Supplementary Information

Assessing the Viability and Costs of Managing Wastewater from Hydraulic Fracturing in the UK

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S.I. 1 – Contaminant discharge limits for the UK and US, selected contaminants with discharge data available.

Contaminant	ug/L (unless otherwise denoted)					ug/L (unless otherwise denoted)	
	UK					USA	
	Fresh Water		Salt Water		Drinking Water	Drinking Water	
	Long-Term (mean)	Short-Term (95th %-ile)	Long-Term (mean)	Short-Term (95th %-ile)	Prescribed Concentration Value (PCV)	Maximum Concentration Limit (MCL)	Public Health Goal
Alpha Photon Emitters†						15pCi/L	0
Beta Photon Emitters†						4 millirems/yr	0
Ammonia * ϕ (unionised)			21		500		
Aluminium◊ϕ	15		15		200	200	
Antimony†ϕ					5	6	5
Arsenic*†ϕ	50		25		10	10	0
Asbestos†						7 million fibres per litre (MFL)	7 MFL
Barium†						2000	0
Beryllium†						4	4
Boronϕ					1000		
Bromate†ϕ					10	10	0
Bromine	2	5	none	10			
Cadmium†ϕ	0.25		0.2		5	5	5
Chromium (III) *†ϕ	4.7	32			50	100	100
Chromium (VI) *†ϕ	3.4		0.6	32	50		
Chlorine*†◊ϕ	2	5		10	none	4000	4000
Chloride◊ϕ	250000				250000		
Cobalt	3	100	3	100			
Copper*†◊ϕ	1 (bioavailable)		3.76 where DOC ≤1mg/l		2000	1300	1300
Cyanide*†	1	5	1	5		200	200
Fluoride†◊ϕ	1000 (<50 mg CaCO3/l) 5000 (>50 mg Ca\CO3/l)	3000 (<50 mg CaCO3/l) 15000 (>50 mg Ca\CO3/l)	5000	15000	1500	4000	4000
Iron*◊ϕ	1000		1000		200	300	
Lead†◊ϕ					10	15	0
Manganese*◊ϕ	123 (bioavailable)				50		
Mercury†ϕ					1	2	2
Nickelϕ					20		
Nitrate†◊ϕ					50000	10000	10000
Nitrite†◊ϕ					500	1000	1000
Radium $^{226+228}$ †						5 pCi/L	0
Selenium†ϕ					10	50	50
Silver	0.05	0.1	0.5	1			
Sodium ◊ϕ	none proposed	none proposed	none proposed	none proposed	200000		
Sulphate ◊ϕ	4000000	-	none	-	250000		

			proposed				
Thallium†						200	0.5
Uranium†						30	0
Vanadium	20 (class 1) - 60 (class 2)	-	100	-			
Zinc*	10.9 (bioavailable) + ambient background		7.9				

S.I. 2 - Monte Carlo Simulation Methods

Each Monte Carlo simulation was run with 10,000 iterations using R[1]. The input parameters used are listed in the following table, and the input equations are also described below. Uniform distributions were assumed between end-member data points. Results are presented showing the $P_{2.5}$, P_{50} and $P_{97.5}$ values, therefore indicating the 95% confidence interval and the median of each simulation. Cumulative frequency distributions (CDFs) are also provided, with the $P_{2.5}$ and $P_{97.5}$ values marked in solid colour corresponding lines, and the P_{50} values with dashed lines.

2.1 Input Parameters

		Minimum	**Maximum**	**Source**
Volume$_{injected}$		7,000m^3	18,000m^3	See S.I.4
Percentage$_{returned}$		10%	70%	See S.I.5
Cost$_{treatment}$	RO	\$0.50/m^3	\$12.33/m^3	See S.I.3.1
	MVC	\$0.47/m^3	\$25.16/m^3	See S.I.3.1
	CBD	\$50.31/m^3	\$164.50/m^3	Eureka Resources [1]
Energy$_{treatment}$	RO	0.13 kWh/m^3	6.4 kWh/m^3	See S.I.3.2
	MVC	6 kWh/m^3	16.26 kWh/m^3	See S.I.3.2
	CBD	*unknown*	*unknown*	*not provided*
Cost$_{disposal}$	Injection	\$1.2/m^3	\$25.16/m^3	See S.I.3.1

