NORTHERN
TERRITORY
GOVERNMENT

DEPARTMENT OF
ENVIRONMENT AND
NATURAL RESOURCES

Chief Executive Officer
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25 Chung Wah Terrace
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[redacted]

File Ref:

The Hon Justice Rachel Pepper
Chair
Hydraulic Fracturing Taskforce
GPO Box 4396
DARWIN NT 0801

Dear Justice Pepper

RE: HYDRAULIC FRACTURING INQUIRY – INFORMATION REQUEST

In response to your information request of 11 September 2017, the Department of Environment and Natural Resources has prepared the attached Response to Request for Information.

Should you require any further clarification or information on the response please contact this office.

Yours sincerely

JOANNE TOWNSEND
Acting Chief Executive Officer

Date: 20 September 2017

RESPONSE TO REQUEST FOR INFORMATION

Request for Information by the Hydraulic Fracturing Taskforce on 11 September 2017

1. Surface spills and groundwater contamination

a) *Comment on EHS report*

DENR is only able to comment on the appropriateness of the hydraulic parameters and conceptualisation applied to the Green-Ampt Infiltration model.

- The analysis presented by EHS Support appears to be highly conservative.
- The model is developed with 52m of shallow clay/claystone/siltstone overlying the permeable limestone of the Tindall/Gum Ridge Formation and assumes Tanumbirini-1 represents the geological section. There is uncertainty regarding whether the upper 52m represents Cretaceous aged sediments, Anthony Lagoon Formation sediments or both. This necessitates the assumption that the permeability of the material is similar in the horizontal and vertical directions. However, if it is predominantly Anthony Lagoon Formation, there is evidence that indicates that this Formation is vertically impermeable as it confines the underlying Gum Ridge Formation. Notwithstanding this, the hydraulic parameters used to represent this layer are appropriate for the material described.
- For the underlying limestone layer, a porosity value of 0.4 is used. This value is 10 times the actual value applied by Knapton (2009). This would result in conservative modelling outcomes (ie. the estimated travel times would be much shorter than actual).
- No comment is made regarding the VLEACH modelling except that it should be recognised that one of the functions of drilling mud is to create an impervious lining on the borehole thus limiting fluid loss. Therefore, ongoing infiltration loss from a pit should not be expected.

b) *Summary of conditions overlying various aquifers*.*

* It is important to note the distinction between an aquifer which will occur within permeable layers or features below the water table, and the top of the geological formation which may exist above the water table.

Beetaloo Basin (between Larrimah and Daly Waters)

The Tindall/Gum Ridge Formation hosts the only known aquifer underlying this region. The average depth to the top of the Formation is 30m. The water table lies at approximately 45m depth and an aquifer could be expected to be intersected within 15m of the top of the water table (ie. at 60m).

Most of the region is covered by a layer of Cretaceous sediments. Surface expression of collapse structures in the limestone exist. However, open sinkholes that provide a preferential pathway to the aquifer are rare.

Beetaloo Basin (between Daly Waters and Elliott)

There are two known aquifers underlying this region:

The Anthony Lagoon Formation

The Anthony Lagoon Formation hosts aquifers across the central part of the Barkly region where the Formation exists either below 50m of Cretaceous sediment, or subcrops at shallow depth. The water table is at approximately 60m and aquifers may be intersected within 60m below the water table.

The uppermost horizon covering a large part of the Barkly Tablelands area is low permeability black soils. Collapse structures generally do not develop in the underlying Anthony Lagoon Formation.

The Gum Ridge Formation

The Gum Ridge Formation hosts an aquifer across the Barkly region. In most parts, it underlies the Anthony Lagoon Formation at depth, but subcrops at shallow depth on the basin margins. Towards the centre of the basin, the top of the Gum Ridge Formation may be intersected at approximately 300m depth. On the western margin near Elliott, the top of the Formation is at 40m depth. An aquifer could be expected to be intersected within 30m of the top of the Formation (ie. at 60m).

