.

In this regard it should be noted that both models are particularly sensitive to the initial flowback rate, q_i, and unfortunately the initial flowback rates during the first few days are highly erratic. It is suggested, therefore, that the "initial" value that is used represent an average of the first three to five days or otherwise adjusted so that the resulting flowback rate and production curves follow a reasonable course.

In reviewing the graphs for the eleven individual sites in the Appendix it is noteworthy that for many sites flowback was interrupted for one or more extended periods. Such seemingly random interruptions pose obvious difficulties in using predictive models. Nevertheless, if the purpose of modeling flowback is primarily to assist in the better management of these waters then it becomes a matter of operational judgment as to whether it is better to predict high or low. The overestimation of flowback will ensure that enough operational infrastructure and capacity are available, but this needs to be balanced against the financial cost of doing this. Extensive practice with using mathematical models to predict flowback behavior in a given area will enable engineers to use them wisely. There is no substitute for such experience nor can any mathematical model or software product compensate for its lack.



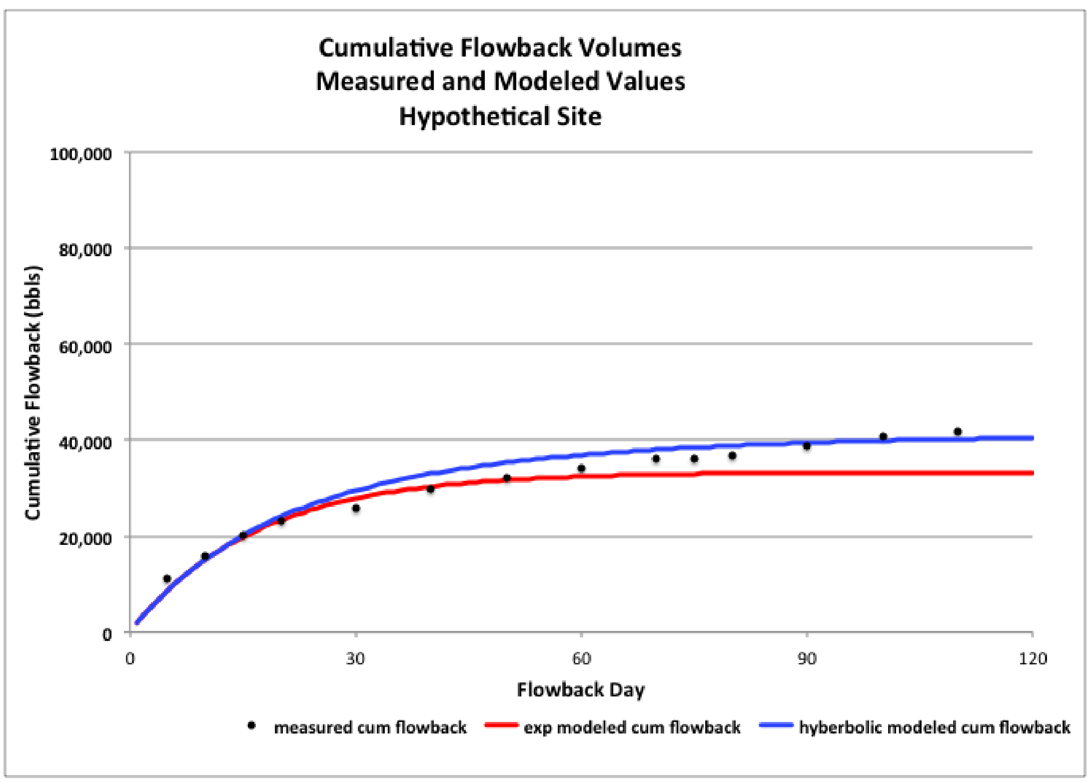
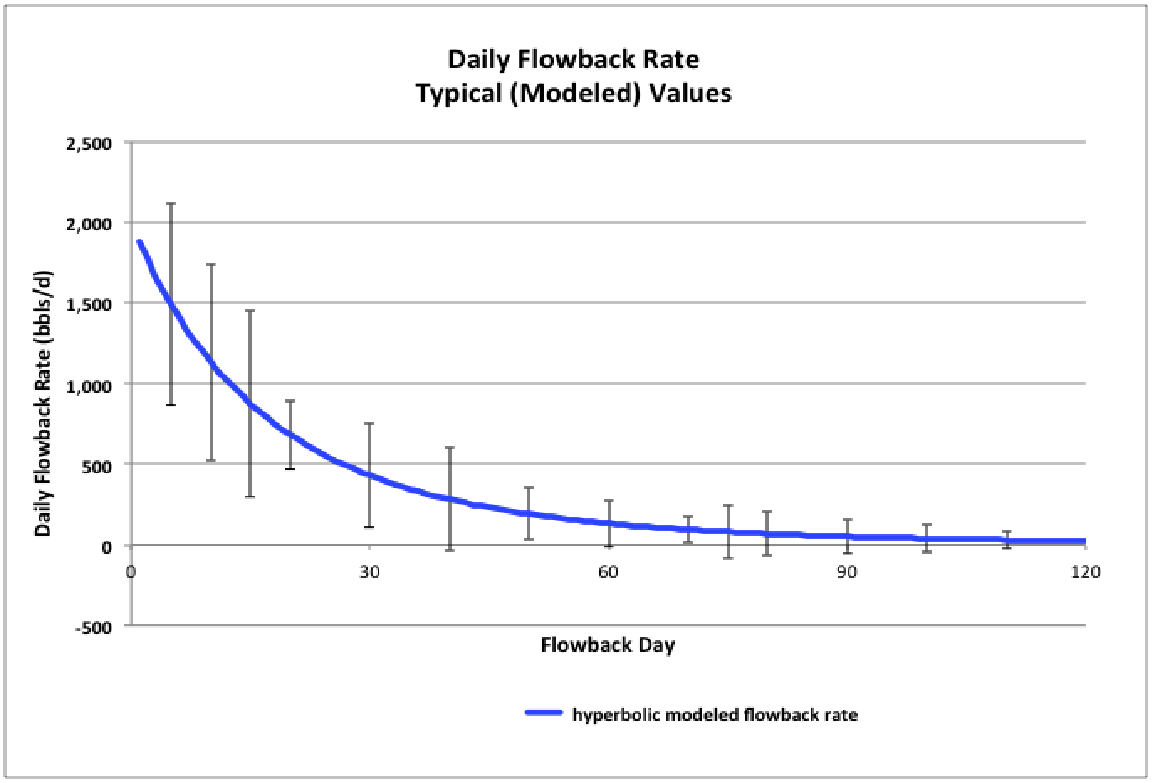


Figure 1: 1a (above) and 1b (below) – Daily flowback rates (Figure 1a) and accumulated daily volumes (Figure 1b) averaged among eleven Barnett Shale locations (black dots) and modeled using exponential (red lines) and hyperbolic (blue lines) functions.



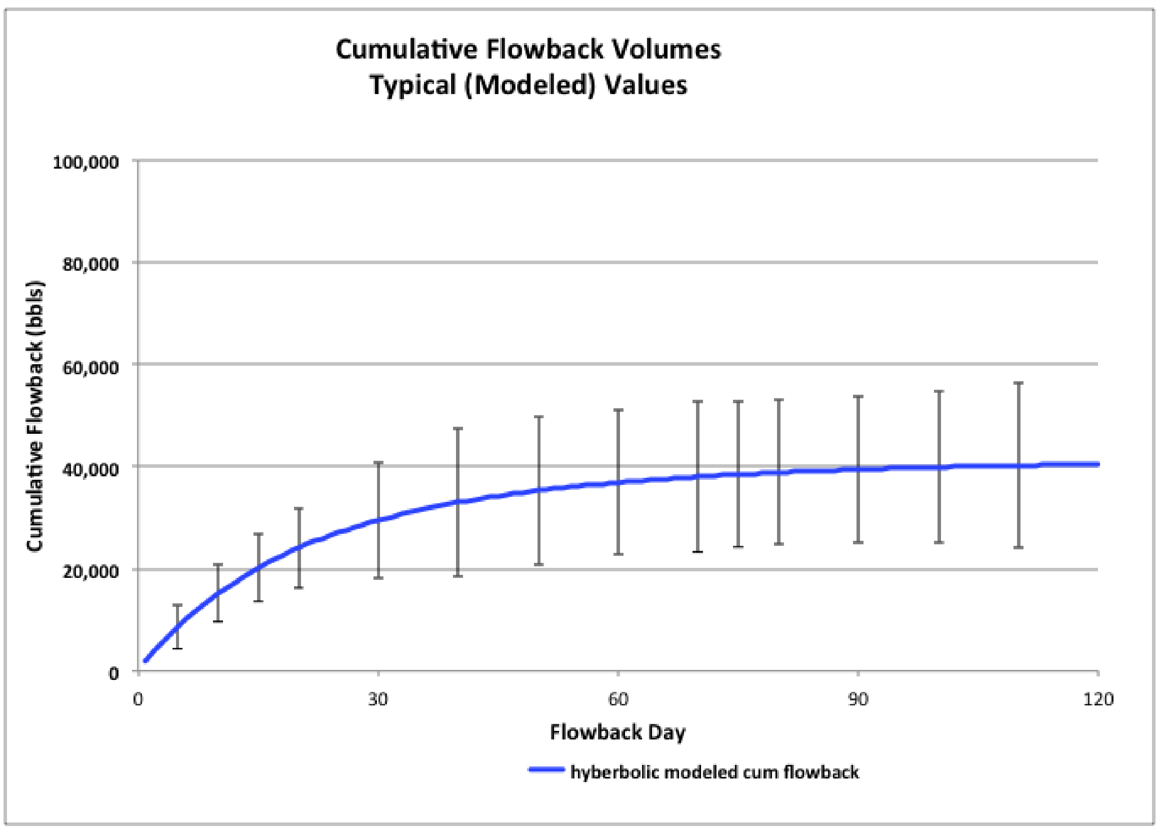


Figure 2: (above) and 2b (below) – Modeled flowback rates (Figure 1a) and accumulated volumes (Figure 1b) estimated for eleven averaged Barnett Shale locations. Error bars indicate the magnitudes of +/- one standard deviations among the eleven locations.

Flowback Chlorides and Total Dissolved Solids

Chlorides and total dissolved solids (TDS) are two parameters that alone or together provide a simple indication of the ionic strength of shale flowback waters. As flowback water is recovered both parameters generally increase from relatively negligible concentrations in fresh influent frac water to levels commonly found in oil field brines. This is illustrated in Figure 3, where the chloride concentrations of frac water are averaged among six sites in the study area. The relationships between flowback chloride concentrations versus cumulative percent of flowback recovery are shown for individual sites in Appendix B.

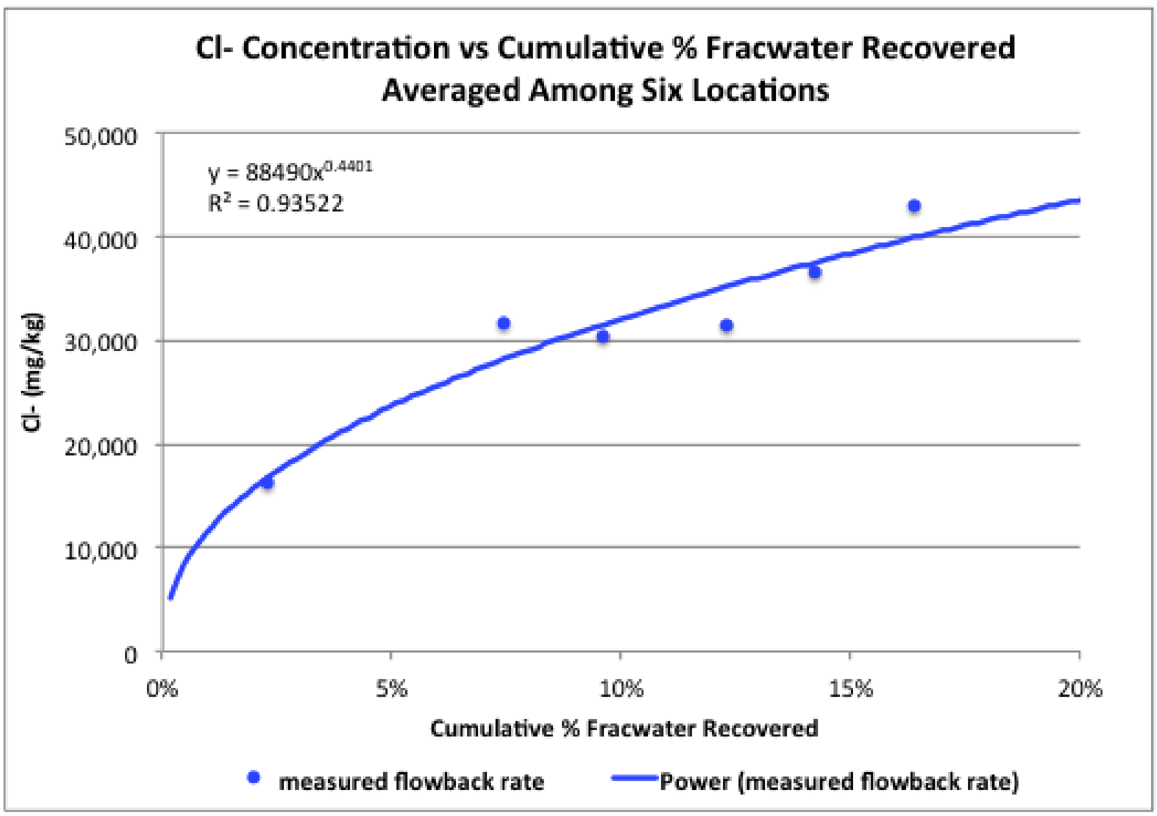


Figure 3: Flowback chloride concentration versus cumulative fraction of frac water recovered, averaged among six locations in the Barnett Shale.

It is not immediately straightforward to directly measure TDS concentrations in the field. However, chlorides and electrical conductivity, both of which can be accurately and reliably measured in the field using simple instruments, provided excellent surrogate measures for TDS as shown by their excellent linear relationships with TDS (Figure 4 and Figure 5).

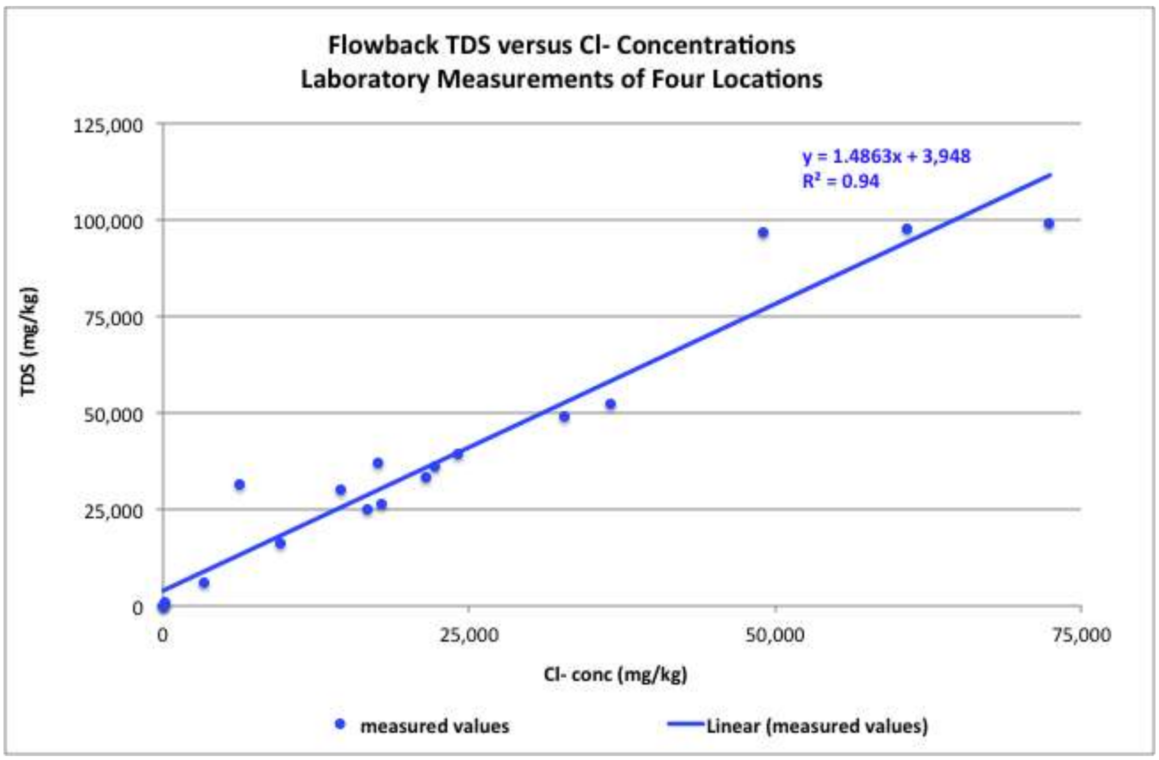


Figure 4: TDS versus chloride from four Shale Barnett locations.

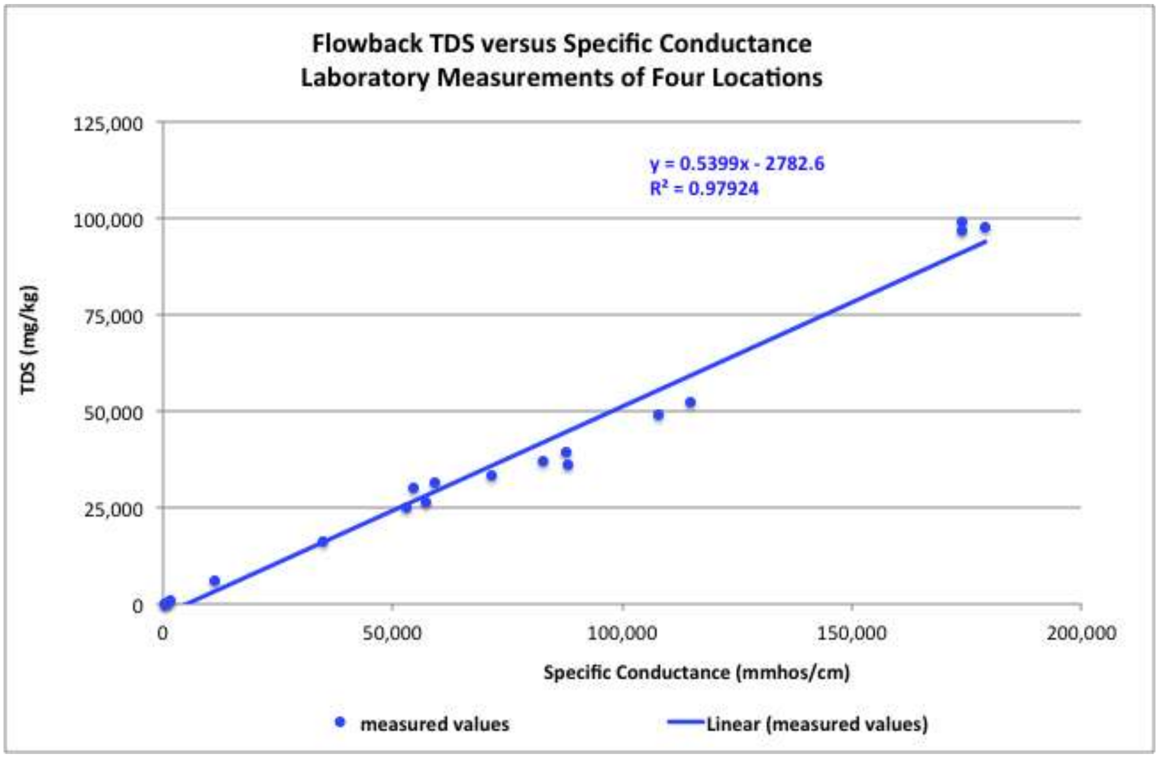


Figure 5: TDS versus specific (electrical) conductance from four Shale Barnett locations.

Flowback chloride concentrations and electrical conductivity can both be readily measured in the field using a hand-held optical refractometer or an electronic chloride probe (the latter being similar in size and operation to a pH meter). Electrical conductance can be similarly measured using a hand-held instrument.

TDS concentrations rise asymptotically as flowback rate declines exponentially (Figure 6). In contrast, the rate of accumulation of TDS mass initially rises rapidly because of high flowback rates and rising TDS concentrations but then declines due to the drop-off in flowback (Figure 7).