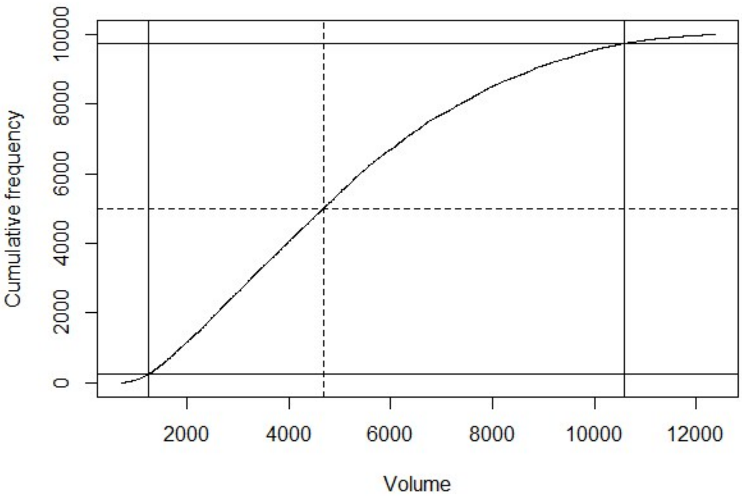
2.2 Input Equations

1. $Volume\ (V_{returned}) = Volume\ (V_{injected})\ .\ Percentage\ (P_{returned})$
2. $Cost\ (C_{total}) = Volume\ (V_{injected})\ .\ Percentage\ (P_{returned})\ .\ Cost\ (C_{treatment})$
3. $Energy\ (E_{total}) = Volume\ (V_{injected})\ .\ Percentage\ (P_{returned})\ .\ Energy\ (E_{treatment})$

2.3 Volume Simulation Results

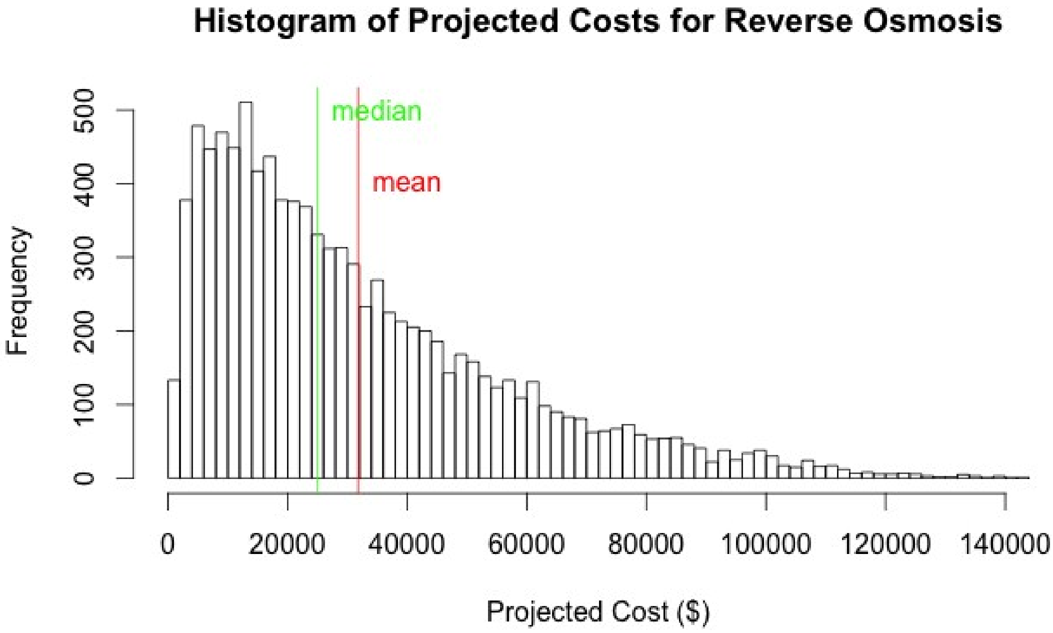
Projected Volumes (m^3) (95%^{CI})	$P_{2.5}$	P_{50}	$P_{97.5}$

