Techical Memo

To:	Michael Hartley Agrimin	From:	Dean Lanyon Stantec, Adelaide
File:	TM Recharge assessment program	Date:	January 23, 2020

Reference: **Recharge assessment program for Lake MacKay**

Recharge assessment overview

Recharge has been identified as a key variable in the Agrimin Mackay Potash Project that impacts the brine concentration and sustained flows to extraction trenches over the life of the mine. Annual net recharge to the groundwater is variable and is dependent on:

- Soil physical properties of the surface and the unsaturated zone
- Rainfall and seasonal distribution
- Evaporation and seasonal distribution
- Depth to groundwater
- Dispersion/diffusion characteristics and concentration of solutes

An assessment regime was developed to provide the necessary recharge inputs to a regional groundwater flow and transport model (MODFLOW-SURFACT) that will result in a robust quantification of the likely impact that recharge will have on groundwater flow and solute concentration during harvesting and depletion of brine over the mining life. The assessment regime consisted of both infield measurements and laboratory analysis of intact profile cores of the top 0.5 meters. The assessment regime aimed to quantify profile hydraulic and solute transport properties that could be used to assess recharge at various groundwater depletion levels expected during mining operations.

The assessment regime broadly consisted of the following:

1. Infield infiltrometer assessments
    - defines the rate of rainfall infiltration
2. Infield closed lysimeters
    - allows for evaporation calibration
3. Lab initial conditions assessment
    - defines the bulk physical properties of the top 0.5m
    - defines the bulk solute properties of the top 0.5m
4. Lab column leaching tests
    - defines profile saturated conductivity
    - defines solute leaching behavior
5. Lab core multi step outflow curves with inverse modelling using Hydrus 1D
    - defines the pore distribution function
    - defines the unsaturated hydraulic function
6. Recharge modelling using Hydrus 1D
    - defines the average level of recharge at different groundwater depletion levels

Sampling regime

It's acknowledged that the surface properties of Lake MacKay are variable. Hence, the assessment regime included sampling across the playa as shown in Figure 1. Not all sites were used for each assessment method. The following summarizes the sites selected for each assessment method.

1. Infield infiltrometer assessments
    - all 40 sites
2. Infield closed lysimeters
    - 2 sites (T2AH-001, T13H-001)
3. Initial conditions assessment[1]

[1] refer to *Recharge Assessment Perth Laboratory Program (Stantec 2019) for results*

- 16 sites (T2AH-001, T13H-001, T13H-006, CTH-001, CTH-002, CTH-003, CTH-004, CTH-005, CTH-006, CTH-008, CTH-009, CTH-011, CTH-013, CTH-014, CTH-017, CTH-018)

4. Column leaching tests
    - 16 sites (T2AH-001, T13H-001, T13H-006, CTH-001, CTH-002, CTH-003, CTH-004, CTH-005, CTH-006, CTH-008, CTH-009, CTH-011, CTH-013, CTH-014, CTH-017, CTH-018)
5. Core multi step outflow curves with inverse modelling using Hydrus 1D
    - 16 sites (T2AH-001, T13H-001, T13H-006, CTH-001, CTH-002, CTH-003, CTH-004, CTH-005, CTH-006, CTH-008, CTH-009, CTH-011, CTH-013, CTH-014, CTH-017, CTH-018)

