Cameco

NUMERICAL GROUNDWATER FLOW AND SOLUTE TRANSPORT MODEL OF THE YEELIRRIE URANIUM DEPOSIT

Yeelirrie

January 2015
Geo-environmental Engineering, SHEQ,
Environmental Affairs

EXECTUTIVE SUMMARY

This report documents the results of groundwater flow and solute transport modelling related to the development of the Yeelirrie uranium deposit within the Yeelirrie Catchment. The model uses as a starting point a calibrated groundwater flow model which previously was developed for the Yeelirrie Catchment by URS Australia Pty Ltd. (URS, 2011a). All the predictions presented in this report supersede the results of the predictive simulations presented by URS (URS, 2011a).

The project timeline is 22 years. Mining starts two years before milling to create space for tailings deposition. Dewatering, needed for safe mining, will commence one year ahead of mining. Mining will be completed at the end of year 16, milling at the end of year 18. Decommissioning of the project site and placing a cover will be completed at the end of year 22.

The only groundwater input source is recharge derived from rainfall and the primary groundwater discharge mechanism is through evapo(trans)piration. A comparative small portion of the recharge (11 to 13%) leaves the catchment as groundwater flow to Lake Miranda. The water table is a subdued reflection of the surface topography, with deep water tables (up to 20 m below the ground surface along the flanks of the valley) and shallow water tables along the valley floor (2 – 5 m below ground surface). The general flow pattern is from the flanks toward the valley floor and then longitudinal toward Lake Miranda.

The quality of the water extracted from the mine pit area as part of mine dewatering is saline with Total Dissolved Solids (TDS) values ranging from approximately 15,000 to 33,000 mg/L. Water from the proposed Eastern, Northern and Western wellfields has a TDS in the range of 2,000 to 2,500 mg/L. The TDS of water from the paleochannel ranges from approximately 4,000 mg/L west of the deposit to 38,000 mg/L beneath and east of the deposit.

The annual average daily water requirement for the project, comprising potable water produced via a reverse osmosis facility, process water and saline water ranges from about 1,140 kL/day at the beginning and end of project to 8,724 kL/day when both mining and milling are in operation.

Findings of the predictive groundwater flow model include:

- The predicted total volume of water from mine pit dewatering is 18.90 Gl, ranging from 0.04 Gl/a to 2.73 Gl/a.
- The combined withdrawals from the proposed wellfields would be 50.72 Gl over the lifetime of the project, ranging from 0.44 Gl/a in the final years of the project to 3.21 Gl/a during milling.
- As a water conservation measure, water becoming available in the initial years of dewatering when supply exceeds demand, will be re-injected into groundwater in the vicinity of the western part of the deposit. It is predicted that 2.27 Gl will be injected.
- Drawdown of the water table occurs as a result of dewatering and withdrawals from the wellfields. The drawdown model indicates the following:
  - The extent of water table drawdown increases slowly over time, indicating a relative abundance of groundwater resources in the project area.
  - The model predicted water table drawdown indicates a small interference with the water table drawdown caused by the Albion Downs wellfield, assuming this wellfield is operated at historical withdrawals for the period of the operational model.

  - The water table drawdown will not impact existing pastoral groundwater users and the water level drawdown in the paleochannel will have no impact on the withdrawals from this aquifer in the Albion Downs wellfield.
  - As the demand for water from the proposed wellfields will be greatly reduced after milling ceases, recovery of the water table starts at the end of milling (project year 18).
  - Within 50 years after cessation of withdrawals a significant water table recovery will have taken place. Near the proposed pit the water level will have recovery within 100 years. Small residual drawdowns may locally exist for more than 200 years.
  - An option study indicates that a barrier wall would have a limiting drawdown effect on water table upgradient of the wall.

The groundwater flow model presents a conservative case as low recharge was assumed and the modelled total groundwater withdrawals were 20% higher than the predicted required volume.

Solute transport modelling (15,000 years) was conducted to predict the impact of selected constituents of concern (COC) originating from the tailings on the environment. Developed source terms and conservative K_d values were used in modelling the transport of COC’s.

The long-term solute transport modelling predicts the following:

- Chloride (conservative constituent) plume front (0.01 mg/L) could travel as far a 50 km from the tailings storage facility. However, except for up to 1,000 m from the facility, the concentration increase is negligible compared to the baseline concentrations.
- Other simulated COCs (including uranium, vanadium, arsenic and molybdenum) plume fronts (0.01 mg/L) can travel several hundred meters longitudinally along the valley, but typically not beyond the eastern boundary of the pit.
- The uranium, vanadium, arsenic and molybdenum plume fronts (0.01 mg/L) can extend up to 600 m north and 200 south of the facility.
- Vertically the plume fronts (0.01 mg/L) may reach the paleochannel underlying the facility

Sensitivity analyses indicate that COC transport is more sensitive to K_d, infiltration through tailings and backfill cover and the extinction depth, rather than source concentration in the respective simulated range of these parameters.

TABLE OF CONTENTS

List of Figures

List of Tables

ABBREVIATIONS

Abbreviation	Description
AHD	Australian Height Datum
ºC	Degrees Celcius
COC	Constituent of Concern
DEM	Digital Elevation Model
Gl	Gigalitres (1 billion litres, 10^9 L, 1 million cubic metres)
Gl/a	Gigalitres per annum
kL	Kilolitres (1 thousand litres, 1 cubic metre)
kL/day	Kilolitres per day (1 cubic metre per day)
km	Kilometre
L/s	Litre per second
m	Metre
mAHD	Metres above Australian Height Datum
MAR	Managed Aquifer Recharge
m/day	Metres per day
m^2/day	Metres squared per day
m^3/day	Cubic metres per day
m^3/s	Cubic metres per second
mg/L	Milligrams per Litre
mm	Millimetre
mm/day	Millilitre per day
Ma	Million years
ML	Megalitres (1 million litres)
ML/day	Megalitres per day
Mtpa	Million tonne per annum
t	Tonne (1,000 kg)
TDS	Total Dissolved Solids (mg/L)

1.0 INTRODUCTION

1.1 Background – History

The Yeelirrie deposit (“Site”) was discovered in 1972 by the Western Mining Corporation (“WMC”). Numerous studies were conducted, culminating in the submission of an Environmental Impact Statement (EIS) by WMC in 1978, which was approved by both the State and the Commonwealth government in 1979. Since 1983, the Site was put into “care and maintenance” and Site rehabilitation was completed in 2004. In 2005, WMC was taken over by BHP Billiton (“BHPB”). BHPB re-activated the Site in 2008 and conducted numerous groundwater related studies, including drilling of a large number of boreholes for the construction of monitoring wells, until the Site was sold to the Cameco Corporation (“Cameco”) in December 2012.

After careful review, Cameco accepted the conceptual hydrogeological model and numerical groundwater flow model developed by URS Australia Pty Ltd (“URS”) for BHPB (URS, 2011a).

This report summarizes the development and calibration of the URS groundwater flow model. It presents and discusses the results of numerical groundwater flow and solute transport modelling for the Yeelirrie Site based on the Cameco’s dewatering, mining, tailings deposition and cover placement schedule.

1.2 Previous Work

Based on WMC’s estimated water requirements (WMC, 1978), AGC (1981a,b,c) conducted extensive groundwater investigations. These investigations were mainly focussed on groundwater resources in the Lake Way watershed, located to the north of the Yeelirrie deposit and catchment. Studies in the Yeelirrie catchment area were limited.

In 1972, WMC conducted an extensive trial mining operation, referred to as the Slot 1 trial, to support a pilot scale metallurgical testing program (McKay, 1973). During the actual dewatering (July to October, 1972) of Slot 1 discharge rates were recorded and water levels were measured in numerous monitor wells surrounding the pit. The data were analyzed by AGC (1973) in terms of hydraulic properties. The Slot 1 data were also used by URS for estimation of hydraulic parameters (URS, 2011a, Attachment C).

In the period 1989 to 1994, extensive groundwater studies, including borehole drilling and production well construction, were conducted in the area east of the Yeelirrie deposit, resulting in the development of the Albion Downs wellfield (e.g. WMC 1994; Woodward-Clyde, 1996). This wellfield has provided the Nickel West Mt Keith operations with water since 1994. Wellfield data were used by URS (URS, 2011a) in the development of their groundwater flow model.