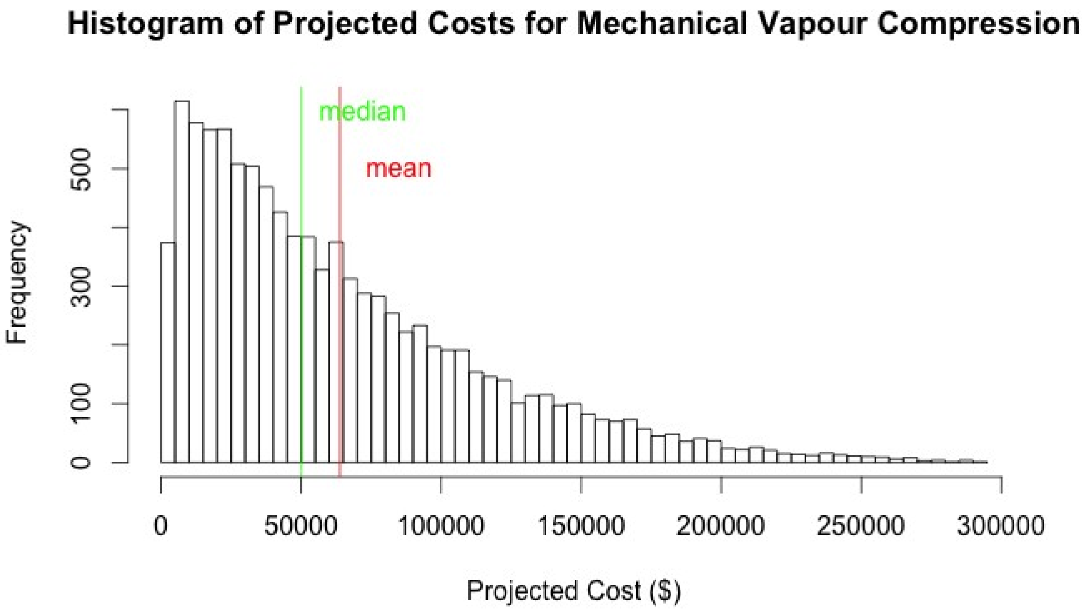
Injected	7287.02	12527.297	17748.43
Returned	1253.07	4676.047	10544.74
Retained	3035.46	7037.632	13889.07