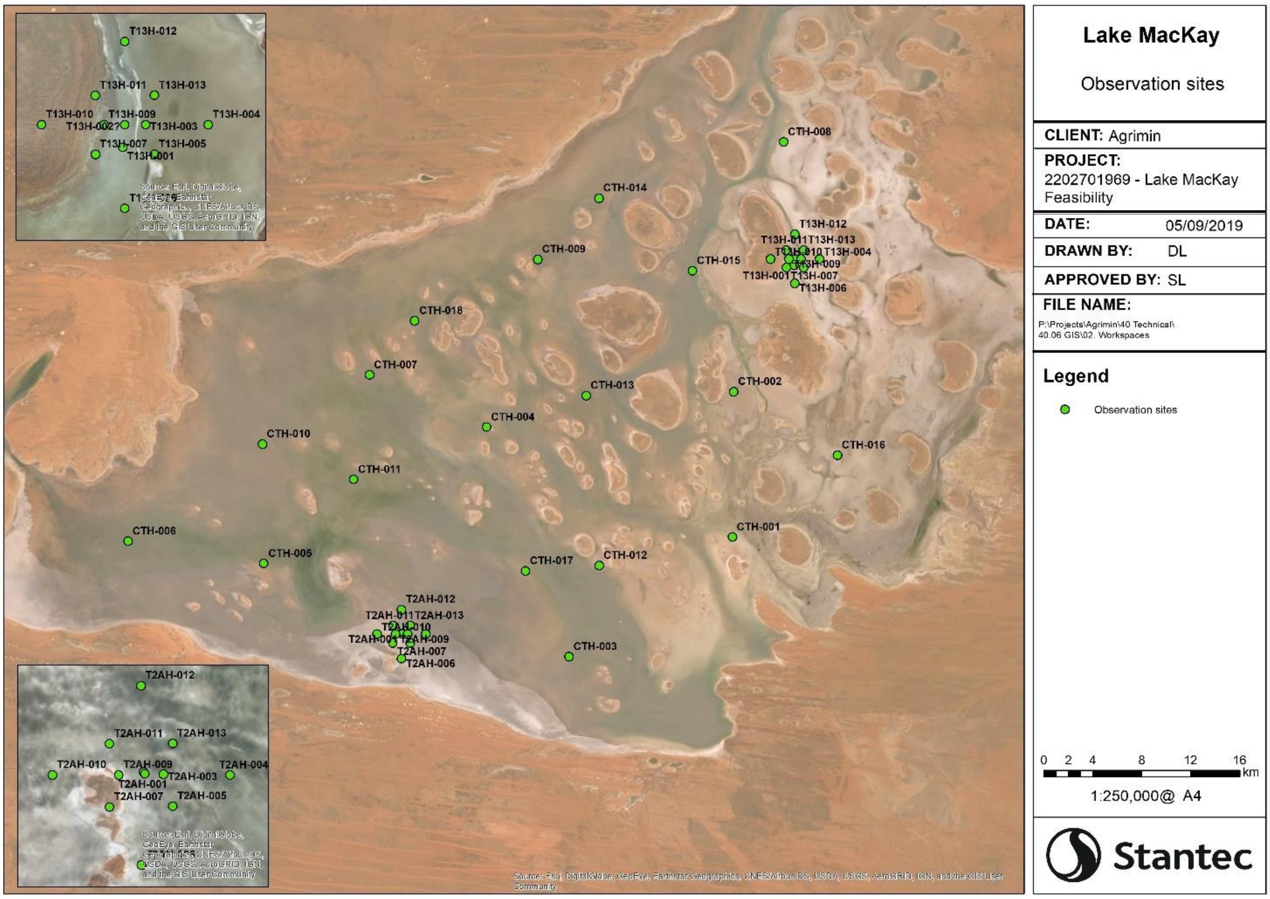

Figure 1: Distribution of profile sampling and assessment sites across Lake MacKay

Surface infiltration

300-320mm diameter single ring infiltrometers were used at each of the assessment sites to determine the infiltration rate variation across the playa. Each infiltration ring was inserted 50mm into the profile with a 100mm head of water controlled by a Mariotte chamber. Infiltration across the Lake varied by orders of magnitude from 1.8 to > 2500 mm/h. The average coefficient of variation of replicate infiltration rates at each assessment site was 51%, which is on the lower side of typical variability experienced with infiltration measurements (Peck 1983). A summary of average infiltration rates is presented in Table 1. Infiltration rates were converted to saturated conductivities based on the insertion depth, head of water and capillary length parameter (Reynolds *et al* 2002).

Table 1: Average infiltration rates (I) at each assessment site across Lake MacKay

Site	I (mm/h)	Site	I (mm/h)	Site	I (mm/h)	Site	I (mm/h)
T2AH-001	26.2	T2AH-013	6.3	T13H-012	2287.5	CTH-009	40.4
T2AH-003	2.7	T13H-001	1794.0	T13H-013	1683.5	CTH-010	8.9
T2AH-004	7.6	T13H-003	2435.7	CTH-001	81.6	CTH-011	14.4

Site	I (mm/h)	Site	I (mm/h)	Site	I (mm/h)	Site	I (mm/h)
T2AH-005	18.9	T13H-004	2816.7	CTH-002	1285.3	CTH-012	42.3
T2AH-006	8.2	T13H-005	4688.0	CTH-003	70.7	CTH-013	543.0
T2AH-007	414.7	T13H-006	5753.0	CTH-004	246.7	CTH-014	21.6
T2AH-009	287.7	T13H-007	2649.7	CTH-005	1.8	CTH-015	24.3
T2AH-010	7.2	T13H-009	2010.5	CTH-006	3.4	CTH-016	5000.0
T2AH-011	22.0	T13H-010	258.3	CTH-007	38.7	CTH-017	49.1
T2AH-012	16.8	T13H-011	223.3	CTH-008	4429.0	CTH-018	42.5

