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Ashburton Salt Project
Groundwater Modelling Independent Review
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Executive Summary

CyMod Systems was appointed to undertake an independent review of the numerical groundwater model, which was constructed and calibrated to assess the potential impacts of the proposed K+S Ashburton Salt Project on environmental receptors.

The review found a significant amount of site-specific data has been collected by GHD and the report provides a summary of the field and laboratory analysis undertaken. As a general comment, the field data could have been collected over a larger area, and for longer periods of time, however ongoing monitoring prior to construction should address this issue.

The conceptual model of the area is consistent with field investigations and includes all important processes relevant to the development area.

Based on the review of the numerical model presented in the report it is considered that the model is fit for purpose. However, there are two important limitations in the model that may result in model predictions having significant uncertainty: the lack of vertical resolution of the grid in the 1A/B geological unit, and an overly simplified estimate of evapotranspiration (EVT) on the supratidal area, where salt crusts are formed. In both cases the uncertainty may result in the overestimate of salinity changes in the upper layer of the model.

The lack of vertical grid resolution results in the model using an average salinity value in the top cell that includes dense high salinity groundwater below 0.3 m. Consequently, shallow effects such as flushing by inundation and tides will not be simulated accurately. The demonstration of a viable flushing mechanism using a two-dimensional cross sectional model supports enhancing the existing 3D model with additional vertical resolution, to better estimate the likely impacts in mangrove areas.

The potential overestimate of EVT due to ignoring the effects of salt crusting is important as it directly affects the water and salt balance of model in these areas. This effect is most obvious on the water and salt balance in the vicinity of the proposed salt ponds where low salinity water is trapped by high evaporation rates on the downstream side of the embankments, resulting in dense brines near the surface. In practice, the formation of salt crusts at the surface, downstream of the embankment, results in a plume of low salinity water (i.e., similar to source water in the impoundment), that resides at or near the surface some distance from the embankment.

Both of the above effects may result in increased uncertainty in the nature and magnitude of model predicted impacts, potentially resulting in an overestimate of salinity changes in the upper layer of the model. This could be addressed by further modelling, monitoring and management planning prior to project construction.

Specifically, it is recommended that:

- An improved estimate of EVT be developed for the supratidal area, that includes the potential impact of salt crusting on the rate of water evaporation.

- The existing model be rerun for the 1000-year simulation, with reduced EVT (as developed in step 1), on the supratidal flats, to provide an assessment of the uncertainty in the model.

- Additional layers should be used to simulate the 1A formation to ensure that density effects are accounted for with respect to mixing of seawater and groundwater, and that the flushing of the shallow groundwater in the intertidal zone is more accurately accounted for.

Given that the model is characterized as Level 1, additional transient data should be collected in the following areas:

- Intertidal area of mangroves, with water level, and water quality measured at a sub-daily interval, to better characterize tidal influences.

- The installation of additional piezometers immediately downstream of proposed ponds, to provide baseline data prior to pond construction and filling.

- After pond filling, monitoring of water levels and water quality at various distances from filled ponds should be taken at sub monthly intervals.

The above data should then be used to improve the conceptual hydrogeological model by better quantifying the relevant processes in the project area.

An updated transient numerical model should then be constructed and calibrated that has sufficient vertical resolution to simulate pond seepage and intertidal and supratidal inundation, given the potential for steep salinity gradients that may occur near surface in these areas.

It is recommended that updated modelling methodology and revised modelling results, as well as a detailed monitoring program, should be documented in a Groundwater Management Plan for the project, which should be prepared and assessed by the regulator prior to the commencement of construction.

Baseline groundwater monitoring, in consultation with the regulator should also commence as soon as possible, to ensure an adequate time period of data acquisition, to enable required modelling revisions.

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Tables

1. Introduction

K+S appointed CyMod Systems to undertake an independent review of the numerical groundwater model of the area proposed for the Ashburton Solar Salt Operations. The model was constructed and calibrated to assess the potential impacts of the proposed Ashburton Salt Operations on environmental receptors in the vicinity of the development, due to seepage of high salinity water from solar salt ponds.

GHD Pty Ltd (GHD) undertook the numerical groundwater modelling on behalf of K+S, utilising the MODFLOW-USG-T software. Please note that CyMod Systems has not received the input and output model files for inspection/evaluation and has only conducted a review of the report. The review is based on the document *GHD, 2021. K+S Salt Australia Ltd Ashburton Solar Salt Project Hydrogeological Investigation, Report 12516706*. Consequently, CyMod Systems cannot make any comment on the veracity of information presented in the GHD report.

The objectives of the review are:

1. to meet the requirements of the WA Environmental Protection Authority (EPA), who require a peer review of a groundwater model submitted in support of a regulatory approval process; and
2. provide feedback in the form of recommendations to K+S to ensure the model is fit for purpose.

The scope of work for the review consisted:

1. Reviewing the modelling report, as submitted by GHD, against the Australian Groundwater Modelling Guidelines (National Water Commission 2012).
2. Review the supporting documents and reports; and
3. Provide recommendations that may improve the results of the model in terms of level of confidence and reduced uncertainty.

CyMod Systems conducted an independent model review based on the Australian Groundwater Modelling Guidelines (NWC, 2012). These guidelines are generic, in the sense they are applicable to any specific modelling application and represent a reasonable standard framework in which to assess groundwater modelling. The guidelines provide a series of modelling components to be considered, which includes:

- Planning;
- Conceptualization;
- Design;
- Construction;
- Calibration;
- Predictions;
- Uncertainty; and
- Solute Transport.

Each of these components was assessed by completing the relevant sections in Table 9.2 of the Australian Groundwater Modelling Guidelines.

2. Compliance Review

Table 2-1 summarizes the compliance review as set out in the Australian Groundwater Modelling Guidelines Table 9.1. The use of the term “maybe” implies that the project complies with the majority of the requirements, as set out in the question, but the lack of documentation or missing information prevents assigning a yes. Outstanding issues and deficiencies are discussed in more detail below, using Table 9.2 of the Australian Groundwater Modelling Guidelines.