Where the Gum Ridge Formation exists close to surface, the soprolitic horizon appears to be highly clayey with occasional disaggregated limestone beds. There is unlikely to be preferential pathways in this horizon. However, permeability will exist.

Barney Creek Formation

There are relatively few bores drilled in this region and no detailed studies have been undertaken. Aquifers overlying the Barney Creek Formation generally occur at shallow depth and may be developed in shallow Cretaceous sediments, Proterozoic sandstone or in the karstic terrain of the Karns Dolomite Formation. A water table may exist at approximately 20 to 30m depth.

There is a surface layer of sand and clay soils in this region. Open sinkholes occur on the areas underlain by Karns Dolomite and these will represent pathways to the aquifer.

Arthur Creek Formation (Georgina Basin)

No hydrogeological studies have been undertaken in this region. Aquifers overlying the Arthur Creek Formation mostly exist in limestone or sandstone. The water table lies at approximately 80 to 100m in depth.

The surface of the region is covered by a sandy and clayey weathered horizon to approximately 50m depth. However, a comment regarding its permeability cannot be made other than the existence of weathering in the upper profile implies a degree of permeability.

Bonaparte Basin

The only hydrogeological studies conducted in this region are in the vicinity of the Keep River Plains. A palaeochannel aquifer exists directly beneath the black soil floodplain and small fractured rock aquifers exist in the Proterozoic rocks surrounding the floodplain. The palaeochannel aquifer may be intersected between 20 and 30m below surface, whilst bores in the Proterozoic fractured rock aquifers typically intersect supplies below 30m from surface. The water table lies at approximately 10 to 20m in depth.

Upper soil profile studies have been undertaken to provide information regarding the potential for salinisation under irrigation of various land types in the region of the Keep River Plains. Tickell et al (2006) find that under natural conditions, the black soil areas of the plains are low in permeability (recharge rate ~ 0.1 mm/y) and receive no fresh recharge, while the red soils which generally overlie the sandstone bedrock, receive moderate recharge (~40 mm/y) through the wet season. There are no areas where sinkholes occur that represent preferential pathways to the aquifer.

Amadeus Basin

The predominant aquifers in the Amadeus Basin have developed in sandstones, dolomites and shales. They occur in primary (intergranular) and secondary porosity (fractures, karst). Depending on location, the depth to aquifers will vary from near surface (say 30m) to over 100m. Similarly, the water table may lie close to surface to below 100m.

The only study of permeability undertaken in the Amadeus Basin is by Cook (2016) over the Mereenie Sandstone in the Rocky Hill region. This region is outside the area mapped as overlying prospective shale gas source rocks. However, the results could be indicative of weathered Mereenie Sandstone across the Amadeus Basin. The drainage rate established by this study was between 80 and 130 mm/y.

There are no features such as sinkholes which could represent a preferential pathway to the underlying aquifer.

Pedirka Basin

The main aquifer overlying the Pedirka Basin comprises mainly sandstones within the sediments of the Great Artesian Basin (GAB). The permeable sediments that form the aquifer may be intersected from ground surface around the margin areas of the basin with the water table existing at approximately 60m. Fulton (2012) reports that recharge to this aquifer occurs readily through ephemeral flow in the rivers that incise the outcropping sediments, although diffuse recharge through rainfall infiltration can occur. Beyond the subcropping margins, the sediments of the GAB are overlain and the aquifer is confined by the impermeable mudstones of the Cretaceous aged Rolling Downs Group of rocks. As the mudstone layer thickens to the south-east, the depth to the top of the GAB sediments increases to hundreds of metres. In the area underlain by the Pedirka Basin, the top of the GAB sediments may be intersected from surface in the western margin to hundreds of metres beneath mudstone towards the centre of the basin.

Fulton (2012) established that the sediments of the GAB are highly permeable where they outcrop. Where they are overlain by the Rolling Downs Group, the aquifer is confined and is not susceptible to surface infiltration.