Column leaching

Undisturbed 100mm diameter 0.5m length Shelby tube cores were collected in duplicate at selected sampling sites. The column leaching methodology and data are used is described in "*Recharge Assessment Perth Laboratory Program (Stantec 2019)*". The percentage reduction in retained salts after leaching (L) from the 0-0.5m profile as a function of pore volume leached (P) was modelled using an exponential decay function given by the following:

$L = R(1 - e^{-c.P})$, where c is a rate constant and R is the maximum reduction in salts.

An example of the fit is given in Figure 2 with all fitting parameters presented in Table 2.

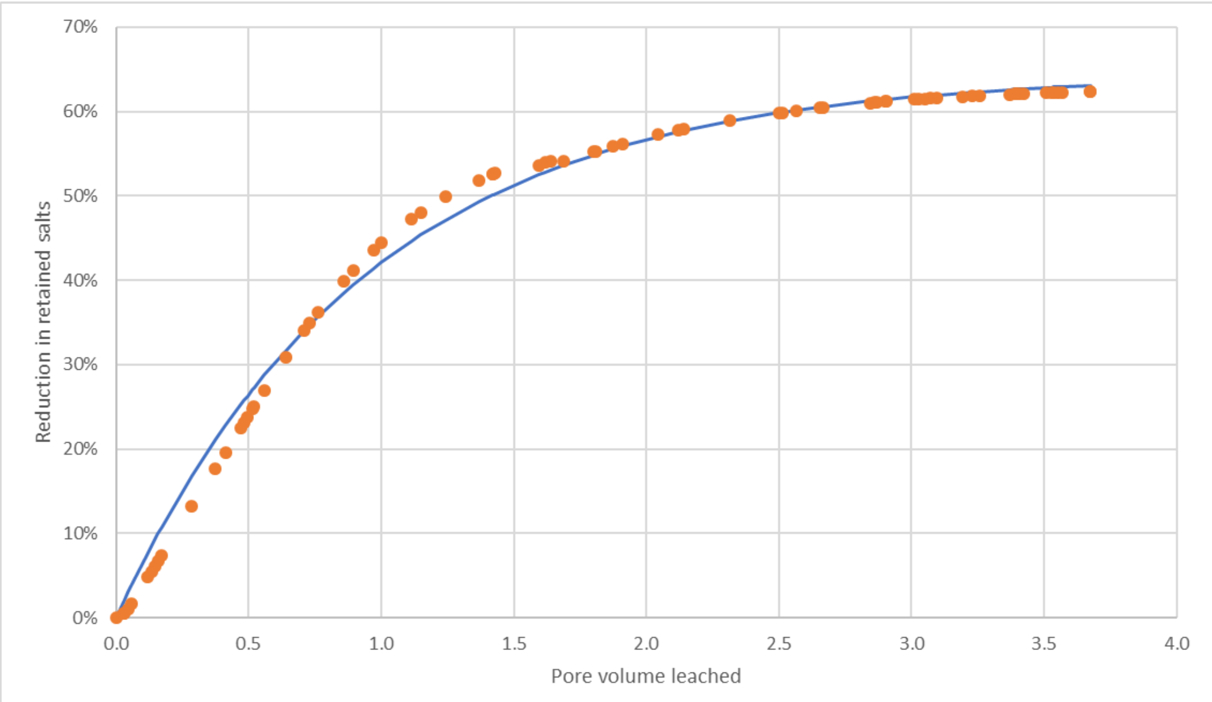

Figure 2: Example (CTH-001) of TDS variation in leachate as a function of leached volume expressed in pore volumes

Table 2: Salt reduction fitting parameters derived from the column leaching test data (R% is the maximum reduction in salts and C defines the rate of salt reduction)

Site	*R (%)*	*C (-)*	Site	*R (%)*	*C (-)*
T2AH-001	100	0.789	CTH-006*	-	-
T13H-001	93.4	1.125	CTH-008	63.7	1.257