Taken together these analyses indicate that the opportunity for identifying and segregating relatively low TDS flowback waters is limited to the first few days in the flowback process.

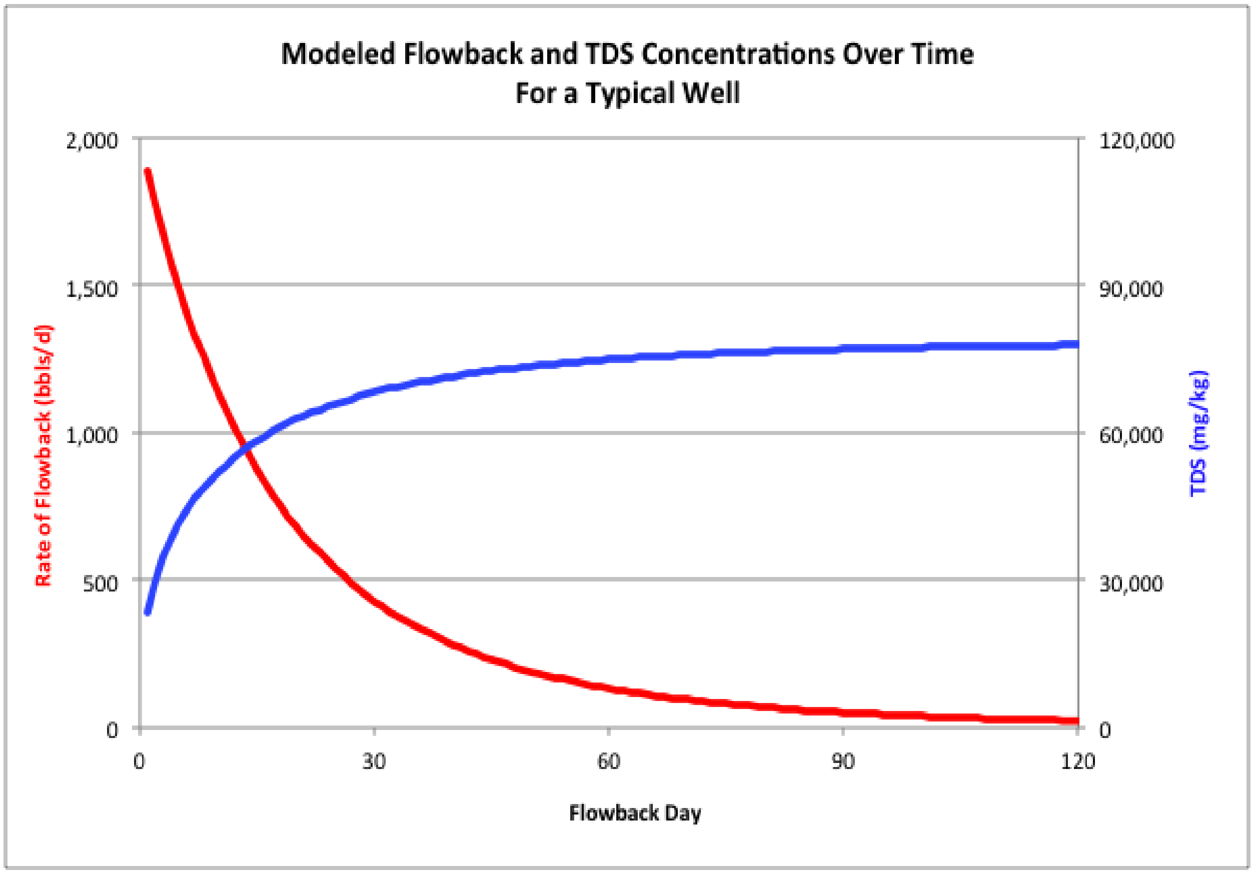


Figure 6: TDS concentrations shown with the drop in flowback rate, calculated for a typical well by modeling flowback rate using hyperbolic decline with parameters averaged among eleven Barnett locations.

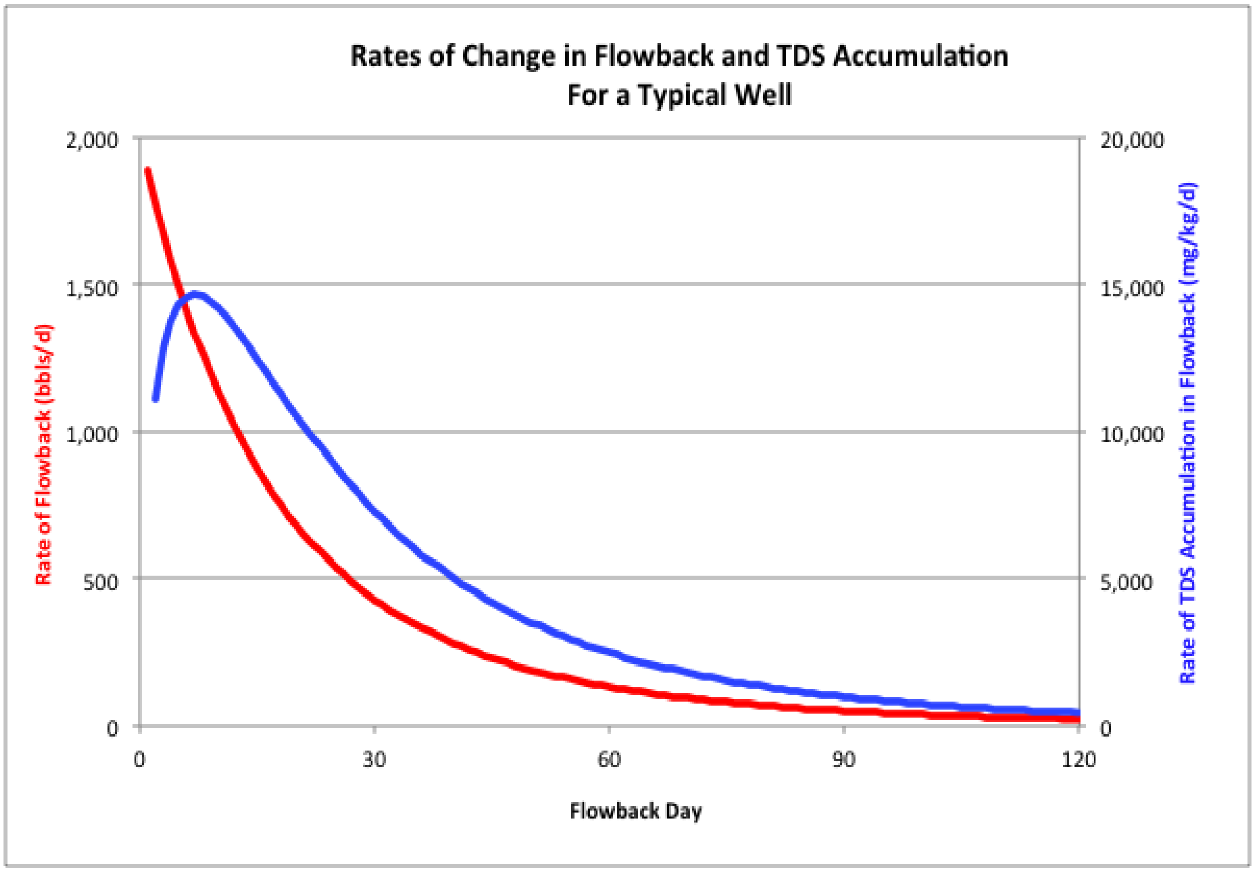


Figure 7: The rate of change in TDS accumulation shown with the drop in flowback rate, calculated for a typical well by modeling flowback rate using hyperbolic decline with parameters averaged among eleven Barnett locations.

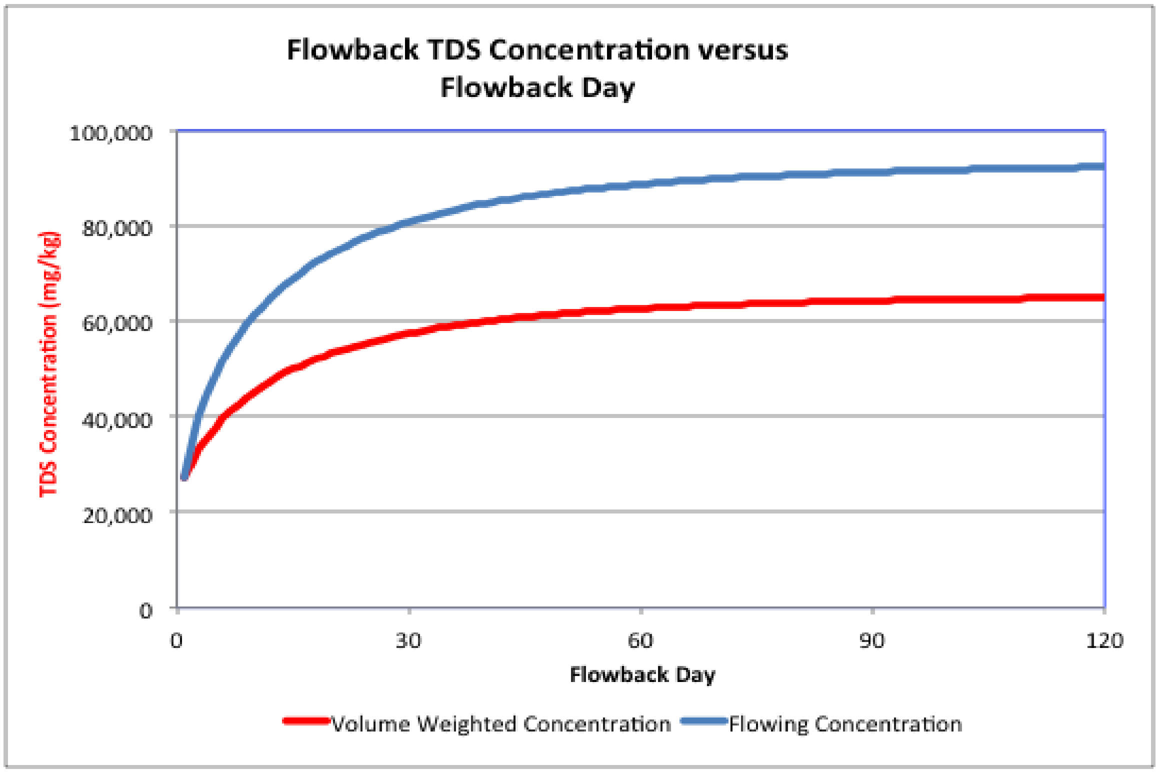
Observed Relationships in Flowback Water Quality versus Flowback Quantity

On first consideration it would seem that the present practice of disposing flowback waters from Barnett Shale wells is simply wasteful, that these waters could be collected and readily recycled for use in subsequent frac jobs. There are, however, substantial concerns, which have made completion engineers reluctant to reuse frac water in the Barnett Shale. TDS increases the downhole friction of the frac water with the target formation causing a substantial increase in the compressive horsepower required to push the frac water into the shale rock. There are also concerns over scale formation in the well bore and shale rock as well as other potential geochemical incompatibilities in high TDS waters with the producing formation. The safe handling and transport of large volumes of these highly saline waters from site to site poses additional risks and logistical challenges of its own.

Nevertheless, and although the use of freshwater for well drilling and completion represents a relatively small fraction of the available supply (Galusky, 2007 & 2009), Barnett operators are concerned about optimizing the use of this valuable resource and in reducing costs wherever possible. Since the costs of acquiring, storing and disposing of frac water and flowback water are considerable there is a clear economic incentive for operators to consider the reuse of flowback water for subsequent frac jobs wherever this is logistically and economically feasible. In this regard it is relevant to mention that most of the frac water in the Marcellus shale play is now recycled (Rassenfoss, 2011).

Approximately one third of the frac water used for a typical Barnett Shale well is recovered from the initiation of flowback until the time that the well produces salable volumes of natural gas, typically an interval of several weeks. After this point, any further flowback that occurs is comingled with produced formation water (particularly if the underlying water bearing rock is penetrated during the frac job) such that the ultimate volume of water that is recovered may approach or even be greater than that used to originally frac the well. In any case, the maximum potential for reducing freshwater use to complete new wells will not exceed the quantity of water produced by the wells that have previously been completed.

In order to consider and to plan for the potential reuse of flowback waters it is necessary to understand the relationships between flowback water quality (which will be considered here simply as TDS concentration) and flowback rates and cumulative volumes. It was found that flowback chloride concentration was a power function of cumulative flowback (Figure 3) and that TDS was linearly related to chloride concentration (Figure 4). Thus the relationship between TDS and flowback may also be described by a power function similar to that of chlorides versus flowback (Figure 8 a & b and Figure 9).



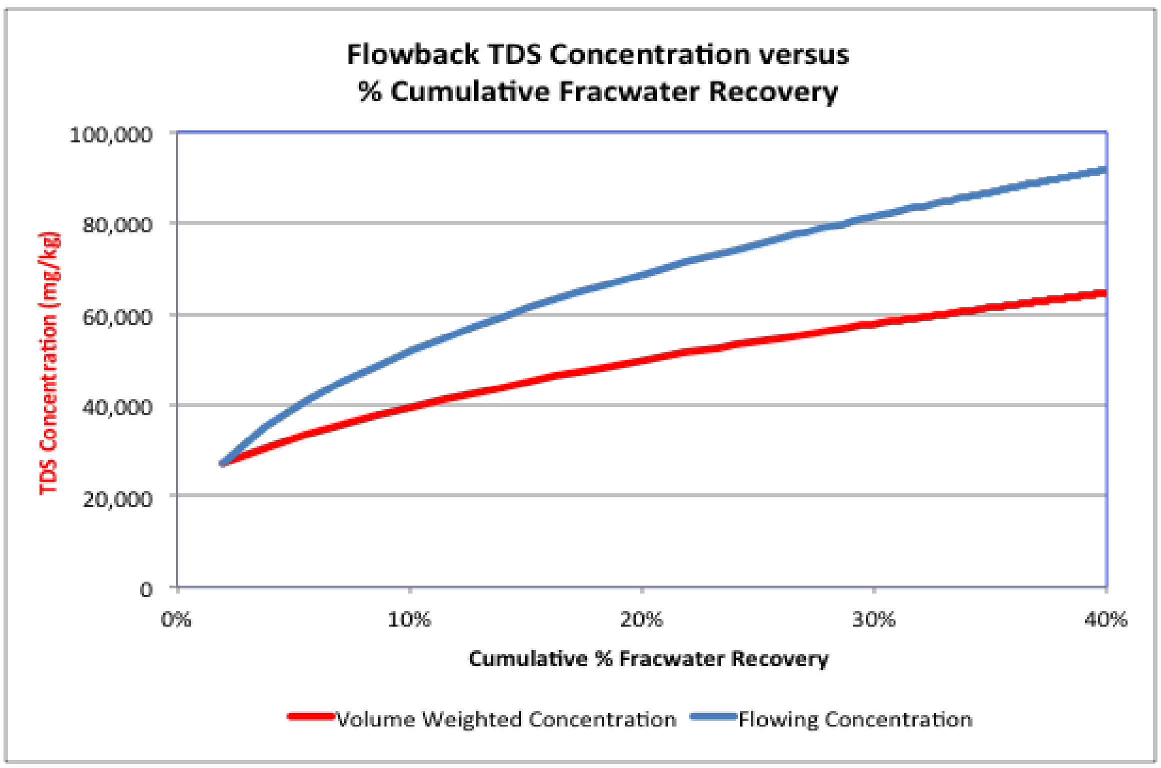


Figure 8: 8a & 8b– Flowback TDS concentrations (projected based on the average pattern observed from six locations) versus flowback day (8a, above) and cumulative percent frac water recovery (8b, below).

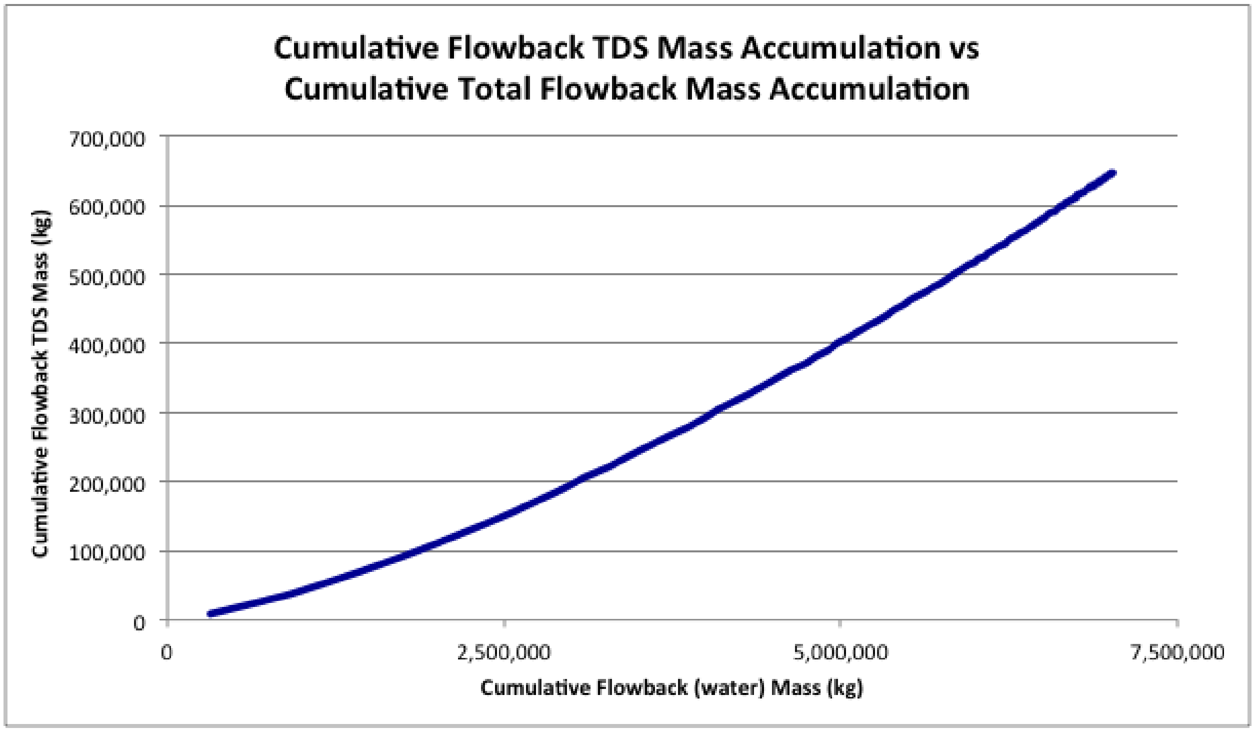


Figure 9: Cumulative mass of recovered TDS (in flowback) versus cumulative flowback water mass.

Water sampled from the flowback pipe has a higher TDS than the (calculated) cumulative volume (Figure 8 a & b). This is because TDS from the pipe was always rising even as flowback rates were falling over time (Figure 6). In reality, flowback is typically not mixed in a single reservoir but is collected in a series of frac tanks. This potentially provides a convenient basis for segregating flowback according to TDS for reuse in subsequent frac jobs, which will be discussed subsequently.

TDS mass accumulates more quickly, and at an accelerating pace, compared to the mass of recovered flowback (Figure 9). This simply reflects the increasing concentration of flowback TDS as the rate of flowback recovery decreases over time.

It should be noted that flowback waters become saline early on, exceeding 20,000 mg/l TDS during the first day.

Optimizing Flowback Water Segregation for Potential Reuse

Although all flowback waters could potentially be reused if they were diluted to the requisite water quality criteria, of immediate interest is the fraction of flowback that could be reused directly without dilution or other pre-treatment. It stands to reason that the more lenient the water quality requirements are the greater the proportion of flowback that could be reused directly. This is illustrated in Figure 10, where TDS is used as the measure of acceptable limits for flowback water reuse. Summarized briefly, if completions engineers can accommodate the use of high TDS flowback then most (potentially all) of it can be directly reused for subsequent well completions.

