Joanne Townsend
Chief Executive Officer
Department of Environment and Natural Resources
PO Box 496
PALMERSTON NT 0830

By email: [redacted]

Dear Ms Townsend

RE: HYDRAULIC FRACTURING INQUIRY – INFORMATION REQUEST

I refer to the *Scientific Inquiry into Hydraulic Fracturing of Unconventional Reservoirs in the Northern Territory* (**the Inquiry**), which was established by the Northern Territory Government under the *Inquiries Act 1945* (NT) in late 2016 to investigate the impacts and risks of hydraulic fracturing of onshore shale gas reservoirs and associated activities on the environmental, social, economic and cultural conditions in the Northern Territory.

1. **Surface spills and groundwater contamination**

One of the key risks that the Inquiry has identified is the risk that surface spills of fracking chemicals and wastewater will reach and contaminate surface aquifers. The Inquiry has asked interest holders currently operating in the Beetaloo sub-basin, incluing Pangaea, Origin and Santos, to comment on the possibility that contaminants in surface spills will reach surface aquifers. The companies responded with varying levels of detail.

Santos advised that it had commissioned EHS Support Pty LTD (**EHS**), a specialist consultancy group, to model the likelihood of a spill reaching the Cambrian Limestone Aquifer on exploration permit 161 (**Attachment A**). EHS's assessment concluded that, even for a 1ML spill, it would take at least a decade to reach the water table, allowing plenty of time for, among other things, interception, clean up, and chemical degradation. The time frame was attributed to the large distance (80 metres) between the surface and the aquifer combined with the relatively low permeability of the overlying strata at that location.

The Inquiry's Terms of Reference require it to consider the risks of surface spills to groundwater across the whole of the Northern Territory – not just the Beetaloo sub-basin. In that regard, the Inquiry requests the Department of Environment and Natural Resources to:

1. comment on the approach that has been adopted by EHS and its potential general applicability to locations elsewhere in the Northern Territory; and

2. for each of the regions listed below, provide a consolidated summary of:

    a. the distance from the surface down to the closest surface beneficial use aquifer (that is, an aquifer used for drinking, stock watering or agriculture); and

    b. the permeability of the horizons overlying the water, including any areas where there may be preferential pathways to the aquifer (e.g. sink holes).

The regions to be considered are the Beetaloo Basin (between Larrimah and Daly Waters), Beetaloo Basin (between Daly Waters and Elliot), Barney Creek Formation, Arthur Creek formation (Georgina Basin), Bonaparte Basin, Amadeus Basin, and the Perdika Basin.

2. Oxygen

The Inquiry is assessing possible microbrial decomposition of organic contaminants in groundwater systems. To the extent practicable, please provide the Inquiry with information about the dissolved oxygen concentrations that have been measured in any of the Beetaloo (or surrounding) aquifers, including the depths that the measurements were made at and the method of sampling used.

In order to meet current reporting timeframes, could I please have your response no later than **<u>Wednesday 20 September 2017</u>**. Please also note that your response will be published on the Inquiry's submission library. To the extent your submission includes confidential information that should not be publicly disclosed, please identify that information and explain why it is confidential.

Yours sincerely

THE HON JUSTICE RACHEL PEPPER
Chair
11 September 2017

Please direct all correspondence regarding the Scientific Inquiry into Hydraulic Fracturing to:
Hydraulic Fracturing Taskforce
GPO Box 4396, Darwin NT 0801
T 08 8999 6573
E fracking.inquiry@nt.gov.au
W frackinginquiry.nt.gov.au

15 August, 2017

EHS Support Pty Ltd
PO Box 297
Port Melbourne,
Victoria, 3207

Santos Ltd
32 Turbot Street,
Brisbane QLD 4000

Please find attached, EHS Support Pty Ltd technical memorandum for the assessment of potential risk to groundwater associated with hypothetical shale gas activities in the Northern Territory.

Should you have any questions or require additional information, please feel free to contact me at [redacted]

Sincerely,
EHS Support Pty Ltd

Chris Smitt
Principal Hydrogeologist

Nigel Goulding
Chief Technical Officer

Preliminary

1. INTRODUCTION

The following memorandum provides an assessment of the potential for impacts on groundwater associated with hypothetical shale gas activities in the Northern Territory. For the purpose of this assessment two primary modes of potential impact were identified (releases to the land surface and the strategic burial of drilling mud) and technical assessment and modelling is provided in the sections below.