Site	*R (%)*	*C (-)*	Site	*R (%)*	*C (-)*
T13H-006	75.9	1.677	CTH-009*	-	-
CTH-001	64.4	1.060	CTH-011*	-	-
CTH-002	60.3	1.367	CTH-013*	-	-
CTH-003	85.1	0.496	CTH-014*	-	-
CTH-004	61.9	1.088	CTH-017	100	1.060
CTH-005	82.7	1.050	CTH-018	58.2	0.805

* core was compromised during leaching procedure

The saturated hydraulic conductivity of the 0-0.5m profile was split into two depths for calculation purposes, 0-0.2m and 0.2-0.5m. The saturated hydraulic conductivities of the 0-0.2m was derived from the infiltration data. The 0.2-0.5m saturated hydraulic conductivities were then derived from the flow rates observed during the column leaching tests under variable head conditions. The saturated hydraulic conductivity over the 0-0.5m unsaturated interval for each site is shown in Table 3.

Table 3: Average profile saturated hydraulic conductivities (K_{sat}) based on infiltration data and column leaching tests

Site	Depth (cm)	K_{sat} (mm/h)	Site	Depth (cm)	K_{sat} (mm/h)
T2AH-001	0-20	13.9	T2AH-001	20-50	0.25
T13H-001	0-20	950	T13H-001	20-50	43.0
T13H-006	0-20	3050	T13H-006	20-50	135.4
CTH-001	0-20	43.2	CTH-001	20-50	0.35
CTH-002	0-20	681	CTH-002	20-50	3.9
CTH-003	0-20	37.5	CTH-003	20-50	4.9
CTH-004	0-20	131	CTH-004	20-50	12.3
CTH-005	0-20	0.9	CTH-005	20-50	8.4
CTH-006	0-20	1.8	CTH-006	20-50	0.05
CTH-008	0-20	2300	CTH-008	20-50	127
CTH-009	0-20	21.4	CTH-009	20-50	0.55
CTH-011	0-20	7.6	CTH-011	20-50	0.9
CTH-013	0-20	-	CTH-013	20-50	80.2
CTH-014	0-20	11.5	CTH-014	20-50	0.15
CTH-017	0-20	26.0	CTH-017	20-50	0.5
CTH-018	0-20	22.5	CTH-018	20-50	7.0

Multi-step outflow and inverse modelling

Undisturbed 3.5 inch (90mm) diameter soil plugs were sampled from selected depth of each Shelby profile core. The core sampling and tempe cell setup and methodology used are described in "*Recharge Assessment Perth Laboratory Program (Stantec 2019)*". Hydrus inverse modelling (Tuli *et al* 2001) was used to fit modelled water fluxes at the base of the core to observed fluxes (Figure 3). The porosity characteristics were modelled using a dual porosity van Genuchten function with the saturated hydraulic conductivity defined as reported in Table 3. The total porosity was also pre-defined from the initial condition assessment of the profile (see *Recharge Assessment Perth Laboratory Program, Stantec 2019*). The fitted parameters are summarized in Table 4.

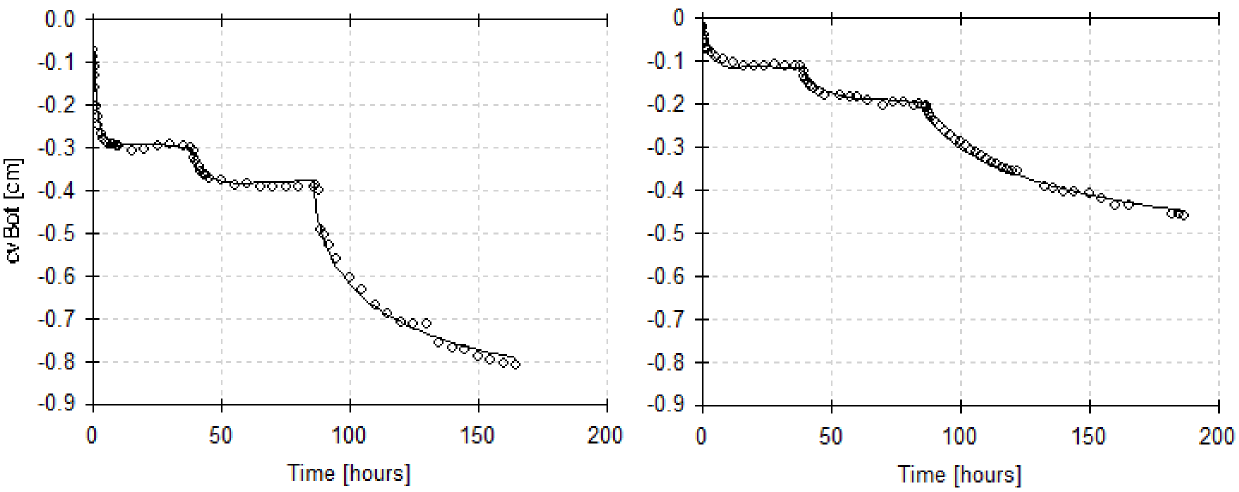

Figure 3: Examples of Hydrus inverse modelling fits to observed multi step outflow data for two contrasting sites, CTH-008 (left) and CTH-005 (right)