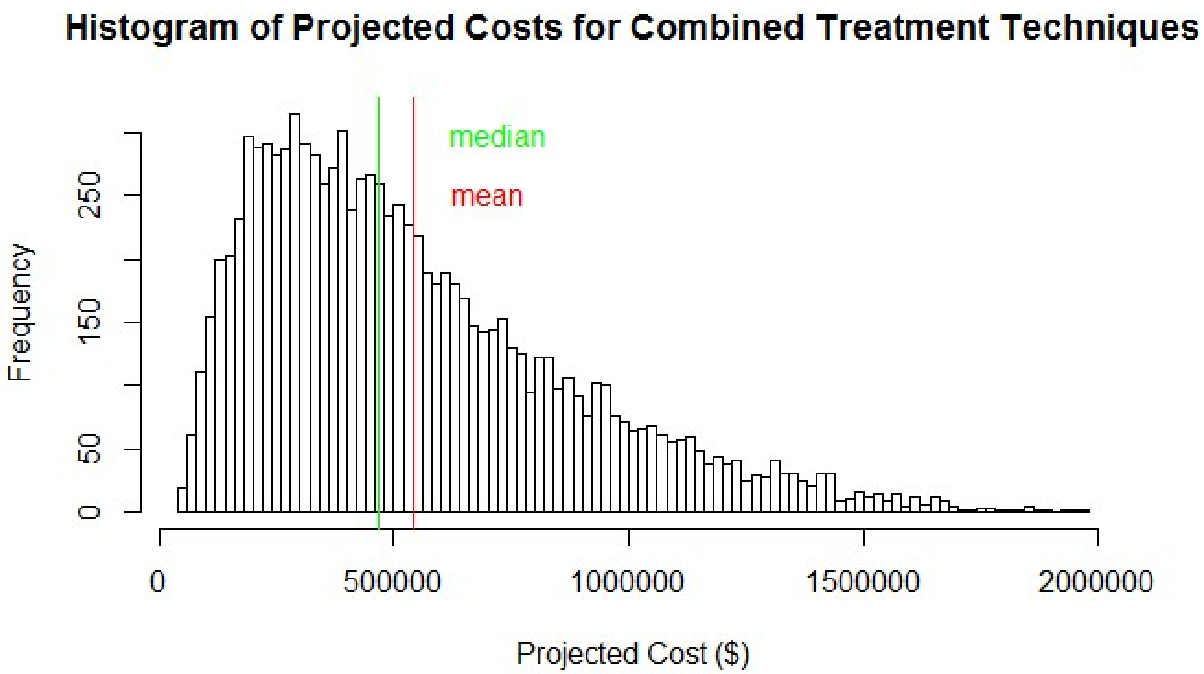


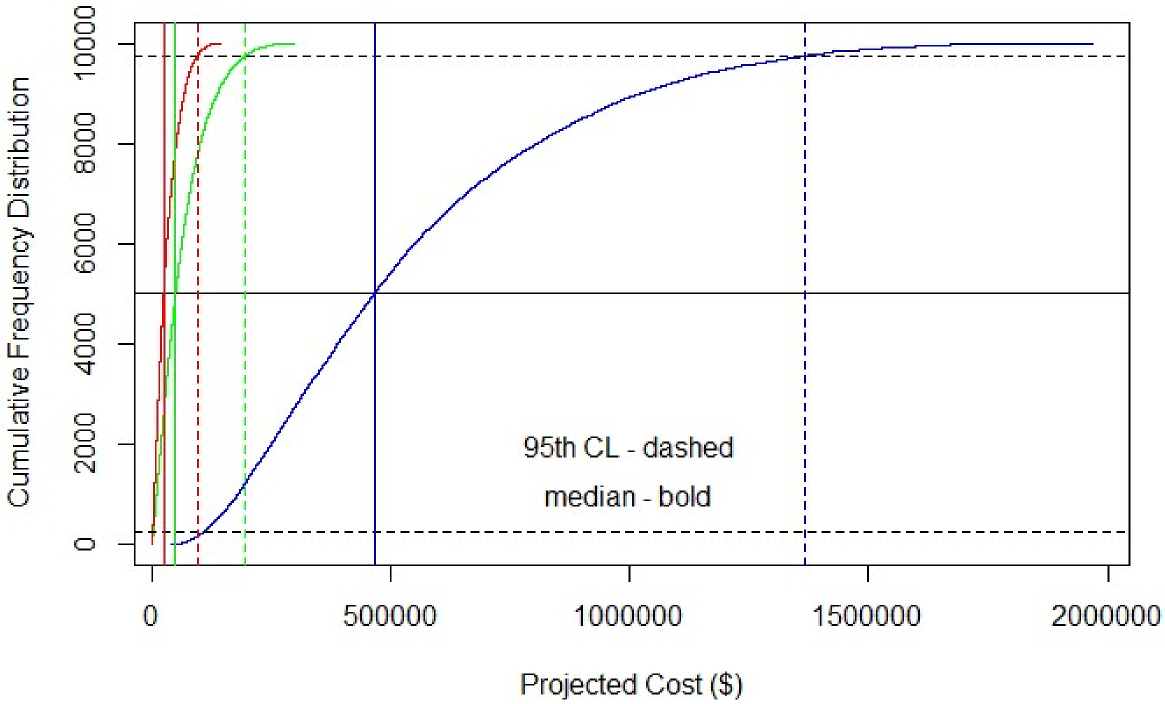
2.4 Cost Simulation Results

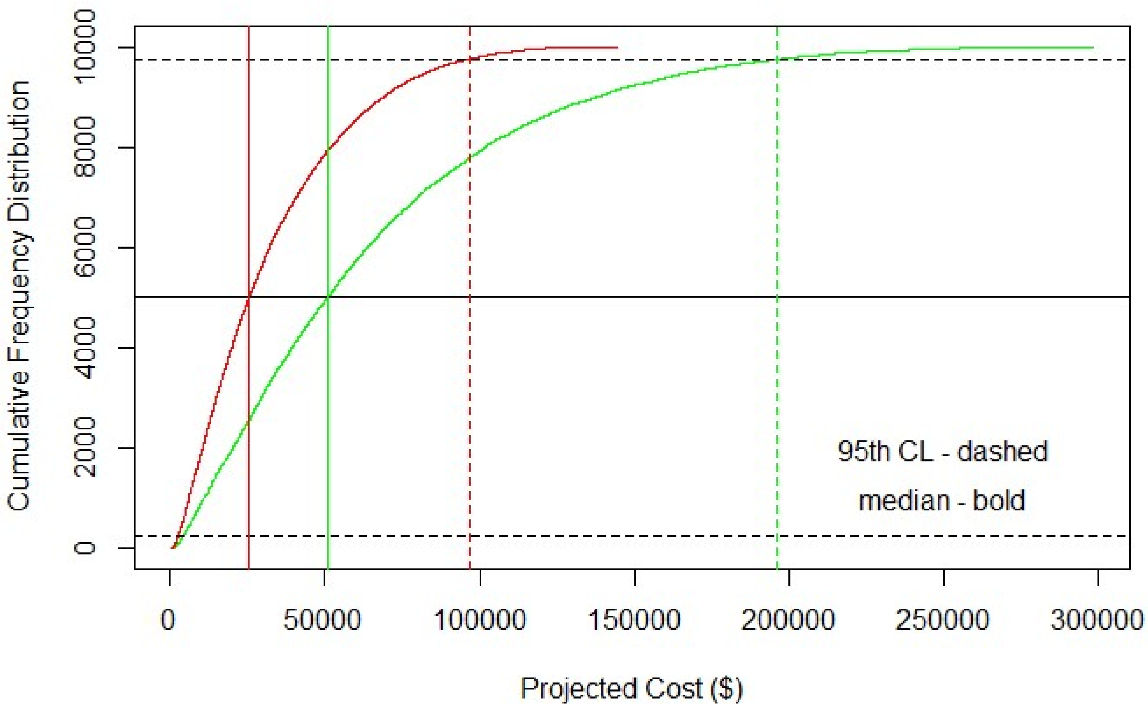
Projected Costs ($)	P_1	$P_{2.5}$	P_{50}	$P_{97.5}$	P_{99}
Reverse Osmosis	814.96	2,701.73	24,846.46	94,815.38	132,904.08
Mechanical Vapor Compression	955.61	3,952.76	50,506.23	196,484.74	270,996.33
Combined (Eureka Resources)	57,815.40	107,683.1	459,472.27	1,376,093.80	1,819,846.90






Histogram of Projected Costs for Combined Treatment Techniques
median
mean
Frequency
0
50
150
250
0
500000
1000000
1500000
2000000
Projected Cost ($)


Cumulative Frequency Distribution
0
2000
4000
6000
8000
10000
95th CL - dashed
median - bold
0
500000
1000000
1500000
2000000
Projected Cost ($)


Cumulative Frequency Distribution
0
2000
4000
6000
8000
10000
95th CL - dashed
median - bold
0
50000
100000
150000
200000
250000
300000
Projected Cost ($)