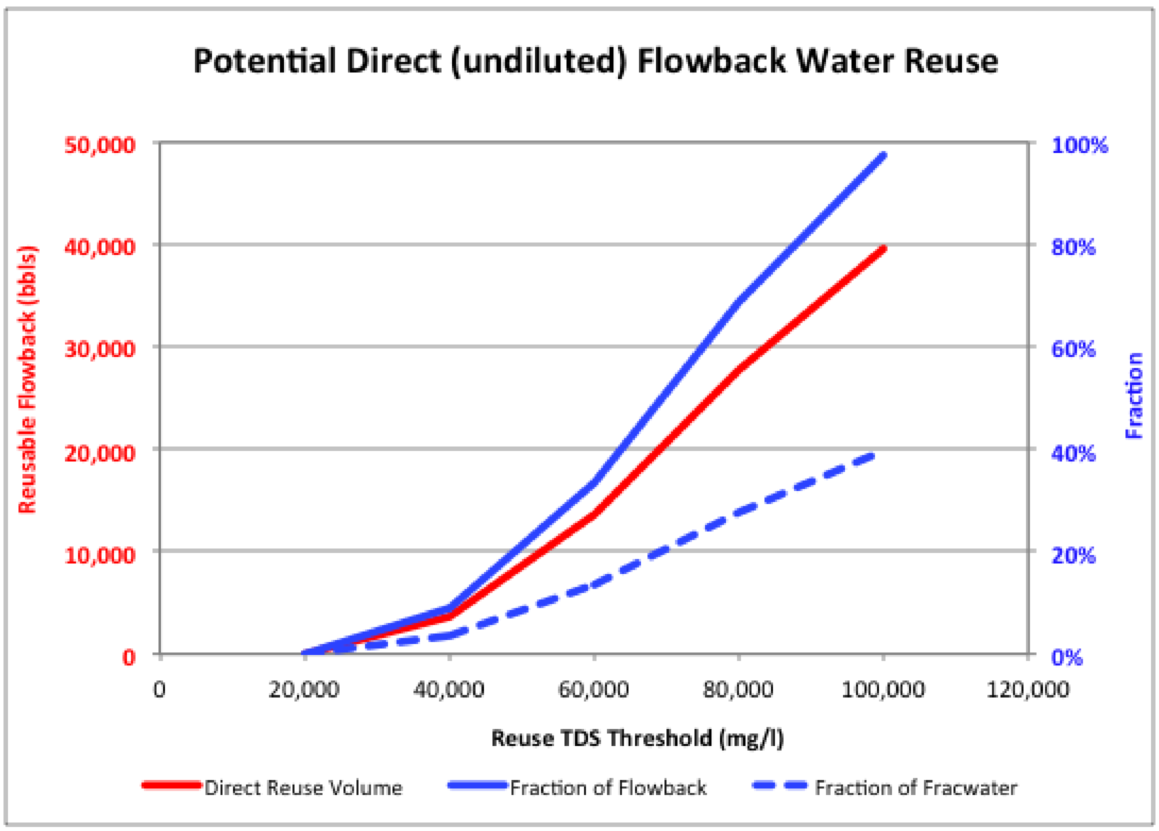


Figure 10: Potential direct reuse of flowback as a function of maximum TDS threshold. These projections are based on a well completed with 100,000 bbls of frac water flowing back at an initial rate of 2,000 bbls/d and yielding 40,000 bbls of recovered frac water as flowback.

Dilution to achieve a desired TDS concentration is not the only criterion on which frac water reuse will be considered. There are other criteria, particularly suspended solids, floc-iron and the like which may impose additional constraints and/or require varying degrees of pre-treatment before frac water can be reused.

If the maximum TDS concentration that can be accommodated for new well completions is less than the highest flowback TDS concentration for a given well, then only some fraction of that flowback may be used directly (pre-treatment for solids and other constituents notwithstanding) for subsequent well completions. The question then turns to the level of dilution required for flowback reuse once a defined TDS reuse threshold is exceeded.

Flowback dilution factors are presented in Figure 11, which indicate the relative magnitude of flowback dilution required to meet specified TDS criteria at specific points of flowback recovery[1]. (A dilution factor of 1.0 indicates that no dilution is required. A dilution factor of 2.0 indicates that one volume of flowback must be diluted with one volume of freshwater). The most stringent TDS requirement (20,000 mg/l) imposes a substantially greater degree of dilution than higher TDS thresholds and this continues to increase as flowback is recovered. The 40,000 mg/l TDS threshold requires no dilution (indicated by the dilution factor of 1.0) until approximately 10% of the frac water is recovered. The highest TDS thresholds (80,000 and 100,000 TDS) retain a dilution factor of 1.0 (meaning no dilution is required for flowback reuse) throughout the range of frac water recoveries because the volume-weighted TDS concentration of the flowback is less than 80,000 mg/l (Figure 8b).

Using these dilution factors, the cumulative volume of freshwater required to effect specified TDS given the cumulative quantity of flowback recovered is given in Figure 12. Whereas approximately 90,000 bbls of freshwater would be required to dilute 40,000 bbls of flowback to 20,000 TDS only approximately 25,000 bbls of freshwater would be required to achieve a TDS threshold of 40,000 mg/l.

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[1] These projections follow from the patterns illustrated in Figures 6 through 8 and are based on a hypothetical well completed with 100,000 bbls of frac water flowing back at an initial rate of 2,000 bbls/d and exhibiting TDS versus flowback characteristics averaged from six Barnett Shale locations.

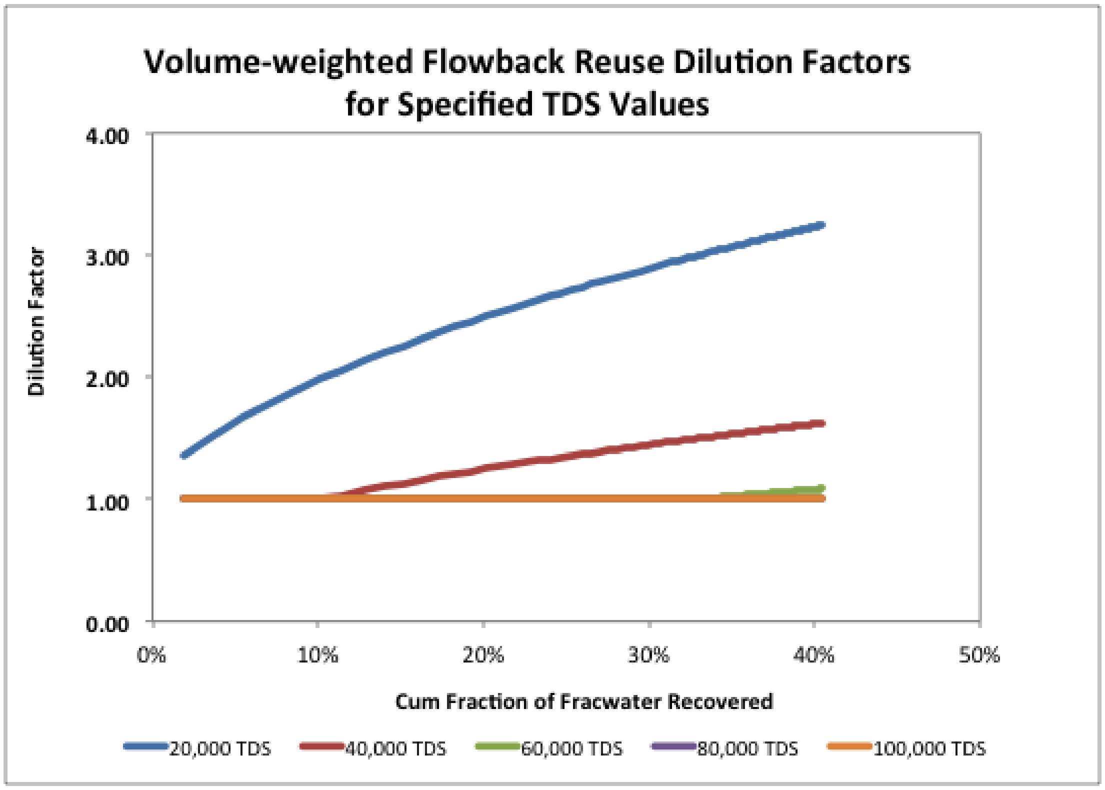


Figure 11: Volume-weighted flowback dilution factors to meet specified TDS criteria in relation to the cumulative fraction of frac water recovered.

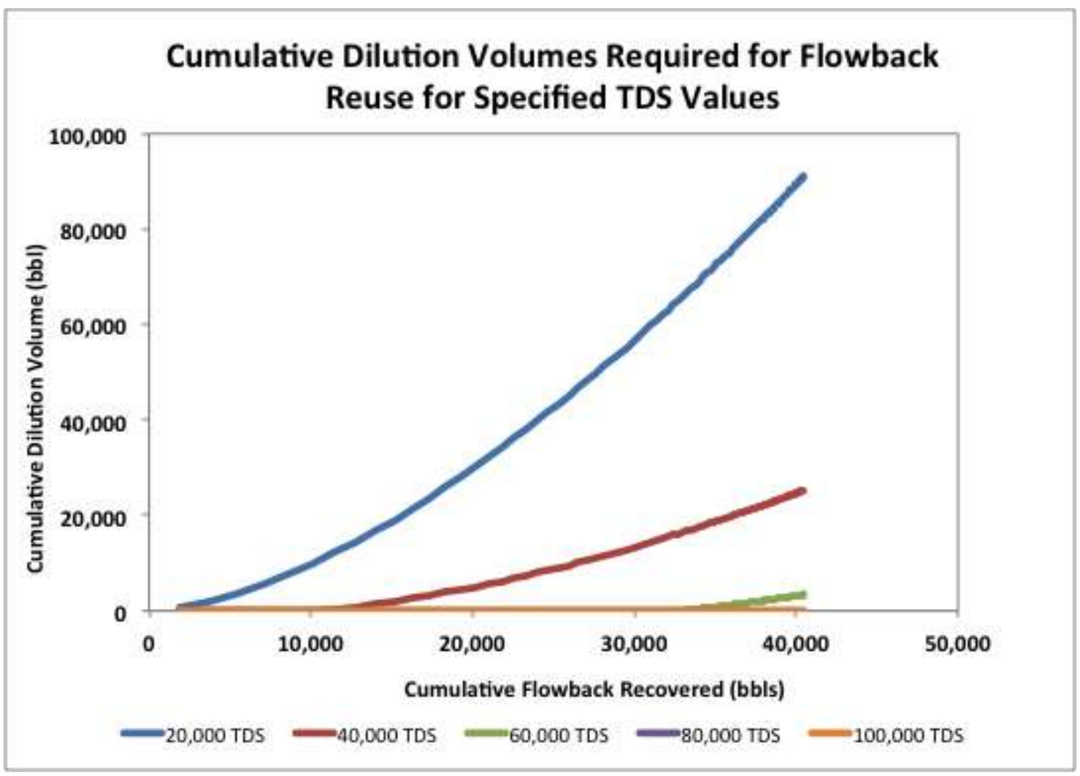


Figure 12: Cumulative flowback dilution volumes required to meet specified TDS criteria in relation to the cumulative volume of frac water recovered.

These projections are based on a well completed with 100,000 bbls of frac water flowing back at an initial rate of 2,000 bbls/d and yielding 40% (40,000 bbls) of recovered frac water as flowback.

If logistics and cost were not an issue it would be reasonable to simple ask as to why we would not simply recover, dilute and reuse all of the flowback. The constraints to this are addressed in the next section.

Total Flowback Water Reuse – Possibilities and Constraints

In the following discussion we present an analysis of projected (modeled) flowback reuse statistics considered at the field scale for a hypothetical drilling project consisting of 25 wells. In this exercise we applied the hyperbolic model of flowback recovery basing this on an initial flowback recovery rate of 2,000 bbls/day, a daily exponential decline exponent of 0.06/day and a hyperbolic coefficient of 0.5/day. We applied the same TDS versus cumulative flowback relationship used previously. We assumed that each well will use 100,000 bbls for well completion. The per-well modeled daily and cumulative flowback are given in Figure 13 and the time course of TDS and Cl- concentrations in Figure 14.

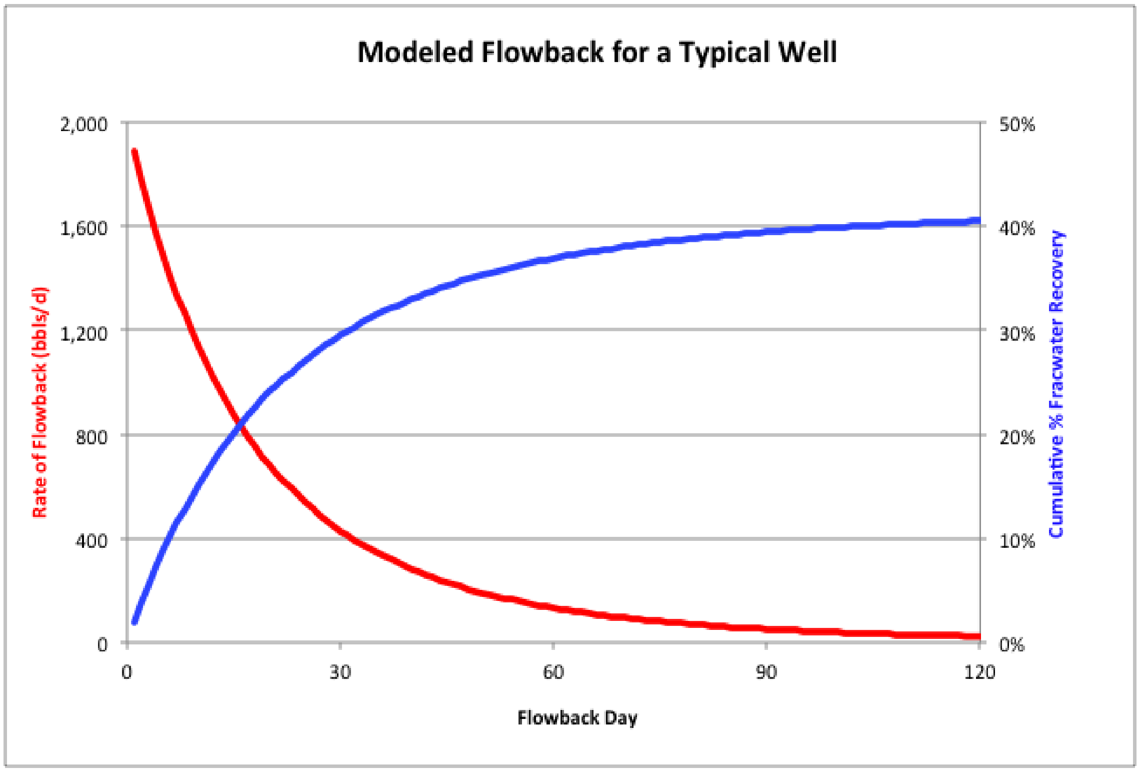


Figure 13: Per-well modeled flowback rate and cumulative volume.

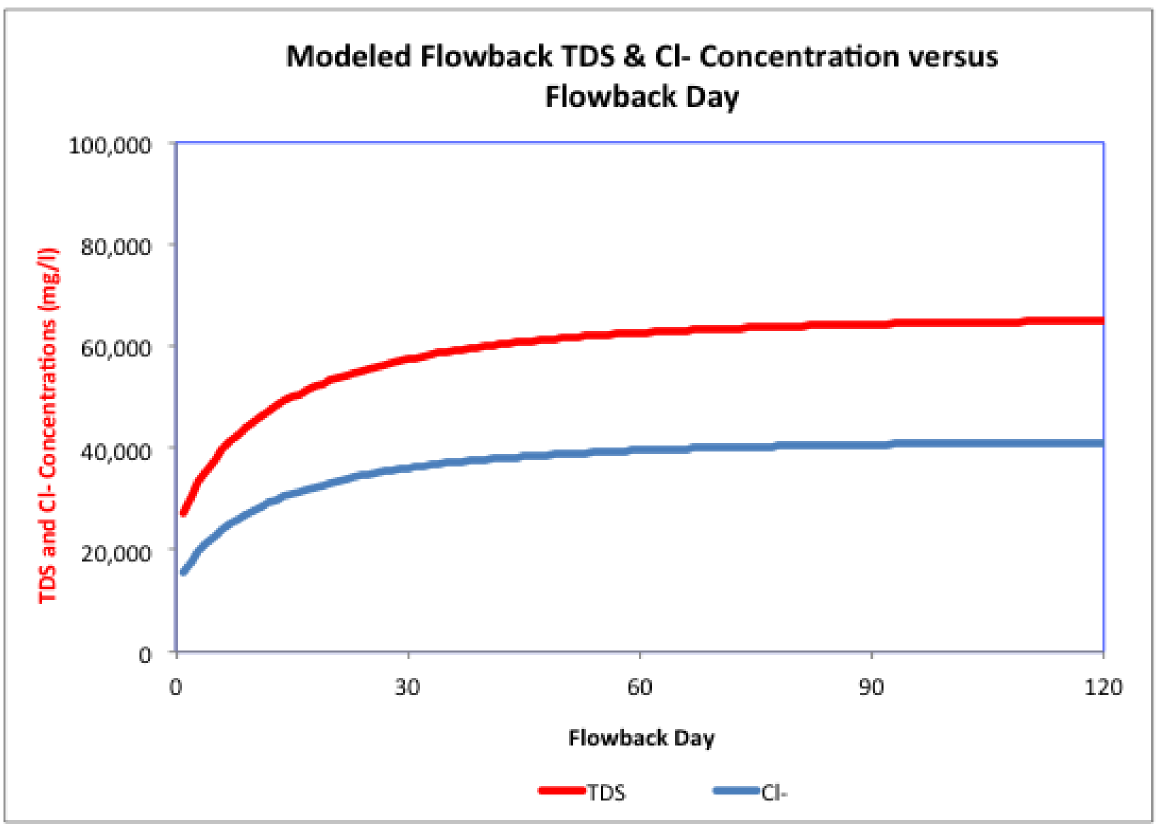
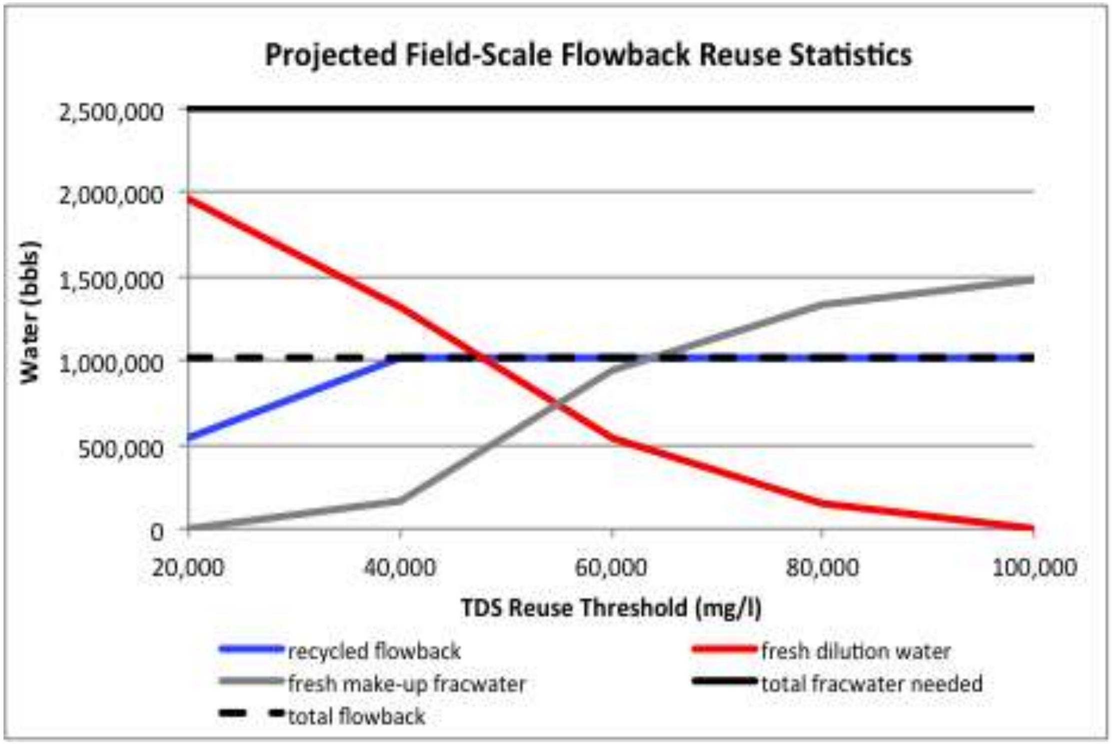


Figure 14: Time course of per well modeled TDS and chloride concentrations.

We first consider the total volume of frac water needed (and able to be accommodated) for the field, which is 25 wells * 100,000 bbls/d = 2,500,000 bbls . This represents the maximum amount of water that can be injected down-hole for use in fracturing and completing the 25 wells in the field. Any water above this volume produced in the field must, for the purposes our discussion, be treated and disposed as waste. We now consider the relationships between key flowback statistics and the TDS threshold for in-field reuse, which are summarized in Figure 15a and Figure 15b.

