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**Subject: PEER REVIEW OF HYDROGEOLOGICAL MODEL FOR THE YEELIRRIE PROJECT**

## 1. Summary

Predictive groundwater simulations presented by Cameco in support of the Yeelirrie Project are based on a very well supported hydrogeological model. A high level of confidence can be placed in the models' predictive simulations presented based on:

- The relatively simple hydrogeological regime
- Extensive regional data sets available to support the model
- Intensive site hydrogeological delineation works undertaken for the project
- Extensive and detailed hydrogeological assessment and model formulation
- Calibration to large scale pumping operations
- Clearly defined development stresses

It is expected the model can produce simulations of sufficient accuracy for any resource management or impact assessment matters relating to groundwater level and solute transport responses arising from proposed developments on the Yeelirrie project tenements.

## 2. Background

Cameco have requested that MWES undertake a review of hydrogeological modelling submitted for the Yeelirrie Project approvals. This relates to the simulations and predictions presented in the report: NUMERICAL GROUNDWATER FLOW AND SOLUTE TRANSPORT MODEL OF THE YEELIRRIE URANIUM DEPOSIT, Cameco, 2015. The model development is reported separately in: FINAL REPORT - GROUNDWATER STUDY - PROPOSED YEELIRRIE DEVELOPMENT, URS, 2011. Comments and checklist responses presented here relate to the combined content of these reports and selected supporting references.

The author has previously reviewed the model development by URS for the preceding project proponent (BHP Billiton 2009-2011) and has provided independent comments to the Cameco project team during the implementation of predictive modelling.

# 3. Conceptual Model

The conceptual model was developed by URS (2011). The regional geological context is relatively simple and well defined and the conceptual model is consistent with several previous quantitative hydrogeological evaluations in the region.

It is demonstrated that groundwater is stored in Cenozoic sediments forming an elongate basin which hosts the Yeelirrie uranium deposit. The “valley-fill” sedimentary deposit includes a narrow deep permeable layer an intermediate clayey aquitard and upper variable and moderately permeable sediments. The internal geometry and stratigraphy of the aquifer system at the project site is consistent with its’ well known regional characteristics.

At the local scale the model is very well supported by detailed hydrogeological delineation investigations. The overall extent of saturated sediments and their internal stratigraphy has been defined by appropriate drilling and geophysical methods with suitable coverage and intensity. The delineation work is very well supported by and integrated with, pre-existing regional and neighbouring data sets.

The conceptual model development clearly shows that the critical consideration for modelling is discretisation/parametrisation which will allow the accurate prediction of the extent and magnitude of water table drawdown induced by dewatering and water supply pumping.

# 4. Numerical Model Structure

The lateral and vertical extent of the model are more than adequate to ensure lateral boundary conditions do not artificially constrain the simulations. The model is so large as to essentially eliminate sensitivity of the simulation to the lateral boundary configuration.

The horizontal discretisation (as low as 50 m) is very fine considering the large scale development being simulated. The vertical discretisation, comprising 9 layers is very detailed relative to the defined stratigraphy.

The model geometry is sufficiently extensive and detailed to allow accurate simulation of much greater or more localised stresses than the scenarios which are presented for assessment of the project impacts.

# 5. Model Calibration

Extensive and rigorous model calibration was undertaken including nominal steady state and transient calibration. The calibration process and results are well described in the URS (2011) report which shows that normal and appropriate methods of calibration and checks on calibration were undertaken and that good results were achieved.

The process benefited from several key data sets, including the extensive dewatering trial undertaken on the deposit in the 1970’s and the drawdown impacts from the long term operation of the adjacent Albion Downs Borefield.

The report shows a relatively accurate calibration for a wide array of observation wells and the normalised root mean square error of 4.2 % is considered acceptable.

## 6. Model Confidence Level

It is considered that the model currently has a high level of confidence, appropriate to a H3 hydrogeological assessment as defined by Department of Water criteria. The model has benefited from the very extensive data sets available for its' construction and calibration. In addition, the lengthy period project development has ensured multiple refinements and reviews.

It is considered unusual for a remote "green-fields" type development in Western Australia to be supported by such a strongly founded, well-developed and detailed groundwater model.