1.1. OBJECTIVE

The objective of this assessment is to define the potential extent of the area impacted by a release or "spill" of fluids. Specifically, the following questions were addressed:

1. Using three spill scenarios (1,000L; 100,000L and 1ML), determine the maximum pooled area in which a spill would inundate;
2. Over the size of the pooled area, determine infiltration rates to gain an understanding of vertical groundwater movement and associated travel times;
3. Evaluate the potential impacts on groundwater from burial/management of drilling muds at the well sites (where muds are blended and buried with soils); and.
4. Provide a description of what remedial actions could be implemented if impacts to groundwater were observed.

1.2. SCOPE OF WORK

To meet the objectives described above, the following work tasks were undertaken:

1. Establishment of applicable soil/aquifer characteristics within the area of interest based on a literature review and geological log from Santos exploration bore Tanumbirini-1;
2. Assessment of the water pooling area on a flat surface using the formulae proposed by Grimaz et al. (2007);
3. Assessment of the infiltration capacity of surface soils and ponding time using the analytical Green and Ampt infiltration equation;
4. Evaluation of potential migration and attenuation of common drilling fluid constituents if materials were buried below surface as part of the management of drilling muds; and
5. Discuss the remedial technologies that would be employed if impacts to groundwater occurred due to surficial releases and associated infiltration.

2. OVERVIEW OF HYDROGEOLOGY/GEOLOGY

The area of interest where this assessment will occur is within Santos exploration areas of the Beetaloo Sub-Basin (refer **Figure 1**).

The hydrogeological unit of interest is the Cambrian Limestone Aquifer (CLA) defined as the Top Springs Limestone (also commonly referred to as the Tindal Limestone or Gum Ridge Formation) depending on which part of the basin you are in. The unit comprises massive and commonly dolomitised (and often fractured and karstic) limestone beds with minor siliclastic mudstone. Results from Santos exploration bore Tanumbirini-1 (refer **Figure 1** for location and **Figure 2** for stratigraphy), reveal that the Top Springs Limestone can be found at a depth of 52mbgl with a thickness of 150m. For detailed broad scale geological interpretation of the regions geology refer to Fulton, 2009; Kruse et al, 2013.

In the vicinity of exploration bore, Tanumbirini-1, the CLA is confined by Cretaceous siltstones mudstones. The permeability of the CLA is highly dependent on the development of dissolution and fracture features

(Fulton and Knapton, 2015). A review of water bores that intersect cavities or record circulation loss during drilling suggests that the karst development is widespread across the Beetaloo Sub-Basin and that aquifer permeability is generally not spatially correlated. Within the broader basin over 415 operational and abandoned water bores screen the CLA, with bore depths ranging from 34 – 221 m (average 105 m) (*ibid*).

Fulton and Knapton, (2015), reported airlift yields range from 0.3 – 20 l/s (average 3.5 l/s), with the standing water level (SWL) in the Gum Ridge Formation ranging from 23 to 155 metres below ground level (mBGL). Water levels along the Carpentaria Highway on Amungee Mungee and Tanumbirini stations are reported to be (125 mBGL) (*ibid*). Results from 21 pumping tests undertaken by WRD report a Transmissivity (T) range of 3 – 3377 m^2/d. The lowest T values (<50 m^2/d) occur in the northwest of the basin where the CLA has limited saturated thickness and aquifer development is restricted to the unconformity with the underlying Antrim Plateau Volcanics (Yin Foo, 2002).