S.I. 3 – Treatment Technologies: Energy and Cost Intensiveness

3.1 Range in Cost of Treatment Techniques

Treatment	**Comparative Mean**	***units***	**Minimum**	***units***	**Maximum**	***units***
Reverse Osmosis <50,000 mg/L	2.16[2]	$\$/m^3$	0.19 10,000 mg/L	$/Bbl	0.50 35,000 mg/L	$/Bbl
	2.14[3]	$\$/m^3$	0.13	$/Bbl	0.21	$/Bbl
	5.03[4]	$\$/m^3$	0.2	$/Bbl	0.6	$/Bbl
	12.33[5]	$\$/m^3$	0.42	$/Bbl	3.5	$/Bbl
Mechanical Vapour Compression >50,000 mg/L	0.5[2]	$\$/m^3$	0.08 >40,000ppm	$/Bbl	0.08	$/Bbl
	1.32[3]	$\$/m^3$	0.21	$/Bbl	0.21	$/Bbl
	25.16[5]	$\$/m^3$	3.00	$/Bbl	5.00	$/Bbl
	0.83[6]	$\$/m^3$	0.42	$\$/m^3$	1.24	$\$/m^3$
Underground Disposal by Injection	1.20[3]	$\$/m^3$	0.19	$/Bbl	0.19	$/Bbl
	16.98[7]	$\$/m^3$	0.05	$/Bbl	2.65	$/Bbl
	6.8[8]	$\$/m^3$	0.59	$\$/m^3$	13.00	$\$/m^3$
	10.50[4]	$\$/m^3$	0.07	$/Bbl	1.6	$/Bbl
	25.16[9]	$\$/m^3$	1	$/Bbl	3	$/Bbl
	16.98[10]	$\$/m^3$	0.05	$/Bbl	2.65	$/Bbl