2. Oxygen

Water Resources has no record of any analysis for dissolved oxygen undertaken for bores in aquifers overlying the Beetaloo Basin. The only data available within the region is for bore RN035927 in the Tindall Limestone near Mataranka. The dissolved oxygen was 0.1 mg/L.

References

Cook PG, Knapton A and White N., 2016, *The Potential Impact of Irrigated Agriculture on Groundwater Quality in the Rocky Hill Region, Northern Territory*. National Centre for Groundwater Research and Training, Australia (not yet published).

Fulton S. A., 2012., Technical Report *Great Artesian Basin Resource Assessment*, Department of Land Resource Management, Report 14/2012A, Darwin, October 2012

Tickell, S.J., Cook, P., Sumner, J., Knapton, A. & Jolly, P., 2006, *Evaluating the Potential for Irrigation Induced Salinisation of the Keep River Plains*, Northern Territory Department of Natural Resources the Environment and the Arts, Technical Report No. 30/2006D

Addendum to Request for Information by the Hydraulic Fracturing Taskforce on 11 September 2017 in relation to the area west of Stuart Highway adjacent to Beetaloo Sub-basin

1. Surface spills and groundwater contamination

Summary of conditions overlying various aquifers.*

* It is important to note the distinction between an aquifer which will occur within permeable layers or features below the water table, and the top of the geological formation which may exist above the water table.

Area west of Stuart Highway adjacent to Beetaloo Sub-basin

The aquifers known to exist in this area are:

The Montejinni Limestone

The Montejinni Limestone is extensive across the Sturt Plateau beneath approximately 50m of Cretaceous Sediments. The karstic weathered formation overlies an undulating surface of the Cambrian aged Antrim Plateau Volcanics which exists at approximately 70m depth. As the water table is 50 to 60m below surface, the aquifer is thin in most places, and is only prospective for water where it has infilled the troughs of the basement .

The region is mostly covered by Cretaceous sediments. A significant number of collapse structures in the limestone are expressed on the surface as sinkholes. However, open sinkholes that provide a preferential pathway to the aquifer are rare. At Gorrie Station where the Cretaceous Sediments are thinnest (about 30m), the potential for preferential pathways to the aquifer may exist.

Basalt Aquifers

Low yielding aquifers may develop in structural features or within the layering of the Antrim Plateau Volcanics. These are believed to be localised, isolated systems and are not able to be detected beneath the cover of Cretaceous Sediments. The depth at which the features may be intersected is variable as is the depth to the water level.

In the northern Beetaloo Basin, the layer of Cretaceous Sediments is thin and surface spills may potentially infiltrate if directly overlying areas where recharge occurs. However, collapse structures do not exist in this Formation and therefore preferential pathways will not develop through the layer of Cretaceous Sediments.

Deep Sandstone aquifer

This aquifer in sandstone is known to exist at depth (between 200 and 300m) below the basalt and is confined by it. It is not vulnerable to ingress due to surface spills.

EHS Support
consider it done

15 August, 2017

EHS Support Pty Ltd
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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

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).