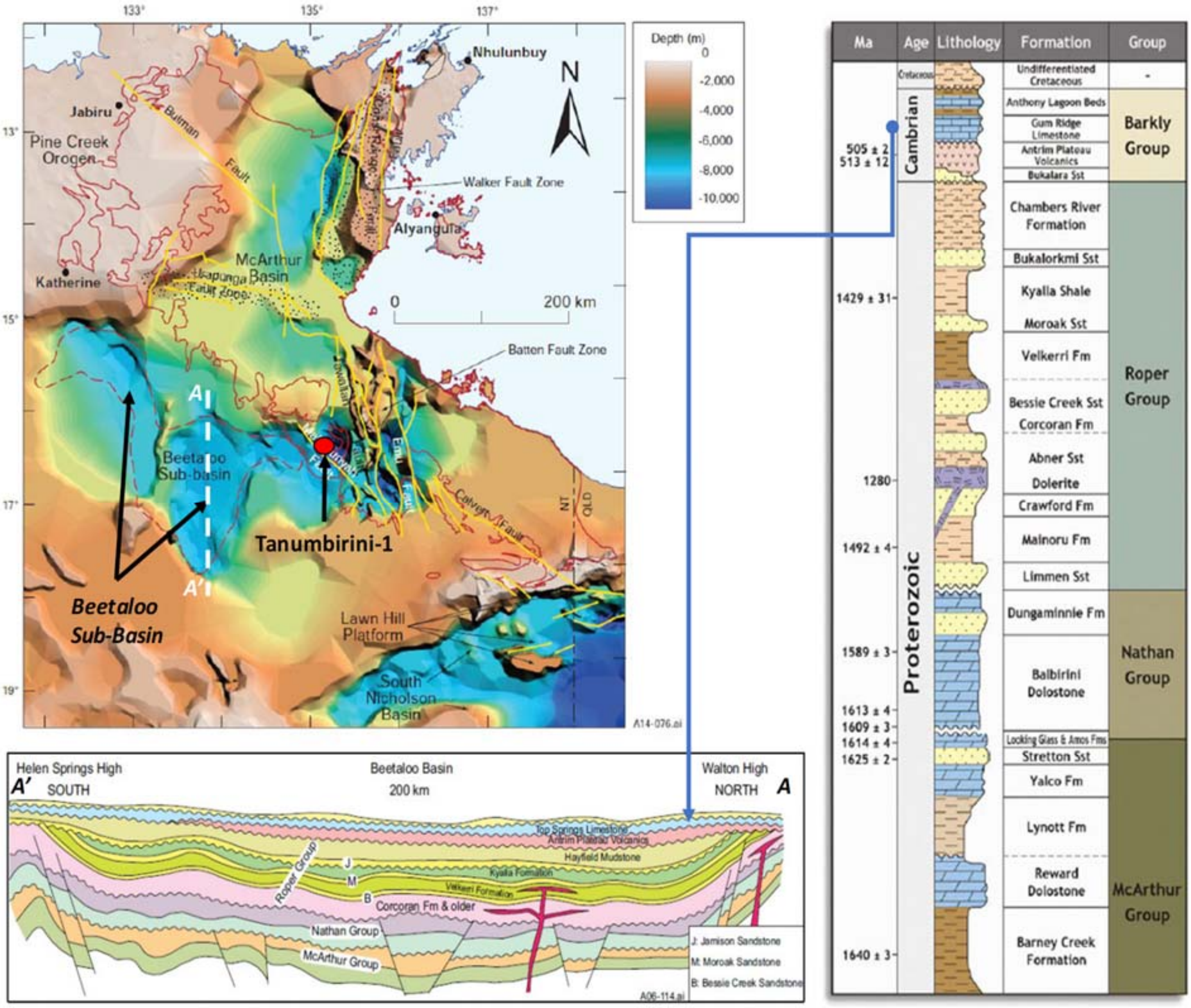


Figure 1. Location of the Beetaloo Basin along with Santos assets, stratigraphy and a north-south section. Reference used to create Figure 1: Silverman et al. (2008) [geological cross-section], and Close et al: 2016 [SEEBASE™ depth-to-basin image & stratigraphic column]