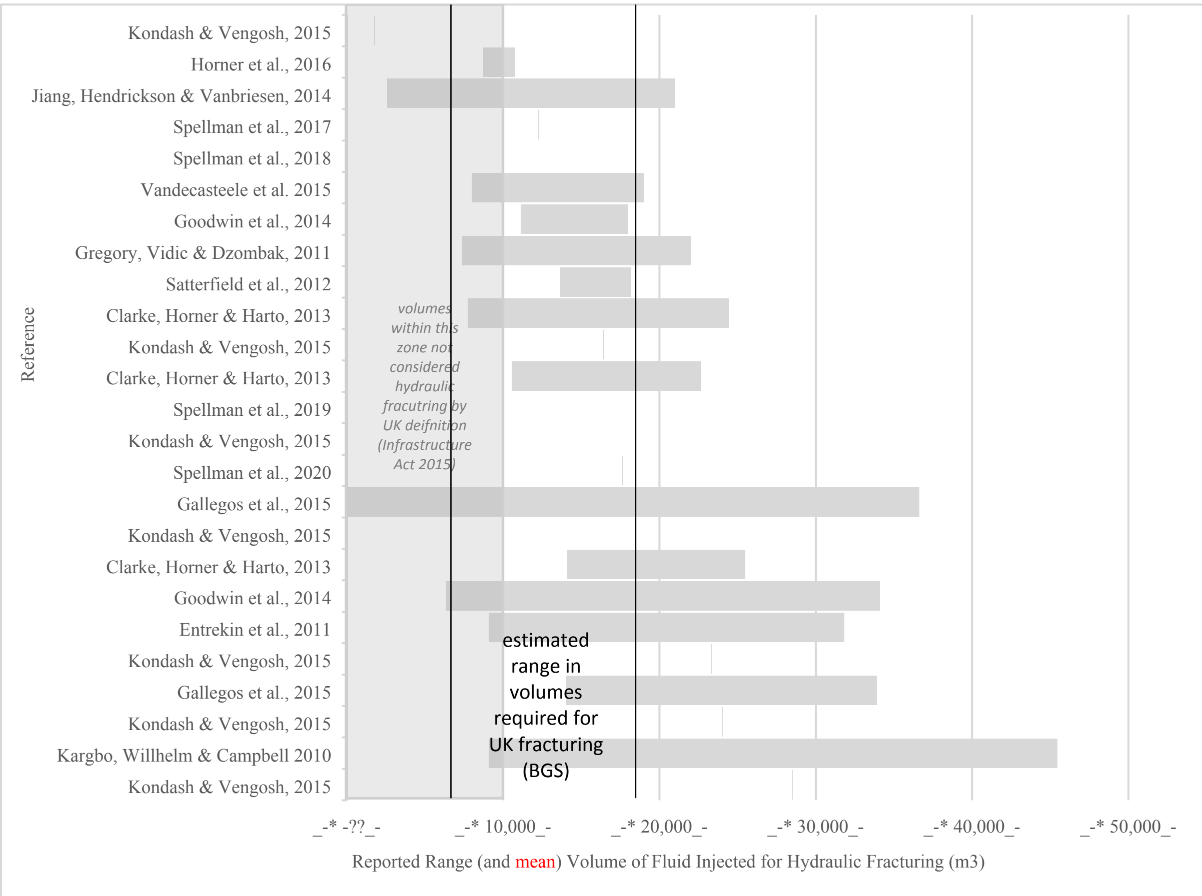
3.2 Range in Energy Requirements of Treatment Techniques

Treatment Technique	**Abbreviation**	**SINGLE VALUE**	**LOW**	**HIGH**
		kWh/m3	**kWh/m3**	**kWh/m3**
Mechanical Vapour Compression	MVC[11]	13.6		
Mechanical Vapour Compression	MVC[11]		10.4	11.2
Membrane Distillation	MD[11]	680		
Membrane Distillation	MD[11]	40		
Multi-Stage Flash Distillation	MSF[12]		15.32	16.72
Multi-Effect Distillation	MED[12]		9.73	13.65
Mechanical Vapour Compression	MVC[12]		11	12
Thermal Vapour Crystallisation	TVC[12]	14.56		
Reverse Osmosis	RO[12]		2.1	6.4
Electrodialysis	ED[12]		2.64	5.5
Multi-Stage Flash Distillation	MSF[13]		19.58	27.25
Multi-Effect Distillation	MED[13]		14.45	21.35
Mechanical Vapour Compression	MVC[13]		7	12
Thermal Vapour Crystallisation	TVC[13]	16.26		
Sea-Water Reverse Osmosis	SWRO[13]			