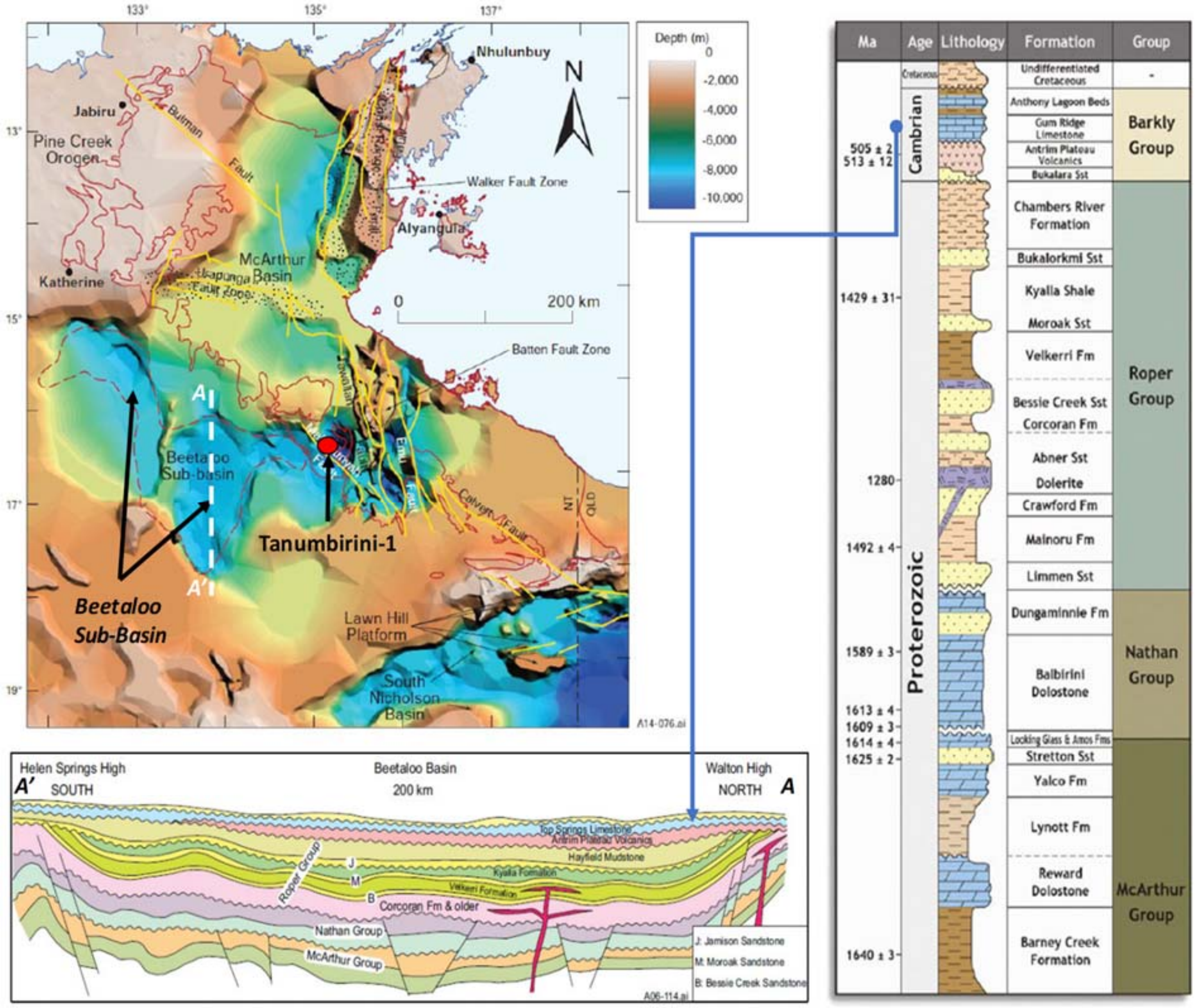


Figure 1. Location of the Beetaloo Basin along with Santos assets, stratigraphy and a north-south section. Reference used to create Figure 1: Silverman et al. (2008) [geological cross-section], and Close et al: 2016 [SEEBASE^{TM} depth-to-basin image & stratigraphic column]