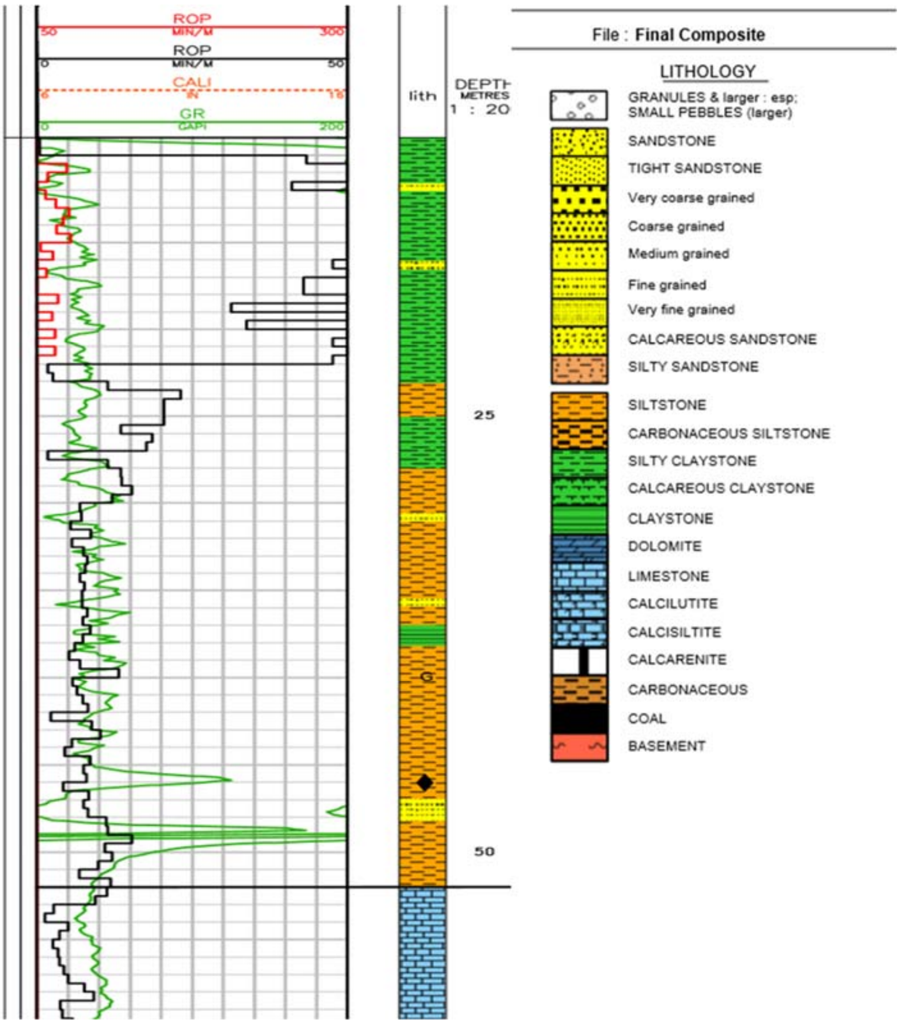


Figure 2 Shallow Lithology from Santos well "Tanumbirini-1

3. ANALYTICAL ASSESSMENT (METHODOLOGY)

3.1. WATER POOLING ON FLAT SURFACES

For instantaneous releases on flat surfaces, the formulae (**Equation 1**) proposed by Grimaz et al. (2007) was used to estimate the area of the pool of liquid on flat ground. This method is used for oil spills but can allow for water by varying the liquid properties (primarily viscosity and permeability).

$$A_{pool} \cong 2.3782 \frac{Q^{4/5}}{(k_i k_r)^{1/5}} \quad (1)$$

Where: A_{pool} *is the area of the pool of liquid on the surface [m2]; q is the flow rate of release [m3 s-1]; Q is the total amount of liquid released [m3]; ϑ is the kinematic viscosity of the liquid [m2 s -1]; g is the gravitational acceleration [ms-2]; ki is the intrinsic permeability of soil [m2]; kr, is the relative permeability of the liquid [-]*

3.2. TIME FOR WATER TO REMAIN ON SURFACE

Equation (**2**) taken from Grimaz et al. (2007), can be used to estimate the duration of the pool on the surface t_{ep}. and can be considered equal to the time of complete infiltration of the fluid into the porous medium. The method (**Equation 2**) is based on Darcy's Law and considers a theoretical depth of water pool and the seepage velocity at complete saturation:

$$t_{ep} = \frac{h_{tp}}{v_{p,s}} = \frac{V_{spill}}{A_{pool}} \frac{\theta}{K_w K} \frac{\emptyset_{fluid}}{\emptyset_{water}} \quad (2)$$

where; t_{ep} *is the estimated duration of the liquid pool on the surface [s];* h_{tp} *is the depth of the liquid pool [m];* $v_{p,s}$ *is the velocity of penetration of the liquid into soil in saturated conditions [ms-1];* V_{spill} *is the volume of the liquid spilt [m3]; K is the soil hydraulic conductivity [ms-1];* θ *is the porosity of soil [-],* $\emptyset$ *the kinematic viscosity [m2 s -1]; and* K_w *is the is the relative permeability of the liquid [-].*

Then, in order to estimate the percentage of fluid evaporated from the pool in t_{ep} the daily pan evaporation rate can be applied. (Fulton and Knapton, 2015) report pan evaporation ranges between 5 and 11 mm/d (average about 7-8 mm/d) in the region.

3.3. INFILTRATION INTO UNSATURATED ZONE

The spilt fluid will not only tend to spread out over the surface of the soil and evaporate, but will also penetrate into the ground (unless it is impermeable). Infiltration to the unsaturated zone, and in particular infiltration capacity and time for ponding to occur can determined using the infiltration equation of Green and Ampt (1911).