# APPENDIX

## COMPLETED CHECKLIST FOR PEER REVIEWERS

Checklist is from Barnett et al (2012)

| *Question* | *Yes/No* |
|---|---|
| 1. Are the model objectives and model confidence level classification clearly stated? | Yes |
| 2. Are the objectives satisfied? | Yes |
| 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? | Yes |
| 7. Are the calibrated parameter values and estimated fluxes plausible? | Yes |
| 8. Do the model predictions conform to best practice? | Yes |
| 9. Is the uncertainty associated with the predictions reported? | Yes |
| 10. Is the model fit for purpose? | Yes |

| *Review questions* | *Yes/N* | *Comment* |
|---|---|---|
| **1. Planning** | | |
| 1.1 Are the project objectives stated? | Yes | |
| 1.2 Are the model objectives stated? | Yes | |
| 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 | |
| 1.5 Is the target model confidence-level classification stated and justified? | Yes | Presented as DoW H3 type assessment and meets that specification |
| 1.6 Are the planned limitations and exclusions of the model stated? | Yes | |
| **2. Conceptualisation** | | |
| 2.1 Has a literature review been completed, including examination of prior investigations? | Yes | |
| 2.2 Is the aquifer system adequately described? | Yes | |
| 2.2.1 hydrostratigraphy including aquifer type (porous, fractured rock ...) | Yes | Well delineated, described conceptualised and discretised |
| 2.2.2 lateral extent, boundaries and significant internal features such as faults and regional folds | Yes | Well defined lateral boundaries |
| 2.2.3 aquifer geometry including layer elevations and thicknesses | Yes | |
| 2.2.4 confined or unconfined flow and the variation of these conditions in space and time? | Yes | |
| 2.3 Have data on groundwater stresses been collected and analysed? | Yes | |
| 2.3.1 recharge from rainfall, irrigation, floods, lakes | Yes | Semi-quantitative assessment used as basis for input values |
| 2.3.2 river or lake stage heights | | Not applicable |
| 2.3.3 groundwater usage (pumping, returns etc) | Yes | |
| 2.3.4 evapotranspiration | | Estimated through calibration process |
| 2.3.5 other? | | Not applicable |
| 2.4 Have groundwater level observations been collected and analysed? | Yes | |
| 2.4.1 selection of representative bore hydrographs | Yes | |
| 2.4.2 comparison of hydrographs | Yes | |
| 2.4.3 effect of stresses on hydrographs | Yes | |
| 2.4.4 watertable maps/piezometric surfaces? | Yes | |
| 2.4.5 If relevant, are density and barometric effects taken into account in the interpretation of groundwater head and flow data? | Yes | Salinity related density effects are accounted for |
| 2.5 Have flow observations been collected and analysed? | | Unavailable |
| 2.5.1 baseflow in rivers | | Not applicable |
| 2.5.2 discharge in springs | | Not applicable |
| 2.5.3 location of diffuse discharge areas? | Yes | Ground elevation input to evapotranspiration module |
| 2.6 Is the measurement error or data uncertainty reported? | Yes | |
| 2.6.1 measurement error for directly measured quantities (e.g. piezometric level, concentration, | Yes | |

| *Review questions* | *Yes/No* | *Comment* |
|---|---|---|
| flows) | | |
| 2.6.2 spatial variability/heterogeneity of parameters | Yes | Well discretised and defined |
| 2.6.3 interpolation algorithm(s) and uncertainty of gridded data? | | Not applicable |
| 2.7 Have consistent data units and geometric datum been used? | Yes | |
| 2.8 Is there a clear description of the conceptual model? | Yes | |
| 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 | |
| 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? | | Not applicable – the conceptual model is simple and based on regionally defined and accepted precedent |
| **3. Design and construction** | | |
| 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 | |
| 3.2.3 Is the software included in the archive or are references to the software provided? | Yes | |
| 3.3 Are the spatial domain and discretisation appropriate? | Yes | |
| 3.3.1 1D/2D/3D | | 3D |
| 3.3.2 lateral extent | Yes | Adequate |
| 3.3.3 layer geometry? | Yes | Adequate |
| 3.3.4 Is the horizontal discretisation appropriate for the objectives, problem setting, conceptual model and target confidence level classification? | Yes | |
| 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? | Yes | |
| 3.4 Are the temporal domain and discretisation appropriate? | Yes | |
| 3.4.1 steady state or transient | | Both |
| 3.4.2 stress periods | Yes | Appropriate |
| 3.4.3 time steps? | Yes | Appropriate |
| 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? | Yes | |