Table 2-1: Compliance Review

Question	Yes/No	Comments
1. Are the model objectives and model confidence level classification clearly stated?	Yes	Model objectives are clearly stated Model is assessed as Level 1, which is correct for this model.
2. Are the objectives satisfied?	Maybe	Refer to Table 3-1
3. Is the conceptual model consistent with objectives and confidence level classification?	Yes	
4. Is the conceptual model based on all available data, presented clearly, and reviewed by an appropriate reviewer?	Yes	
5. Does the model design conform to best practice?	Yes	
6. Is the model calibration satisfactory?	Maybe	Calibration error is similar in magnitude to changes in salinity that may be important to ecological receptors. However, comparing models or the change in state of the model over time should be more accurate.
7. Are the calibrated parameter values and estimated fluxes plausible?	Yes	
8. Do the model predictions conform to best practice?	Maybe	Model needs to better account for the export of salt and nutrients from the intertidal and supratidal areas.
9. Is the uncertainty associated with the predictions reported?	Yes	
10. Is the model fit for purpose?	Yes	Model may be conservative in that it could over predict the change in groundwater quality in environmental sensitive areas.

3. Model Planning

Table 3-1: Model Guidelines - Planning

Question	Yes Maybe No	Comments
1.1 Are the project objectives stated?	Yes	
1.2 Are the model objectives stated?	Yes	Model objectives are clearly stated
1.3 Is it clear how the model will contribute to meeting the project objectives?	Yes	
1.4 Is a groundwater model the best option to address the project and model objectives?	Yes	Provides quantitative estimates of impacts of ponds on water quality around mangroves and algal matts in the short and medium term
1.5 Is the target model confidence-level classification stated and justified?	Yes	A classification 1 is appropriate for this model, as limited time series data are available, and the model uses time invariant average values for most processes.
1.6 Are the planned limitations and exclusions of the model stated?	Yes	Model limitations are discussed in section 9.7. However, the discussion is generic and does not address the specific limitations of this model.

4. Conceptualisation

Table 4-1: Model Guidelines - Conceptual Model

Question	Yes Maybe No	Comments
2.1 Has a literature review been completed, including examination of prior investigations?	Yes	Literature review is incomplete with respect to flushing and the estimate of EVT
2.2 Is the aquifer system adequately described?	Yes	
2.2.1 hydrostratigraphy including aquifer type (porous, fractured rock ...)	Yes	
2.2.2 lateral extent, boundaries, and significant internal features such as faults and regional folds	Yes	
2.2.3 aquifer geometry including layer elevations and thicknesses	Yes	Aquifer geometry has been generalized
2.2.4 confined or unconfined flow and the variation of these conditions in space and time?	Yes	Limited analysis of time varying flows
2.3 Have data on groundwater stresses been collected and analysed?	Yes	Stresses defined as long term averages – hence quasi steady state
2.3.1 recharge from rainfall, irrigation, floods, lakes	Yes	Stresses defined as long term averages – hence quasi steady state It is also likely that the supratidal area is a discharge area, with net negative recharge
2.3.2 river or lake stage heights	Yes	The effects of supratidal inundation at spring tides have been addressed with respect to the export of mass, while avoiding the complexity of simulating surface flow.

2.3.3 groundwater usage (pumping, returns etc.)	NA	There is no abstraction from the model area, other than what was undertaken as part of the field investigations.
2.3.4 evapotranspiration	Yes	Conceptualization may be too simple, as work done on salt crusts show they reduce evaporation significantly. Consequently, the assumption of high evaporation may only apply when the areal extensive salt crust is absent, such as after inundation or rainfall, and then only for a few days until it is re-established by evaporation of brine.
2.3.5 other?		
2.4 Have groundwater level observations been collected and analysed?	Yes	
2.4.1 selection of representative bore hydrographs	No	Only successfully measured two bores, both of which are away from the supratidal flats in the pond areas. Limited time series data restricts the model classification to Level 1.
2.4.2 comparison of hydrographs	Yes	
2.4.3 effect of stresses on hydrographs	Yes	Effect of rainfall on water levels on the tidal and supratidal flats has been established. Pumping test
2.4.4 water table maps/piezometric surfaces?	No	A constrained, density-corrected water level elevation map needs to be provided.
2.4.5 If relevant, are density and barometric effects taken into account in the interpretation of groundwater head and flow data?	Yes	Density effects have been accounted for, as shown in Table 7.2. The equivalent freshwater heads are significantly higher than measured levels, suggesting hydraulic gradients are steeper and that dense groundwater under the supratidal flats may be acting as a groundwater mound
2.5 Have flow observations been collected and analysed?	Yes	Reported by Water Technology (2021)
2.5.1 baseflow in rivers	Yes	Reported by Water Technology (2021)
2.5.2 discharge in springs	NA	
2.5.3 location of diffuse discharge areas?	Yes	
2.6 Is the measurement error or data uncertainty reported?	No	
2.6.1 measurement error for directly measured quantities (e.g., piezometric level, concentration, flows)	No	
2.6.2 spatial variability/heterogeneity of parameters	Yes	
2.6.3 interpolation algorithm(s) and uncertainty of gridded data?	No	Conceptual geological model constructed in Leapfrog
2.7 Have consistent data units and geometric datum been used?	Yes	
2.8 Is there a clear description of the conceptual model?	Yes	The conceptual hydrogeological model is well described, with complete water and mass balances provided for the model area.

2.8.1 Is there a graphical representation of the conceptual model?	Yes	
2.8.2 Is the conceptual model based on all available, relevant data?	Yes	
2.9 Is the conceptual model consistent with the model objectives and target model confidence level classification?	Yes	The model is consistent with model classification The model adequately accounts for processes in supratidal and algal mats areas.
2.9.1 Are the relevant processes identified?	Yes	
2.9.2 Is justification provided for omission or simplification of processes?	Yes	
2.10 Have alternative conceptual models been investigated?	No	

4.1 Conceptual Model Uncertainties

The conceptual model as described in the report is similar to that proposed by Blandford and Associates (2005) but includes additional mechanisms that account for the export of salt from the supratidal zone and flushing in the intertidal zone. The modified conceptual model tends to have greater fidelity to actual process occurring in the project area.