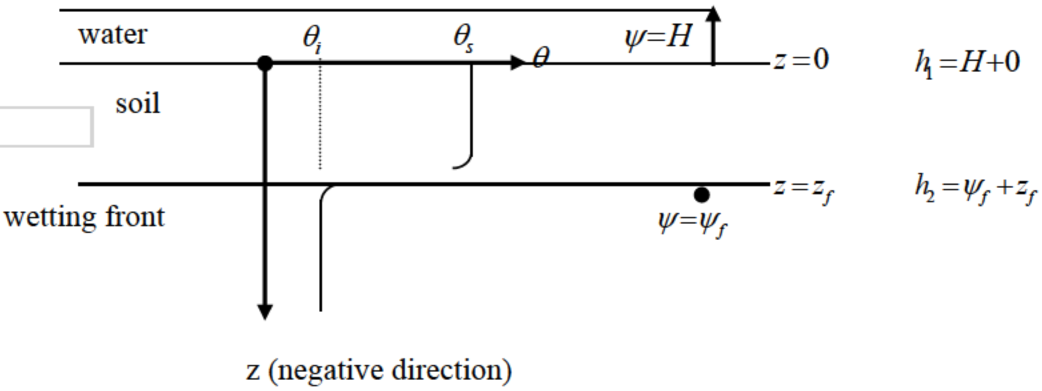
The infiltration rate actually experienced in a given soil depends on the amount and distribution of soil moisture and on the availability of water at the surface with a maximum rate at which the soil in a given condition can absorb water. This upper limit is called the infiltration capacity, f_c and is a limitation on the rate at which water can move into the ground. If surface water input is less than infiltration capacity, the infiltration rate will be equal to the surface water input rate (w). If irrigation (analogous to a release) intensity exceeds the ability of the soil to absorb moisture, infiltration occurs at the infiltration capacity rate until the soil is saturated and ponding and associated runoff occurs. Infiltration capacity declines over time until a steady state is reached.

Several processes combine to reduce the infiltration capacity. The filling of fine pores with water reduces capillary forces drawing water into pores reducing the storage potential of the soil. Clay swells as it becomes wetter and the size of pores is reduced. Coarse-textured soils such as sands have large pores down which water can easily drain, while the fine pores in clays retard drainage. If the soil particles are held together in aggregates by organic matter or a small amount of clay, the soil will have a loose, friable structure that will allow rapid infiltration and drainage.

The calculation of infiltration at a point combines the physical conservation of mass (water) principle expressed through the continuity equation with quantification of unsaturated flow through soils, expressed by Darcy's equation. The downward hydraulic gradient inducing infiltration is from a combination of the effect of gravity, quantified by the elevation head, and capillary surface tension forces, quantified by the pressure head (negative due to suction) being lower at depth due to lower moisture content. If the water input rate is greater than the saturated hydraulic conductivity (i.e. w > Ksat), at some point in time the water content at the surface will reach saturation. At this time, the infiltration capacity drops below the surface water input rate and runoff is generated. This time is referred to as the ponding time. After ponding occurs, water continues to infiltrate and a zone of saturation begins to propagate downward into the soil as the wetting front. After ponding, the infiltration rate is less than the water input rate and the excess water accumulates at the surface and becomes infiltration excess runoff. As time progresses and the depth of the zone of saturation increases, the contribution of the suction head to the gradient inducing infiltration is reduced, so infiltration capacity is reduced. Once the soil profile is completely saturated no further water can infiltrate.

3.3.1. GREEN AND AMPT INFILTRATION MODEL

The Green – Ampt (1911) model (**Equation 3**) is an approximation of the infiltration process described above and was utilised to assess infiltration capacity and time for ponding for various soils.



$$q = -K_s \frac{dh}{dz} = -K_s \frac{h_2 - h_1}{z_2 - z_1} = -K_s \frac{(\psi_f + z_f) - (H + 0)}{z_f - 0} = -K_s \frac{\psi_f + z_f - H}{z_f} \qquad (3)$$

Where: H = *the depth of ponding, cm, Ks = saturated hydraulic conductivity (cm/s), q = flux at the surface (cm/h) and is negative, f = suction at wetting front (negative pressure head),* θ_i *= initial moisture content (dimensionless) and* θ_s *= saturated moisture content (dimensionless).*

The following assumptions are implicit in the Green and Ampt equation:

1. As water infiltrates, the wetting front advances at the same rate with depth, which produces a well-defined wetting front;
2. The volumetric water content remains constant above and below the wetting front as it advances; and
3. The soil-water suction immediately below the wetting front remains constant with both time and location as the wetting front advances.

As described in the results discussion (**Section 4**), the travel times for surface releases to reach groundwater are very long and therefore the potential for impacts to groundwater are low

3.4. ASSESSMENT OF LEACHING TO GROUNDWATER

The potential risk associated with the leaching of constituents from drilling muds over time was evaluated using the VLEACH model. This model determines vertical contaminant transport from materials placed in the unsaturated zone and its response to recharge over time. VLEACH was developed by the United States Geological Service for the United States Environmental Protection Agency (USEPA) and is an industry recognised model. This model allows for very conservative modelling of organic constituents moving through the unsaturated zone towards groundwater systems.

4. ANALYTICAL ASSESSMENT (RESULTS)

4.1. WATER POOLING ON FLAT SURFACES

The "pooled area" for the instantaneous releases of fluid was determined for the following release volumes:

- 1000L (1m^3);
- 100,000 L (100m^3); and
- 1,000,000 L (1000m^3).