Table 4: Average fitted van Genuchten parameters for the Hydrus dual porosity model for the 0-20cm depth

Site	Qr (v/v)	α_1 (1/cm)	n_1 (-)	α_2 (1/cm)	n_2 (-)	w_2 (%)	l (-)
T2AH-001	0.151	0.0051	2.170	0.3831	2.070	36.4	0.3933
T13H-006	0.138	0.0068	1.633	0.0392	4.889	93.6	0.8500
CTH-001	0.130	0.0043	2.555	0.1014	6.872	38.3	3.3750
CTH-003	0.131	0.0051	1.450	0.0938	45.150	45.9	0.7846
CTH-006	0.121	0.0009	1.513	0.0216	5.942	51.8	0.0000
CTH-009	0.245	0.0035	1.244	0.0612	47.530	44.4	1.5790
CTH-011	0.250	0.0118	1.787	0.0277	44.900	58.7	0.0001
CTH-014	0.241	0.0158	1.300	0.0571	13.200	53.1	0.0325
CTH-017	0.250	0.0154	1.397	0.0611	42.990	61.3	0.3095
CTH-018	0.145	0.0066	1.394	0.0635	4.595	48.2	0.3033

Qr is the residual water content, α defines the air-entry value, n defines the shape of the water retention function, w is macro porosity the portion, l is the tortuosity parameter and the subscripts 1 and 2 notates micro and macro porosity, respectively

Table 5: Average fitted van Genuchten parameters for the Hydrus dual porosity model for the 20-50cm depth

Site	Qr (v/v)	α_1 (1/cm)	n_1 (-)	α_2 (1/cm)	n_2 (-)	w_2 (%)	l (-)
T2AH-001	0.257	0.0043	6.210	0.0255	7.499	48.9	0.1611
T13H-001	0.242	0.0113	1.559	0.1004	54.883	58.9	0.2189
T13H-006	0.182	0.0072	1.386	0.0914	41.669	47.0	7.0030
CTH-001	0.137	0.0038	7.495	0.1350	1.385	37.0	0.0000
CTH-002	0.277	0.0069	1.663	0.0258	9.932	55.3	0.0001
CTH-003	0.298	0.0037	6.104	0.0645	7.810	51.0	0.4943
CTH-004	0.118	0.0102	1.873	0.0392	17.980	50.5	0.0000
CTH-005	0.225	0.0030	2.891	0.0469	23.000	57.6	1.1830
CTH-006	0.306	0.0047	23.700	0.0294	6.087	38.3	0.4672
CTH-008	0.269	0.0024	2.062	0.1108	2.969	47.5	1.7160
CTH-009	0.210	0.0045	31.770	0.0776	2.306	16.4	3.2740
CTH-011	0.316	0.0037	1.567	0.0303	34.360	27.3	2.8750
CTH-013	0.188	0.0050	2.864	0.2955	52.800	53.9	0.5258
CTH-014	0.235	0.0017	1.957	0.0279	5.819	81.1	0.0000
CTH-017	0.204	0.0041	3.240	0.0526	4.737	16.3	1.0500

Site	Qr (v/v)	α_1 (1/cm)	n_1 (-)	α_2 (1/cm)	n_2 (-)	w_2 (%)	l (-)
CTH-018	0.216	0.0015	1.455	0.0220	5.142	51.3	0.0000

Qr is the residual water content, α defines the air-entry value, n defines the shape of the water retention function, w is macro porosity the portion, l is the tortuosity parameter and the subscripts 1 and 2 notates micro and macro porosity, respectively

Zonation of playa

Modeling of the recharge potential across the playa was split into zones according to surface infiltration characteristics. Zonation of the playa is show in Figure 4 along with assessment points within each zone. Each zone represents an order of magnitude change in infiltration rate.

These zones are used to define the profile physical properties and the salt reduction function based on the above assessments. Average values were taken for all the assessments metrics that were located within each zone as shown for the reduction in salts as a function of pore volume leached (Figure 5).