In 2009 and 2010, URS conducted several groundwater related field investigation programs in support of establishing a conceptual hydrogeological model which, in turn, formed the basis for developing a numerical groundwater flow model (URS, 2011a):

Groundwater monitoring wells:
Constructed:

- 143 single groundwater monitoring wells;
- 7 multi-level monitoring wells (typically three monitoring wells were completed in a single borehole at each of the multi-level sites);
- 8 test production wells;
- 95 wells for characterizing stygofauna; and
- 77 wells for troglofauna characterization.

The wells were constructed along 14 planned cross section lines and eight “in-fill” lines. Completion details were provided by URS (URS, 2011a, Attachment G).

Pumping tests:
The following pumping tests were conducted to obtain an estimate of the hydraulic conductivity and transmissivity of the various hydrostratigraphic units at the site:

- Short-term pumping tests (5 to 30 min) were conducted on 50 monitoring wells (URS, 2011a, Attachment H).
- Longer term tests were conducted on the eight test production wells. The tests included: step-drawdown, constant-rate (up to 48 hrs) and recovery test. The results were presented in URS (2011a, Attachment I).

In addition to these pumping tests, laboratory test were conducted on eight undisturbed core samples from the clayey alluvium to determine the vertical hydraulic conductivity (URS, 2011a, Attachment M).

Groundwater quality:
In addition to compiling historical groundwater quality data, URS conducted a large groundwater sampling program in 2009 to 2010. This program was mainly focussed on the newly installed monitoring wells and test production wells, but also included existing pastoral wells. Analyses are available for 215 sites. Samples, obtained using the low-flow sampling technique were analyzed for major ions, metals (dissolved and total), nutrients and radiochemicals. At the time of sampling, field water quality measurements were obtained. The collection of samples is described in detail in URS (2011a): the results of the chemical analyses are provided in URS (2011a, Attachment K).

Miscellaneous investigation:
Furgo (2009) conducted a ground-based gravity survey in 2009 to define the deepest parts of the Yeelirrie paleochannel along selected cross sections in support of optimizing subsequent drilling. Their report is provided in URS (2011a, Attachment F).

2.0 SITE DESCRIPTION

2.1 Location

The Yeelirrie Uranium Deposit is located approximately 70 km south of Wiluna, and 110 km north-west of Leinster, in the in the Northern Goldfields of Western Australia (Fig 2.1). The deposit is situated entirely on the Yeelirrie pastoral station in the Shire of Wiluna. Land use in the area surrounding the proposed site is typical to the Northern Goldfields area of Western Australian and consists predominantly of mining activities, pastoral stations and conservation reserves.

2.2 Topography

The Yeelirrie uranium deposit occurs in the central drainage channel of a wide, flat and long drainage valley flanked by granitic breakaways of low topographic relief; including the Barr Smith Range to the north-east and the Montague Range to the west.

The valley floor has an elevation of about 500 mAHD, while the breakaways are 50 to 100 m higher. In the vicinity of the deposit, the valley is 25 to 30 km wide. In relation to the Yeelirrie deposit, the valley runs northwest to southeast, extending at least 50 km to the north-west and approximately 80 km to the southeast, where it joins the Lake Miranda basin at 460 mAHD.

Surface gradients are very low and while the total valley has an overall slope angle of approximately 3.5% on the north-eastern side and 5% on the south-western side, the edges of the valley floor are generally around 0.3 to 0.4%. Longitudinal gradients are typically less than 0.1%.

2.3 Climate

The climate in the Yeelirrie catchment area is classified as arid with a variable temporal and spatial rainfall distribution.

Meteorological data collected over 87 years (1928 to 2014) for the Yeelirrie Station (BoM station No.12090) shows an average annual rainfall of 239 mm. The mean annual precipitation in the climatic period 1981 to 2010 was 288 mm, indicating wetter conditions in recent decades (Bureau of Meteorology, 2014).

Yeelirrie receives 61% of its mean annual rainfall from November to April. Summer rains are normally of high intensity, caused by localised thunderstorm activity or much larger weather systems associated with cyclones and tropical lows.

The lowest annual rainfall of 43 mm was recorded in 1950 and the highest of 507 mm was recorded in 1975 (Bureau of Meteorology, 2014).

Rainfall is overwhelmed by the large evaporation rates that exist in the area. The Wiluna BoM Station No. 013012 (1957 to 1985) recorded an average pan evaporation rate of 2,412 mm a year. The next closest meteorological station, Meekatharra Airport (BoM Station No 007045), recorded a mean annual pan evaporation rate of 3,548 mm. In the absence of evaporation data at Yeelirrie, long-term (1889 to 2014) SILO synthetic rainfall and evaporation data were generated for the Yeelirrie catchment. An average annual pan evaporation rate of 2,918 mm was predicted.

Evapotranspiration is the transfer of water as vapour to the atmosphere from both vegetated and barren land surfaces (i.e. the sum of evaporation and transpiration). Evapotranspiration is affected by numerous variables including climate, the availability of water, vegetation, the depth to shallow groundwater, water salinity and soil properties. The actual areal evapotranspiration rate within the project area is estimated to be 200–300 mm/y, suggesting that most incident rainfall in the catchment is subsequently lost as evapotranspiration.

2.4 Regional Geology

The Yeelirrie deposit is hosted within a broad, Cenozoic aged, drainage channel which is incised into the crystalline, Archaean aged basement rocks of the northern Yilgarn Craton (Figure 2.2). An understanding of the catchment geometry and paleochannel sediment fill is important when defining the best hydrological parameters to use in groundwater modelling.

2.4.1 Archaean Basement

Regionally the crystalline basement is composed of NNW-SSE trending “greenstone” belts, typically composed of poly-deformed, ultra-mafic to mafic intrusives and extrusives, acid volcanics and both clastic and chemical sediments (WMC, 1975). The greenstone belts are intruded and enveloped by extensive metamorphosed felsic to intermediate granitoids and ortho-gneiss variably dated between 2,900 and 2,500 Ma, collectively called “granite terrain” in the literature, which make up the bulk of the northern portion of the craton (Cameron, 1990).

The distribution of the greenstone and granite terrain is largely controlled by a series of district scale, anastomosing deep seated faults and shear zones (Figure 2.2). Where these faults are developed within or along the margins of the greenstone belts, second order faults and shear systems are preferentially developed within the meta-sediments. This results in the formation of zones within the basement with significantly higher, structurally controlled secondary permeability.

2.4.2 Oligocene to early Miocene Regolith Development

The Archaean basement rocks, including those in the Yeelirrie area, were extensively weathered under humid tropical climatic conditions during the Oligocene to early Miocene period (Butt et al., 1984) when this portion of Australia sat at equatorial latitudes. This resulted in the development of a full, lateritic profile consisting of a red, ferruginous and siliceous concretionary cap underlain by extensively leached and weathered kaolinite-dominated, saprolitic clay transitioning into partly weathered and then fresh bedrock (Bourman and Ollier, 2002; Figure 2.3). In many locations in the Yilgarn, the fully preserved lateritic profile can be up to 100 m deep, suggesting prolonged weathering under these climatic conditions. In the Yeelirrie district, this lateritic, peneplained surface is referred to as the “Old Plateau” with the preserved relicts, topped by siliceous caps, occurring as regional topographic highs often defining the margins of catchment areas (Figure 2.4; WMC, 1975).

Regolith development within the greenstone belts tends to extend to greater depths than those observed in the granite terrain. The lithologies that comprise the greenstone belts are generally much more susceptible to weathering and have zones of elevated secondary permeability associated with faulting and shearing.

The mineralogy of the upper portions of the regolith profile is dominated by iron and manganese oxides, quartz, kaolinite, illite and minor montmorillinte (smectite). In the deeper parts of the profile where the basement is only partially weathered, minerals like muscovite and K-feldspar are often preserved. Mafic minerals persist only in the fresh unweathered basement.

2.4.3 Miocene/Pliocene Paleovalley Development

Rejuvenation of the drainage system in the mid to late Miocene/Pliocene (Butt et al., 1984) resulted in erosion of the Old Plateau, with new streams and rivers variably incising down through the regolith profile and into bedrock. This resulted in the development of the “New Plateau” surface (Figure 2.4) which regionally consisted of a system of broad, shallow, south-easterly draining paleovalleys (WMC, 1975) that included the Yeelirrie catchment.

The Yeelirrie catchment is approximately 75 km long and is on average 30 km wide. The valley margins are defined by 5 to 10 m high breakaways outcropping in an otherwise highly subdued terrain. There are multiple first order channels incised into the sides of the main valley draining off of the basin margins, and coalescing into one main channel down the axis of the catchment.