4.2 Specific Yield

A brief review of estimates of specific yield from particle size distribution of field samples is shown in Table 4-2. Estimates of specific yield have been taken from Figure 4-1 based on silt/clay content measured in soil samples. The data suggests that a specific yield of 0.05 and an effective porosity of 0.10 as suggested in the conceptual model for the 1A/B formation are reasonable but conservative. The limited data for the 2A and 2B formations suggests a low specific yield may also be conservative.

The effective porosity of 0.10 as used in the 1A/B unit is consistent with conservative estimates of these properties, as indicated in the report. The low effective porosity will increase the impact of seepage and EVT, in terms of rate of change in salinity and groundwater level changes.

It is also noted that test pumping of BH7 TB, BH10 TB measured responses primarily in the 2A/B formation and indicated a specific yield of 0.05. It is likely the 1A/B formation will have higher specific yield, given higher sand content.

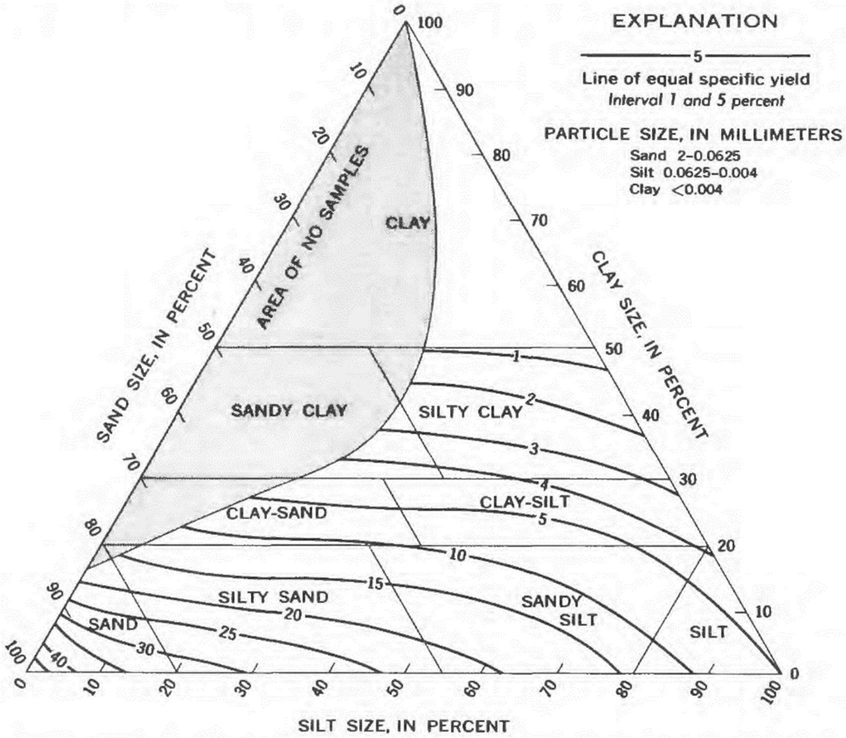


Figure 4-1: Soil Classification showing Relationship between Particle Size and Specific Yield (Johnson, 1968)

Table 4-2: Review of Specific Yield Estimates from Particle Size Distribution of Field Samples

Sample	Depth	<0.075 mm	%Clay	%Silt	Sy
BH1	4	20	10	10	0.2
BH7	2	20	10	10	0.2
BH7	7	20	10	10	0.2
BH9	1	30	10	20	0.22
BH9	5	30	10	20	0.22
BH9	13	30	10	20	0.22
BH10	2	40	20	20	0.10
BH10	7	90	50	50	0.01
BH10	11	20	10	10	0.25
AU-1	2	0	0	0	0.40
AU-2	2	25	10	15	0.15
AU-2	0.5	25	20	10	0.12
AU-2	3	30	20	10	0.12
AU-3	1	42	20	20	0.10
AU-22	1	60	30	30	0.04
AU30	2	28	15	13	0.15
AU-60	2	40	20	20	0.10
AU-101	1	50	30	20	0.04
AU-101	3	30	20	10	0.12
AU-102	1	35	20	15	0.10
BH-1	2	26	18	8	0.12
BH-07	1	34	20	14	0.10
BH-10	2	47	27	20	0.05
BH-11	1	41	30	11	0.05
BH-14	3	33	27	4	0.07
AU-74	1	58	35	24	0.04
AU-75	2	72	22	50	<0.01
AU-102	2	36	24	12	0.07
HA-10	1	40	32	8	0.04
HA-11	0.5	73	60	13	<0.01
DCP-05	0.5	51	30	20	0.045
IT-05	0.5	50	6	45	0.20