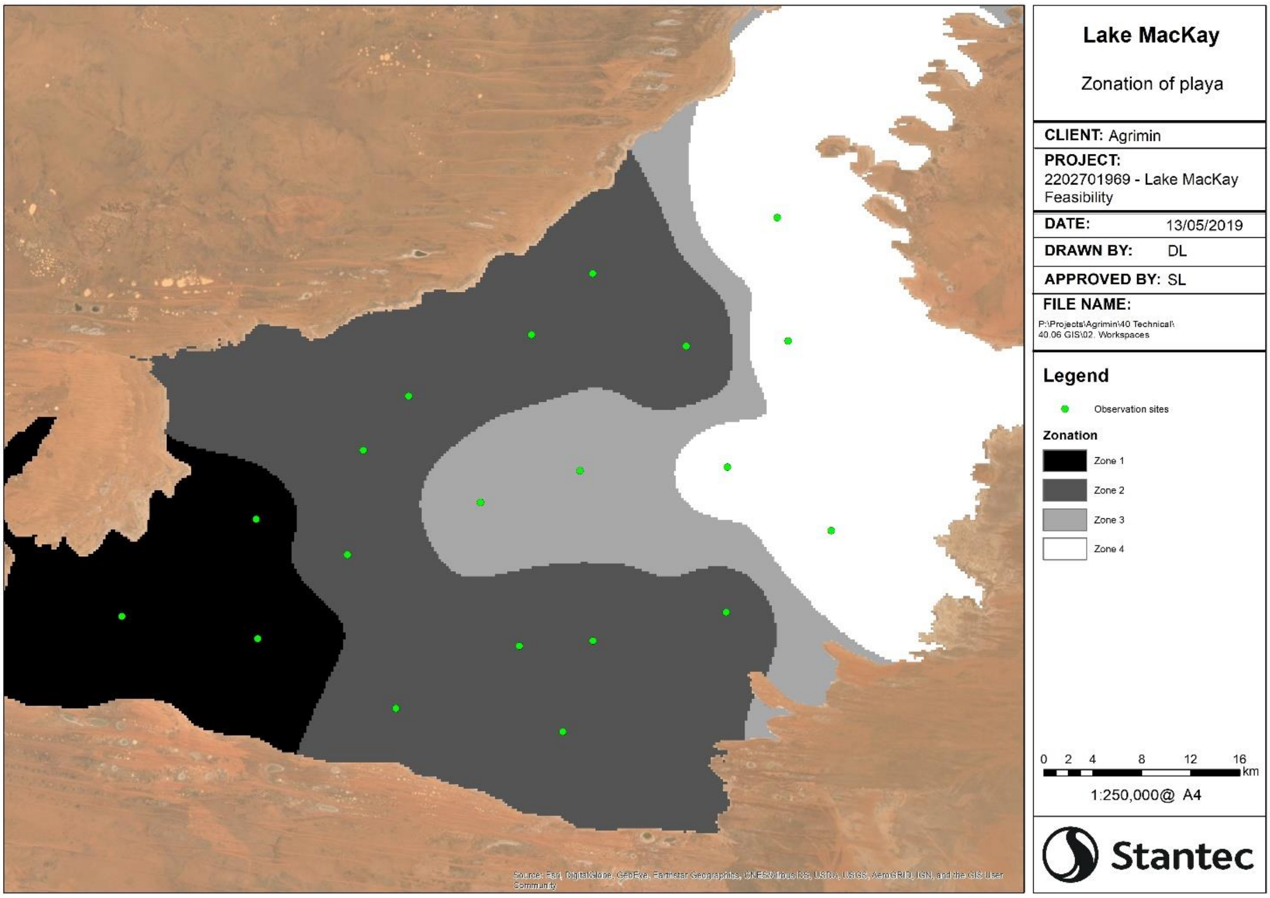

Figure 4: Zonation of Lake MacKay based on variation in surface infiltration data