The total recovered flowback volume in our hypothetical example is approximately 1,000,000 bbls, which represents 40% of the total volume of frac water used to complete the twenty-five wells in the field. The maximum projected flowback TDS concentration is approximately 65,000 mg/l. Therefore, if the TDS threshold criterion is above this value all of the flowback water can be reused (since its total volume is less than that which is needed to frac all of the wells). However, if the TDS threshold for reuse is too low, say 20,000 mg/kg, then it becomes impossible to reuse all of the flowback water since the combined volumes of the flowback (1,000,000 bbls) and the water needed for its dilution (2,000,000 bbls) exceed the total volume of frac water (2,500,000 bbls) needed to complete all of the wells in the field.

In our hypothetical example, the fraction of flowback that can be recycled reaches 100% above a TDS threshold of approximately 40,000 mg/l. Above this level less the combined volumes of recovered flowback and freshwater needed for dilution is less than the total volume needed to complete all of the wells in the field … thus all of the flowback (1,000,000 bbls in this case) is potentially recycled. The difference (1,500,000 bbls) between the recycled flowback (1,000,000 bbls) and the total volume of water needed to complete the field (2,500,000 bbls)



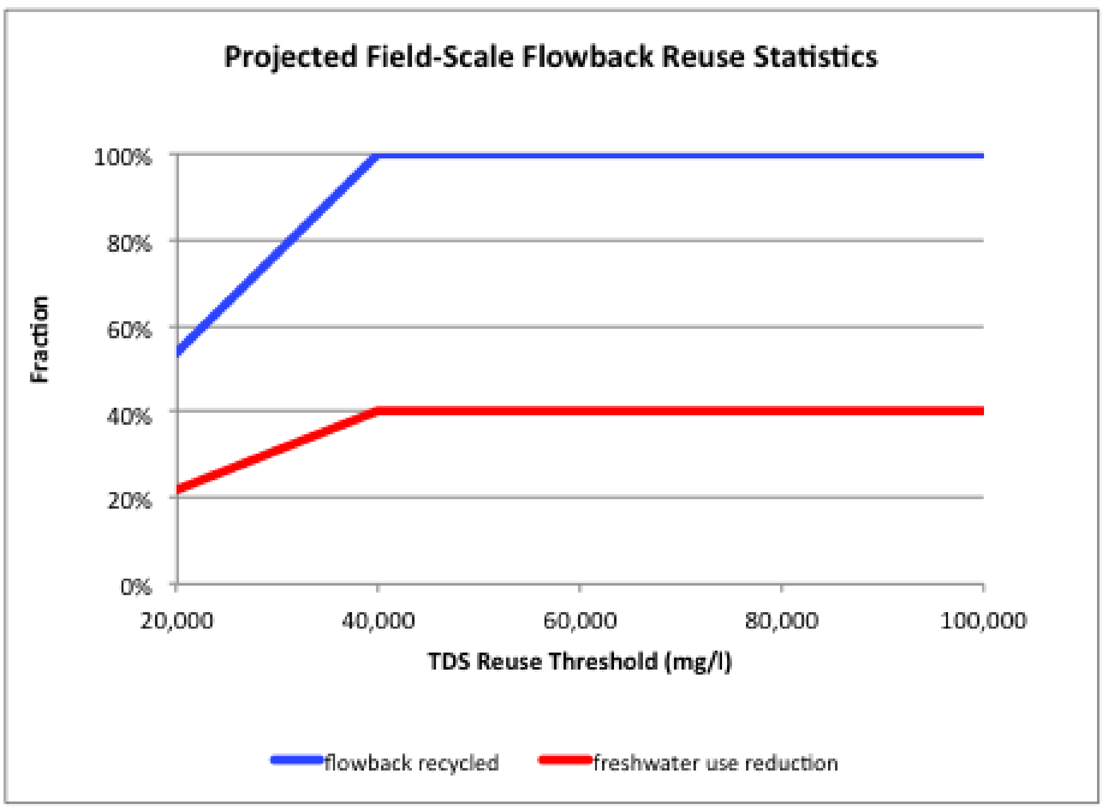


Figure 15: a (above) and b (below) - Summary of key metrics for flowback reuse for a hypothetical scenario in the Barnett Shale.

must be provided from other sources, this being indicted as “make-up frac water” in Figure 15a. Nevertheless, the potential for reducing freshwater demand for completing wells in the field rises from approximately 20% at a TDS threshold of 20,000 mg/l to 40% at a TDS reuse threshold of 40,000 mg/l or higher.

Conclusions

Patterns of water and salt generation in the period following hydraulic fracturing of a shale gas well indicate a large fraction (>50%) of the flowback water is likely to be generated in the first weeks following the frac job event; salt concentrations in the water stream increase steadily from below 20,000 mg/l to high concentrations over a period of months to a level above 60,000 mg/l. There may be considerable variation in these characteristics from site to site, but the general pattern of decreased flow and increased salt concentration with time is generally observed in a preponderance of cases. This presents the opportunity of collecting the initial fractions of flowback water that have low concentrations of salts that can be reused with minimal need for demineralization. In this circumstance of water management, the early flowback water can be taken directly to the next shale gas well for blending with freshwater for subsequent use in the next completion. The remainder of the water emerging from the original shale gas well can be demineralized for recovery of additional water for reuse – or the more concentrated flowback water can be disposed of in a Class II well (which is a common disposal practice in the Barnett Region).

Considering only TDS dilution as the sole limiting factor, and leaving logistical and economic considerations aside, it should be theoretically possible to recycle a substantial portion of flowback waters from the Barnett Shale, assuming that the limited data upon which this study and modeling exercise were based is generally representative of the field. The primary reasons that this is possible are: 1- only a portion (25-40%) of the frac water used to complete a well is typically recovered as flowback during the first several weeks following well completion, and 2 – The volume-weighted TDS concentration is low enough so that the recovered flowback can be diluted for effective reuse. The primary benefits of recycling flowback water is a potentially substantial reduction in the volume of freshwater needed to complete future wells as well as a concomitant reduction in the volume of wastewater that must otherwise be disposed.

The modeling results of this report indicate that, in many cases, the collection of early flowback water can be an effective approach to obtaining relatively low-to-moderate strength flowback water for reuse with minimal or no processing for demineralization. Mathematical models, like the one described in this report, can be employed to predict the benefits of early flowback water capture prior to determine potential benefits of the approach before implementing such systems.

This study is not intended to be definitive for the purpose of demonstrating technical feasibility for any given project, but is offered as an approach for considering flowback water recycling based on site-specific data. We did not address here the considerable technical and logistical difficulties of segregating, collecting and transporting high TDS flowback waters. Nor did we address regulatory permitting or economic factors. Nor did we consider potential geochemistry problems associated with the reuse of high TDS flowback waters. However, the modeling indicates that the level of potential benefits of early flowback water recovery may result in reducing fresh water demand by 5-10% or more for shale gas completions with minimal cost required for water demineralization. Recovery of relatively low salt content flowback water can be achieved using readily available equipment comprising a separation system that is capable of realtime, in-line measurement of conductance and flow controls to achieve the capture of early, low-salinity flowback water; the conceptual design for this automated early flowback water system is described in a previous report submitted to RPSEA (Galusky, 2011).

The information developed in this report suggests that in many shale gas plays it may be worthwhile for drilling companies to take a fresh look at early flowback water capture for the purpose of recycling flowback waters. Preliminary modeling to forecast potential water conservation benefits could utilize readily available well field design data and cost information. Further, although the total water use by Barnett shale operators has been demonstrated to be small relative to other users (Galusky, 2007, 2009), the development of pro-active water conservation measures would likely engender good will with industry stakeholders in the face of the current and extensive drought presently gripping the State of Texas.

Sealed

L. Peter Galusky, Jr. Ph.D., P.G., P.E.

Acknowledgments

The author would like to thank the Gas Technology Institute and the Barnett Shale Water Conservation and Management Committee, whose member companies provided the fracwater samples analyzed for this report.

Laboratory analyses were performed by Test America, Inc. Test America Pittsburgh 301 Alpha Drive RIDC Park Pittsburgh, PA 15238. Tel: (412) 963-7058 Fax: (412) 963-2468 www.testamericainc.com .

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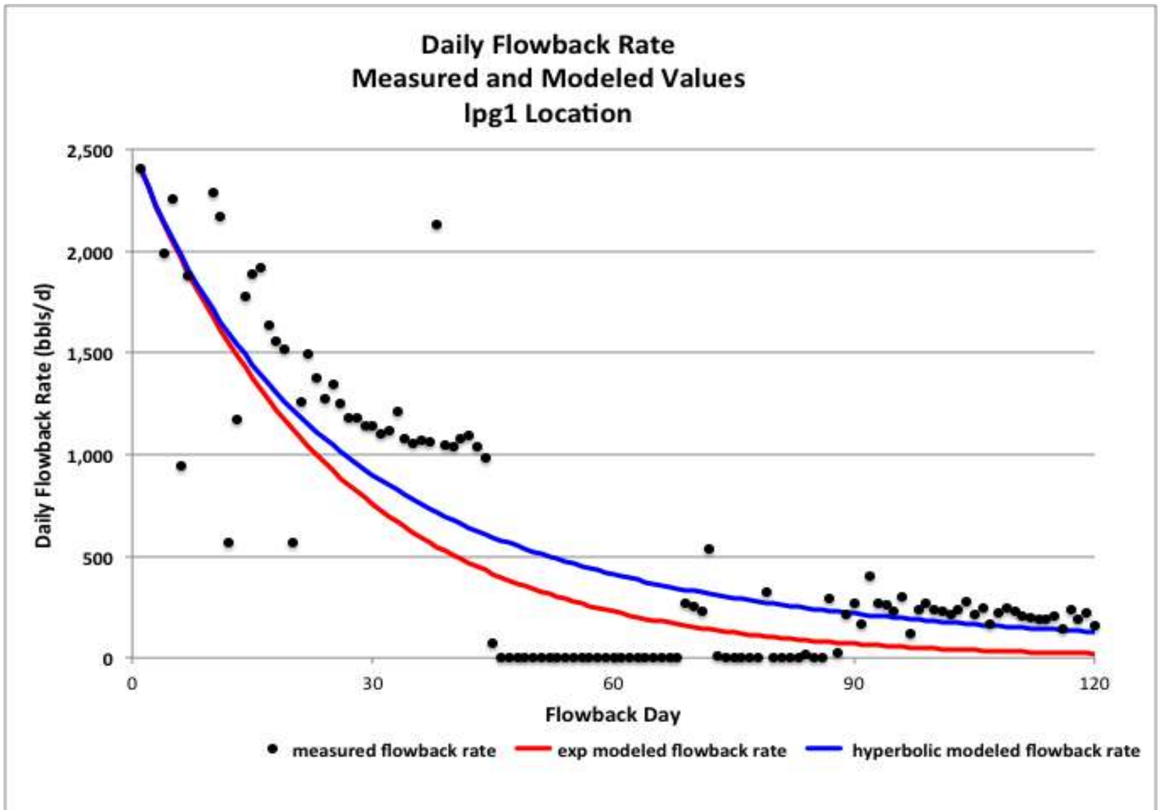
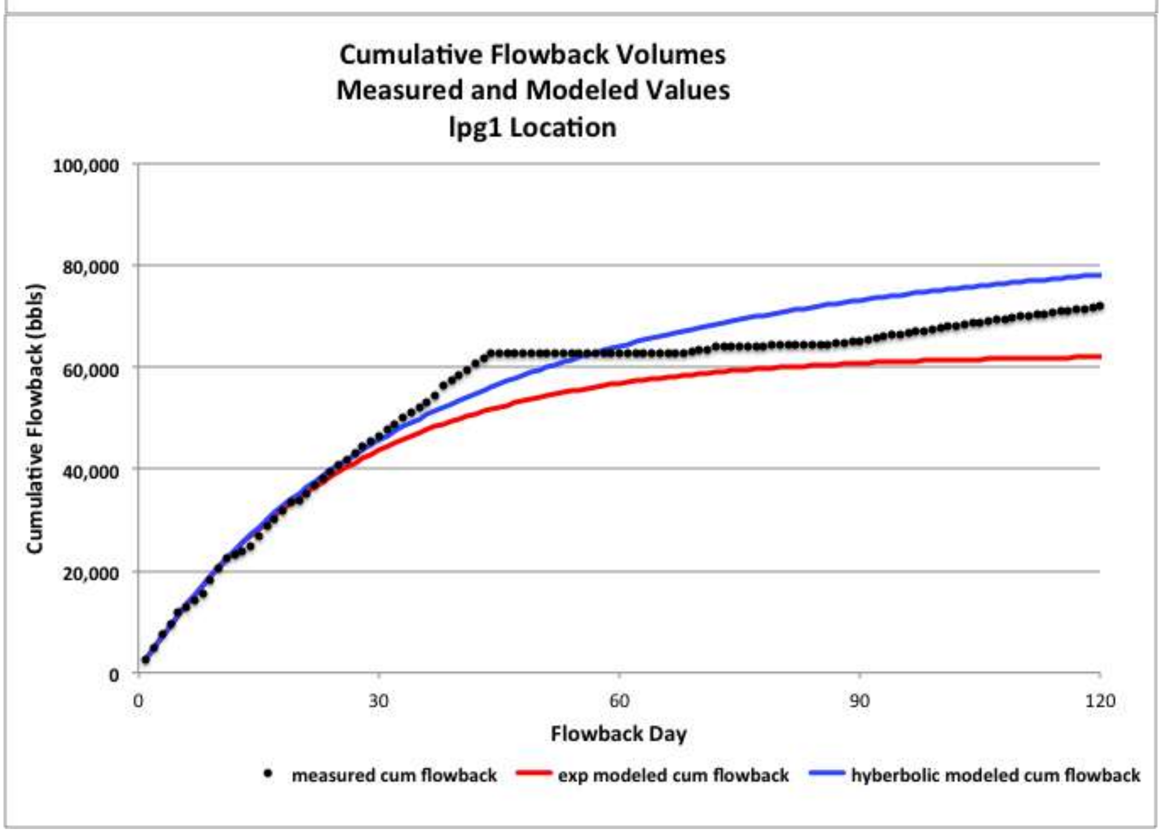
Appendix

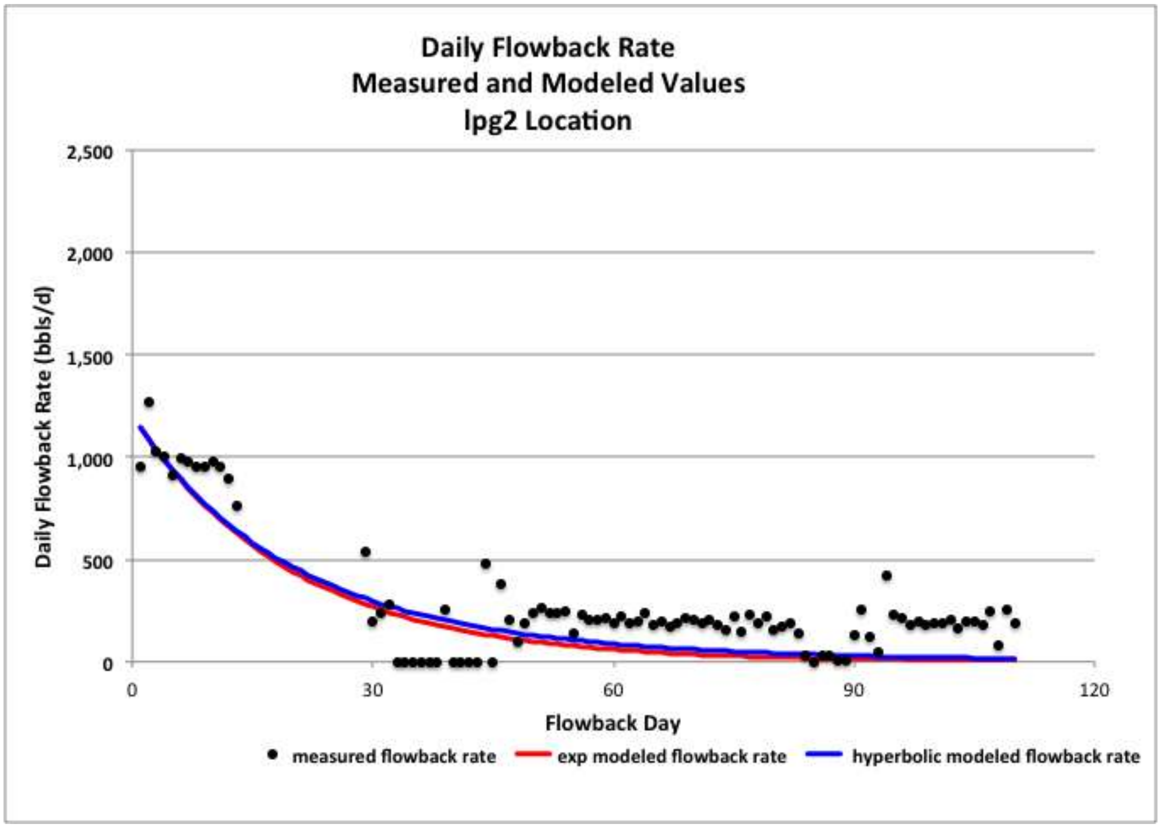
APPENDIX A – Individual Well Flowback Measurements and Model Estimates