5. Model Design and Construction

Table 5-1: Model Guidelines - Design and Construct

Question	Yes Maybe No	Comments
3.1 Is the design consistent with the conceptual model?	Yes	
3.2 Is the choice of numerical method and software appropriate?	Yes	
3.2.1 Are the numerical and discretisation methods appropriate?	Yes	
3.2.2 Is the software reputable?	Yes	MODFLOW USG-T
3.2.3 Is the software included in the archive or is references to the software provided?	Yes	Panday, S., 2020: USG-Transport version 1.5.0: The Block-Centred Transport process for MODFLOW-USG. GSI Environmental.
3.3 Are the spatial domain and discretisation appropriate?	No	Non-uniform grid accounts for both calibration and forward prediction models. Vertical discretisation is coarse given the near surface processes that dominate in the model.
3.3.1 1D/2D/3D	3D	
3.3.2 lateral extent	Yes	Model covers an extensive area beyond the bounds of the development area.
3.3.3 layer geometry?	Maybe	Layering is consistent with the simple geological model proposed for the area in the conceptualization. Additional layers near surface may improve the simulation of supra and intertidal processes, in particular the vertical salinity gradient in the areas of mangroves and embankments.
3.3.4 Is the horizontal discretisation appropriate for the objectives, problem setting, conceptual model and target confidence level classification?	Yes	Discretisation meets solute transport criteria. Minimum grid resolution is consistent with model classification and the characteristic length of hydrogeological features. Resolution is consistent with expected hydraulic and solute gradients
3.3.5 Is the vertical discretisation appropriate? Are aquitards divided in multiple layers to model time lags of propagation of responses in the vertical direction?	No	On inspection of the 8 layers used to discretise the model, 6 are in the 2/3 layer which has lower permeability and salinity is likely to be relatively stable given the kh and kv values, whereas layer 1 has only two layers, but will have recharge, evaporation, inundation, steep solute gradients, and steep hydraulic gradients near the proposed ponds (Table 9-1). Vertical discretisation limits the simulation of important processes in the intertidal and supratidal areas, in particular the implied steep vertical gradients caused by tidal flushing and pond seepage.
3.4 Are the temporal domain and discretisation appropriate?	Maybe	Long stress periods and timesteps may not account for tidal and seasonal inundation of salt flats
3.4.1 steady state or transient	Transient	Calibration is quasi steady state – in that no time varying stresses are used. Consists of two epochs, a 2500 year and 1000 year, based on whether the area is intertidal (regular flushing) or supratidal (intermittent flushing)
3.4.2 stress periods	Yes	Calibration is based on 10 stress periods or 250 years, which is viable for simulating the present hydrogeological conditions of the salt flats.
3.4.3 time steps?	Yes	Model generated based on stability criteria.

3.5 Are the boundary conditions plausible and sufficiently unrestrictive?	Yes	
3.5.1 Is the implementation of boundary conditions consistent with the conceptual model?	No	• Inland boundary is unlikely to be a constant head, more likely to be due to variable long term recharge. • Not sure that the use of time invariant boundary conditions is viable for forward scenarios, as it excludes the modelling of tides, inundation, and seasonal recharge. • A variable constant flux eastern boundary may be more appropriate, assuming the aquifer extends eastward beyond the model extent.
3.5.2 Are the boundary conditions chosen to have a minimal impact on key model outcomes? How is this ascertained?	Yes	Sensitivity analysis
3.5.3 Is the calculation of diffuse recharge consistent with model objectives and confidence level?	Maybe	Recharge has been estimated and then calibrated.
3.5.4 Are lateral boundaries time-invariant?	Yes	
3.6 Are the initial conditions appropriate?	Yes	Dynamic calibration for 2500 years while area is intertidal, and 1000 years after area becomes supratidal
3.6.1 Are the initial heads based on interpolation or on groundwater modelling?	Modelling	Dynamic calibration of quasi-steady model
3.6.2 Is the effect of initial conditions on key model outcomes assessed?	Yes	Sensitivity analysis
3.6.3 How is the initial concentration of solutes obtained (when relevant)?	Suitable	Dynamic calibration to field measurements in 2020
3.7 Is the numerical solution of the model adequate?	Yes	cumulative mass balance error is 0.03% and 0.05% for the flow and transport simulations, respectively
3.7.1 Solution method/solver	Yes	SSM solver
3.7.2 Convergence criteria	Unknown	Not described
3.7.3 Numerical precision	Unknown	Not described

Table 5-2: Characteristics of a Class 1 Model

Data	*Calibration*	*Prediction*	*Key indicator*	*Examples of specific uses*
• Few or poorly distributed existing wells from which to obtain reliable groundwater and geological information. • Observations and measurements unavailable or sparsely distributed in areas of greatest interest. • No available records of metered groundwater extraction or injection.	• No calibration is possible. • Calibration illustrates unacceptable levels of error especially in key areas. • Calibration is based on an inadequate distribution of data. • Calibration only to datasets other than that required for prediction.	• Predictive model time frame far exceeds that of calibration. • Temporal discretisation is different to that of calibration. • Transient predictions are made when calibration is in steady state only. • Model validation* suggests unacceptab	• Model is uncalibrated or key calibration statistics do not meet agreed targets. • Model predictive time frame is more than 10 times longer than transient calibration period. • Stresses in predictions are more than 5 times higher than those in calibration. • Stress period or calculation interval is different from that used in calibration. • Transient predictions made but calibration in steady state only. • Cumulative mass-balance closure error	• Design observation bore array for pumping tests. • Predicting long-term impacts of proposed developments in low-value aquifers. • Estimating impacts of low-risk developments. • Understanding groundwater flow processes under various hypothetical conditions. • Provide first-pass estimates of extraction volumes and rates required for mine dewatering. • Developing coarse relationships between groundwater extraction locations and rates

- Climate data only available from relatively remote locations. - Little or no useful data on land-use, soils or river flows and stage elevations.		le errors when calibration dataset is extended in time and/or space.	exceeds 1% or exceeds 5% at any given calculation time. - Model parameters outside the range expected by the conceptualisation with no further justification.	and associated impacts. - As a starting point on which to develop higher class models as more data is collected and used.

Table 5-3: Model Guidelines - Surface/Groundwater Interaction

5.1 Surface Groundwater Interaction

The evaluation of surface groundwater has been placed in this section, as it is primarily concerned with how the conceptual model addresses processes associated with surface/groundwater interaction.