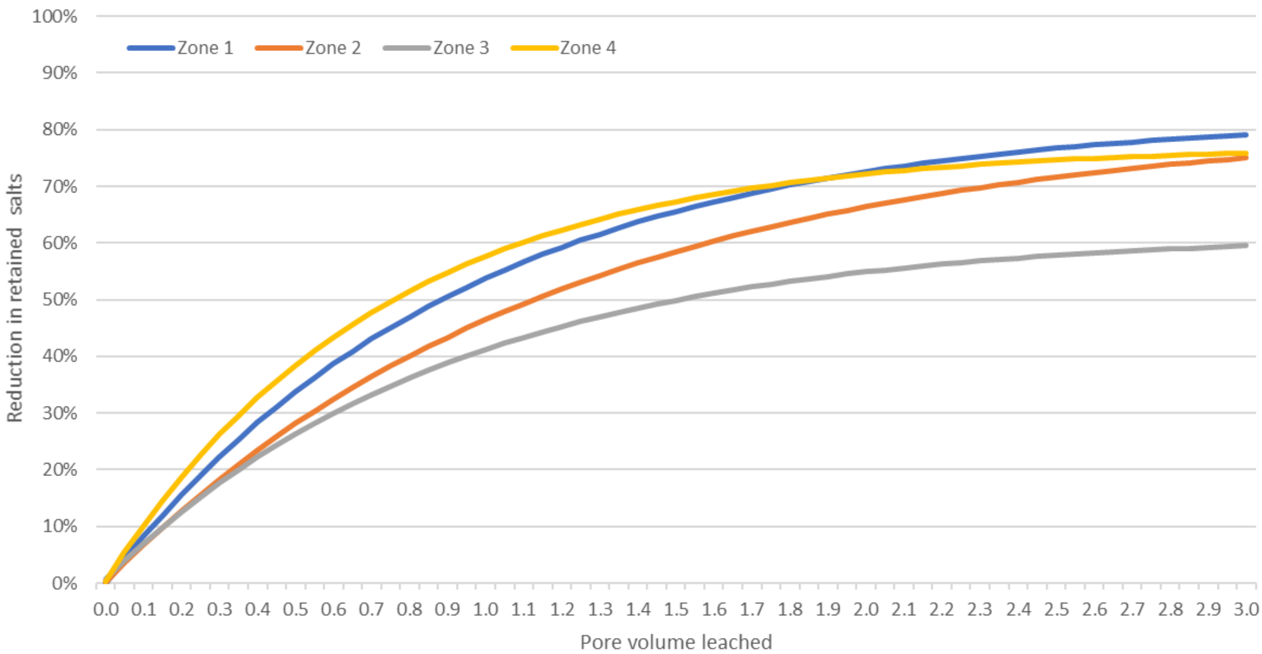

Figure 5: Resultant salt reduction function for each zone based on the percentage reduction in retained salts observed during the column leaching test

Recharge modelling

Hydrus 1D modelling (Šimůnek *et al* 2013) was used to determine the net recharge to the groundwater for each zone. Net recharge was defined as the net downward flux past the groundwater equilibrium depth.
A five metre profile was created with five different material properties with a lower boundary of 0.2, 0.5, 1.0, 3.0 and 5.0 metres. The physical properties of the layers were derived from the above field and lab assessments, data from the preliminary feasibility study and specific yield (S_y) from long-term trench pumping tests. The vertical saturated hydraulic conductivity of the layers below 0.5 metres were taken as 2 orders of magnitude smaller than the horizontal hydraulic conductivity observed in the trench pumping tests based on the anisotropic nature of the profile sediments and consistent with hydraulic conductivity for this interval used in the regional groundwater flow and transport modeling. Table 9 is a summary of the physical properties of the profile for each zone.
The surface boundary condition was set as an atmospheric boundary. The surface conditions were based on daily rainfall and pan evaporation derived from a patch point query[2] of the nearest Bureau of Metrology (BoM) weather station (15664) at Kintore (approximately 100 km distance from Lake Mackay) from 1st January 1993 to 27th October 2019, representing the period of actual weather data collection at the Kintore station. The evaporation rate from the soil surface was calibrated against the closed lysimeter data to set the maximum matric suction at the soil surface (125cm).
The bottom boundary condition was set as a constant head boundary. The head at the bottom boundary was calibrated so that the groundwater (GW) level equilibrated to the target groundwater depth below ground level (bgl). The required head at the bottom boundary is summarized in Table 6.