The studies completed by WMC, BHPB and URS demonstrate that the basement topography of the Yeelirrie channel is highly variable both longitudinally and in cross-section (Figure 2.5) with incised channels (thalwegs) in excess of 80 m depth occurring within the larger channel which averages 50 m in depth.

The erosive cycle was terminated by the onset of arid conditions (Butt et al., 1984; WMC, 1975), and the resultant valley/s became active alluvial deposition centres.

2.4.4 Tertiary Sedimentation

Sedimentological studies completed by Johnson et al. (1999), WMC (1975) and URS (2011a) on both the Yeelirrie and adjacent catchment areas, suggest the majority of the fill deposited in the Yilgarn paleovalleys during the Tertiary were originally of fluviatile origin. Erosion, sediment transport and deposition occurred in a moderately arid climate where seasonal rainfall fluctuations resulted in the formation of an ephemeral river system. Initially, river systems would have largely been confined to the deepest part of the incised valley (Figure 2.5).

The weathering regime under these climatic conditions would have been dominantly physical in nature resulting in the rapid erosion of the exposed regolith on the catchment margins. The sediment derived from the erosion of the regolith profile would be dominated by quartz and kaolinitic clay (Butt et al., 1984) with minor amounts of feldspar, illite, montmorillinite, haematite and goethite. Due to the short sediment train and the ephemeral nature of the fluvial system, there would have been very little physical abrasion or winnowing of the sediments resulting in immature and poorly sorted successions.

Stratigraphically the basal member of the Tertiary fill, which is observed within the deep incised, basement lows (Figure 2.5), is an arkosic sand member, the Wollubar Sandstone. This unit is overlain by a thick sequence of grey green clay sediments of the Perkolilli Shale (URS, 2011a). Discrete sand lenses are developed throughout the Perkolilli Shale and are thought to represent fluvial channel facies associated with flood-flow dominated deposition.

Early sedimentary facies observed on the channel margins were dominated by alluvial fans developed from first order streams flowing down the flanks of the lateritic breakaways. The alluvial fans continued to grow into the channels and along the margins inter-fingering with the channel fill and eventually amalgamating along strike.

A depositional hiatus in the sedimentological history resulted in the formation of a desiccated clay band with a ferricrete overprint (Figure 2.5). This is referred to by Johnson et al. (1999) as the “Tertiary Unconformity Marker Unit” and may represent a period of particularly high aridity where there was minimal rainfall, resulting in sediment dehydration and no associated fluvial sedimentation.

2.4.5 Late Tertiary – Quaternary Sedimentation

In the late Tertiary to early Quaternary sedimentation commenced again but this time on a more topographically subdued plain. The seasonal surficial water inflow was no longer confined to the basement paleo-topographic lows, resulting in the formation of an ephemeral braided river system. The resultant sedimentation consisted of a sequence of inter-fingering ***Sandy Alluvium*** (river channel facies) and ***Clayey Alluvium*** (overbank and flood deposit facies).

2.4.6 Quaternary Sedimentation

The sedimentation cycle was terminated with the onset of more arid conditions, and the trunk valleys became choked with sediment (BHPB, 2010).

Quaternary sedimentation is predominantly aeolian in origin, consisting of a sand dominated loam, fixed by plant matter to create a loose soil. The loamy soil layer is dominantly acidic (Noble et al., 2011) and generally lacks carbonate horizons except along the axes of significant channels.

The current surficial drainage system consists of ephemeral streams linking a series of small playa lakes in topographic depressions developed parallel to, but often offset from, the paleochannel axis. The dominant clay in the upper portion of these playa lakes is interpreted to be smectite.

2.4.7 Post Sedimentation Groundwater Modification

The roles of diagenesis and in situ paleochannel sediment modification processes due to groundwater interaction are instrumental in the genesis of surficial uranium deposits. These processes generate the main host unit (carbonate), can result in the formation of authigenic gangue minerals, and control the formation and distribution of uranium mineralisation.

The minerals comprising the bulk of the paleochannel sediment fill prior to groundwater modification were dominantly quartz, K-feldspar, kaolinite, illite, minor montmorillinte (smectite), haematite and goethite. Post sedimentation groundwater modification resulted in the addition of Mg-smectite, dolomite, calcite, gypsum and celestine to the upper portion of the paleochannel fill along the drainage axis. The formation of these new mineralogical components involved the modification, and hence apparent loss, of feldspar, kaolinite and illite.

Carbonate System

The main calcrete body within the Yeelirrie channel is described by authors (Butt et al., 1977; Mann and Horwitz, 1979; and Arakel et al., 1982) as a “valley calcrete”. A valley calcrete is a non-pedogenic, authigenic calcrete formed in the phreatic zone above and at the top of a perched water table, and within the capillary fringe zone. This is illustrated in Figure 2.6 from Chen et al. (2002).

A valley calcrete typically forms in large catchments with a low topographic relief (gradients of < 1%), and developed in highly to semi-arid environments characterized by irregular, heavy but infrequent rainfall (Mann and Deutscher, 1978). Further information on the specifics of the formation environment can be obtained from Mann and Deutscher (1978) and Carlisle (1984).

The carbonate precipitated in valley calcrete systems occurs in several different morphologies due to the nature of the carbonate growth. Carbonate precipitation within the profile may either replace or displace other regolith components.

In the replacement style of precipitation, the host components are dissolved and/or removed and are replaced by precipitating carbonate. Constituents which may get replaced include organic material, sulphate minerals, some silicate minerals and, in favourable environmental conditions, iron oxides (Chen et al., 2002). This style of precipitation typically generates a buff, friable “earthy” carbonate in which the relicts of the sediment are retained within a matrix of powdery to indurated carbonate (Cameron, 1984).

The displacement mechanism consists of carbonate precipitation resulting in an increase in volume which physically displaces the host rock components. From the point of nucleation the carbonate zone pushes substrate out of the way forming large bulbous/domal masses of carbonate (Arakel et al., 1982), which, when well developed, often incorporate large caverns/void spaces (Chen et al., 2002). The resultant calcrete is generally more indurated, nodular and “porcellaneous” in nature. It can contain growth bands and may incorporate minor components of the surrounding sediment.

These two carbonate types represent end members of a spectrum of carbonate types. These end members and the mixtures in between can have very different groundwater characteristics.

The main carbonate body hosting mineralisation at Yeelirrie as interpreted by BHPB is approximately 20 km long and averages 2 km in width. The carbonate unit within the resource area which has been confirmed by drilling is approximately 11 km long and 2 km wide and, on average, 6 m in thickness.

2.5 Aquifer Systems

The geological and hydrogeological model of the mining area is based on existing borehole logs and the data obtained from fieldwork conducted in 2009, URS (2011a). The interpreted hydrostratigraphical setting is shown in Table 1.

The distribution of the various aquifer types on a large regional scale is shown on Figure 2.7. Figures 2.8 and 2.9 show schematic sections of these various units and their stratigraphic relationships in the form of a block diagram and cross section, respectively.

The interpreted stratigraphy of the proposed development area is shown in Figure 2.10 (transverse cross sections) and Figure 2.11 (longitudinal cross section).

The following descriptions of the main aquifers are taken from the URS report (URS, 2011a).

Table 1 Regional and Yeelirrie Catchment Stratigraphy

Hydrostratigraphic Unit		Potential Aquifer Description	
		Storage Characteristics	Broad Lithology
Quaternary/Recent Superficial Formations			
Hard Pan		Unconfined	Loam and Hard Pan
Calcrete			Calcrete
			Transitional Calcrete
			Carbonated Clay-Quartz
Alluvium		Unconfined to Semi-Confined	Sandstone
			Sandy Alluvium
			Clayey Alluvium
Early-Tertiary Successions – Yeelirrie Palaeochannel			
Channel Upper	Unconformity Marker Bed	Confined	Ferricrete/Desiccated Clay
	Carbonaceous Marker Bed		Dark Grey Clay
	Upper Palaeochannel Sands		Palaeochannel Sand
Lower Channel	Perkolilli Shale		Lacustrine Clay
	Wollubar Sandstone		Palaeochannel Sand
Archaean - Yilgarn Shield			
Weathered Bedrock		Confined	Granite, Greenstone and Dolerite
Fresh Bedrock		Confined Fractured Rock	Granite, Greenstone and Dolerite

Note: Table after URS (2011a)

🟨 Units considered potential aquifers

2.5.1 Calcrete Aquifers

Valley calcrete/carbonate deposits, as described in section 2.4.7, have been developed along the axis of the paleochannel. These deposits partially have replaced and cemented the near-surface Quaternary and recent alluvial successions in and around the perched water table.