8. Surface water–groundwater interaction		
8.1 Is the conceptualisation of surface water–groundwater interaction in accordance with the model objectives?	Yes	Model objective is to estimate solute mobility due to surface water flows, and hence modelling of accrual surface flows in not required.
8.2 Is the implementation of surface water–groundwater interaction appropriate?	Maybe	Irregular inundation and subsequent flushing of solutes from the supratidal and tidal zone has not been account for with respect to flow. Solute interaction is accounted for by using zero order decay
8.3 Is the groundwater model coupled with a surface water model?	No	
8.3.1 Is the adopted approach appropriate?	NA	
8.3.2 Have appropriate time steps and stress periods been adopted?	NA	
8.3.3 Are the interface fluxes consistent between the groundwater and surface water models?	NA	

6. Calibration and Sensitivity

Table 6-1: Model Guidelines - Calibration

Questions	Yes Maybe No	Comments
4.1 Are all available types of observations used for calibration?	Yes	Static and pumping test water levels are used for calibration of regional model Pumping test data at BH07 and BH10 are used to confirm kh, kv and infiltration
4.1.1 Groundwater head data	Yes	
4.1.2 Flux observations	No	
4.1.3 Other: environmental tracers, gradients, age, temperature, concentrations etc.	Yes	Concentrations
4.2 Does the calibration methodology conform to best practice?	Yes	
4.2.1 Parameterisation	Yes	The range of model parameter scaling factors, as used in PEST, may be too small to allow flexibility in the calibration process.
4.2.2 Objective function	Yes	
4.2.3 Identifiability of parameters	Yes	
4.2.4 Which methodology is used for model calibration?	Automated	Pest with Pilot Points
4.3 Is a sensitivity of key model outcomes assessed against?	Yes	Range of parameters may too be small to allow an effective sensitivity analysis
4.3.1 parameters	Yes	
4.3.2 boundary conditions	Yes	
4.3.3 initial conditions	Yes	
4.3.4 stresses	Yes	
4.4 Have the calibration results been adequately reported?	Yes	
4.4.1 Are there graphs showing modelled and observed hydrographs at an appropriate scale?	Yes	Pumping analysis
4.4.2 Is it clear whether observed or assumed vertical head gradients have been replicated by the model?	No	
4.4.3 Are calibration statistics reported and illustrated in a reasonable manner?	Yes	Head error 15.2% Salinity error 13.5%
4.5 Are multiple methods of plotting calibration results used to highlight goodness of fit robustly? Is the model sufficiently calibrated?	No	
4.5.1 spatially	No	
4.5.2 temporally	Yes	Pumping Test
4.6 Are the calibrated parameters plausible?	Yes	Based on pilot point interpolation, resulting “bull-eyes” which may or may not be an accurate representation of parameter distributions
4.7 Are the water volumes and fluxes in the water balance realistic?	Maybe	Water balance shows that the model is quasi steady state Solute balance shows the model is not in quasi-steady state
4.8 has the model been verified?	No	Assessed against Sept 2020 measurements, but not against transient data.

The calibration and sensitivity analysis shown in Figure 9.9 of the GHD report highlights the sensitivity of the model to horizontal and vertical hydraulic conductivity (k), recharge and storage terms. This further supports the need to model recharge processes with greater fidelity, and to expand the bounds on estimates of parameters. The sensitivity to hydraulic conductivity in layer 2A/B reflects the inclusion of the pumping test in the calibration.

7. Predictions

Table 7-1: Model Guidelines - Predictions

Questions	Yes Maybe No	Comments
5.1 Are the model predictions designed in a manner that meets the model objectives?	Maybe	Intertidal and supratidal inundation may be oversimplified as a steady state process
5.2 Is predictive uncertainty acknowledged and addressed?	Yes	
5.3 Are the assumed climatic stresses appropriate?	Maybe	Climate stresses have been averaged and input as time invariant daily average based on historical data for the area.
5.4 Is a null scenario defined?	Yes	
5.5 Are the scenarios defined in accordance with the model objectives and confidence level classification?	Yes	
5.5.1 Are the pumping stresses similar in magnitude to those of the calibrated model? If not, is there reference to the associated reduction in model confidence?	NA	No pumping occurs in model area
5.5.2 Are well losses accounted for when estimating maximum pumping rates per well?	NA	
5.5.3 Is the temporal scale of the predictions commensurate with the calibrated model? If not, is there reference to the associated reduction in model confidence?	Yes	The Calibrated model was run for 1000 years, predictions are run for 50 years No time varying inputs specific to the site are used in the predictions. Class 1 models are limited in the confidence over the 50 year timeframe, due to a lack of time varying data
5.5.4 Are the assumed stresses and timescale appropriate for the stated objectives?	Maybe	EVT may be overestimated in areas that may have salt crusts
5.6 Do the prediction results meet the stated objectives?	Maybe	Model predicts water level and salinity changes with model outputs provided to AECOM to assess impacts to mangroves and algal mats
5.7 Are the components of the predicted mass balance realistic?	Maybe	None presented for the prediction model.
5.7.1 Are the pumping rates assigned in the input files equal to the modelled pumping rates?	NA	
5.7.2 Does predicted seepage to or from a river exceed measured or expected river flow?	NA	
5.7.3 Are there any anomalous boundary fluxes due to superposition of head dependent sinks	No	
5.7.4 Is diffuse recharge from rainfall smaller than rainfall?	Yes	
5.7.5 Are model storage changes dominated by anomalous head increases in isolated cells that receive recharge?	No	
5.8 Has particle tracking been considered as an alternative to solute transport modelling?	No	Changes in concentration are the primary criteria for determining impacts

The results of the predictive scenarios show that leakage from salt ponds causes increased groundwater salinity in the vicinity of the ponds, even those that are filled with much fresher seawater. These results reflect that the calibrated EVT is relatively large, and that pond seepage salinity is averaged in layer 1 with existing groundwater salinity. The application of a large EVT effectively removes seepage water from layer 1, resulting in increasing solute concentration in areas immediately outside of the pond embankment, relative to the initial conditions.

Monitoring undertaken at existing seawater filled ponds (*Gordon,1988),* show that seepage from seawater filled ponds acts to freshen shallow groundwater immediately outside of the embankment, and cause water levels to rise, resulting in a salt crust. The movement of lower salinity pond water is facilitated by the low EVT that occurs due to the formation of the salt crusts. These salt crusts are common on salt lakes and supratidal flats. As summarized in the abstracts by Chen and Hollins, salt crusts can reduce EVT by 98% in the absence of rainfall and inundation, compared to freshwater evaporation rates. Rainfall and inundation cause a short term increase in evaporation, until a new salt crust is established. Based on this analysis it is likely that the naturally salt encrusted supratidal flats evaporation is less than 300 mm/year in most areas, compared to the calibrated model EVT over most of the model area of 1100 mm/year. This suggests that EVT will not act to trap high salinity pond leakage as concluded in the report, but instead, in the absence of significant EVT, pond seepage water will move laterally (as groundwater) away from the pond, resulting in increasing water levels and freshening of shallow groundwater in the vicinity of ponds.