Table 6: Head requirement at the bottom boundary to maintain the required equilibrium groundwater level

Equilibrium GW depth bgl (m)	0.5	1.0	1.5	2.0	2.5	3.0
Zone 1	455	400	350	300	250	200
Zone 2	453	400	350	300	250	200
Zone 3	465	400	350	300	250	200
Zone 3	452	400	350	300	250	200

[2] https://www.longpaddock.qld.gov.au/silo/

Recharge modeling outcomes

Table 7 summarises the average recharge into the groundwater as a function of zone and groundwater depth below ground level. As groundwater levels drop the amount of recharge increases. The most recharge is experienced in zones 1 and 2 with the least in zone 4. Whilst infiltration is high in zone 4, evaporation of stored water in the profile is quickly evaporated reducing the amount of time for perched water to migrate past the groundwater reference depth. Nevertheless, infiltration of rainfall does reach the groundwater resulting in periodic rises in groundwater level. Table 8 shows the variation in frequency and magnitude of groundwater rises associated with significant rainfall events as function of zone. Groundwater rises from 2.0m bgl to within 0.4-0.8m of the soil surface only occurred twice for all zones during the 25 year model period. These events had a net 7 day rainfall addition (rainfall less evaporation) of more than 150mm (or rainfall > 250mm). On a monthly basis, rainfall would need to be greater than 300mm for these groundwater rises to occur.

Recharge and ET boundary conditions in the regional groundwater flow and transport model were then established based on the net recharge versus groundwater depth in Table 7.

Table 7: Average annual recharge (mm) into the groundwater as a function of groundwater depth and zone

Equilibrium GW depth bgl (m)	0.5	1.0	1.5	2.0	2.5	3.0
Zone 1	-32.7	84.1	99.5	111.8	118.6	122.6
Zone 2	-31.6	88.8	109.0	121.4	129.6	138.7
Zone 3	-433.8	41.9	54.2	57.2	58.4	59.0
Zone 4	-51.8	36.3	39.8	40.9	41.4	41.7

Table 8: The frequency and magnitude of groundwater rises within the 25 year modelling period when the equilibrium groundwater level is at 2.0m bgl

Rebound depth bgl (m)	0-0.4	0.4-0.8	0.8-1.2	1.2-1.6
Zone 1	0	2	13	31
Zone 2	0	2	12	26
Zone 3	0	2	8	11
Zone 4	0	2	4	8

Table 9: Physical properties of the profile for each zone used in Hydrus 1D to assess recharge

Zone	Depth (cm)	Qr (v/v)	Qs (v/v)	Ks (cm/d)	α_1 (1/cm)	n_1 (-)	α_2 (1/cm)	n_2 (-)	w_2 (%)	l (-)
Zone 1	0-20	0.132	0.551	3.1	0.0033	1.732	0.0359	12.590	50.7	0.563
	20-50	0.266	0.557	1.6	0.0039	13.296	0.0381	14.544	48.0	0.825
	50-100	0.385	0.439	2.2	0.0039	13.296	0.0381	14.544	48.0	0.825
	100-300	0.398	0.455	2.2	0.0039	13.296	0.0381	14.544	48.0	0.825
	300-500	0.352	0.417	2.2	0.0039	13.296	0.0381	14.544	48.0	0.825
Zone 2	0-20	0.188	0.497	45.9	0.0081	1.718	0.1369	23.264	47.0	0.797
	20-50	0.237	0.495	1.6	0.0035	7.334	0.0512	8.506	42.0	0.891
	50-100	0.353	0.420	3.8	0.0035	7.334	0.0512	8.506	42.0	0.891
	100-300	0.417	0.479	3.8	0.0035	7.334	0.0512	8.506	42.0	0.891
	300-500	0.407	0.425	3.8	0.0035	7.334	0.0512	8.506	42.0	0.891
Zone 3	0-20	0.199	0.569	314.4	0.0102	1.553	0.0479	24.344	65.4	0.366
	20-50	0.153	0.515	75.4	0.0076	2.369	0.1674	35.390	52.2	0.263
	50-100	0.362	0.432	4.1	0.0076	2.369	0.1674	35.390	52.2	0.263
	100-300	0.393	0.457	4.1	0.0076	2.369	0.1674	35.390	52.2	0.263
	300-500	0.392	0.440	4.1	0.0076	2.369	0.1674	35.390	52.2	0.263
Zone 4	0-20	0.141	0.642	3687.2	0.0068	1.633	0.0392	4.889	93.6	0.850
	20-50	0.233	0.550	53.6	0.0077	1.602	0.0867	34.334	52.4	2.693
	50-100	0.346	0.433	5.9	0.0077	1.602	0.0867	34.334	52.4	2.693
	100-300	0.393	0.472	5.9	0.0077	1.602	0.0867	34.334	52.4	2.693
	300-500	0.392	0.453	5.9	0.0077	1.602	0.0867	34.334	52.4	2.693

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