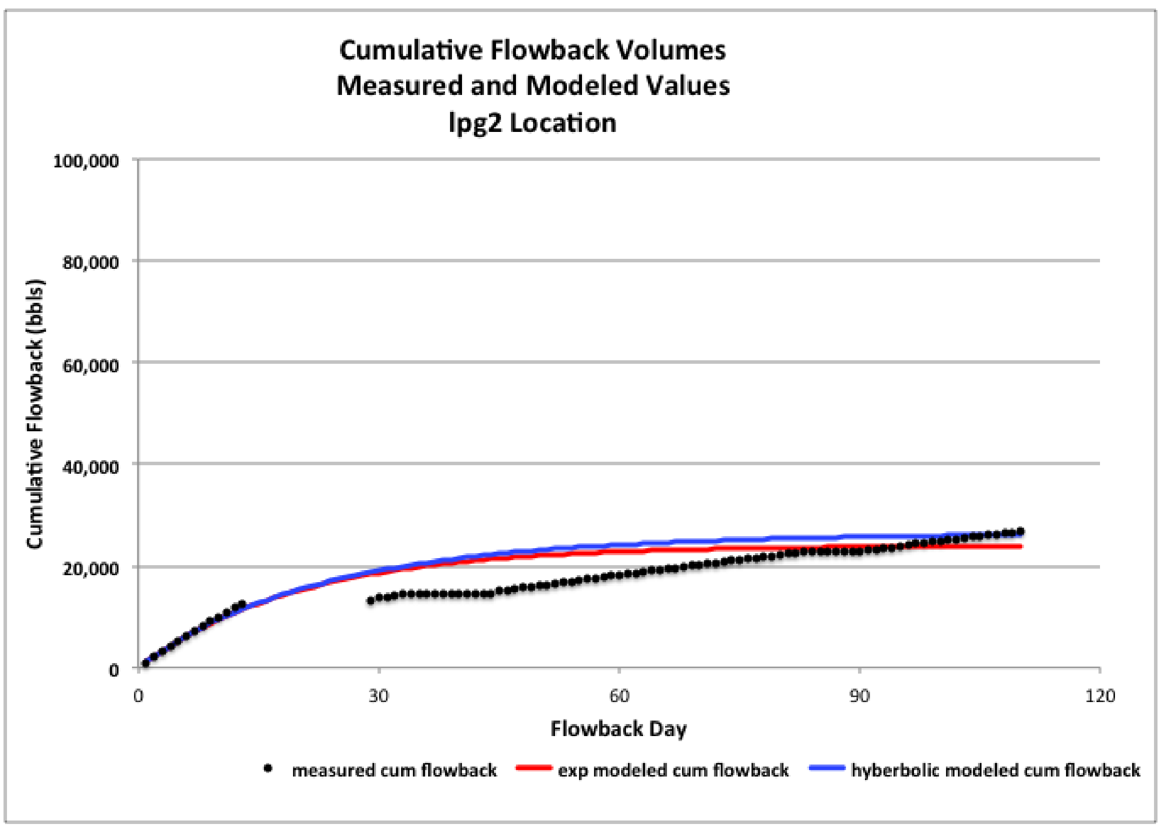


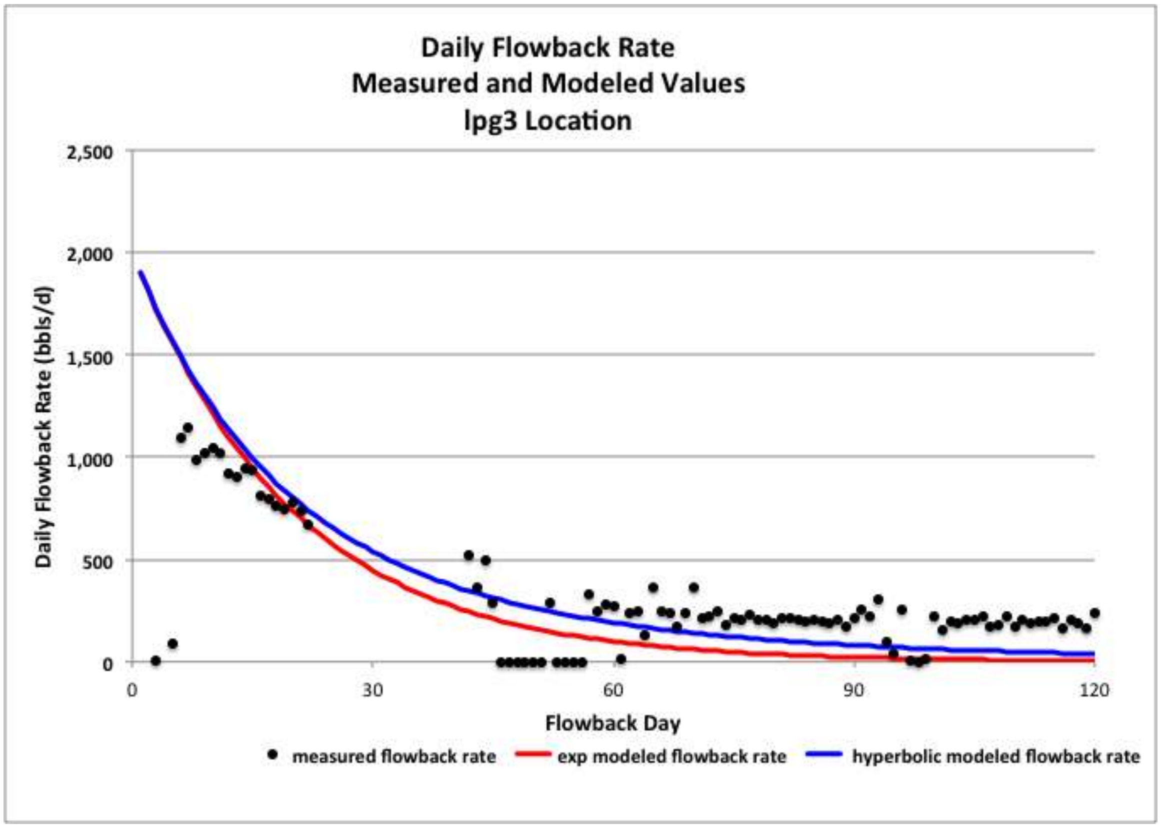
Daily Flowback Rate
Measured and Modeled Values
lpg1 Location
2,500
2,000
1,500
1,000
500
0
Daily Flowback Rate (bbls/d)
0
30
60
90
120
Flowback Day
measured flowback rate
exp modeled flowback rate
hyperbolic modeled flowback rate



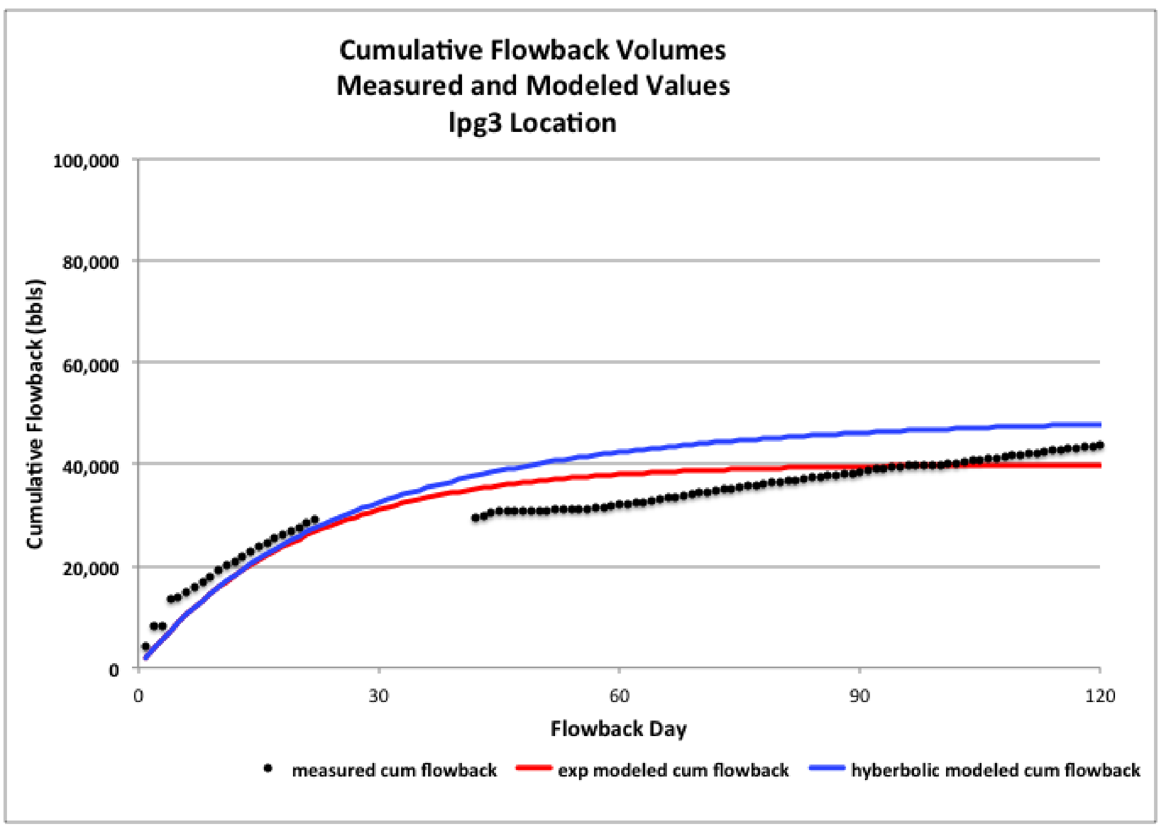
Cumulative Flowback Volumes
Measured and Modeled Values
lpg1 Location
100,000
80,000
60,000
40,000
20,000
0
Cumulative Flowback (bbls)
0
30
60
90
120
Flowback Day
measured cum flowback
exp modeled cum flowback
hyberbolic modeled cum flowback


Daily Flowback Rate
Measured and Modeled Values
lpg2 Location
Daily Flowback Rate (bbls/d)
2,500
2,000
1,500
1,000
500
0
0
30
60
90
120
Flowback Day
measured flowback rate
exp modeled flowback rate
hyperbolic modeled flowback rate

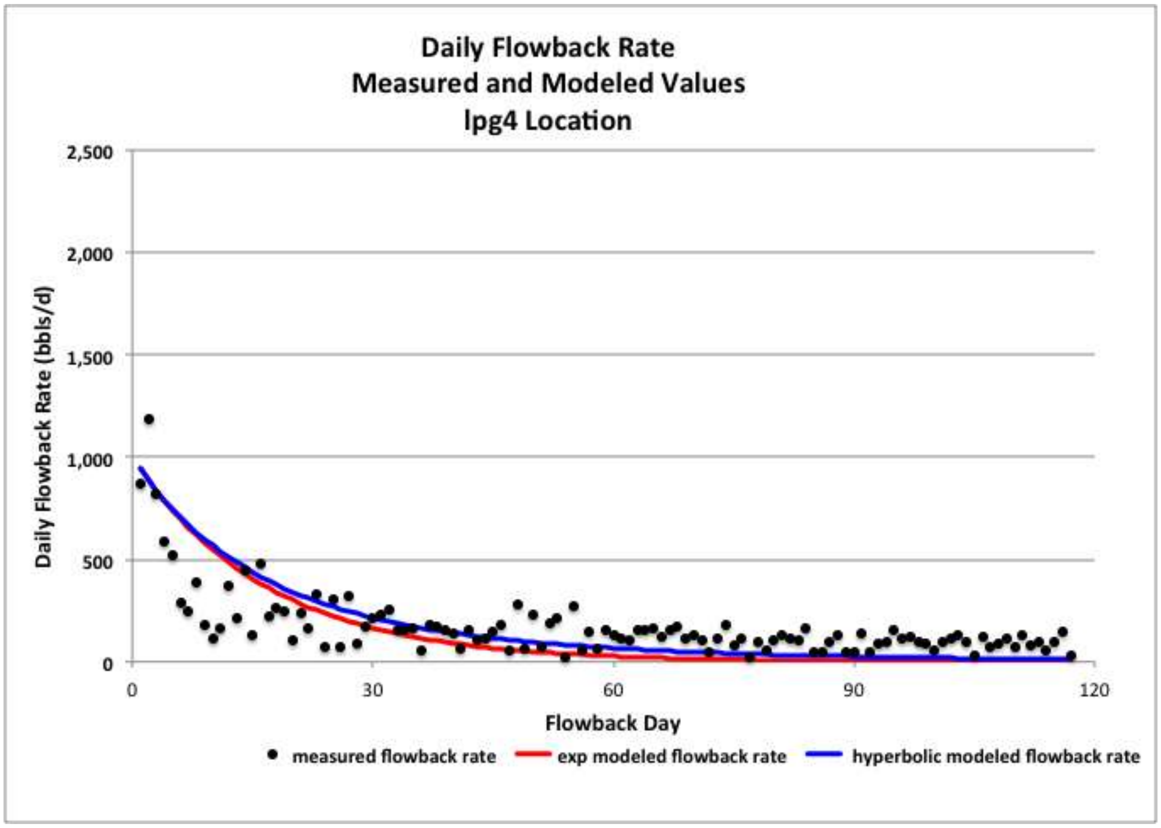

Cumulative Flowback Volumes
Measured and Modeled Values
lpg2 Location
Cumulative Flowback (bbls)
100,000
80,000
60,000
40,000
20,000
0
0
30
60
90
120
Flowback Day
measured cum flowback
exp modeled cum flowback
hyberbolic modeled cum flowback

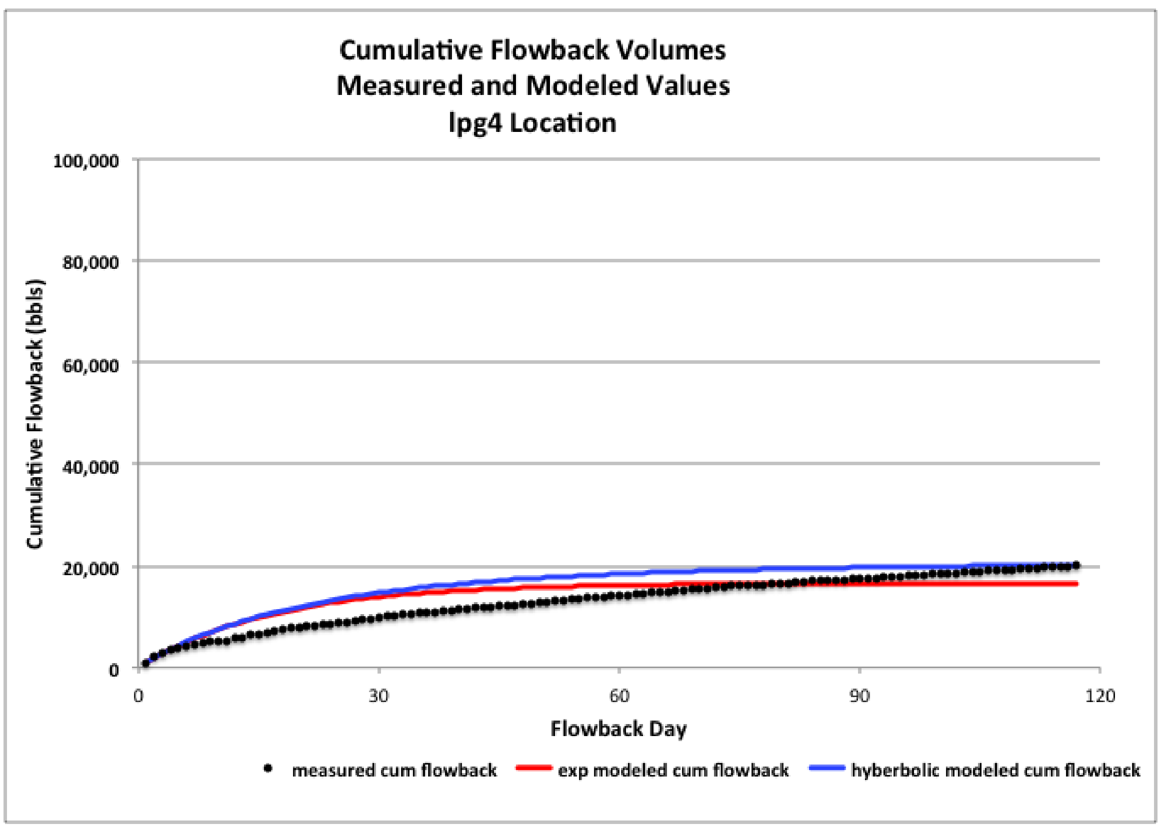


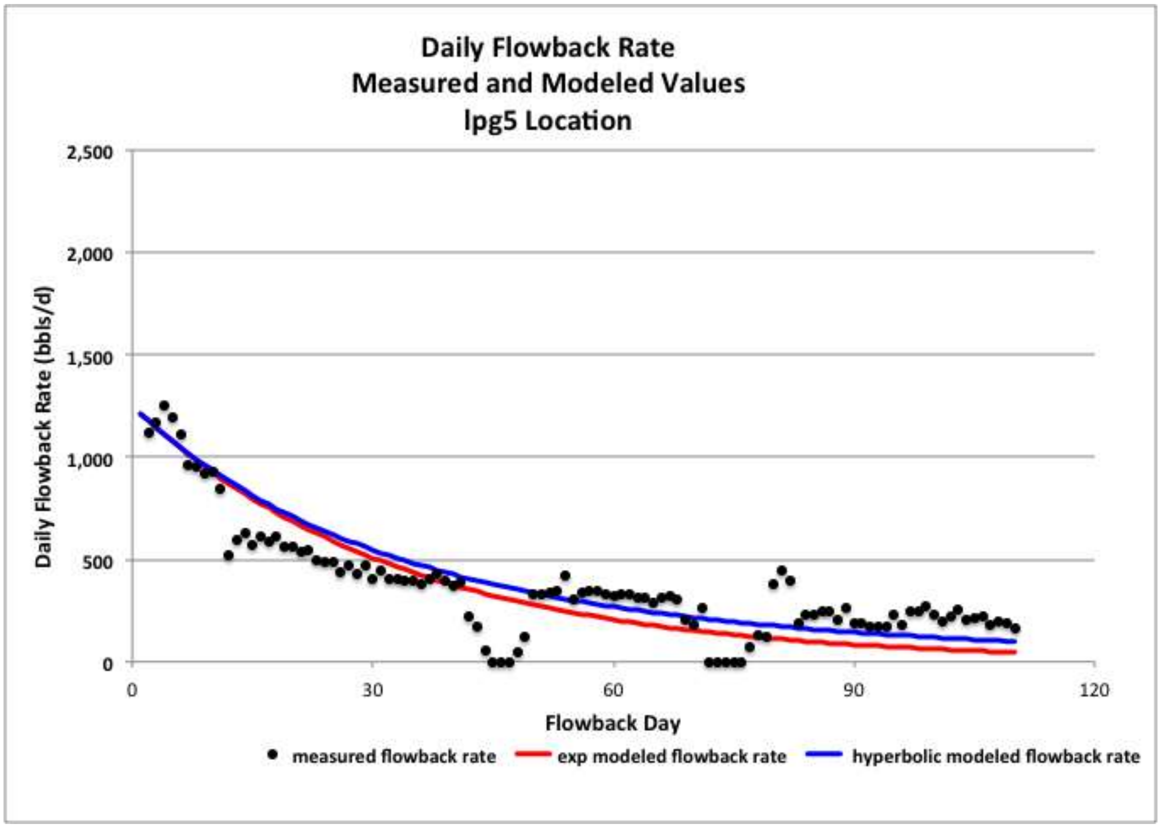
Daily Flowback Rate
Measured and Modeled Values
lpg3 Location
Daily Flowback Rate (bbls/d)
2,500
2,000
1,500
1,000
500
0
0
30
60
90
120
Flowback Day
measured flowback rate
exp modeled flowback rate
hyperbolic modeled flowback rate

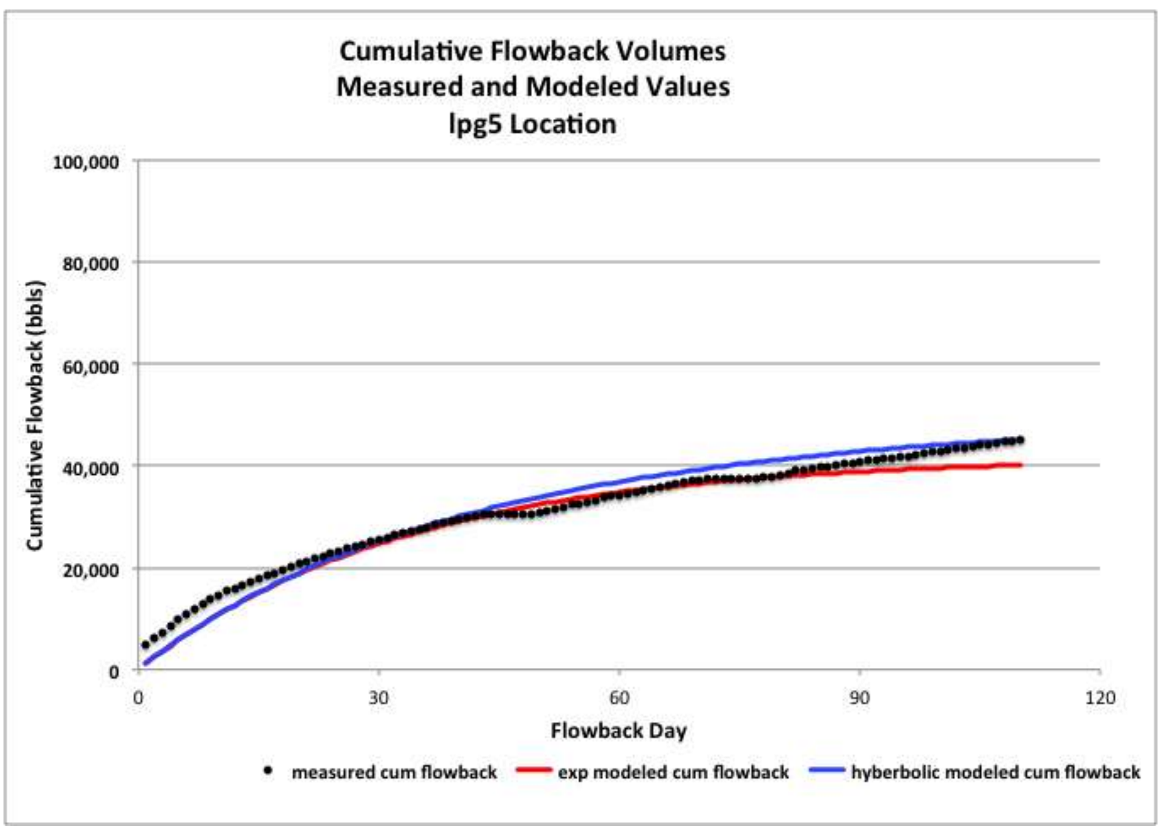


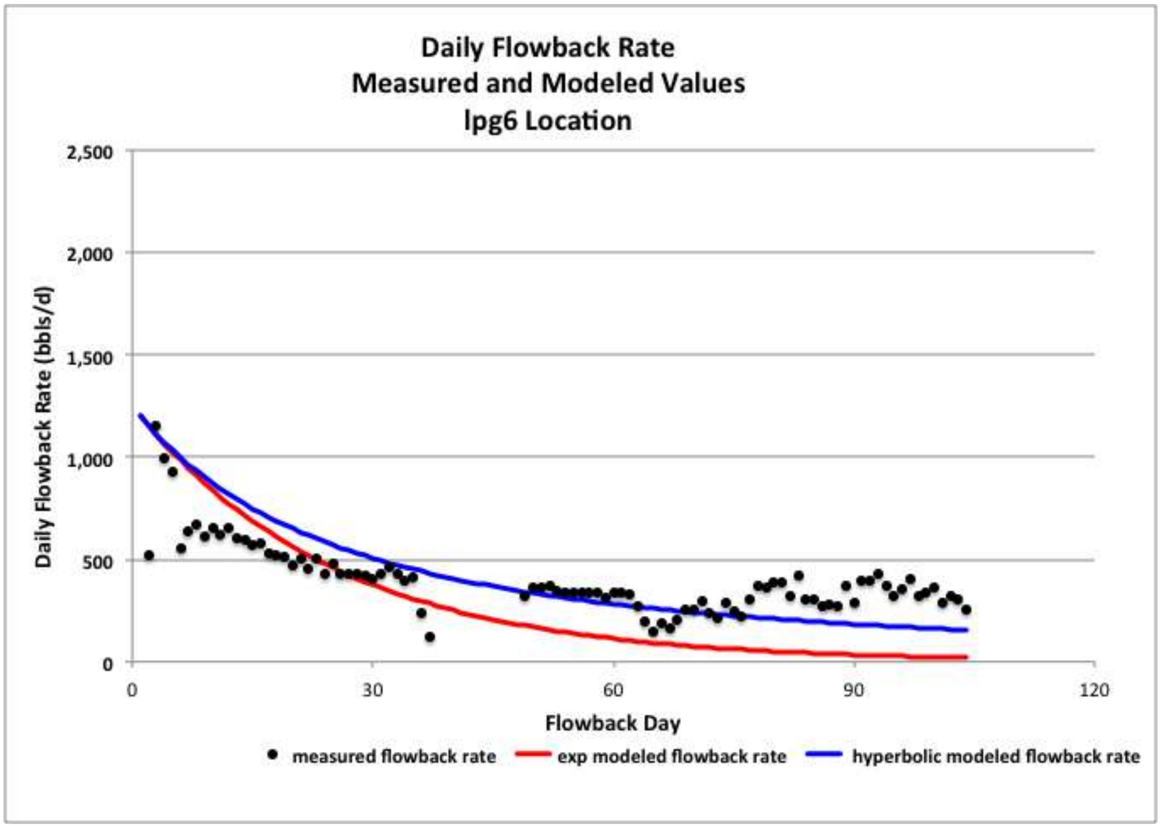
Cumulative Flowback Volumes
Measured and Modeled Values
lpg3 Location
Cumulative Flowback (bbls)
100,000
80,000
60,000
40,000
20,000
0
0
30
60
90
120
Flowback Day
measured cum flowback
exp modeled cum flowback
hyberbolic modeled cum flowback