It is also noted that the 0.3m extinction depth for evapotranspiration is not a physical constraint but based on measured depth to water and is being used as an upper boundary condition of the aquifer. The use of a high EVT rate and shallow extinction depth in the model, causes EVT to effectively control the water table. Small changes in the model of depth to water (for example due to seepage from a pond) results in a large increase in EVT, and subsequent large increase in predicted salinity.

A more physical based model, accounting for the salt crusting, would have a small EVT rate constrained by crust as dry litter, with the extinction depth defined by the thermal and hydrogeological properties of the formation and prevailing climate conditions such as temperature. The water table then becomes defined by the balance between water inflow and the energy required to remove this water as vapour under increasing salinity, as simulated by the EVT rate as a function of depth. This conceptualization does not require EVT to be zero at the existing water table and is specified to a depth that may occur given the prevailing aquifer and climatic conditions.

The extensive application of an EVT that is too large (i.e., no salt crust) implies that:

- Rainfall recharge also needs to be large to sustain observed water levels;
- Local groundwater flow is reduced, and salinity is increased in those areas, compared to an EVT that includes the effect of salt crusts; and
- Due to the shallow extinction depth, small increases in the water level will result in large changes in EVT and hence in salinity.

As noted in the report, evaporation and recharge are the major flow components of the model, and hence the relative magnitude of these flows will have a significant effect on model outcomes (i.e., estimates of impact).

It is recommended to rerun the 1000 year run with a reduced EVT, in the range of 300 mm/year, on the supratidal flats and determine what impacts are predicted in the project area. This model run is essentially a test of an alternative conceptualization, without calibration.

> **Evaporation from a salt encrusted sediment surface - Field and laboratory studies**
> *XY Chen*
>
> *Australian Journal of Soil Research 30(4) 429 - 442*
> *Published: 1992*
>
> **Abstract**
> *Estimates of hydrologic budgets from arid zones are constrained by difficulties in evaluating evaporation loss from groundwater discharge areas, especially playa surfaces. Evaporation from a salt-encrusted playa surface (Lake Amadeus, central Australia) is estimated by field measurement of*

> *moisture loss from sediment blocks in plastic receptacles set into the playa. The evaporation process consists of two distinctively different evaporative patterns. E1 is a very low rate (70 mm/year, 2.4% of pan evaporation) from the salt-encrusted surface. E2 is a much higher rate which occurs after rain dissolves the surface salt crust. The total E2 evaporation is lower than the rainfall, indicating that a portion of rainfall recharges the playa brine. Therefore, the total E1(70 mm/year) can only be used as an upper limit of the net evaporation and the actual value may be significantly lower. In a laboratory analogue experiment, a very thin (2 mm) salt crust diminishes the evaporation to about 2% of that from a freshwater surface, even though the sediments underlying the crust remain saturated. When distilled water was added to the salt crust, the evaporation rate increased by nearly 20 times for a short period, then returned to the previous low rate. However, a portion of the distilled water infiltrated to the water table and became part of the brine supply to the sediments. Both the salt crusts of Lake Amadeus and those formed in the laboratory experiment are porous and buckled, and significantly drier than the underlying sediments. The significant reduction of evaporation from salt-encrusted sediment surface seems to be mainly due to the porous, buckled and dry nature of the crust which inhibits the removal of the vapour from the underlying sediments. The vapour pressure decrease of the brine has relatively less effects.*

Similar results were also found in work done Suzanne Hollins and Peter V. Ridd for salt flats, as shown below.

Evaporation over a tropical tidal salt flat

Mangroves and Salt Marshes ***volume 1****, pages 95–102(1997)*

Abstract

> *Measurements of temperature, wind speed and humidity within 6 m of the surface of a mangrove-fringed tidal tropical salt flat were performed. Using the aerodynamic method, this data was used to infer evaporation rates from the salt flat. For a few days after tidal inundation or rain, the salt flats were wet and evaporation rates of about 5×10^{-3} m day^{-1} prevailed. By 8 days after tidal inundation and with no rain, evaporation rates had dropped to less than 2×10^{-3} m day^{-1}. The monthly evaporation rate was about 7×10^{-2} m. This generates high salinity which, together with surface temperatures exceeding 50°C, prevents colonisation of these areas by mangroves.*

A secondary effect on pond seepage is also caused by the lack of vertical resolution in the model. The mixing of pond seepage into the relatively thick layer 1 of the model results in much less dilution than would occur in practice. In practice, pond water salinity in ponds 1, 2 and 3 is much less than that of shallow groundwater, and hence, any seepage will tend to float on top of the denser insitu brine. This light low-salinity seepage will migrate through pond embankments and to a lesser extent displace the in-situ dense brine downstream. The net effect is that shallow groundwater in the vicinity of the salt ponds is likely to have similar salinities to that of pond water floating on denser in-situ brine. This buoyance effect is only effectively modelled using sufficient vertical resolution (i.e., layers) to simulate the vertical salinity gradient in the vicinity of the salt ponds.

The above effects were measured at a site downstream of a salt pond in the Pilbara (Figure 1, Catfish Creek), as shown in Figure 2 *(Gordon et al, 1995)*. Note that mangroves did not recover, even though groundwater salinity declined to viable levels, but water levels remained elevated due to pond leakage (essentially water logging of the mangroves). Such water logging may or may not be an issue for mangroves at the Ashburton Salt Site given the different physical location and distance from the ponds compared with the example provided. However, this requires further project specific investigation via revised modelling.