Brackish Water Reverse Osmosis	BWRO[13]			
Electrodialysis	ED[13]			
Nanofiltration	NF[2]	0.50		
Sea-Water Reverse Osmosis	SWRO[2]		2.89	4.21
Brackish Water Reverse Osmosis	BWRO[2]		0.13	0.82
Multi-Stage Flash Distillation	MSF[2]		21.07	29.56
Mechanical Vapour Compression	MVC[2]		26.42	66.04
Mechanical Vapour Compression	MVC[14]	6.1		
Mechanical Vapour Compression	MVC[15]		10.4	11.2
Mechanical Vapour Compression	MVC[16]		6	16
Mechanical Vapour Compression	MVC[17]		10	14
Multi-Effect Distillation	MED[17]	15		
Multi-Stage Flash Distillation	MSF[17]	18		
Reverse Osmosis	RO[17]	5		
Multi-Stage Flash Distillation	MSF[18]		19.58	27.25
Multi-Effect Distillation	MED[18]		14.45	21.35
Mechanical Vapour Compression	MVC[18]	16.26		
Reverse Osmosis	RO[18]		1.5	2.5
Electrodialysis	ED[18]		0.7	5.5

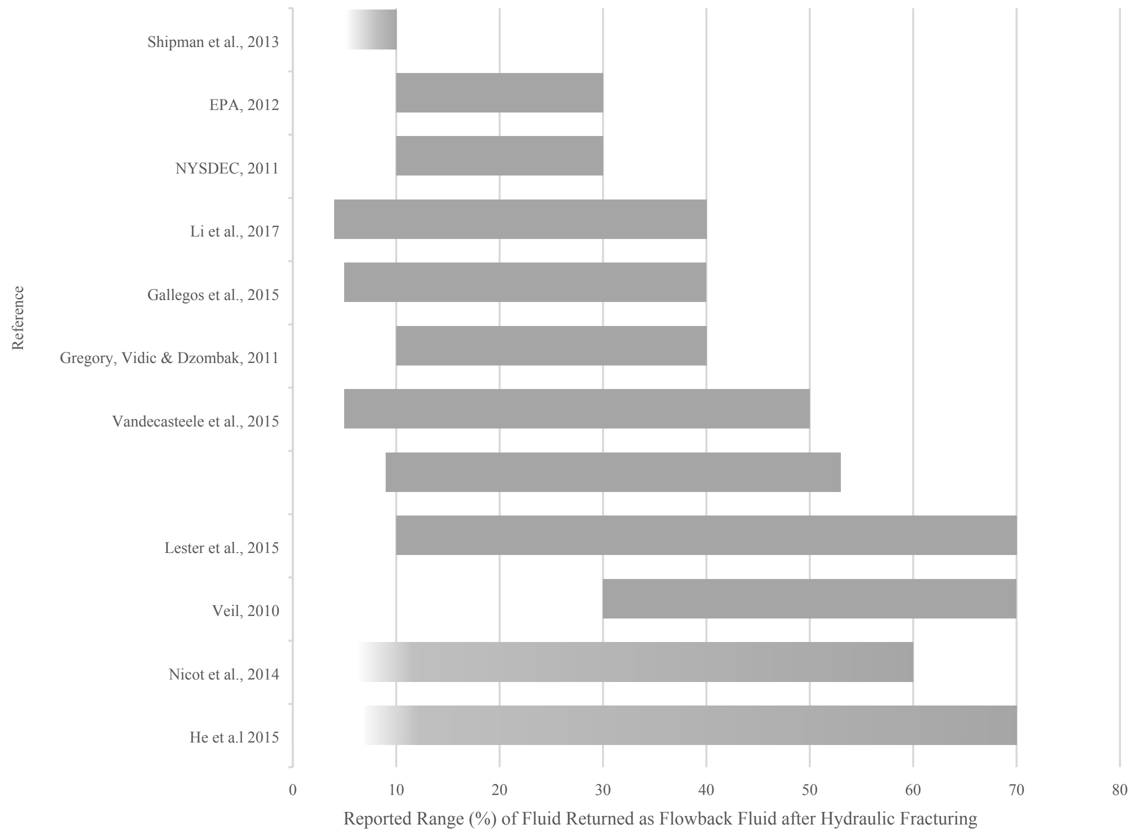
S.I.4 - Range in Water Volumes Required for Hydraulic Fracturing