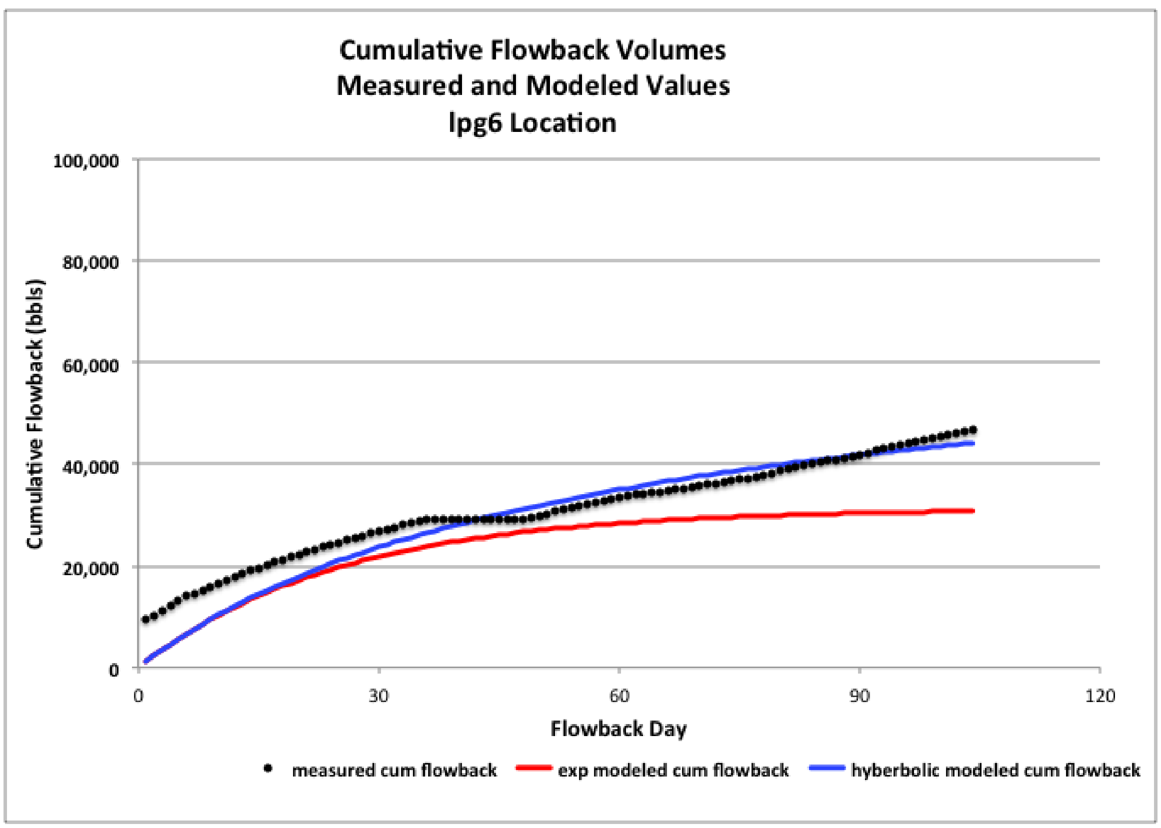

Daily Flowback Rate
Measured and Modeled Values
lpg4 Location
Daily Flowback Rate (bbls/d)
2,500
2,000
1,500
1,000
500
0
0
30
60
90
120
Flowback Day
measured flowback rate
exp modeled flowback rate
hyperbolic modeled flowback rate

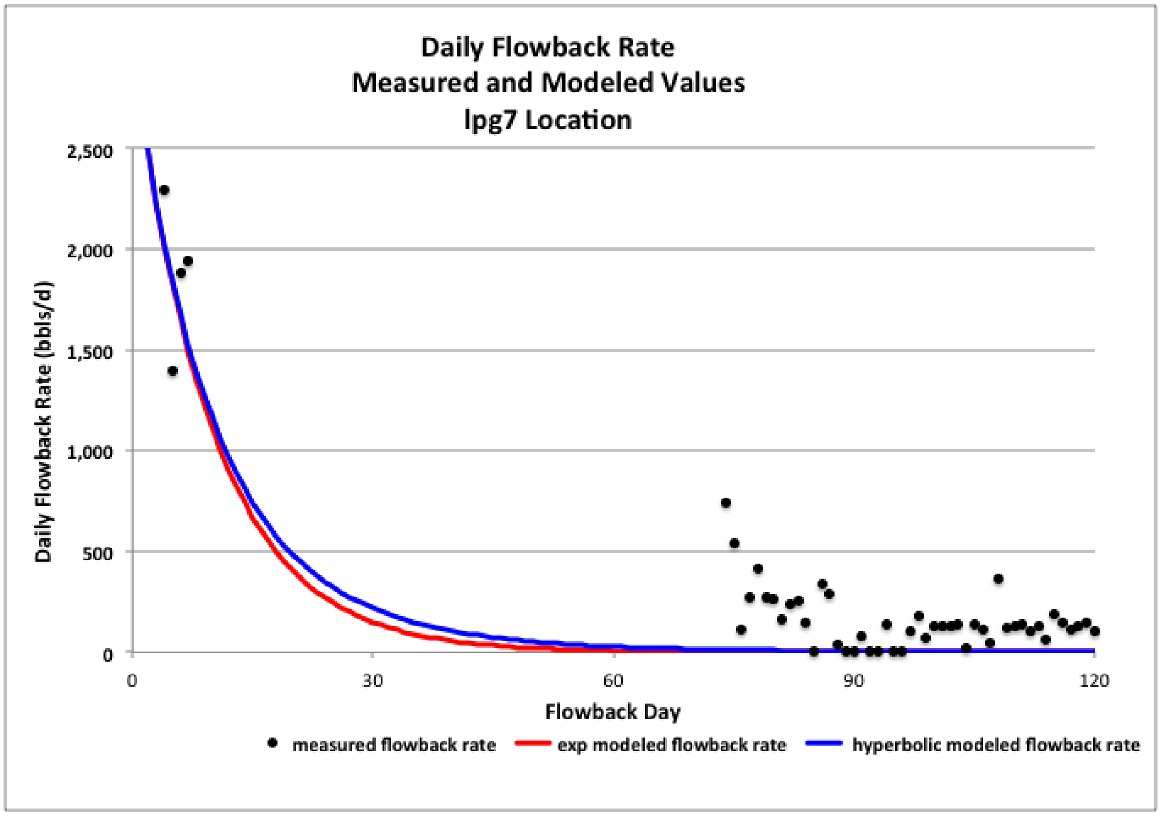

Cumulative Flowback Volumes
Measured and Modeled Values
lpg4 Location
Cumulative Flowback (bbls)
100,000
80,000
60,000
40,000
20,000
0
0
30
60
90
120
Flowback Day
measured cum flowback
exp modeled cum flowback
hyberbolic modeled cum flowback


Daily Flowback Rate
Measured and Modeled Values
lpg5 Location
2,500
2,000
1,500
1,000
500
0
Daily Flowback Rate (bbls/d)
0
30
60
90
120
Flowback Day
measured flowback rate
exp modeled flowback rate
hyperbolic modeled flowback rate

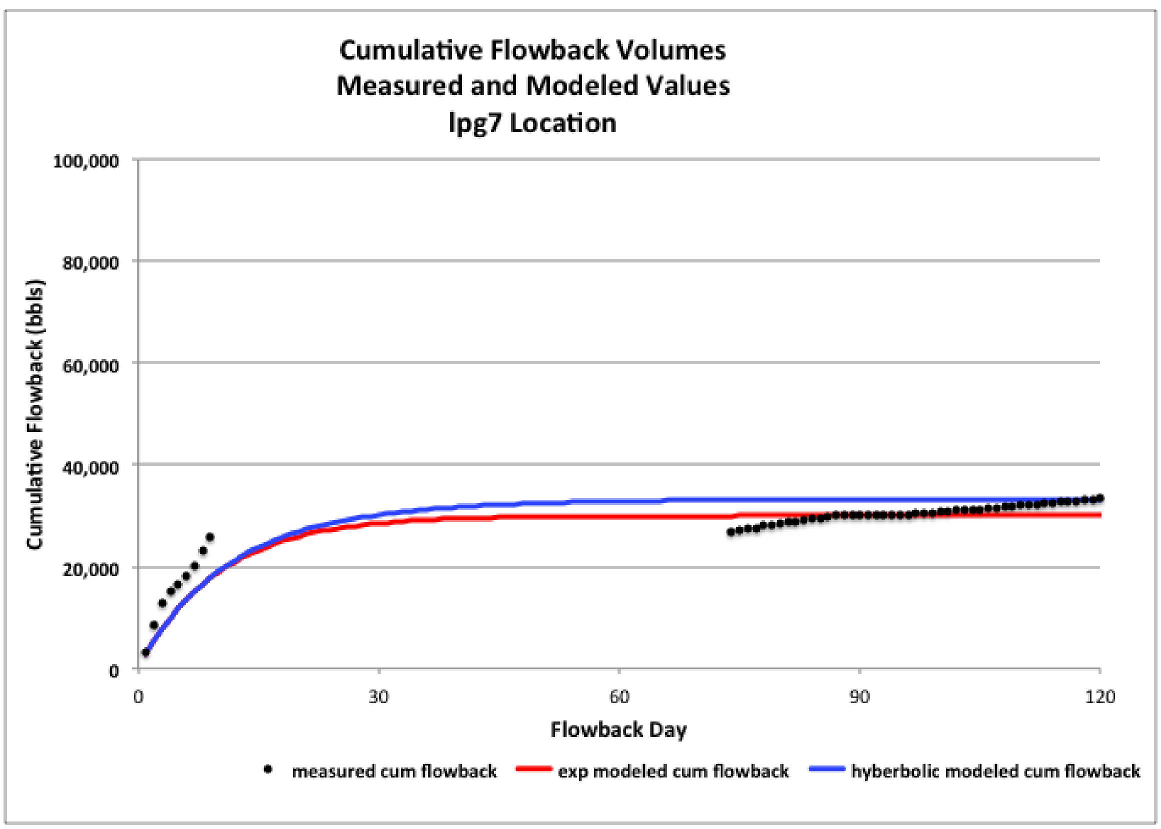

Cumulative Flowback Volumes
Measured and Modeled Values
lpg5 Location
100,000
80,000
60,000
40,000
20,000
0
Cumulative Flowback (bbls)
0
30
60
90
120
Flowback Day
measured cum flowback
exp modeled cum flowback
hyberbolic modeled cum flowback


Daily Flowback Rate
Measured and Modeled Values
lpg6 Location
Daily Flowback Rate (bbls/d)
2,500
2,000
1,500
1,000
500
0
0
30
60
90
120
Flowback Day
measured flowback rate
exp modeled flowback rate
hyperbolic modeled flowback rate

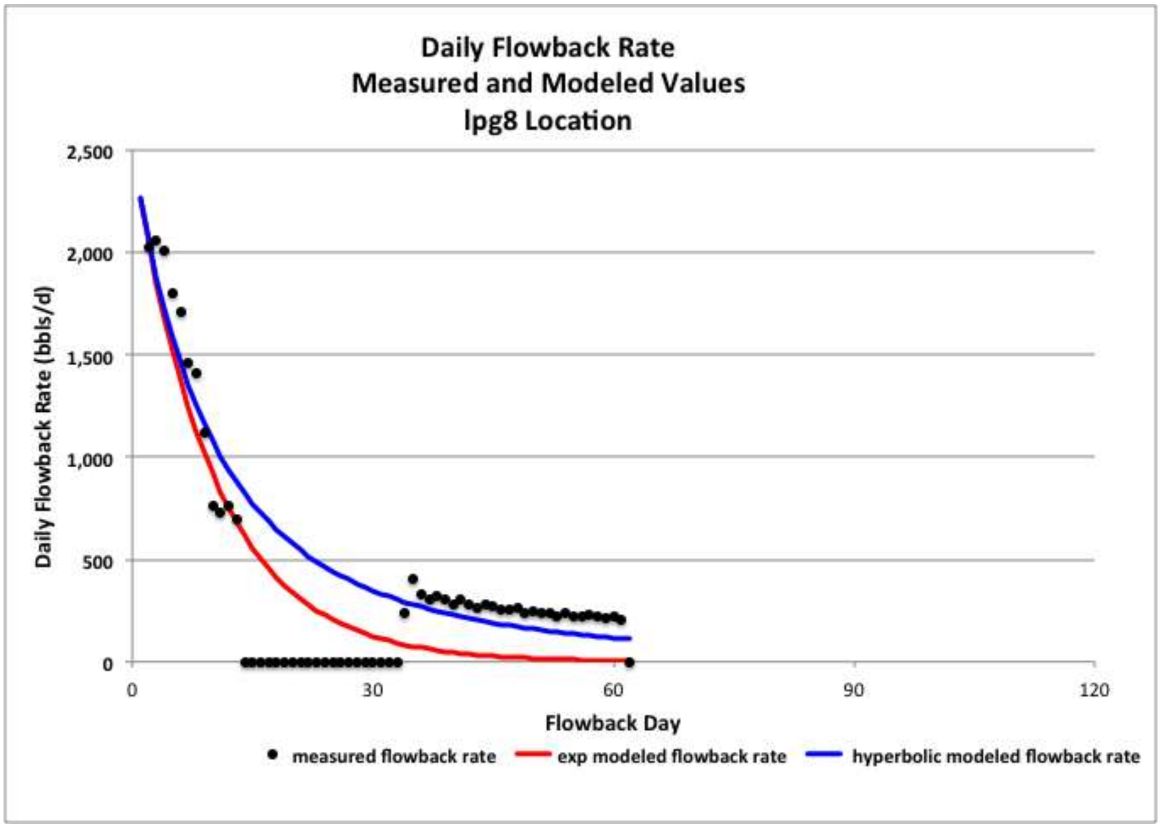

Cumulative Flowback Volumes
Measured and Modeled Values
lpg6 Location
Cumulative Flowback (bbls)
100,000
80,000
60,000
40,000
20,000
0
0
30
60
90
120
Flowback Day
measured cum flowback
exp modeled cum flowback
hyberbolic modeled cum flowback



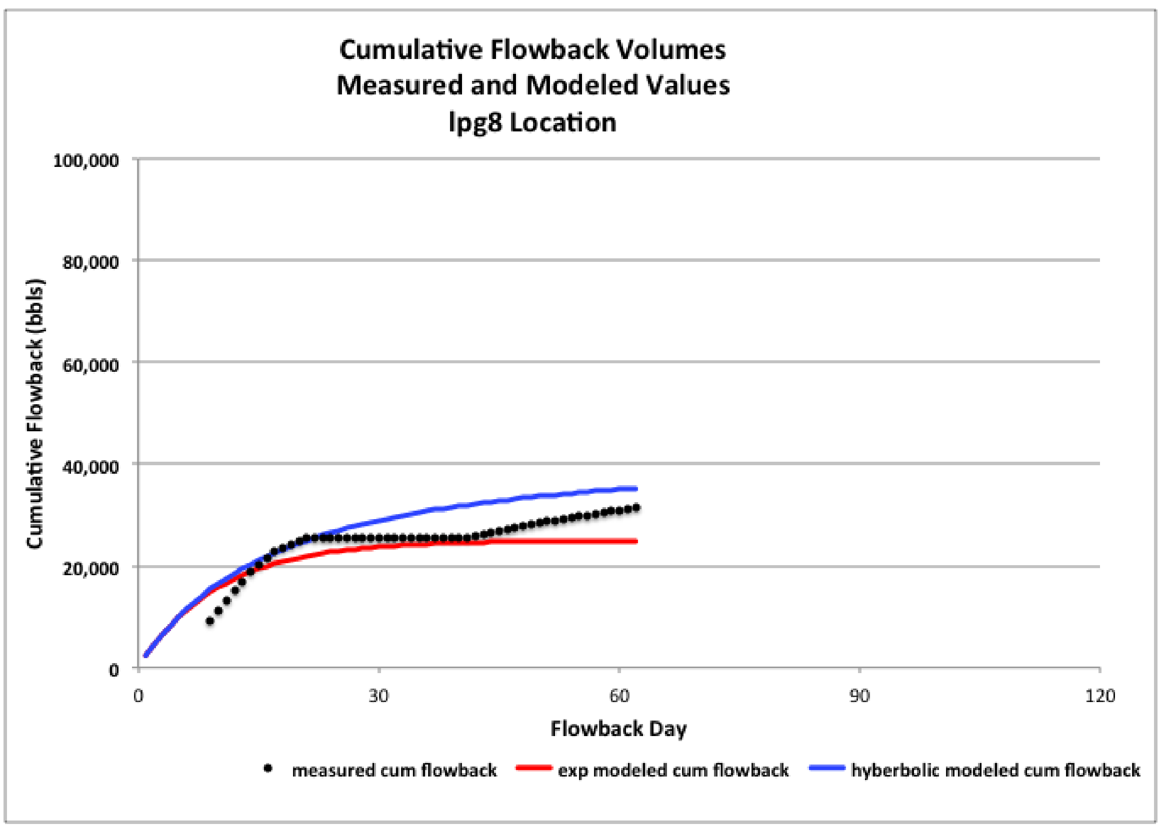
Daily Flowback Rate
Measured and Modeled Values
lpg7 Location
Daily Flowback Rate (bbls/d)
2,500
2,000
1,500
1,000
500
0
0
30
60
90
120
Flowback Day
measured flowback rate
exp modeled flowback rate
hyperbolic modeled flowback rate