The calcrete deposits form the most significant water table (unconfined) aquifers in the central valley areas of the region, with transmissivity enhanced by karstic secondary porosity characteristics. Well yields in calcrete are known to be widely variable, due to the karst development. Yields at Depot Springs (Johnson, et al., 1999) ranged from 300 to 5,000 kL/day in massive and strongly karstic calcrete.

The calcrete and transition calcrete may be the most transmissive aquifers in the Yeelirrie Catchment due to the vuggy texture and dissolution features which form large connected voids. The transmissivity is expected to vary widely, however, due to textural changes within the calcrete and the limited saturated thicknesses. Where the unit is porcellaneous, groundwater flow occurs through preferential pathways formed by open voids. Where the unit is earthy, there may be comparatively high primary porosity, but limited secondary porosity. Beneath the transitional calcrete, beds of carbonated clay-quartz (Table 1) may also provide preferred local groundwater flow paths.

It is important to note that the distribution of the valley calcrete aquifer system used in the URS models and in the current Cameco model assumes that the calcrete is a continuous unit from 10 km to the west of the resource area through to the southern end of the known mineralisation. The calcrete system to the west of the resource area is not well-defined by drilling; therefore there is some question regarding the continuity and extent of the calcrete body in this area.

2.5.2 Alluvial Aquifers

The majority of the alluvial aquifers occur between the base of the carbonated clay-quartz unit and above the unconformity marker horizon (Table 1). The alluvial sediments commonly form an unconfined water table aquifer with a saturated thickness from 5 to 15 m. Typically, the water table is comparatively shallow at depths of 2 to 10 m beneath the valley-floor and foot-slope areas.

The effective transmissivity of the alluvial successions is variable due to changes in the silt and clay content; it is highest where the alluvium is characterised by sand and gravel beds of comparatively high hydraulic conductivity. Water yields of 50 to 330 kL/day from wells completed in the alluvium successions at the Albion Downs Wellfield downstream of Yeelirrie in the Carey Paleo drainage, reflect variations in effective transmissivity.

Typically, the alluvial sand and clay is interbedded with both lateral and vertical facies changes. The sand dominated facies become more volumetrically significant from the middle of the catchment to the Albion Downs Wellfield with the sand content progressively increasing. Where saturated, the sand dominant successions form aquifers of comparatively high effective transmissivity, making them effective pathways for groundwater flow.

2.5.3 Basal Paleochannel Sand Aquifer (Woolubar Sandstone)

The basal sands in the paleochannel successions form important regional aquifers capable of providing substantial groundwater supplies (Johnson, et al., 1999). Paleochannel sands were initially identified in the Yeelirrie Catchment in areas east of the Yeelirrie Homestead and between the granitic breakaways (WMC, 1978). Within the paleochannel, sediment thicknesses vary due to irregularities in the basement profile. The basal sands tend to be narrow and discontinuous in the upper portion of the catchment where basement topographic gradients are relatively low. In the lower reaches of the paleochannel, where basement gradients are elevated, higher energy sedimentary environments resulted in the deposition of coarser sands and gravels. These lower catchment basal sands tend to be more extensive and in the vicinity of Lake Miranda reach thicknesses of up to 85m (Johnson, et al., 1999).

The hydraulic conductivity of the basal paleochannel sand has been determined from aquifer tests in the Carey Paleodrainage in the range of 1 to 40 m/day (average 10 m/day). Such variations in hydraulic conductivity are probably related to grain size, silt and clay contents and the degree of sediment sorting. Coarse basal paleochannel sands intersected in the Albion Downs Wellfield are characterised by higher hydraulic conductivity (Johnson, et al., 1999).

The Woolubar Sandstone forms the majority of this basal aquifer but in the upper reaches of the catchment, where this basal sandstone is narrow and discontinuous, sandy portions of the overlying alluvial successions form part of this aquifer.

2.5.4 Archaean Basement

Basement rocks within the Yeelirrie Catchment are typically considered to have a low transmissivity, consistent with assessments made in other similar geological settings (Johnson, et al., 1999). Weathered and fractured fault/shear zones may be associated with localised aquifer zones but these zones would have relatively a low transmissivity. Outside of structural corridors the weathered granite basement is interpreted to have comparatively low transmissivity, despite potentially contributing to the groundwater flow system. Importantly the weathered granite is interpreted to form a hydraulic link between the Early Tertiary sediments and the near surface alluvial/calcrete aquifers.

Fresh granite forms the base of the groundwater flow system within the Yeelirrie Catchment.

2.6 Groundwater levels

An interpretation of baseline (pre-development) water table elevations is essential for groundwater flow modelling as it constitutes a key reference for model calibration. URS (2011a) prepared a map of the baseline water table elevations for the Yeelirrie catchment based on data for pastoral wells, pre-development water level data for the Albion Downs wellfield, measurements related to a census.

Figure 2.12 shows the undisturbed (2007) water table elevations for the entire Yeelirrie catchment area. The interpreted water table topography closely reflects the land surface topography. As indicated by the groundwater flow lines, groundwater moves from the catchment divides towards the valley floor areas and then in a general southeast direction towards the Yeelirrie Playa, Albion Downs Playa and Lake Miranda. With elevations ranging from 530 to 610 mAHD, the groundwater levels are the highest in the northwest (headwaters) of the Yeelirrie catchment. Down-gradient, across the deposit, it ranges from 490 to 492 mAHD and is about 480 mAHD at the Yeelirrie Homestead. In the vicinity of Miranda Lake the water table is about 460 mAHD.

The baseline water table configuration in the vicinity of the deposit is shown in Figure 2.13. In general terms, along the valley floor the hydraulic gradients are flat, reflecting the high transmissivity of the calcrete and sandy alluvium aquifers.

Production from the Albion Downs wellfield started in 1994. The interpreted drawdown of the water table, to December 2007, caused by the withdrawals is shown in Figure 2.14. Figure 2.14 indicates that the influence of interpreted drawdown associated with the Albion Downs wellfield does not propagate upgradient to the proposed development area.

Subtracting the interpreted baseline water table elevations from the Yeelirrie Catchment DEM, Figure 2.15 shows the interpreted depth to the water table within the watershed (URS, 2011a). Depths to the water table provide indications of the potential recharge and discharge. The greatest depths to the water table are found in the headwater area of the catchment and along the flanks. In these areas the depth to the water table ranges from 10 to 20 m below ground surface and locally is greater than 20 m. Along the valley floor, the depth to the water table is typically less than 5 m. Within the area of the deposit the depth to the water table is in the 3 to 5 m range (Fig 2.16).

A groundwater-level, whether it is the water-table of an unconfined aquifer or the potentiometric surface of semi-confined aquifer, is never at rest due to a variety of influences. The hydrographs obtained from wells are the cumulative result of the superposition of several different types of fluctuations. Seasonal fluctuations are superimposed on longer-term water-level trends which are caused by variations in climate. Superimposed on the seasonal fluctuations are short-term fluctuations due to changes in barometric pressure, earthquakes, earth tides, and transpiration of vegetation. Man-made influences such as those due to pumping and artificial recharge (*e.g.* injection wells, reservoirs, canals) are superimposed on these natural fluctuations.

The sporadic temporal nature of water table fluctuations in the Goldfields region was investigated by Morgan (1999), specifically in the vicinity of Wiluna. Morgan (1999) suggested that daily rainfall intensities greater than 25 mm are required to generate and concentrate runoff to initiate groundwater recharge at specific locations. Experience elsewhere in the Goldfields region suggests rainfall event thresholds up to 50 mm are required to deliver recharge to shallow water table zones.

A regional network of groundwater level observation wells, equipped with water level dataloggers, was established in 2009. The hydrographs indicate that the range of water level fluctuations since that time is less than 0.2 m. There is no evidence of seasonality in the water level fluctuations. In a small number of shallow water table wells the water level responded to significant rainfall events. These water level data support the observations elsewhere that recharge is highly sporadic, localized, and that up to 50 mm of rainfall, or more, is required for recharge to occur (Cameco, 2014).

2.7 Groundwater Quality

This section provides a brief summary of the available water quality data, based on the URS report (URS, 2011a).