Shallow lithology obtained from exploration well Tanumbirini-1 (Figure 2), summarized in Table 1: reveals two main hydrogeological units; a relatively impermeable siltstone/claystone followed by limestone which has been reported to have highly variable hydrogeological properties (see **Section 2**).

As a result, and for the purposes of assessing surface water pooling, soil properties reflective of a clay have been applied to **Equation 1**. These are presented in **Table 2**. Therefore using, **Equation 1,** and the information presented in **Table 2,** the theoretical area of pooled water over Clay is presented in **Table 3**. For the purpose of providing comparison, a more permeable sandier soils is also presented.

Table 1 Shallow lithology at Tanumbirini-1

Depth From (mbgl)	Depth to (mbgl)	Lithology (Figure 2)	Hydrogeological Unit
0	20	Silty Claystone	Anthony Lagoon Beds?
20	52	Siltstone	
52		Limestone	Tops Springs Formation / Tindal - Gum Ridge Limestone

Table 2 Modelling Input Parameters

Parameter	Clay / Claystone / Siltstone	Permeable Sandstone / Limestone	Literature Source
Porosity	0.482*	0.4**	* Dingman, 1994 **Knapton 2009
Saturated Hydraulic Conductivity (Ksat) (cm/s)	0.0007	0.038**	**Knapton 2006 (based on relevant aquifer transmissivity and thickness)
Air-Entry Tension (cm)	40.5	12.1	Dingman, 1994
Saturated Tension (cm)	30.78	9.2	Dingman, 1994
Intrinsic permeability (m^2)	1x10^{-13}	1x10^{-8}	Dingman, 1994

Table 3 Model Results - Pooled Water Area

	Volume Released (m3)	Area (m2)	Radius (m)
Clay / Claystone / Siltstone	1	947	17
	100,000	37691	110
	1,000,000	237820	275
Permeable Sandstone / Limestone	1	95	6
	100,000	3770	35
	1,000,000	23782	87

4.2. TIME FOR WATER TO REMAIN ON SURFACE

Using **Equation 2**, the results presented in **Table 3** and assuming the kinematic viscosity of the fluid is 1x10-6 m^2/s and a Kh:Kv of 1:100, the time it will take for a 5cm deep pool over the 1ML spill area is ~6 days. For a smaller spill of 1,000L, infiltration time is less than 1 day (~2 hours).

4.2.1. GREEN AND AMPT INFILTRATION MODEL

The results of the Green and Ampt Infiltration equation are present in **Table 4**.

As there are two distinct hydrogeological units (siltstone to a depth of ~50m followed by karstic limestone). The time it takes for water to infiltrate 50m through the siltstone (to the top of the limestone) and the time to migrate through an additional 50 m (to a depth of 100 m) and 150 m of limestone (to a depth of 200m) has been calculated to enable evaluation of travel times based on the potential variable depth to groundwater within the limestone across the field.

Previous studies have indicated the CLA (limestone) can be highly fractured and karstic (refer **Section 2**), a sensitivity analysis assuming k is 100 times greater in this limestone has been undertaken. This has also been applied to the overlying siltstone.

The results indicate that any spill will take ~690 years to move through the initial 50m before rapidly moving though the more permeable limestone. To provide a comparative / conservative case where permeability of the sub surface is increased by 2 orders of magnitude, travel times to the top of the CLA reduce to ~7 years. Furthermore, under each spill scenario, the release rate exceeds the infiltration capacity of the subsurface, therefore as the area increases with each spill (refer **Table 3**), the driving force on the wetting front remains the same and is constrained by the permeability.

It should be noted that the assessment is highly conservative. Due to CLA aquifer anisotropy, bulk basin scale hydraulic conductivities are likely to be lower than those modelled. Further the higher hydraulic conductivities used in the sensitivity analysis for the siltstone are considered improbable based on literature information for this unit.

Table 4 Green and Ampt Modelling Results

	Time for wetting front to reach 50 mbgs (days)	Time for wetting front to reach 100 mbgs (days)	Time for wetting front to reach 200 mbgs (days)
Siltstone (K = 0.000007 cm/s; 0.01 m/d)			
Run 1	252267 (690 yrs)		
Run 2	252267 (690 yrs)	-	-
Run 3	252267 (690 yrs)		
Karstic Limestone (K = 0.005 cm/s; 4.3 m/d)			
Run 1	-	252271 (~690 yrs)	252275 (~690 yrs)
Run 2		252271 (~690 yrs)	252275 (~690 yrs)
Run 3		252271 (~690 yrs)	252275 (~690 yrs)

Run 1 = 1,000L spill;
Run 2 = 100,000L spill
Run 3 = 1,000,000 L spill

Table 5 Green and Ampt Modelling Results (Sensitivity Analysis K = 100x Increase)