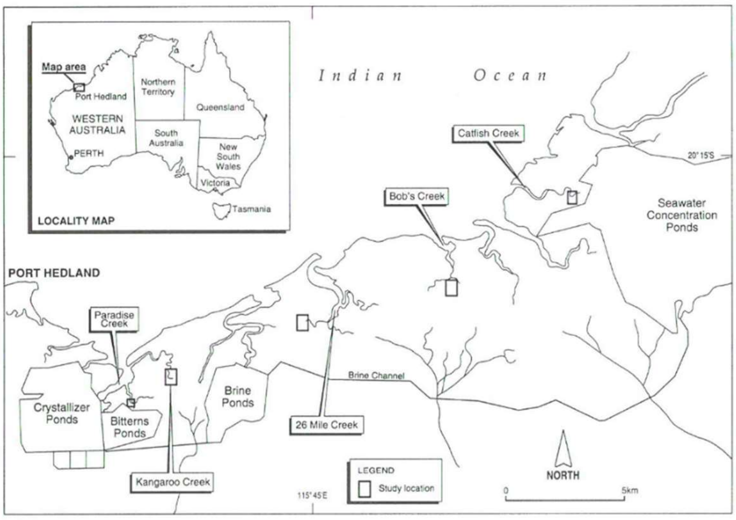
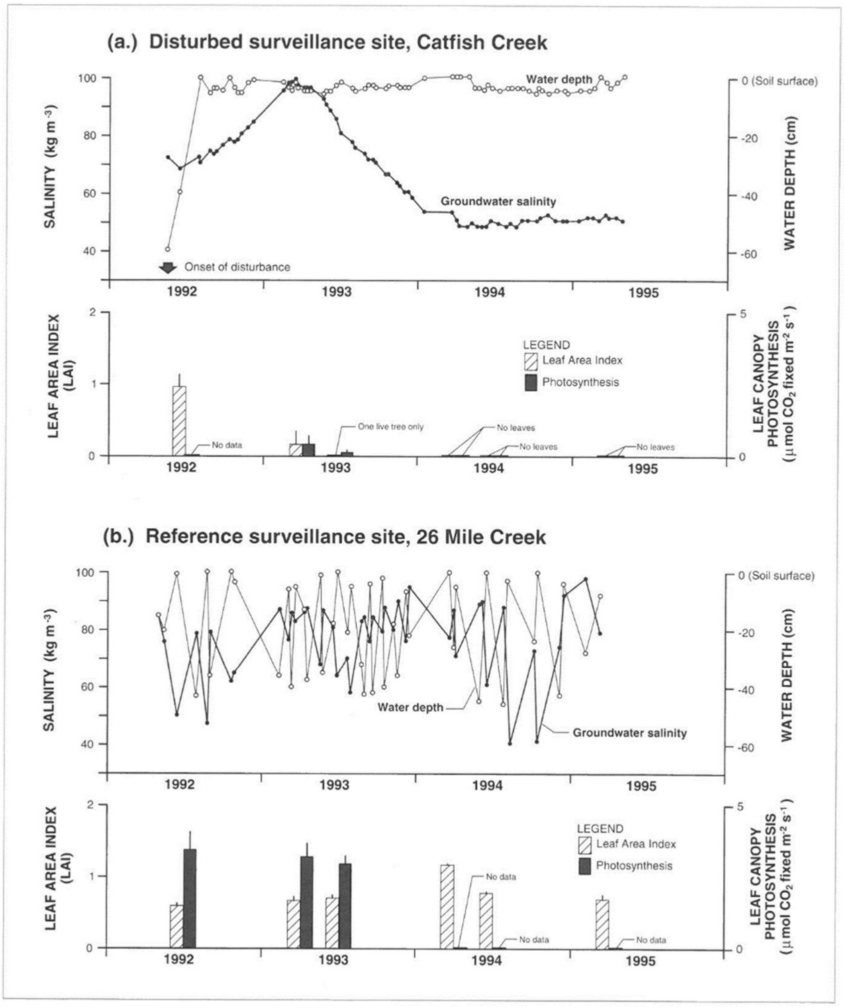


Figure 1: Mangrove Monitoring - Pilbara, 1990


(a.) Disturbed surveillance site, Catfish Creek

(b.) Reference surveillance site, 26 Mile Creek

Figure 2: Impact on Water Levels and Water Quality on Mangrove Mortality, Catfish Creek

8. Uncertainty Analysis

Table 8-1: Model Guidelines – Uncertainty Analysis

Question	Yes Maybe No	Comments
6.1 Is some qualitative or quantitative measure of uncertainty associated with the prediction reported together with the prediction?	Yes	Linear Uncertainty Analysis
6.2 Is the model with minimum prediction-error variance chosen for each prediction?	NA	
6.3 Are the sources of uncertainty discussed?	Yes	
6.3.1 measurement of uncertainty of observations and parameters	Yes	
6.3.2 structural or model uncertainty	Yes	
6.4 Is the approach to estimation of uncertainty described and appropriate?	Yes	
6.5 Are there useful depictions of uncertainty?	Yes	