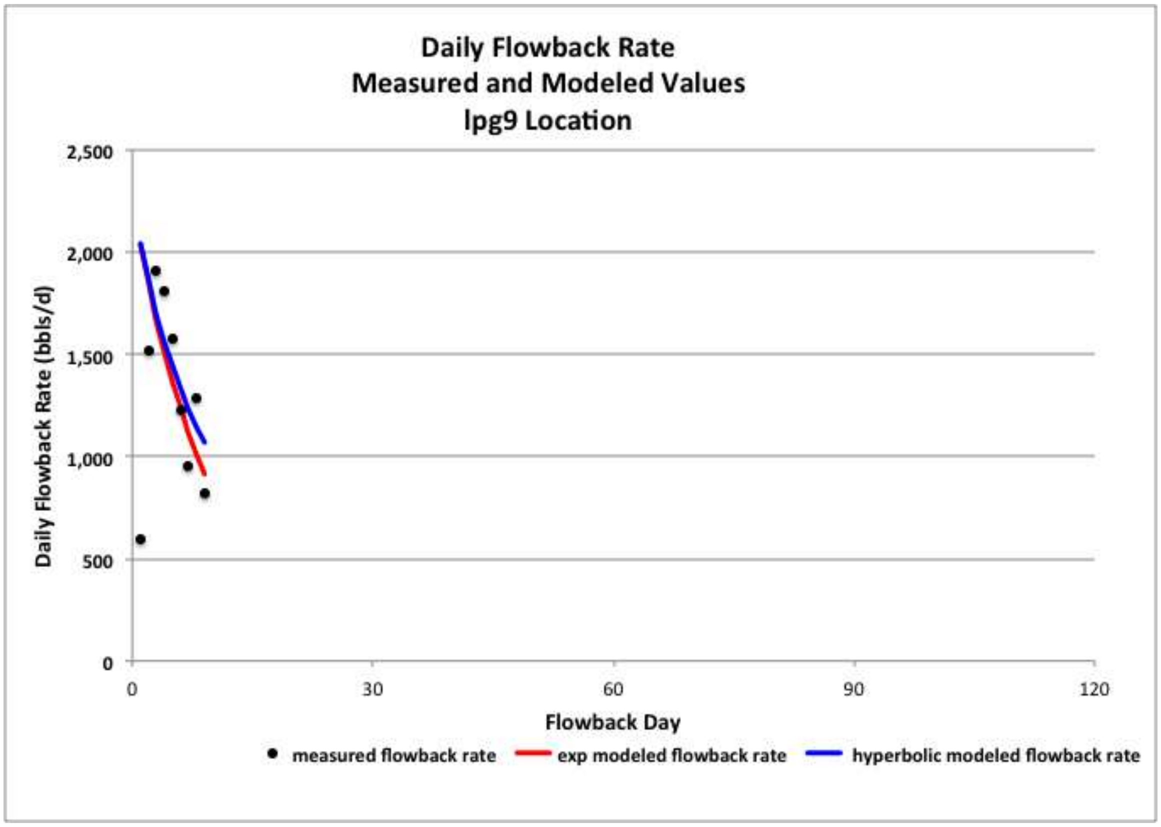
Cumulative Flowback Volumes
Measured and Modeled Values
lpg7 Location
Cumulative Flowback (bbls)
100,000
80,000
60,000
40,000
20,000
0
0
30
60
90
120
Flowback Day
measured cum flowback
exp modeled cum flowback
hyberbolic modeled cum flowback

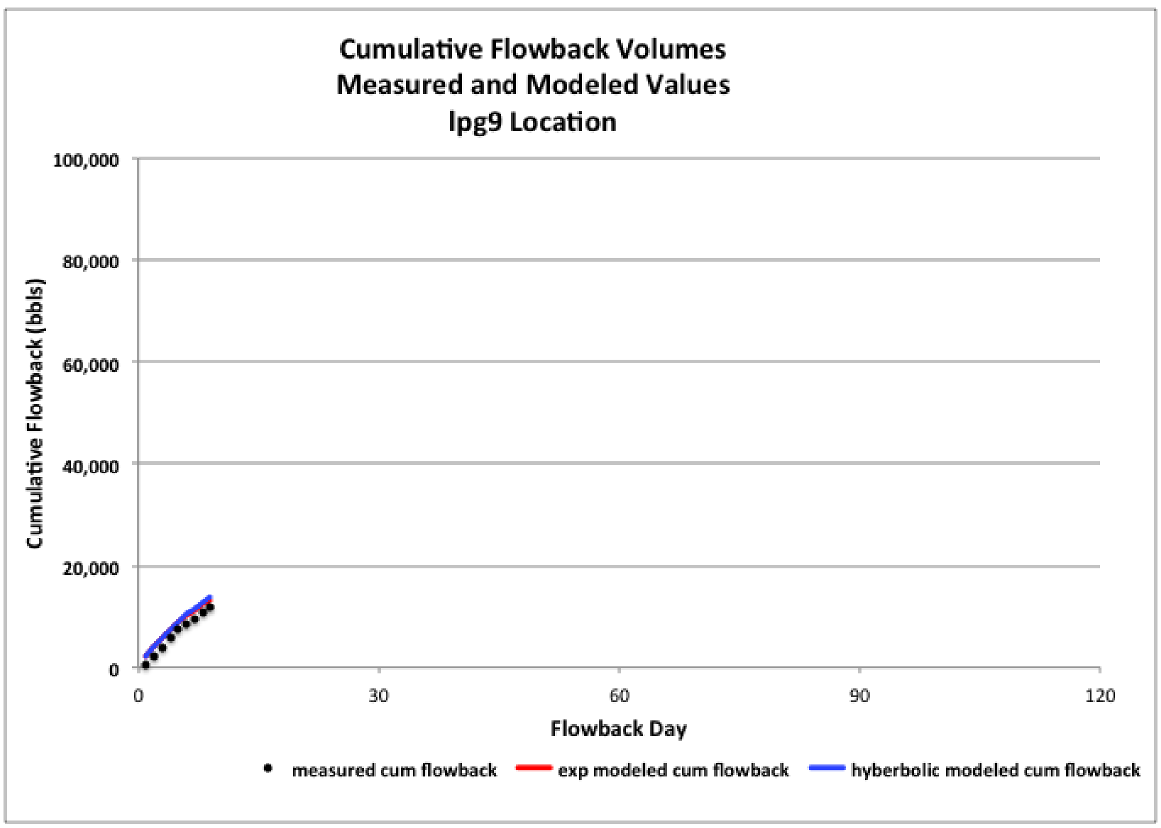


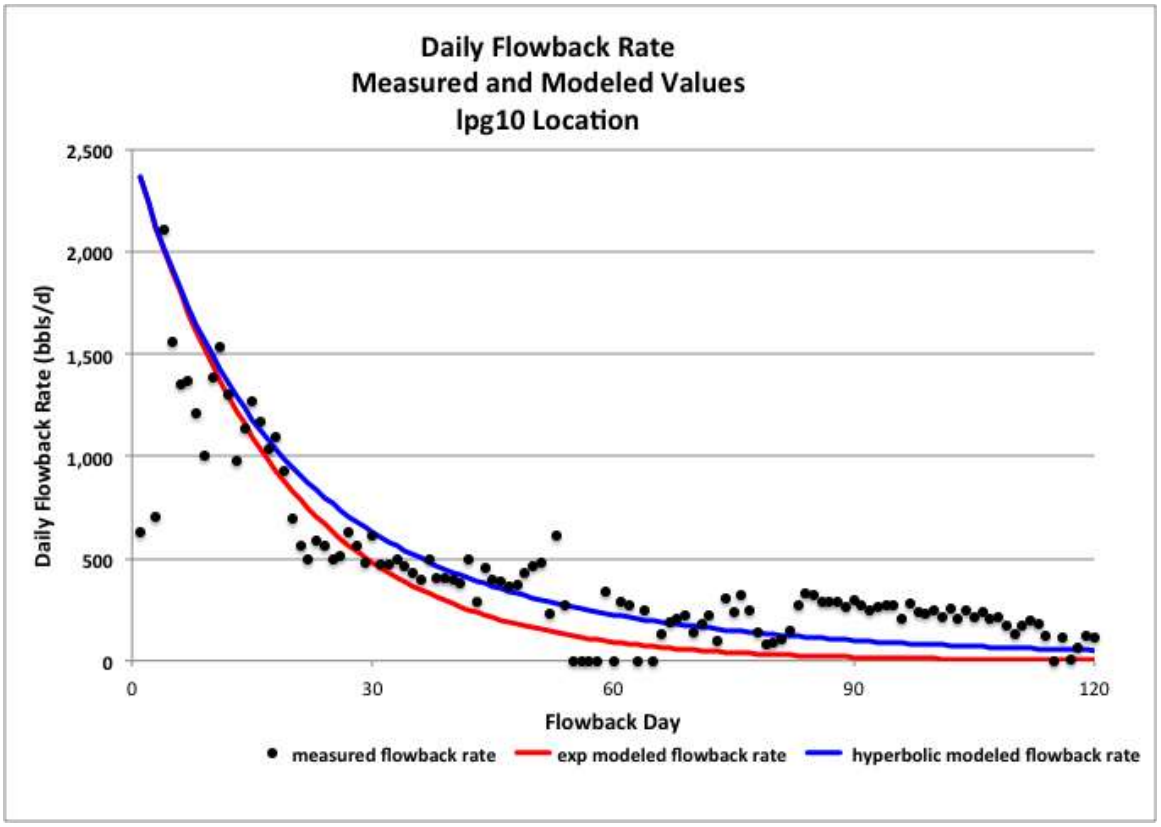
Daily Flowback Rate
Measured and Modeled Values
lpg8 Location
Daily Flowback Rate (bbls/d)
2,500
2,000
1,500
1,000
500
0
0
30
60
90
120
Flowback Day
measured flowback rate
exp modeled flowback rate
hyperbolic modeled flowback rate

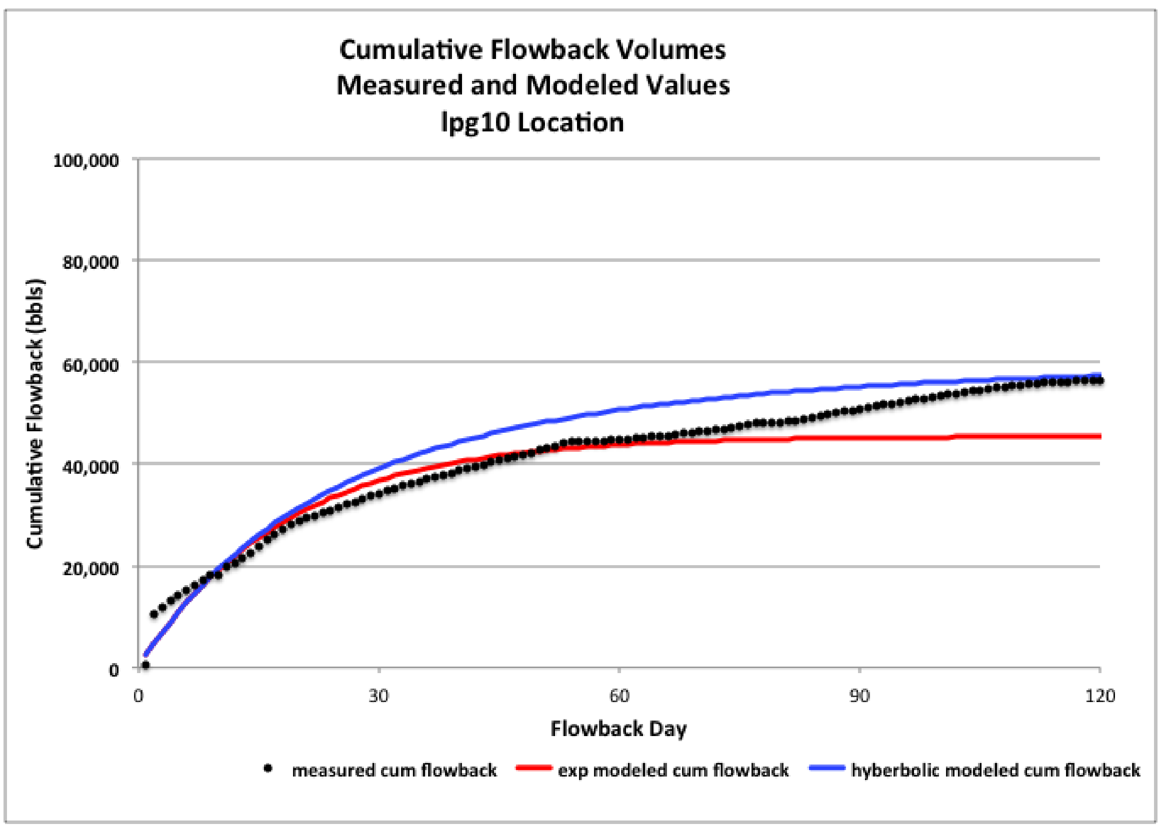


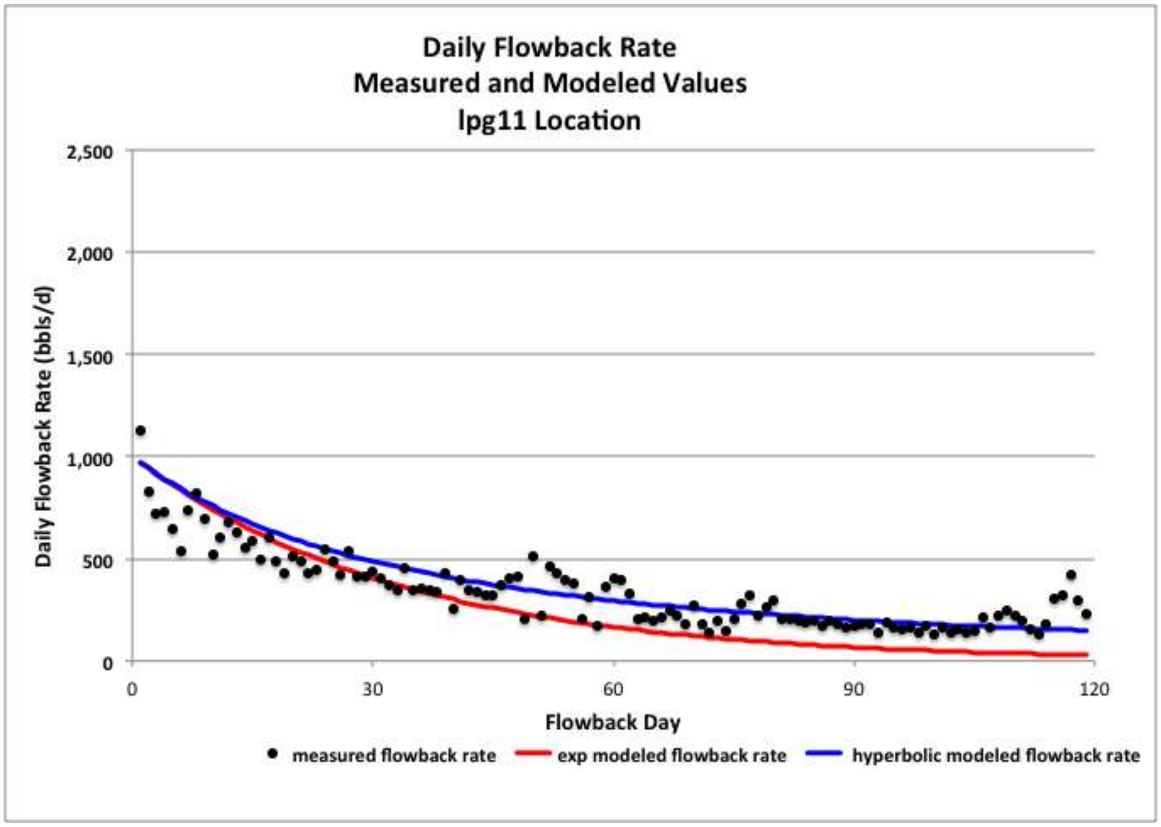
Cumulative Flowback Volumes
Measured and Modeled Values
lpg8 Location
Cumulative Flowback (bbls)
100,000
80,000
60,000
40,000
20,000
0
0
30
60
90
120
Flowback Day
measured cum flowback
exp modeled cum flowback
hyberbolic modeled cum flowback


Daily Flowback Rate
Measured and Modeled Values
lpg9 Location
Daily Flowback Rate (bbls/d)
2,500
2,000
1,500
1,000
500
0
0
30
60
90
120
Flowback Day
measured flowback rate
exp modeled flowback rate
hyperbolic modeled flowback rate

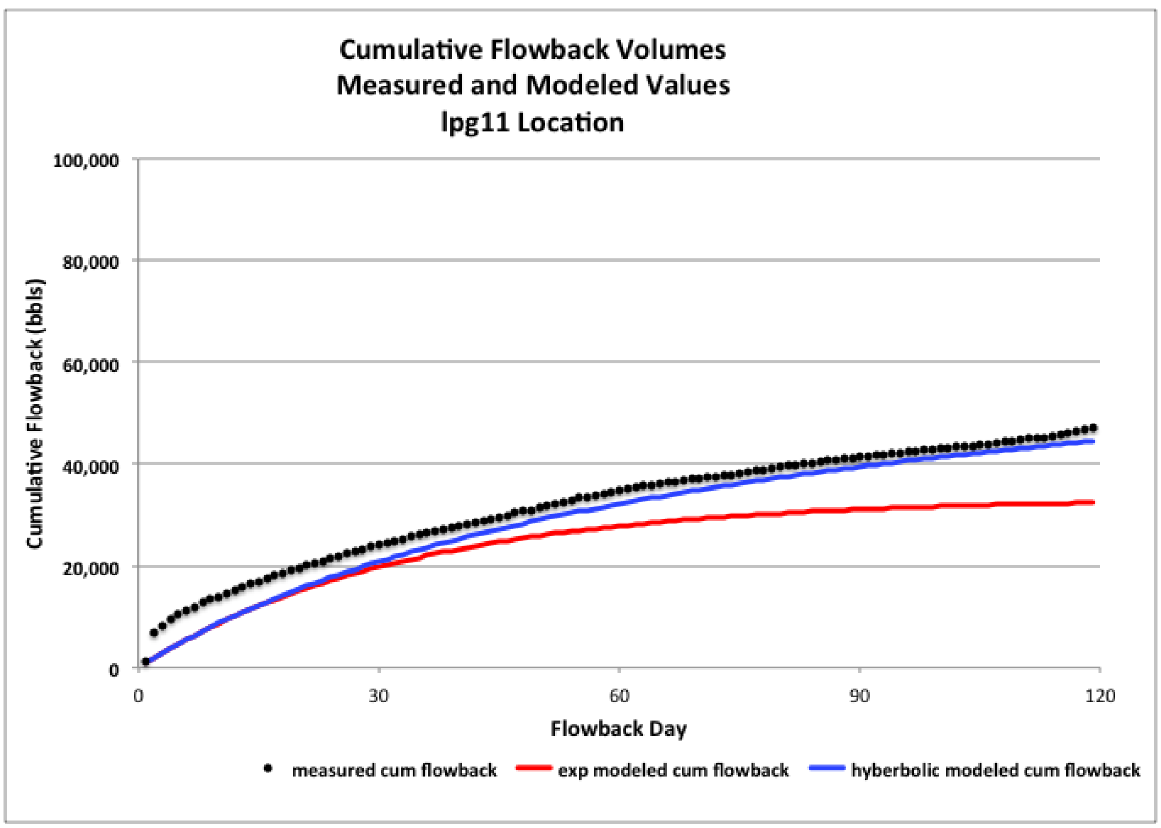

Cumulative Flowback Volumes
Measured and Modeled Values
lpg9 Location
Cumulative Flowback (bbls)
100,000
80,000
60,000
40,000
20,000
0
0
30
60
90
120
Flowback Day
measured cum flowback
exp modeled cum flowback
hyberbolic modeled cum flowback


Daily Flowback Rate
Measured and Modeled Values
lpg10 Location
Daily Flowback Rate (bbls/d)
2,500
2,000
1,500
1,000
500
0
0
30
60
90
120
Flowback Day
measured flowback rate
exp modeled flowback rate
hyperbolic modeled flowback rate


Cumulative Flowback Volumes
Measured and Modeled Values
lpg10 Location
Cumulative Flowback (bbls)
100,000
80,000
60,000
40,000
20,000
0
0
30
60
90
120
Flowback Day
measured cum flowback
exp modeled cum flowback
hyberbolic modeled cum flowback