The locations of groundwater quality data are shown in Figure 2.17.

The groundwater quality data represent natural baseline data that are unaffected by anthropogenic activities. The geochemical characteristics of the groundwater in the catchment have evolved over geologic time due to processes including:

- Precipitation;
- Runoff and ponding of runoff;
- Infiltration of precipitation and runoff;
- Geochemical interactions between infiltrating water and the sediments through which the water flows;
- Groundwater flow patterns (recharge and discharge areas, as developed over time); and
- Evaporation and evapotranspiration.

With respect to the groundwater quality the following observations can be made:

- Groundwater in the catchment typically is of the sodium-chloride (Na-Cl) type (Figure 2.18).
- Areas with low TDS, as shown on Figure 2.19, coincide with zones where the depth to the water table is the deepest (Figure 2.15). These areas represent the weathered granite, clayey and sandy alluviums along the flanks of the valley floor.

- High TDS groundwater is found along the valley floor, in areas where the water table is at shallow depth (Fig 2.19).
- The quality of shallow groundwater in the area of the Yeelirrie deposit is highly variable. The average and standard deviation of the TDS in the eastern part of the deposit (32,700 ± 14,900 mg/L) is higher than in the western part (15,800 ± 10,300 mg/L).
- Within the paleochannel aquifer low TDS water (average 3,800 mg/L) is found west of the deposit but increases eastward to 87,400 mg/L near the Albion Downs wellfield.
- Dissolved uranium is present in all of the hydrostratigraphical units, Overall, the concentration ranges from less than detection limit (<0.001 mg/L) to 2.4 mg/L. Within the deposit the average is 0.29 mg/L (± 0.32 mg/L) and in the paleochannel sediments it is 0.74 mg/L (± 0.69 mg/L).
- The dissolved vanadium concentration typically is less than the detection limit (0.01 mg/L).
- Bromide is present in significant concentrations (up to tens of milligrams per litre) in all hydrostratigraphical units.

2.8 Existing Groundwater Users

A well census conducted in 1972 (ACG, 1972) was updated in 2009 by URS (URS, 2011a). The 2009 census results are shown in Figure 2.20. This figure includes pastoral wells, groundwater investigation and monitoring wells, and production wells related to the Albion Downs wellfield. The historical land use in the Yeelirrie Catchment has been fenced pastoral activities. URS (2011a) noted that many of the pastoral wells have not been used in recent times. An exception is the Big Mill well which is used by the Yeelirrie Homestead as water supply source. Farther away from the Yeelirrie deposit several pastoral wells related to the Albion Down pastoral lease are currently still in use.

The largest groundwater user in the Yeelirrie Catchment is the Nickel West Mt Keith Operation which uses water from the Albion Downs wellfield. This wellfield, starting about 30 km east of the Yeelirrie deposit, consists of 32 production wells, spaced apart about 1.6 km. The field of productions wells stretches over a distance of about 51 km. The Albion Downs wellfield has been in production since 1994 and produces on average approximately 20,000 kL/day (about 7.5 Gl/a).

3.0 PROJECT DESCRIPTION AND WATER BALANCE

3.1 Project Description

3.1.1 Project Overview

The proposed development would produce up to approximately 7,500 tonnes per annum (tpa) of uranium peroxide (UO4.$2H_2O$), more commonly referred to as uranium oxide concentrate (UOC), through the development and operation of an open pit mine and on-site metallurgical plant. This production tonnage would diminish toward the end of the life of the proposed development. The open pit mine would be about 9 km long, up to 1.5 km wide and about 10 m deep. Up to 14 million tonnes (Mt) of overburden and ore would be mined annually during the mining pre-production pre-strip phase, with an average extraction rate of around 8 Mtpa during the production phase. The mined material would be stockpiled near the open pit before being processed within the metallurgical plant, or backfilled into the pit, if it was not economic to process.

The metallurgical plant would use an alkali tank-leaching process, followed by direct precipitation, to produce UOC for containerized transport to Port Adelaide, from where it would be exported. All tailings generated during the metallurgical processing of the ore would be returned to the tailings storage facility (TSF) in the open pit.

3.1.2 Project Timeline

This section provides an indication of proposed project timing. The schedule ultimately will depend on the timing and nature of government approvals and a final decision by the Cameco Board, which will be largely driven by economic factors. The indicative timeline is shown in Figure 3.1.

The Yeelirrie Project has a construction, operation and decommissioning and closure timeline of 22 years. If the Project were approved, Cameco would conclude planning activities, including completion of the Definitive Feasibility Study (DFS) and the detailed design prior to the commencement of the timeline.

The deposit (9 km long and up to 1.5 km wide) will be mined in 15 blocks (MB#1 – MB#15) as shown in Figure 3.2. Mining of the deposit will take 15 years (Runge Pincock Minarco, 2014).

As the uranium bearing calcrete occurs just below the water table, the mining blocks will have to be dewatered prior to mining. The planned dewatering blocks (DB#1 – DB#8, Figure 3.3) have been designed to ensure that dewatering is one year ahead of the mining face.

Each dewatering block consists of a perimeter trench and north-south trenches spaced apart 300 m. Within each dewatering block the top soil will be stripped and stock piled. Subsequently, the calcrete will be removed to just above the water table within each dewatering block. This material will be stock piled. Trenches will be dug to about 3 m below the anticipated pit floor and will have a nominal width of 1 m.

Dewatering will commence three and mining two years prior to the start of milling. This ensures that sufficient ore is available for milling and that there is space for in-pit disposal of the tailings. Milling will continue two years after completion of the mining.

Tailings from mining blocks MB#1 to MB#3 will be deposited in Pond#1 (Figure 3.4), consisting of five cells with an average size of 309,000 m^2. The tailings from mining blocks MB#4 to MB#15 will be placed in Pond#2 which consists of five cells with an average size of 339,500 m^2 (Figure 3.4). Pond#1 will be operated for seven years and Pond#2 for eight years. Deposition of tailings in the cells of Pond#1 and #2 will be on a six day rotation schedule. The annual rate of rise in each cell is 1.2 m.

Placement of a cover will start after filling of Pond#1 has been completed and tailings have consolidated and will be followed by covering Pond#2. Covering MB#8 to MB#14/15 will be done during the decommissioning of the site. The last cell to be filled and covered is MB#14/15.

3.2 Water Balance

The indicative site-wide water balance for the 15 year milling period is shown in Figure 3.5.

The operational water usage demands consist of:

- Industrial water for mineral processing, dust suppression and vehicle washing. Within this category, both low and high quality water is required.
- Domestic or potable water for the camp and administrative building.

There are several sources of water:

- Water derived from drainage of the deposit before the ore can be mined. This water is available throughout the project but the volume diminishes over time (see Section 5.7.1).
- Water pumped from aquifers beneath and in the vicinity of the deposit. This source will be available throughout the operational and decommissioning periods.
- Water naturally contained in the reagents and water in the ore. This source is only available to offset processing water needs.
- Water returned to the plant from the tailings storage facility (TSF). This water will be available during the period that ore is milled (project years four to 18). It is assumed that 10% of liquid disposed of in the TSF will be recycled.

Because of its water quality, none of these water sources can be used untreated for domestic or potable water or as clean water in plant processes. Consequently, a reverse osmosis (RO) plant is included in the design, as shown schematically in Figure 3.5. The RO plant is viewed as a water usage demand and is shown as such on Figure 3.5. Note that the RO Plant produces two streams of water: clean water for industrial and domestic use, and concentrated water which is used in the metallurgical process.

Considering the arid climate and the absence of surface water features, surface water is considered an opportunistic water supply source. It is expected that during some extreme precipitation events a portion of the rainfall that falls within the footprint of the mine site will become available as a source of water. However, this source only will be sporadically available and cannot be quantified or consistently relied upon.

The various demands, as a function of the project timeline, are shown in Figure 3.6. The demands for vehicle was and dust suppression were taken from URS (2011b). The total estimated water demand over the project is 53.4 Gl: 47.8 Gl during the milling period and 5.6 Gl prior to and after the milling. The indicative maximum total demand for water is estimated to be in the order of 8,724 kL/day. This maximum demand occurs during the milling period. The need for water from groundwater resources is a function of the amounts of water that become available from dewatering and the demand. In turn, the volume of water available from dewatering is a function of time. These volumes are further discussed in section 5.7.1.