Location(source)	Drilling (m³)		Fracturing (m³)		Total (m³)	
	Low / Individual	High	Low / Individual	High	Low / Individual	High
Barnett[19]	1,818		10,465		12,274	
Fayetteville[19]	273		12,814		13.456	
Haynesville[19]	4,546		12,274		16,821	
Marcellus[19]	364		17,275		17,639	
Marcellus[20]	400	4,000	7,000	18,000	7,400	22,000
U.S.A.[21]					14,000	33,900
U.S.A.[21]					10	36,620
Barnett[22]	920		6,800	23,500	7,720	24,420
Fayetteville[22]	70		14,000	25,400	14,070	25,470
Haynesville[22]	1,080		129,000	334,000	130,080	335,080
Marcellus[22]	670		9,900	22,000	10,570	22,670
Colorado[23]	311	764	10,820	17,184	11,131	17,948
Colorado[23]					6,365	34,096
Bakken[24]					8,728	10,744
Marcellus[8]	300	380	3,500	26,000	2,600	21,000
Marcellus[25]					9,092	45,461
Barnett[26]			10,600			
Haynesville[26]			21,500			
Eagleford[26]			16,100			
Marcellus[27]			9,092	31,823		
U.S.A.[28]	182	4,546	10,456	17,275		
Barnett[29]			<4,546	36,369		
Haynesville/Bossier[29]			4,546	45,461		
Eagleford[29]			<4,546	59,099		
Woodford/Pearsall[29]			<4,546	22,730		
Marcellus[28]			11,365			
U.S.A.[30]					9,092	31,823
Poland[31]					8,000	19,000
Barnett[32]					17,275	
Eagleford[32]					16,411	
Fayetteville[32]					24,049	
Haynesville[32]					19,321	
Marcellus[32]					1,773	
Niobarra[32]					28,504	
Woodford[33]					13,638	36,369


Kondash & Vengosh, 2015
Horner et al., 2016
Jiang, Hendrickson & Vanbriesen, 2014
Spellman et al., 2017
Spellman et al., 2018
Vandecasteele et al. 2015
Goodwin et al., 2014
Gregory, Vidic & Dzombak, 2011
Satterfield et al., 2012
Clarke, Horner & Harto, 2013
Kondash & Vengosh, 2015
Clarke, Horner & Harto, 2013
Spellman et al., 2019
Kondash & Vengosh, 2015
Spellman et al., 2020
Gallegos et al., 2015
Kondash & Vengosh, 2015
Clarke, Horner & Harto, 2013
Goodwin et al., 2014
Entrekin et al., 2011
Kondash & Vengosh, 2015
Gallegos et al., 2015
Kondash & Vengosh, 2015
Kargbo, Willhelm & Campbell 2010
Kondash & Vengosh, 2015
Reference
volumes within this zone not considered hydraulic fracutring by UK deifnition (Infrastructure Act 2015)
estimated range in volumes required for UK fracturing (BGS)
_-* -??_-
_-* 10,000_-
_-* 20,000_-
_-* 30,000_-
_-* 40,000_-
_-* 50,000_-
Reported Range (and mean) Volume of Fluid Injected for Hydraulic Fracturing (m3)

S.I.5 - Range in Flowback (reported as % of injected fluid)

Location	Low / Individual	High	Reference
Marcellus Shale, USA	10	40	Gregory, Vidic & Dzombak, 2011
USA	5	40	Gallegos et al., 2015
USA	9	53	
Barnett Shale, USA	60		Nicot et al., 2014
Marcellus Shale, USA	10	30	NYSDEC, 2011
Poland	5	50	Vandecasteele et al., 2015
USA	10	30	EPA, 2012
	4	40	Li et al., 2017
	70		He et a.l 2015
USA	10		Shipman et al., 2013
USA	10	70	Lester et al., 2015
USA	30	70	Veil, 2010



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