Daily Flowback Rate
Measured and Modeled Values
lpg11 Location
Daily Flowback Rate (bbls/d)
2,500
2,000
1,500
1,000
500
0
0
30
60
90
120
Flowback Day
measured flowback rate
exp modeled flowback rate
hyperbolic modeled flowback rate



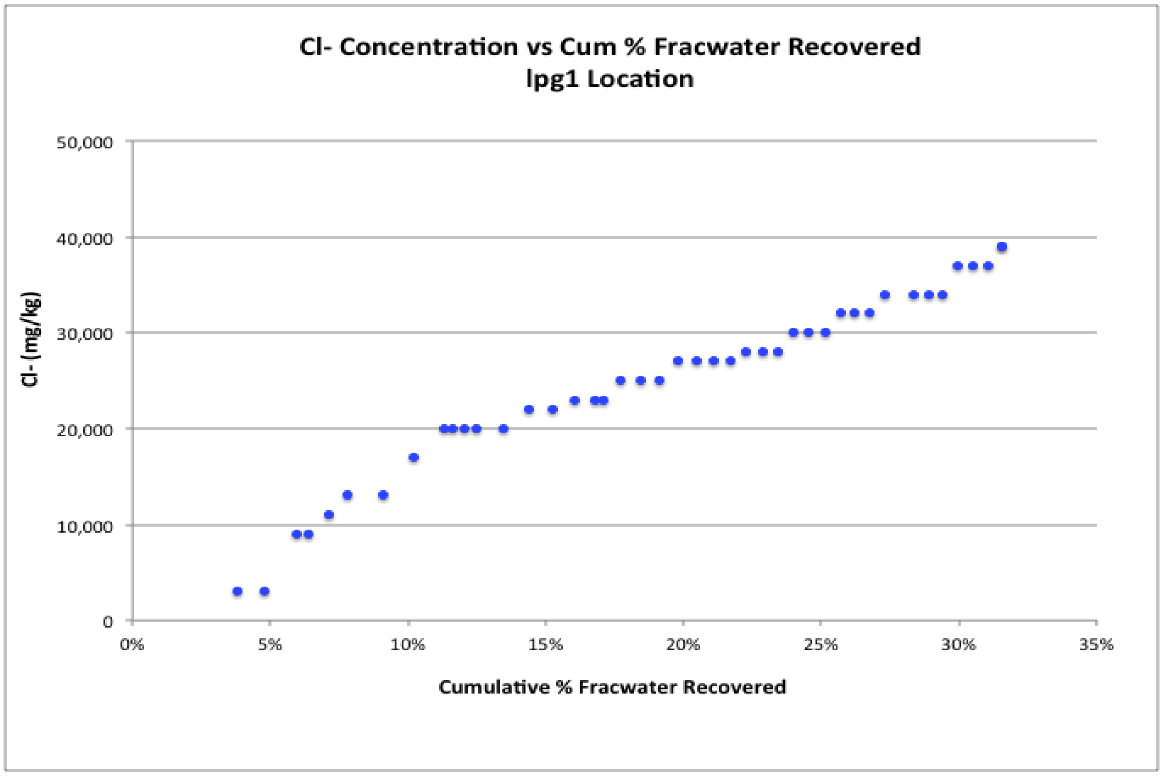
Cumulative Flowback Volumes
Measured and Modeled Values
lpg11 Location
Cumulative Flowback (bbls)
100,000
80,000
60,000
40,000
20,000
0
0
30
60
90
120
Flowback Day
measured cum flowback
exp modeled cum flowback
hyberbolic modeled cum flowback

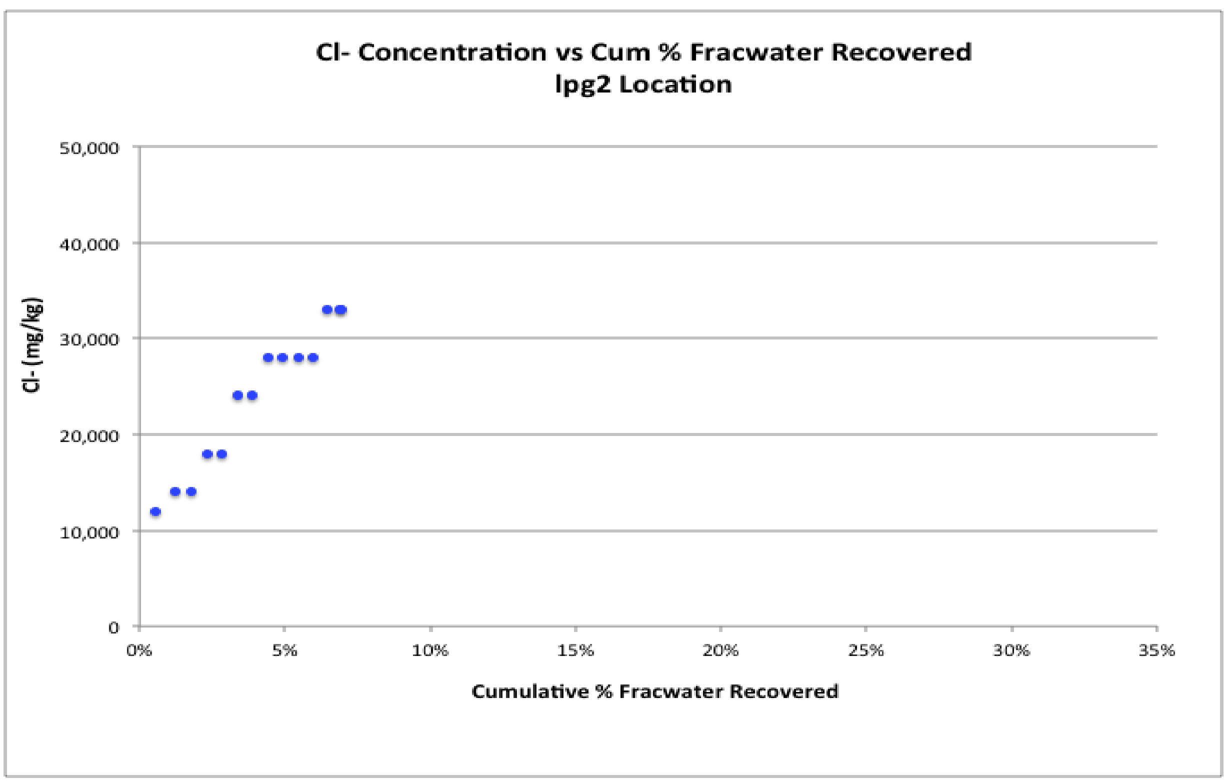
Table A-1: Best-fit model parameter estimates for exponential and hyperbolic flow-back equations

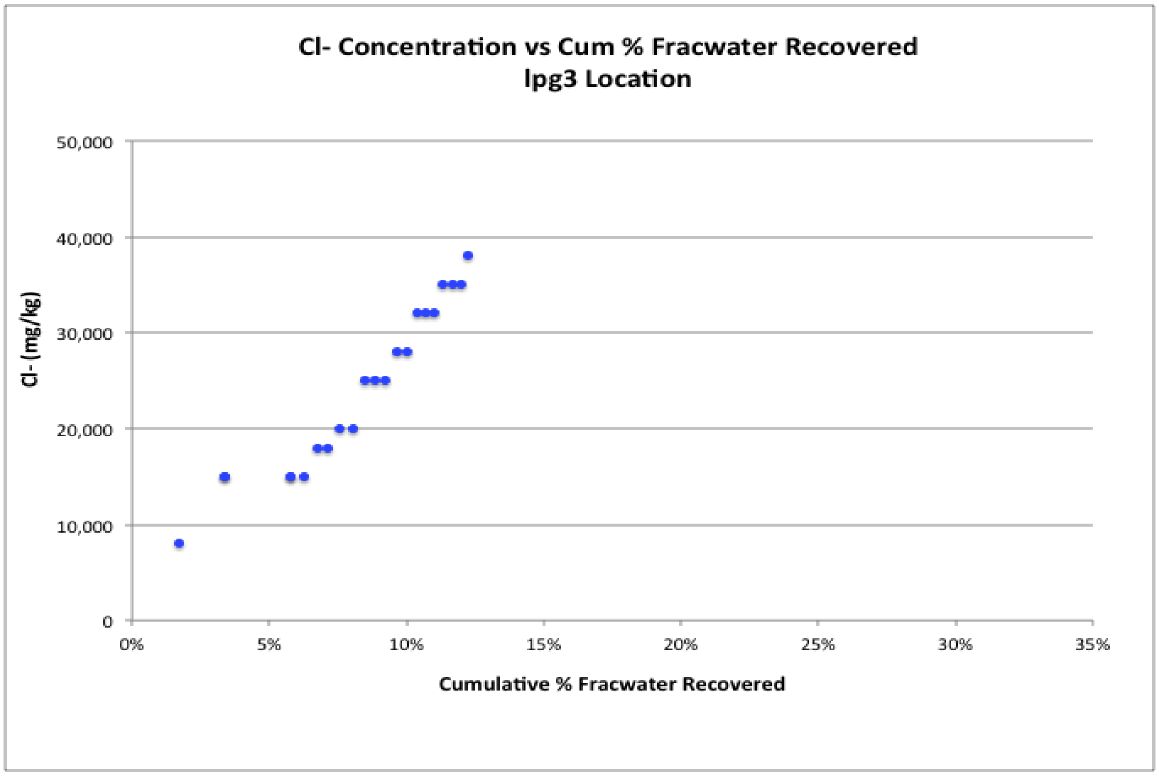
Site ID	**Initial Flowback Rate** (bbls/d)	**Exponential Function Exponent** (day^{-1})	**Hyperbolic Function Exponent**
lpg1	2,500	4.0 %	0.30
lpg2	1,200	5.0 %	0.10
lpg3	2,000	5.0 %	0.20
lpg4	1,000	6.0 %	0.20
lpg5	1,250	3.0 %	0.20
lpg6	1,250	4.0 %	0.60
lpg7	3,000	10.0%	0.10
lpg8	2,500	10,0%	0.40
lpg9	2,250	10,0%	0.50
lpg10	2,500	5.5%	0.25
lpg11	1,000	3.0%	0.60
average	**1,859**	**5.1%**	**0.31**
std deviation	**732**	**2.1%**	**0.18**

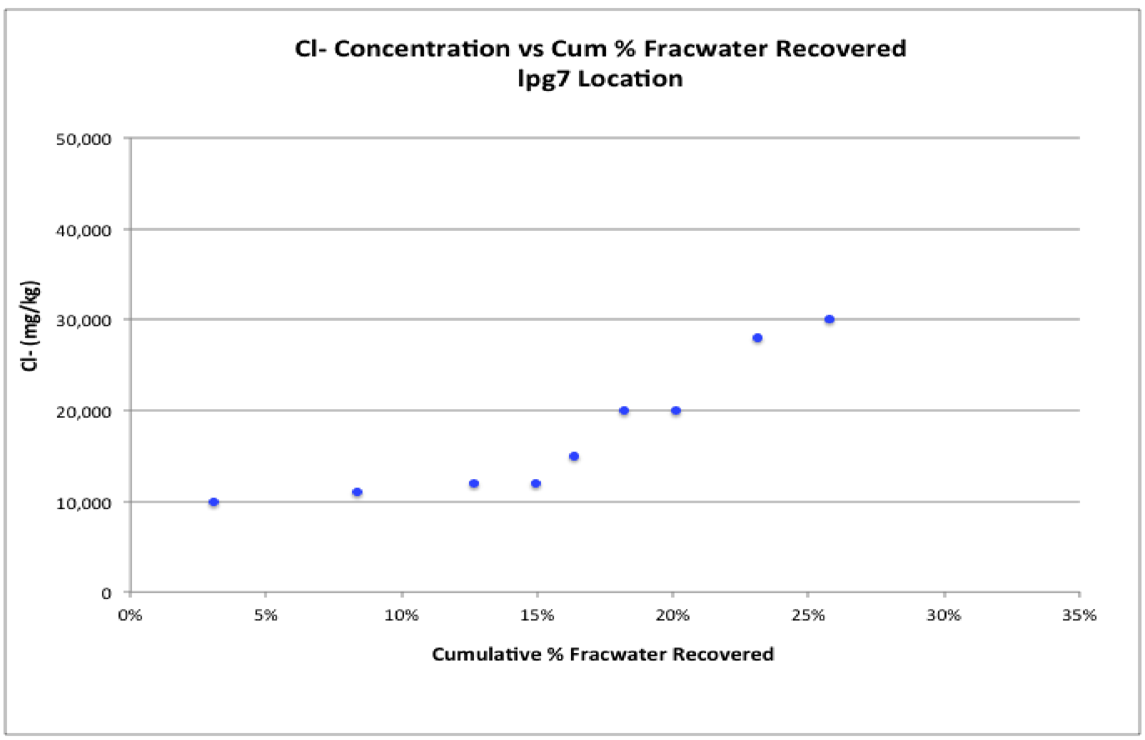
APPENDIX B– Flowback Chloride Concentrations[2] vs Cumulative Frac water Recovery for Six Individual locations

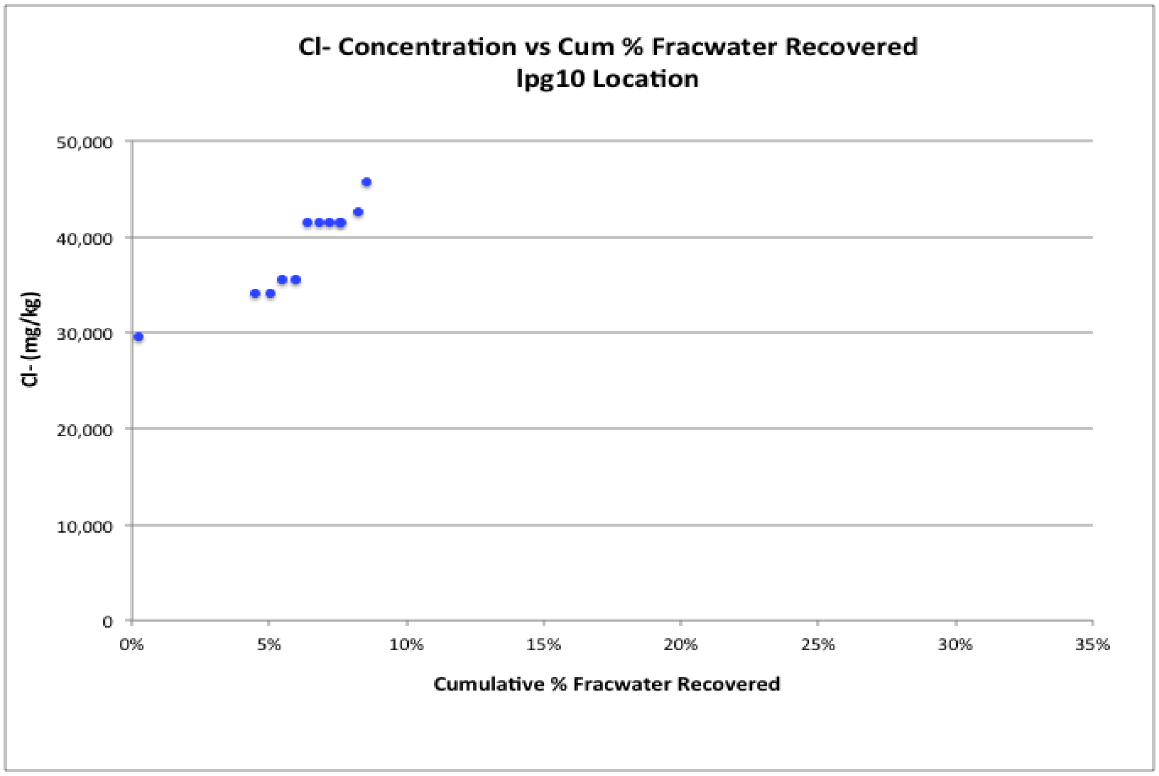
[2] Flowback chloride concentrations are the "instantaneous" values from the pipe. (They are not the chloride concentrations in the "mixed", cumulating flowback tanks).

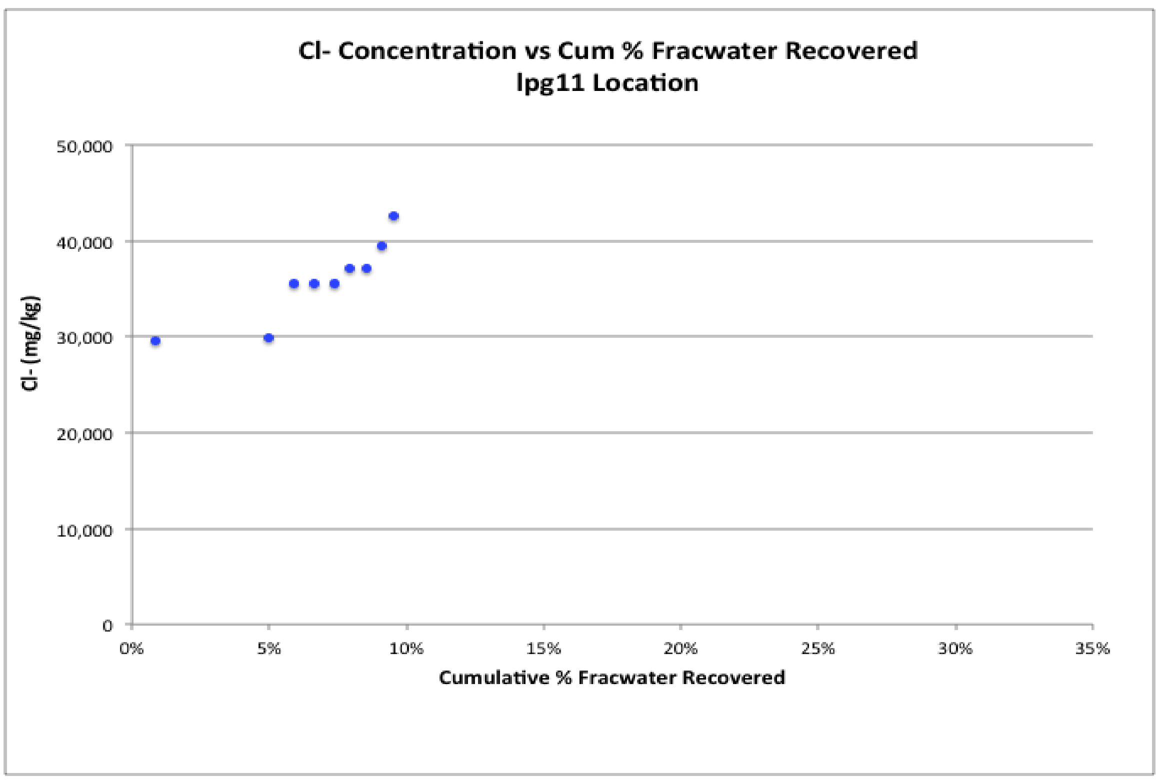

Cl- Concentration vs Cum % Fracwater Recovered
lpg1 Location
50,000
40,000
30,000
20,000
10,000
0
Cl- (mg/kg)
0%
5%
10%
15%
20%
25%
30%
35%
Cumulative % Fracwater Recovered


Cl- Concentration vs Cum % Fracwater Recovered
lpg2 Location
50,000
40,000
30,000
20,000
10,000
0
Cl- (mg/kg)
0%
5%
10%
15%
20%
25%
30%
35%
Cumulative % Fracwater Recovered


Cl- Concentration vs Cum % Fracwater Recovered
lpg3 Location
50,000
40,000
30,000
20,000
10,000
0
Cl- (mg/kg)
0%
5%
10%
15%
20%
25%
30%
35%
Cumulative % Fracwater Recovered


Cl- Concentration vs Cum % Fracwater Recovered
lpg7 Location
50,000
40,000
30,000
20,000
10,000
0
Cl- (mg/kg)
0%
5%
10%
15%
20%
25%
30%
35%
Cumulative % Fracwater Recovered


Cl- Concentration vs Cum % Fracwater Recovered
lpg10 Location
50,000
40,000
30,000
20,000
10,000
0
Cl- (mg/kg)
0%
5%
10%
15%
20%
25%
30%
35%
Cumulative % Fracwater Recovered


Cl- Concentration vs Cum % Fracwater Recovered
lpg11 Location
50,000
40,000
30,000
20,000
10,000
0
Cl- (mg/kg)
0%
5%
10%
15%
20%
25%
30%
35%
Cumulative % Fracwater Recovered