The estimated total amount that will be derived from dewatering during the milling period is 18.9 Gl (see section 5.6.1). In the initial four (4) years of the project the drainage water volume exceeds the water required; the surplus drainage water will be re-injected. The total amount of water to be re-injected during these years is estimated to be 2.27 Gl (see section 5.6.1).

Based on a 2.4 Mtpa throughput, a plant availability and efficiency of 90% and alkaline process to extract uranium from the ore, detailed process modelling was conducted to determine the volumes of water related to the input and output of the plant while ensuring a chemical mass balance. The mill will be operated over a period of about 15 years.

4.0 NUMERICAL GROUNDWATER FLOW MODEL

4.1 Introduction

4.1.1 URS Groundwater Flow Models

A numerical groundwater flow model, referred to as the “Yeelirrie Catchment Model”, was developed by URS (URS, 2011a), based on a calibrations to the baseline groundwater conditions. This model was then used to make predictions of system response to various water management actions during the life of the operation.

The Yeelirrie Catchment Model was developed in stages with the aid of preliminary ‘local scale’ numerical groundwater flow models. The form and parameterisation of all of the groundwater flow models were based on the conceptual hydrogeology model.

The URS groundwater flow model was developed following a three-stage process:

- The development of a “Slot 1” mining trial model: this model is based on the data acquired from the dewatering of the WMC Slot 1 trial in 1972.
- The development of four sub-models: these models are based on data collected from pumping tests in test production wells.
- The parameters derived from the Slot 1 mining trial model and the four sub-models were used in the development of the final Yeelirrie Catchment Model.

The URS groundwater study report (URS 2011a) details the development of the hydrogeological model, the design of the numerical model, selection of input model parameters and sensitivity analyses. These elements were thoroughly reviewed and accepted, and are summarized in section 4.2.

4.1.2 Cameco Groundwater Flow and Solute Transport Model

The present model, referred to as the “Cameco Model”, used the calibrated groundwater flow model developed by URS (2011a) as a starting point. **All the predictions presented in this report supersede the results of the predictive simulations presented by URS (URS, 2011a).**

The objectives of the current modelling are:

- Develop a mine pit dewatering plan based on the Cameco mining plan and predict the drawdown caused by dewatering;
- Support the design of groundwater supply wellfields to meet the estimated water demands; and simulate the drawdown caused by groundwater abstraction;
- Support the design of an managed aquifer recharge (MAR) system for re-injection of dewatering abstractions when volumes exceed water demands, and estimate the groundwater mounding effect caused by the MAR system;

- Predict the drawdown due to dewatering, withdrawals from aquifers and MAR as input into an assessment of the potential impact on groundwater dependent ecosystems (GDEs);
- Assess the impacts on other groundwater users such as pastoral wells and the Nickel West Mt Keith operation Albion Downs wellfield;
- Simulate effect of proposed mitigation measures to minimize impact on the local environment and GDEs;
- Predict the groundwater level recovery process after mine decommissioning; and
- Conduct solute transport modelling to predict transport of elements of concern and their potential impact on environment.

The Cameco model was implemented in Groundwater Vistas (version 6.7) with MODFLOW-SURFACT Version 4 (HydroGeoLogic, Inc.) was used to conduct groundwater flow and for solute transport modelling. Visual MODFLOW Version 2011 was used in the Slot 1 model calibration.

4.2 Model Design and Construction

As the current model is based on the URS calibrated model, Sections 4.2 - 4.4 provide a brief summary of the considerations that URS used in the development of their model. Additional information can be found in URS (2011a).

4.2.1 Model Domain and Extent

The Yeelirrie Catchment Model covers an area of 6,017 km²; traversing the entire Yeelirrie Catchment but also extending beyond the catchment divides (Figure 4.1). The orientation of the rectangular grid follows the principal groundwater flow direction. The model grid comprises 905 columns and 332 rows. A 400 m x 400 m model cell grid was constructed parallel to the grid of the sub-models and the model cells in the proposed development (mining) area were refined to 50 m x 50 m.

4.2.2 Model Layers and Property Zones

The model has nine layers, as shown schematically in Figure 4.2:

- Layer 1 consists of loam and hard pan, calcrete, transitional calcrete, sandy alluvium, clayey alluvium and weathered granite. Bottom elevations of layer 1 range from 460 to 555 mAHD.
- Layer 2 consists of transitional calcrete, sandy and clayey alluvium, loam and hardpan, calcrete in the eastern area of the model and weathered granite. Bottom elevations of layer 2 range from 440 to 550 mAHD.
- Layer 3 consists of calcrete, carbonated clay-quartz, sandy alluvium, clayey alluvium, weathered granite and fresh granite. Bottom elevations of layer 3 range from 440 to 520 mAHD.

- Layer 4 consists of calcrete in the eastern area of the model, sandy alluvium, clayey alluvium, weathered granite and fresh granite. Base elevations of layer 4 range from 440 to 510 mAHD.
- Layer 5 consists of calcrete in the eastern area of the model, sandy alluvium, clayey alluvium, palaeochannel clay, weathered granite and fresh granite. Base elevations of layer 5 range from 430 to 490 mAHD.
- Layer 6 consists of palaeochannel clay, weathered granite and fresh granite. Base elevations of layer 6 range from 400 to 490 mAHD.
- Layer 7 consists of palaeochannel sand, weathered granite and fresh granite. Base elevations of layer 7 range from 390 to 490 mAHD.
- Layer 8 consists of weathered granite and fresh granite. Base elevations of layer 8 range from 380 to 460 mAHD.
- Layer 9 consists of fresh granite with a flat base at 300 mAHD.

Topographical information from LIDAR data (Fugro, 2009), surveyed elevation points (Fugro, 2010) and STRM (Shuttle Radar Topography Mission) data with a 1-degree digital elevation model (DEM) or 90 m resolution were used to create the top elevation of layer 1. Ground surface elevations range from 459 to 652 mAHD within the model domain.

The bottom elevations of each model layer were defined by the geological model.

As is illustrated in Figure 4.2, each layer may include several stratigraphical units. Ten stratigraphic property zones were defined in the model as shown on the left side of Table 4.1. These zones were distributed across nine model layers to create a practical representation of the hydrostratigraphy in the proposed development area (Figure 4.2). Several of the stratigraphic property zones have been sub-divided to provide spatial flexibility in parameterisation of the model in discrete portions of the Yeelirrie Catchment. The distributions of both the property zones and model layers were based on logs of the pastoral bores, the geology block model, findings of the recent site investigations, geology logs from the Albion Downs wellfield and the hydrogeology model.

Table 4.1 Yeelirrie Catchment Model: Correlation of Model Property Zones with Stratigraphic Property Zones

Stratigraphic Property Zone	Model Property Zone	
Loam and Hard Pan	Zone 6	
Calcrete	Zone 17	Surface - Yeelirrie (Upper Catchment)
	Zone 14	Surface Albion Downs (Lower Catchment)
	Zone 7	Deep - Albion Downs
Transitional Calcrete	Zone 16	
Carbonated Clay-Quartz	Zone 11	
Sandy Alluvium	Zone 9	Yeelirrie
	Zone 13	Ferruginous Alluvium
	Zone 15	Albion Downs
Clayey Alluvium	Zone 4	
Upper Palaeochannel Clay	Zone 2	
Lower Palaeochannel Sand/Clay	Zone 6	Yeelirrie Including Proposed Development Area
	Zone 10 and 12	Albion Downs
	Zone 8	Proposed Development Area
Weathered Granite	Zone 5	Yeelirrie
	Zone 3	Albion Downs
Fresh Granite	Zone 1	

Note: *after URS (2011a)*

4.2.3 Boundary Conditions

A constant head boundary condition of 457 mAHD was used in the eastern model domain at the Lake Miranda boundary (Figure 4.1) for layers two to nine. This constant head boundary represents the basin outlet, which is the only place where the basin groundwater leaves the catchment. A no-flow boundary was assigned to the perimeter of the remainder of the model domain, as well as to the model bottom.

4.2.4 Groundwater Recharge

The Recharge Package in MODFLOW is used to simulate distributed recharge from rainfall infiltration to the water table. The final recharge distribution, as developed by URS (URS, 2011a), was based on considerations such as on chloride mass balance, literature review, hydrogeological concepts and calibration modelling.