9. Solute Transport

Table 9-1: Model Guidelines – Solute Transport

Question	Yes Maybe No	Comments
7.1 Has all available data on the solute distributions, sources and transport processes been collected and analysed?	Yes	
7.2 Has the appropriate extent of the model domain been delineated and are the adopted solute concentration boundaries defensible?	Yes	
7.3 Is the choice of numerical method and software appropriate?	Yes	
7.4 Is the grid design and resolution adequate, and has the effect of the discretisation on the model outcomes been systematically evaluated?	Maybe	Vertical resolution may be insufficient to model some shallow near surface processes such as flushing and low salinity pond seepage. A possible solution is demonstrated in the report using a 2-D cross sectional model.
7.5 Is there sufficient basis for the description and parameterisation of the solute transport processes?	Yes	
7.6 Are the solver and its parameters appropriate for the problem under consideration?	Yes	
7.7 Has the relative importance of advection, dispersion and diffusion been assessed?	Yes	Implicitly done as part of the uncertainty analysis
7.8 Has an assessment been made of the need to consider variable density conditions?	Yes	Density driven flow is an important process for simulating salinity distributions and is included in the model.
7.9 Is the initial solute concentration distribution sufficiently well-known for transient problems and consistent with the initial conditions for head/pressure?	Yes	Initial condition of model is uniform salinity based on seawater submergence 2500 year ago. Modern conditions are established based on a dynamic calibration over 1000 years.
7.10 Is the initial solute concentration distribution stable and in equilibrium with the solute boundary conditions and stresses?	Maybe	Initial concentration as generated by a total of 1000 years of simulation.
7.11 Is the calibration based on meaningful metrics?	Yes	Measured salinity at monitor bores Model could also be calibrated against measured vertical conductivity as measured in monitor bores.
7.12 Has the effect of spatial and temporal discretisation and solution method taken into account in the sensitivity analysis?	No	
7.13 Has the effect of flow parameters on solute concentration predictions been evaluated, or have solute concentrations been used to constrain flow parameters?	No	Relevant to the analysis of vertical flow due to EVT, and salt crusting
7.14 Does the uncertainty analysis consider the effect of solute transport parameter uncertainty, grid design and solver selection/settings?	Yes	Accounts for uncertainty in solute parameters Uncertainty analysis does not account for grid and solver selection settings.
7.15 Does the report address the role of geologic heterogeneity on solute concentration distributions?	No	

10. Conclusion and Recommendations

Based on the review of the numerical model presented in the report it is considered that the model is fit for purpose. However, there are two important limitations in the model that may result in model predictions having increased uncertainty: the lack of vertical resolution of the grid in the 1A/B geological unit, and an overly simplified estimate of EVT on the supratidal area, with salt crusts. In both cases the uncertainty may result in the overestimate of salinity changes in the upper layer of the model.

The lack of vertical grid resolution results in the model using an average salinity value in the top layer that includes dense high salinity groundwater at depth. Consequently, shallow effects such as flushing by tidal inundation and rainfall will not be simulated accurately. The demonstration of a viable flushing mechanism using a two-dimensional cross sectional model supports enhancing the existing 3D model with additional vertical resolution, to better estimate salinity changes resulting from the project at the water table.

The potential overestimate of EVT due to ignoring the effects of salt crusting is important as it directly affects the water and salt balance of the model. This effect is most obvious on the water and salt balance in the vicinity of salt ponds where low salinity water is trapped by high evaporation rates on the downstream side of the embank, resulting in dense brines near the surface. In practice, the formation of salt crusts at the surface, downstream of the embankment, reduces EVT, and can result in a plume of low salinity water (i.e., similar to the source water in the impoundment) at or near the surface, which floats on denser in situ brine.

Both of the above effects may result in increased uncertainty in the nature and magnitude of model predicted impacts, causing likely overestimation of salinity changes in the upper layer of the model (at the water table). This could be addressed by further modelling, monitoring and management planning prior to project construction.

Specifically, it is recommended that:

- An improved estimate of EVT be developed for the supratidal area, that includes the potential impact of salt crusting on the rate of water evaporation.
- The existing model should be rerun for the 1000-year simulation, with reduced EVT, in the range of 300 mm/year, on the supratidal flats to provide an assessment of the uncertainty in the model.
- Additional layers be used to simulate the 1A/B formation to ensure that density effects are accounted for with respect to mixing of seawater and groundwater, and that the tidal flushing of the shallow groundwater in the intertidal zone is correctly accounted for.

Given that the model is characterized as Level 1, additional transient data should be collected in the following areas:

- Intertidal zone area of mangroves, with water level, and water quality measured at a sub-daily interval, to better characterize tidal influences.
- The installation of additional piezometers immediately downstream of proposed ponds, to provide baseline data prior to pond construction and filling.
- After pond filling, monitoring of water levels and water quality at various distances

from filled ponds should be taken at sub monthly intervals.

The above data should then be used to improve the conceptual hydrogeological model by better quantifying the relevant processes in the project area.

An updated transient numerical model should then be constructed and calibrated that has sufficient vertical resolution to simulate pond seepage and intertidal and supratidal inundation given the potential for steep salinity gradients that may occur near surface in these areas.

It is recommended that updated modelling methodology and revised modelling results, as well as a detailed monitoring program, should be documented in a Groundwater Management Plan for the project, which should be prepared and assessed by the regulator prior to the commencement of construction.

Baseline groundwater monitoring, in consultation with the regulator should also commence as soon as possible, to ensure an adequate time period of data acquisition, to enable required modelling revisions.

11. References

Barnett et al, (2012), *Australian groundwater modelling guidelines*, Waterlines report, National Water Commission, Canberra.

Blandford and Associates (2005) Physical Environment of the Yannarie Salt Project area, Appendix 3, Prepared for Straits Salt

Chen, XY., (1992), *Evaporation from a salt encrusted sediment surface - Field and Laboratory Studies*, Australian Journal of Soil Research 30(4) 429 – 442, 1992.

Gordon, D.M., (1987), *Disturbance to mangroves in tropical-arid Western Australia: Hypersalinity and restricted tidal exchange as factors leading to mortality, 1988,* Environmental Protection Authority, Western Australia,

D.M. Gordon, A.R. Baugher, and M.I. LeProvost, (1995) *Use of Models for Detecting and Monitoring Change in A Mangrove Ecosystem in Northwestern Australia***,** Environment International, Vol. 21, No. 5, pp. 605-6**.**

Johnson, A. I. (1967), *Specific yield: compilation of specific yields for various materials, Water Supply Paper 1662-D, Washington, D.C.: U.S. Government Printing Office*

Hollins, S., Ridd, P.,(1997), *Evaporation over a tropical tidal salt flat,* Mangroves and Salt Marshes volume 1, pages 95–102

Ridd, P., Sandstrom, M.W., and Wolanski, E. 1988. Outwelling from tropical tidal salt flats. Estuarine, Coastal and Shelf (1988) 26, 243-253.

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