	Time for wetting front to reach 50 mbgs (days)	Time for wetting front to reach 100 mbgs (days)	Time for wetting front to reach 200 mbgs (days)
Clay (K = 0.0007 cm/s; 0.6 m/d)			
Run 1	2522 (~7 yrs)	-	-
Run 2	2522 (~7 yrs)	-	-
Run 3	2522 (~7 yrs)	-	-
Karstic Limestone (K = 0.5 cm/s; 432 m/d)			
Run 1	-	2523 (~7 yrs)	2523 (~ 7yrs)
Run 2	-	2523 (~7 yrs)	2523 (~7 yrs)
Run 3	-	2523 (~7 yrs)	2523 (~7 yrs)

Run 1 = 1,000L spill;
Run 2 = 100,000L spill
Run 3 = 1,000,000 L spill

4.3. ASSESSMENT OF BURIAL/MANAGEMENT OF DRILLING MUDS

Based on the chemistry for example drilling muds (refer **Table 6**), leaching assessments were conducted on a scenario where drilling muds were stabilized (by blending with native soils to manage residual moisture) and compacted and placed below ground surface. The blend of drilling muds and cuttings produces a low permeability material with a high cation exchange capacity (CEC). This typically results in metals and metalloids being strongly bound within the muds and the mud and cuttings exhibiting very low permeabilities. Drilling muds by design typically exhibit permeabilities between $1x10^{-8}$ m/s and $1x10^{-10}$ m/s.

For the purposes of this assessment it has been assumed that the hydraulic conductivity of the blended materials it is assumed that the combined material will have a hydraulic conductivity no lower than $1x10^{-6}$ m/s. Typically the drilling muds are buried 1-2 m below ground surface to ensure the materials are below the rooting depth of crops and plants and the area graded to prevent ponding and preferential infiltration of water.

For the purposes of the modelling, only water soluble organic compounds were assessed (insoluble organic compounds like starch and polymers would have no mobility in the formation) and Sodium from Sodium Chloride was evaluated conservatively by assuming no attenuation (although cation exchange with the dominant calcium ions would impede vertical migration of sodium and potassium). Furthermore, as the lithology is likely to be rich in clay, a sensitivity analysis was undertaken on Sodium to increase its “retardation factor” or Distribution Coefficient by 2 orders of magnitude.

The VLEACH model results for each chemical constituent (BOLDED, in **Table 6)** are presented in **Figure 3**.

The results indicate that the modelled constituents take a very long time to move through the subsurface and contain immeasurable concentrations once below several meters depth even before dilution and without taking into account biodegradation.

Table 6 Drilling Mud Chemistry (BOLD values indicate those subject to VLEACH Modelling)

Chemical Name	Concentration in Drilling Mud Solids (mg/kg)
Ethylene oxide/propylene oxide copolymer	24
Polyalkylene	22260
Polypropylene glycol	48
Silicic acid, potassium salt	22200
Sodium Chloride	**45600**
Sodium polyacrylate	1092
Copolymer of acrylamide and sodium acrylate	702
Glutaraldehyde	**300**
Glyoxal	31

Chemical Name	**Concentration in Drilling Mud Solids (mg/kg)**
Methanol	**3**
Potassium Chloride	41520
Sodium Carbonate	78
Sodium carboxymethyl cellulose	3117
Sodium Hydroxide	300
Starch	3058
Xanthan Gum	3060
Methylisothiocyanate (MITC)	30

Table 7 Constituent Properties

	Concentration in drilling (mg/L)	Organic Distribution Coefficient (ml/g)	Henry's Law Constant (atm-m3/mol)	Water Solubility (mg/L)	Free Air Diffusion Coefficient (m2/day)	Source
Methanol	3000	0.014	0.0001937	1000000	1.296	GSI Chemical Properties Database (http://www.gsi-net.com/en/publications/gsi-chemical-database.html)
Glutaraldehyde	300,000	0.07	0.0000108	85500000	0.096	GSI Chemical Properties Database (http://www.gsi-net.com/en/publications/gsi-chemical-database.html)
Sodium Chloride	29,900,000** (converted from **Table 6**)	1930* / 19.3	1E-20	360000**	0	*Bencala (1985) **http://srdata.nist.gov/solubility/index.aspx