| *Review questions* | *Yes/No* | *Comment* |
|---|---|---|
| 3.5.2 Are the boundary conditions chosen to have a minimal impact on key model outcomes? How is this ascertained? | Yes | Model extent is so large as to eliminate sensitivity |
| 3.5.3 Is the calculation of diffuse recharge consistent with model objectives and confidence level? | Yes | |
| 3.5.4 Are lateral boundaries time-invariant? | Yes | Very extensive model domain eliminates any concerns |
| 3.6 Are the initial conditions appropriate? | Yes | |
| 3.6.1 Are the initial heads based on interpolation or on groundwater modelling? | | Both – initial heads carefully constructed from extensive data sets |
| 3.6.2 Is the effect of initial conditions on key model outcomes assessed? | Yes | Three independent steady state calibrations undertaken and conservative low recharge scenario was used in predictive simulation |
| 3.6.3 How is the initial concentration of solutes obtained (when relevant)? | Yes | Calculated independent of the model |
| 3.7 Is the numerical solution of the model adequate? | | Not reported |
| 3.7.1 Solution method/solver | | Not reported |
| 3.7.2 Convergence criteria | | Not reported |
| 3.7.3 Numerical precision | | Not reported |
| **4. Calibration and sensitivity** | | |
| 4.1 Are all available types of observations used for calibration? | Yes | Primarily pumping rates and water level responses |
| 4.1.1 Groundwater head data | Yes | |
| 4.1.2 Flux observations | No | Not available |
| 4.1.3 Other: environmental tracers, gradients, age, temperature, concentrations etc. | Yes | Qualitative consideration of salinity distribution and other hydrochemistry is used in recharge estimation |
| 4.2 Does the calibration methodology conform to best practice? | Yes | |
| 4.2.1 Parameterisation | Yes | Well supported and consistent with regionally accepted values |
| 4.2.2 Objective function | Yes | For each of the calibration processes the objective function is well defined and appropriate to the predictive simulations required for impact assessment |
| 4.2.3 Identifiability of parameters | Yes | Well defined |
| 4.2.4 Which methodology is used for model calibration? | | Both steady state and transient |
| 4.3 Is a sensitivity of key model outcomes assessed against? | | Initial water level is well defined a range of recharge scenarios s considered In particular rainfall recharge |
| 4.3.1 parameters | Yes | |
| 4.3.2 boundary conditions | Yes | In particular rainfall recharge |
| 4.3.3 initial conditions | Yes | Initial water level is well defined a range of recharge scenarios is considered |
| 4.3.4 stresses | Yes | Limited flexibility in development scenarios |
| 4.4 Have the calibration results been adequately | | |

| *Review questions* | *Yes/No* | *Comment* |
|---|---|---|
| reported? | Yes | |
| 4.4.1 Are there graphs showing modelled and observed hydrographs at an appropriate scale? | Yes | |
| 4.4.2 Is it clear whether observed or assumed vertical head gradients have been replicated by the model? | Yes | |
| 4.4.3 Are calibration statistics reported and illustrated in a reasonable manner? | Yes | |
| 4.5 Are multiple methods of plotting calibration results used to highlight goodness of fit robustly? Is the model sufficiently calibrated? | Yes | |
| 4.5.1 spatially | Yes | |
| 4.5.2 temporally | Yes | |
| 4.6 Are the calibrated parameters plausible? | Yes | Well supported and in the range defined by other studies in the region |
| 4.7 Are the water volumes and fluxes in the water balance realistic? | Yes | |
| 4.8 has the model been verified? | No | |
| **5. Prediction** | | |
| 5.1 Are the model predictions designed in a manner that meets the model objectives? | Yes | |
| 5.2 Is predictive uncertainty acknowledged and addressed? | Yes | |
| 5.3 Are the assumed climatic stresses appropriate? | Yes | |
| 5.4 Is a null scenario defined? | | Not Applicable |
| 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? | Yes | Calibration to Albion Downs Borefield which has greater pumping rates than project projected rates |
| 5.5.2 Are well losses accounted for when estimating maximum pumping rates per well? | | Not applicable. There is little sensitivity of impacts to individual well rates and well losses |
| 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 | Maximum impacts over 10-20 years which is similar to the transient calibration duration (Albion Downs Borefield) |
| 5.5.4 Are the assumed stresses and timescale appropriate for the stated objectives? | Yes | |
| 5.6 Do the prediction results meet the stated objectives? | Yes | |
| 5.7 Are the components of the predicted mass balance realistic? | Yes | |
| 5.7.1 Are the pumping rates assigned in the input files equal to the modelled pumping rates? | | No errors evident or reported |