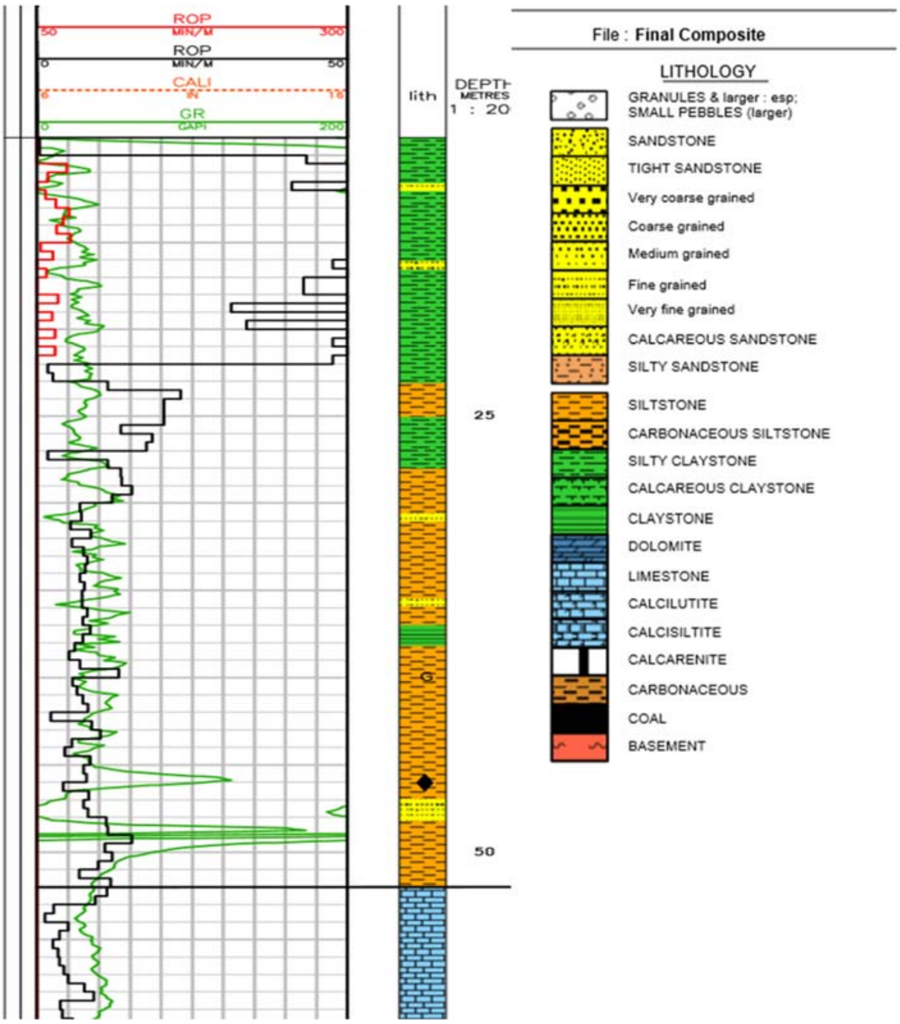


Figure 2 **Shallow Lithology from Santos well "Tanumbirini-1**

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).

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

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:

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

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).

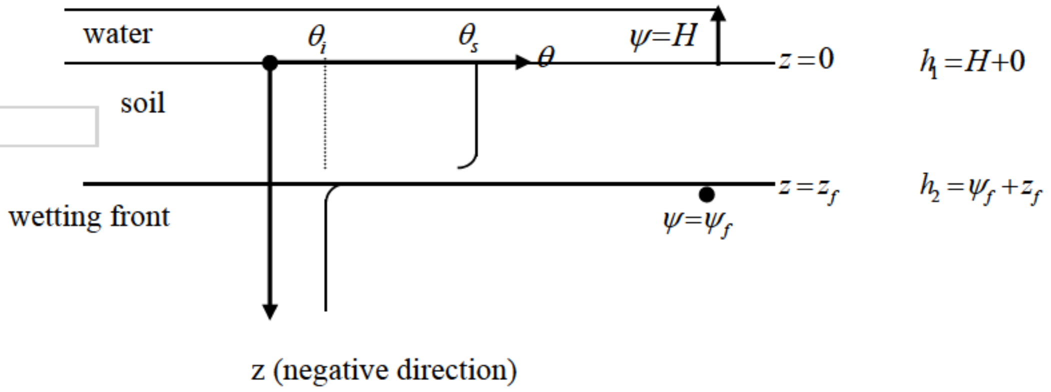
The infiltration rate actually experienced in a given soil depends on the amount and distribution of soil moisture and on the availability of water at the surface with a maximum rate at which the soil in a given condition can absorb water. This upper limit is called the infiltration capacity, f_c and 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