The spatial distribution of recharge rates is shown in Figure 4.3. Beneath the uplands and midlands, reflecting the steeper slopes and lower surface water availability, the recharge rate is 0.4 mm/a (about 0.15 % of annual rainfall). A higher recharge rate of 0.8 mm/a (or about 0.3 % of annual rainfall) is applied along the valley floor. The total recharge volume over the entire catchment is about 6,900 kL/day (2.6 Gl/annum).

4.2.5 Groundwater Evapotranspiration

The Evapotranspiration (ET) Package in MODFLOW simulates the effects of groundwater ET, including direct evaporation and plant transpiration from the water table. The concept of ET extinction depth has been used. This concept stipulates that effective ET is a linear function of depth:

- When the water table is at ground surface, the effective ET is equal to the specified potential ET.
- When the depth to water exceeds the extinction depth, the effective ET is equal to zero.
- Between these limits, the effective ET decreases linearly as the depth to the water table increases.

Figure 4.4 shows the distribution of the evaporation extinction depth and the evaporation rate as developed by URS (URS, 2011a). The majority of the simulated effective ET occurs in valley-floor locations where the water table is shallow and an increased potential exists for transpiration by phreatophytes.

The total effective ET simulated over the catchment area is about 6,200 kL/day (2.2 Gl/a), or about 89 % of the total recharge (URS, 2011a).

4.2.6 Groundwater Levels – Freshwater Equivalent Heads

Within the Yeelirrie Catchment the TDS of the groundwater is highly variably both horizontally and vertically and may range from 620 to 94,300 mg/L. Applying an empirical relationship between TDS and density, the latter may range from 1,000 kg/m^3 to 1,067 kg/m^3. URS (URS, 2011a) used the Lusczynski (1961) approach to determine environmental-water heads in the monitoring wells. These environmental-water heads are used for comparison with model calculated hydraulic heads.

4.3 Hydraulic Parameters

Aquifer parameters have been derived from the following data sources:

- the Slot I mining trial;
- aquifer tests and groundwater flow modelling associated with the development of the Albion Downs Wellfield;
- infiltration tests;
- small-scale pumping tests in monitoring wells; and

- aquifer tests in the test production wells.

A summary of the interpreted effective hydraulic parameters for the predominant hydrostratigraphic units is shown in Table 4.3. The conceptual cross-section distributions and relationships between the different hydrostratigraphic units are shown in Table 4.3.

Based on steady-state and transient modelling the values of the hydraulic parameters were further refined by URS (URS, 2011a) (Table 4.4).

Table 4.3 Summary of Interpreted Effective Hydraulic Parameters

Hydrostratigraphic Unit		Hydraulic Conductivity (m/day)			Specific Yield (dimensionless)	Specific Storage (1/m)
		Lateral Range	Lateral	Vertical		
Loam and Hard Pan		0.5 to 5	1	0.1	0.2	1.0×10^{-5}
Calcrete	Yeelirrie	188 to 833	537	537	0.2	1.0×10^{-5}
	Albion Downs	25 to 200	26	26	0.2	1.0×10^{-5}
Transitional Calcrete		2.4 to 166	70	70	0.3	1.0×10^{-5}
Carbonated Clay Quartz		1.1 to 6.8	6	0.6	0.05	1.0×10^{-5}
Sandy Alluvium		0.006 to 18.5	3.9	0.39	0.1	1.0×10^{-5}
Clayey Alluvium		0.018 to 3.2	0.16	0.016	0.05	8.6×10^{-5}
Ferruginous Alluvium		5 to 20	8	0.8	0.1	1.0×10^{-5}
Clayey Upper Palaeochannel		0.006 to 3.1	0.06	0.006	0.1	1.0×10^{-5}
Sand/Clay Lower Palaeochannel		0.14 to 3.75	1.6	0.16	0.2	9.0×10^{-5}
Weathered Granite		0.00046 to 1.24	0.67	0.067	0.05	3.8×10^{-4}
Fresh Granite		0.00001 to 0.0005	1.0×10^{-4}	1.0×10^{-5}	0.01	1.0×10^{-6}

Source: URS (2011a)

Table 4.4 Calibrated Model Hydraulic Parameters

Stratigraphic Property Zone		Property Zone	Hydraulic Conductivity (m/day)		Specific Yield (dimensionless)	Specific Storage (1/m)
			Lateral	Vertical		
Loam & Hard Pan		Zone 6	0.5	0.05	0.2	$1x10^{-5}$
Calcrete	Surface at Yeelirrie	Zone 17	706	706	0.23	$1x10^{-5}$
	Surface at Albion Downs	Zone 14	13.7	13.7	0.23	$1x10^{-5}$
	Sub-surface at Albion Downs	Zone 7	1	1	0.23	$1x10^{-5}$
Transitional Calcrete		Zone 16	70	70	0.2	$1x10^{-5}$
Carbonated Clay-Quartz		Zone 11	6.8	6.8	0.05	$1x10^{-5}$
Sandy Alluvium	Albion Downs	Zone 15	19	1.9	0.04	$1x10^{-5}$
	Ferruginous	Zone 13	12.5	1.25	0.04	$1x10^{-5}$
	Yeelirrie	Zone 9	3.9	0.39	0.1	$1x10^{-5}$
Clayey Alluvium		Zone 4	0.04	0.004	0.05	$1x10^{-6}$
Clayey Upper Palaeochannel		Zone 2	0.005	$5x10^{-4}$	0.1	$1x10^{-6}$
Sand/Clay Lower Palaeochannel	Albion Downs 1	Zone 10	5.0	0. 5	0.2	$2x10^{-4}$
	Albion Downs 2	Zone 12	8.0	0.8	0.2	$1x10^{-4}$
	Yeelirrie	Zone 8	3.75	0.375	0.2	$1x10^{-4}$
Weathered Granite – Albion Downs		Zone 3	0.0115	0.00115	0.05	$9x10^{-6}$
Weathered Granite – Yeelirrie		Zone 5	0.23	0.023	0.05	$9x10^{-6}$
Fresh Granite		Zone 1	$2x10^{-9}$	$2x10^{-10}$	0.01	$1x10^{-8}$

Source: URS (2011a)

4.4 Model Calibration Strategy

The calibration of the Yeelirrie Catchment Model (URS, 2011a) was an iterative process, including four types of flow model calibrations. Each calibration stage was intended to add rigor to the model and enable compatibility with the hydrogeology model. The four flow model calibrations were:

- Transient flow calibrations based on data from the Slot 1 dewatering trial and Sub-models of selected test production well pumping tests to identify reasonable parameterisation for the regional model and local accuracy.
- Regional steady-state flow model calibration to the interpreted catchment-wide water table elevations.
- Regional transient flow model calibration to the observed drawdown of the water table associated with long-term abstraction by the Albion Downs Wellfield.
- Regional transient model calibration to the observed salinity concentrations in water table settings beneath the valley-floor groundwater discharge zones.

The model prediction results were used by URS (2011a) to adjust both groundwater recharge and ET iteratively during the steady-state model calibration.

4.5 Calibration Performance Measures

The model calibration was assessed as follows (URS, 2011a):

- Point-matching of hydraulic heads: 291 observation points with fresh-water equivalent heads were used as direct calibration targets in the model calibration. This data set was a combination of groundwater level measurements collected in 2009 within the proposed development area and surrounds, and groundwater level measurements collected in 1994 in the vicinity of the Albion Downs Wellfield prior to commissioning of the Wellfield. The goodness of fit between the simulated and measured hydraulic heads is evaluated by statistics and through visual inspection.
- Baseline groundwater elevations: The simulated groundwater level contour is reasonably similar to the interpreted baseline groundwater table.
- Water balance: An accurate water balance was also demonstrated for all the three model variants.

The calibrated models indicate that the Yeelirrie Catchment tends to behave as a semi-closed, compartmentalised groundwater flow system. The only groundwater input source is rainfall recharge and the primary groundwater discharge mechanism is through ET. A comparatively small portion (11 to 13%) of the water balance leaves the catchment as groundwater flow to Lake Miranda.

The resultant calibrated model does not represent a unique solution to achieve the catchment water balance. This is because the model behaviour is dominated by the effects of recharge and discharge potentials. Similar calibration results were achieved for a range of combination of recharge and discharge rates. Therefore, sensitivity analyses were conducted to investigate the sensitivity of modelling results to different combination of recharge and ET, as well as different combination of hydraulic parameters (URS, 2011a).

5.0 GROUNDWATER FLOW MODELLING PREDICTIONS

5.1 Introduction

Implementation of the project will result in local and temporary changes to the groundwater regime in the project area. The purpose of this work is to describe the predictive numerical groundwater modelling and evaluate the potential impact of the proposed Yeelirrie project on the environment during operations and long after closure.