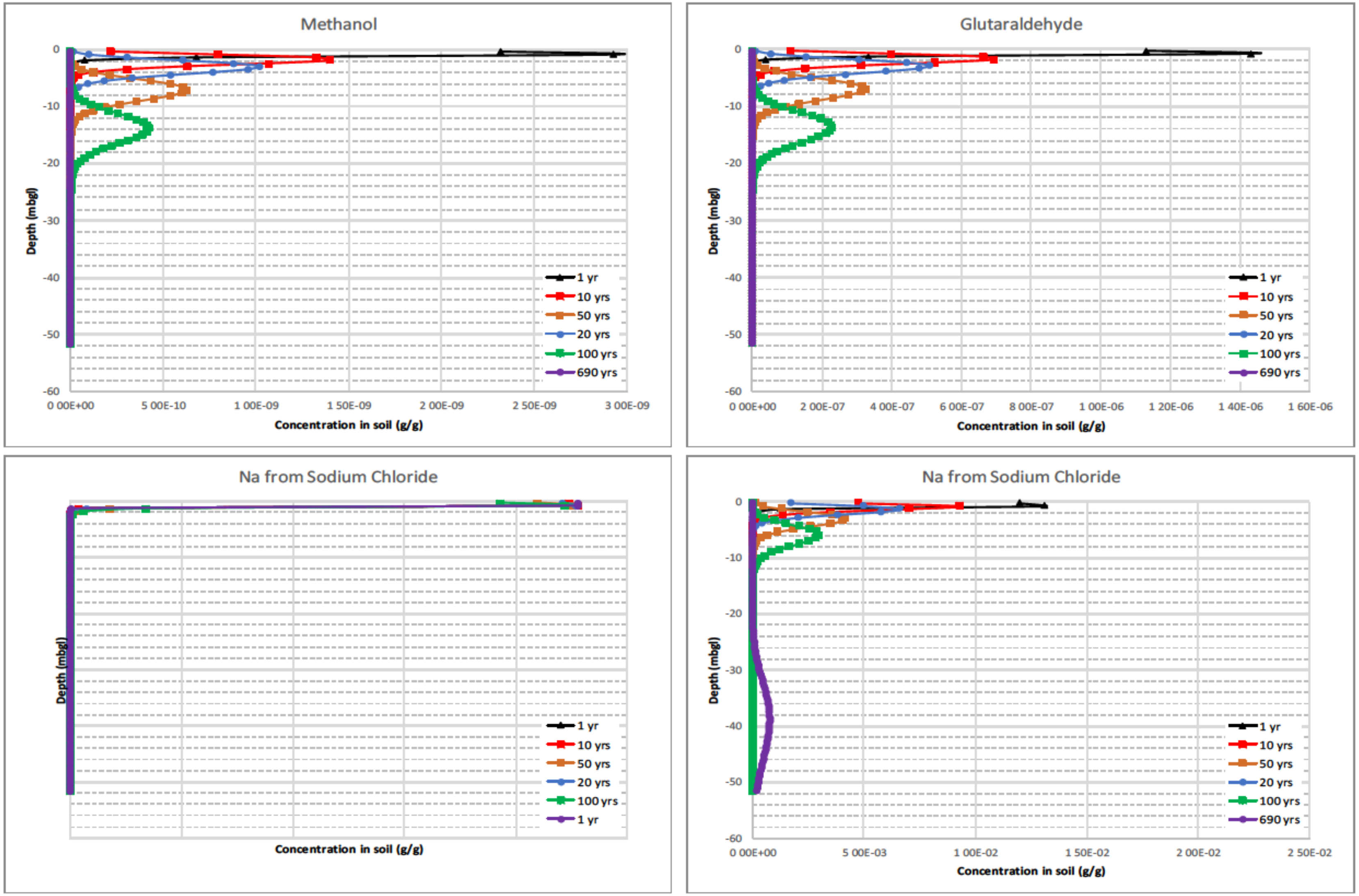


Figure 3 **VLEACH Results. [Note: Bottom left Na assumes a Distribution Coefficient 2 orders of magnitude higher then bottom right results].**

5. REMEDIAL OPTIONS OF GROUNDWATER

Based on the modelling provided above and considering the retardation processes in the formation, only water soluble constituents have the potential to migrate to and impact on groundwater. As demonstrated in the assessment above, the potential for impact on groundwater is considered limited and travel times are sufficient slow (>500 yrs to travel 50m) that management/monitoring and remediation (if required) could be implemented.

In the context of this hydrogeologic system, which has deep and prolific aquifer systems and considering the constituents of potential concern are soluble compounds, groundwater extraction and water treatment provides the best remedial option (if needed).

Based on the drilling fluid constituents that may impact on groundwater a range of treatment options are available including open air storage to facilitate natural dissociation, photodegradation, etc, biological treatment for alcohols, glycols, glutaraldehyde (they biodegrade rapidly in the presence of oxygen), activated carbon absorption (non-polar organics) and ion exchange. All of these technologies are readily available and could be quickly implemented.

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