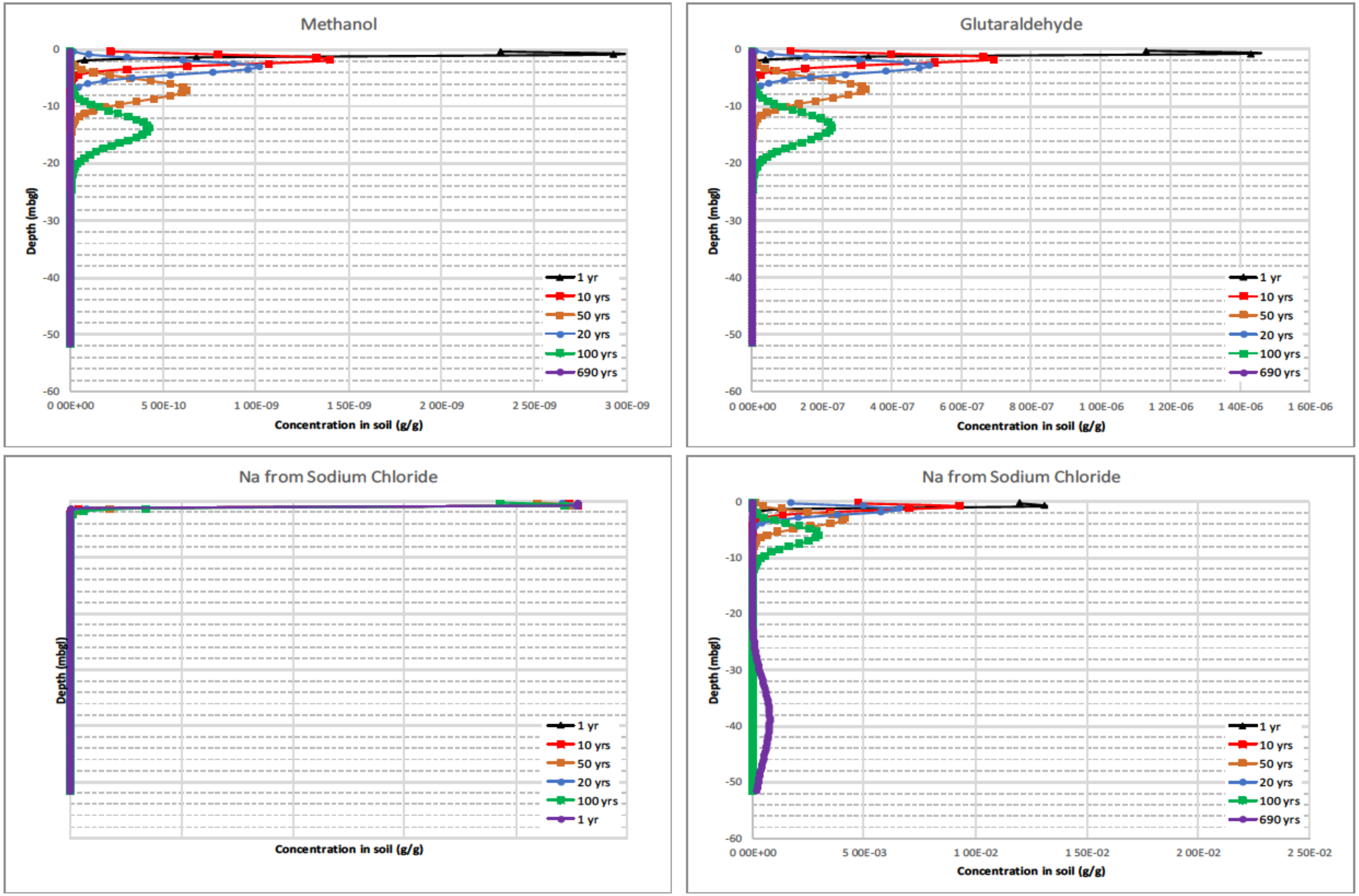


Figure 3 VLEACH Results. [Note: Bottom left Na assumes a Distribution Coefficient 2 orders of magnitude higher then bottom right results].

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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