| *Review questions* | *Yes/No* | *Comment* |
|---|---|---|
| 5.7.2 Does predicted seepage to or from a river exceed measured or expected river flow? | | Not applicable |
| 5.7.3 Are there any anomalous boundary fluxes due to superposition of head dependent sinks (e.g. evapotranspiration) on head-dependent boundary cells (Type 1 or 3 boundary conditions)? | | Not reported and problem is unlikely due boundary type and distance to method of recharge simulation |
| 5.7.4 Is diffuse recharge from rainfall smaller than rainfall? | Yes | Very much less - as expected |
| 5.7.5 Are model storage changes dominated by anomalous head increases in isolated cells that receive recharge? | | Not reported and unlikely due to method of recharge simulation |
| 5.8 Has particle tracking been considered as an alternative to solute transport modelling? | No | Dilution and to a lesser extent dispersion dominate the plume development so the concentration contours are more applicable than particle tracking |
| **6. Uncertainty** | | |
| 6.1 Is some qualitative or quantitative measure of uncertainty associated with the prediction reported together with the prediction? | Yes | Mainly through sensitivity analysis |
| 6.2 Is the model with minimum prediction-error variance chosen for each prediction? | | Not applicable. Conservative and or worst-case scenarios are used |
| 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 | |
| **7. Solute transport** | | |
| 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? | Yes | |
| 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 | |
| 7.8 Has an assessment been made of the need to consider variable density conditions? | Yes | Density variations are accounted for |
| 7.9 Is the initial solute concentration distribution sufficiently well-known for transient problems and consistent with the initial conditions for head/pressure? | Yes | |
| 7.10 Is the initial solute concentration distribution stable and in equilibrium with the solute boundary conditions and stresses? | | Not applicable – predictions are presented as additional solute concentration |

| *Review questions* | *Yes/No* | *Comment* |
|---|---|---|
| 7.11 Is the calibration based on meaningful metrics? | Yes | Note that pre-development solute configuration is not explicitly calibrated - only hydrodynamic calibration (water levels) not hydro-chemical calibration |
| 7.12 Has the effect of spatial and temporal discretisation and solution method taken into account in the sensitivity analysis? | No | Discretisation is conservatively fine. No sensitivity assessment is required |
| 7.13 Has the effect of flow parameters on solute concentration predictions been evaluated, or have solute concentrations been used to constrain flow parameters? | Yes | Sensitivity includes impacts of flow parameters on solute concentration. No calibration to solute concentration possible as no data sets available |
| 7.14 Does the uncertainty analysis consider the effect of solute transport parameter uncertainty, grid design and solver selection/settings? | Yes | Solute transport parameter uncertainty is considered. Grid design and solver effects not reported |
| 7.15 Does the report address the role of geologic heterogeneity on solute concentration distributions? | Yes | |
| **8. Surface water–groundwater interaction** | | |
| 8.1 Is the conceptualisation of surface water–groundwater interaction in accordance with the model objectives? | Yes | Extensive assessment of rainfall recharge rate which is key variable |
| 8.2 Is the implementation of surface water–groundwater interaction appropriate? | Yes | Rainfall recharge and evapotranspiration only |
| 8.3 Is the groundwater model coupled with a surface water model? | No | |
| 8.3.1 Is the adopted approach appropriate? | | Not applicable |
| 8.3.2 Have appropriate time steps and stress periods been adopted? | | Not applicable |
| 8.3.3 Are the interface fluxes consistent between the groundwater and surface water models? | | Not applicable |