Based on the URS (2011a) calibrated base model, the operational model was constructed for the purpose of:

- Developing a mine pit dewatering plan to ensure that mining will be conducted in appropriate (safe and trafficable) conditions;
- Develop wellfields to meet water demands;
- Predicting drawdown caused by mine pit dewatering and groundwater abstraction from supply wells;
- Predicting environmental impact; and
- Evaluating potential mitigation measures.

In addition to the operation model, a closure model was developed to simulate the groundwater level recovery process (closure model: Section 6) and a solute transport model to simulate transport of constituents of concern (long-term solute transport model; Section 7).

All of these models simulate a time sequence (from pre-development to post closure) of the groundwater conditions in the catchment. The initial hydraulic heads used in these models are developed as follows:

- The groundwater levels generated by the steady state calibration model (URS, 2011a) are used as the initial hydraulic heads for the transient calibration model (URS, 2011a).
- The groundwater levels produced by the transient calibrated model at its last time step feed the operational model as initial hydraulic heads.
- The operational model was run through the entire proposed project period to predict changes to the water table caused by pit dewatering, groundwater supply abstractions.
- The predicted water table elevations at the end of the project are used as the initial water table elevations at the beginning of closure model. The closure model assumes that all groundwater abstraction have ceased.
- The long-term solute transport model begins at the same starting point in time as the closure model, and therefore uses the same initial hydraulic heads.

5.2 Modelling of the Proposed Project

The operational model includes pit dewatering (Section 5.2.1), supply wells (Section 5.2.2), disposal of surplus water (due to pit dewatering) through a Managed Aquifer Recharge (MAR) system (Section 5.2.3), and tailings storage facility (TSF) (Section 5.5).

5.2.1 Mine Pit Dewatering

The groundwater levels within the proposed mine pit should be lowered to at least 1 m below the pit floor in order to safely mine the ore. Dewatering blocks and associated trenches are used for this purpose. Figure 3.3 illustrates the planned mining blocks and mining sequence, as well as the proposed dewatering blocks and associated trenches.

The designed bottom elevations are shown in Table 5.1. Dewatering trenches 3 m below the average pit floor were found to be suitable for lowering the water table 1 m below the pit floors.

In the numerical simulation, the Groundwater Vistas “drain” function is used to simulate the dewatering trenches. The drain parameters used in the model are as follows:

- Drain head (bottom elevation of trench): set as transient boundary conditions in Groundwater Vistas. To simulate the dewatering process more realistically, it is assumed that water level in the drain is lowered 2 meters every month, and it takes three or four month for the water level in the drain to reach the bottom elevation of the trench;
- Nominal width of drain: 1 m;
- Length of drain: 50 m (set equal to the length of grid cells);
- Thickness of drain bed: 1 m; and
- Hydraulic conductivity of the drain bed: 100 m/day (and the conductance is 5000 m^2/day).

For the mining plan to progress as scheduled (Figure 3.1), the drain trenches for each dewatering block are activated one year before mining starts in the mining block(s) within each dewatering block. The dewatering in the MB#8 to 15 mining blocks will continue until the end of the project, to keep the blocks dry for back filling. The trenches related to the TSF cells will be deactivated by project year 18 (end of milling).

Table 5.1 Designed trench bottom elevation

Project year	Average elevation of mining block	Average pit floor elevation of mining block	Pit depth	Dewatering block ID (dewatering starts at the beginning of project year)	Mining block ID (mined out at the end of project year	Lowest average pit floor elevation of adjacent dewatering blocks	Elevation bottom of trench	Dewatering trench depth from ground surface
	mAHD	mAHD	m			mAHD	mAHD	m
Year 1	496.4	487.9	8.5	DB#1		487.3	484.3	12.1
Year 2	496.5	487.3	9.2	DB#2	MB#1	487.3	484.3	11.2
Year 3	497.2	486.8	10.4	DB#3	MB#2	486.8	483.8	13.4
Year 4	496.7	486.9	9.8	DB#4	MB#3	486.9	483.9	13.1
Year 5	497	488.1	8.9		MB#4			
Year 6	497.3	488.1	9.2		MB#5			
Year 7	497.1	488.1	9	DB#5	MB#6	488.1	485.1	12.3
Year 8	497.4	488.6	8.8		MB#7			
Year 9	497.8	488.6	9.2	DB#6	MB#8	488.6	485.6	12.2
Year 10	497.6	488.7	8.9		MB#9			
Year 11	497	488.9	8.1	DB#7	MB#10	488.9	485.9	11.3
Year 12	497.2	489.2	8		MB#11			
Year 13	497	489.1	7.9		MB#12			
Year 14	496.2	488.1	8.1	DB#8	MB#13			
Year 15	496	490	6		MB#14	488.1	485.1	11.1
Year 16					MB#15			

Note: In order to provide enough lead time for mining, dewatering blocks cover a larger area than their corresponding mining blocks and, in some cases, may cover several mining blocks (see Figure 3.3). Therefore, the elevation of the bottom of a trench for a dewatering block was taken either as the lowest, or average, of the pit floor elevations of the mining blocks covered by a dewatering block. The elevation of the bottom of a trench is three (3) metres lower than the pit floor elevation. The actual depth of the trenches will be about 4 m shallower than the values indicated as digging of the trenches would start from just above the water table in the dewatering blocks.

5.2.1.1 Determination of Drain Conductance

Drain conductance depends on the characteristics of the convergent flow pattern toward the drain, as well as on the characteristics of the drain itself and its immediate environment (Harbaugh, 2005). During the modelling process, it was found that the simulated dewatering rates are very sensitive to the conductance of the drains, and large values of drain conductance causes numerical oscillation. Sensitivity analyses were therefore conducted by changing drain conductance while keeping all other parameters the same, as illustrated in Figures 5.1 and 5.2. Figures 5.1 and 5.2 show that when the hydraulic conductivity is high (e.g., 1,000 m/day, 700 m/day, or 500 m/day), there is a significant fluctuation in the simulated drain flux, especially in later years. When the drain hydraulic conductivity, and therefore the conductance, is lower (100 m/day or less), the fluctuations in drain flux disappear. Therefore, a hydraulic conductivity of 100 m/day has been used in the model.

5.3 Water Supply from Wellfields

Water demand during the pre-construction, construction, operation and decommissioning phases for the project has been estimated (see Chapter 3, Figure 3.6). The water demand would be met by a combination of sources, including: pit dewatering, water supply wellfields, water reuse, recycling, and (opportunistic) rainfall runoff collection from within the pit and disturbed areas.

The following groundwater supply areas have been identified (URS, 2010, 2011a) and are proposed to be developed as water supply wellfields (Fig 5.3):

- Western Brackish Wellfield: alluvium (Fig 5.4: B8 to B18)
- Northern Brackish Wellfield: alluvium and weathered bedrock source aquifers (Fig 5.4: B19 to B31);
- Eastern Brackish Wellfield: alluvium and weathered bedrock sources (Fig 5,4: B32 to B37); and
- Saline Wellfield: alluvium, Yeelirrie Palaeochannel (Fig 5.4 S1-S2, S8 to S30) and weathered bedrock sources (Fig 5.4: S3 to S7).

The project groundwater supply system would utilise all four groundwater sources. Production well locations specified in the operational model are shown in Figure 5.4. The typical distance between production wells is about1 km.

Brackish water will be used as source water for the reverse osmosis (RO) plant which will provide water needed for potable supplies, reagent mixing and steam generation within the ore processing circuit. Saline water would be the primary source for raw process water (crushing, grinding and leaching) and dust suppression.

In order to minimise the areal extent and impact of water table drawdown due to groundwater abstraction, it is preferred to develop wellfields within the alluvium and weathered granite and deeper palaeochannel aquifers rather than in the central valley aquifers. This strategy is employed as a mitigation measure to minimize quick and/or significant drops in water table levels.

Table 5.2 summarizes the potential sustainable well yield for each individual well based on data recommended by URS (2011a) and professional judgement. The abstraction rates assigned to each individual well in the model are adjusted in order to take a full advantage of water from pit dewatering and recycling while meeting the total water demand. The strategy of making effective use of the saline water becoming available from dewatering results in less water needed from other groundwater resources and reduction of the drawdown footprint. Section 5.6.1 presents the simulated well production rates over time.

Table 5.2 Production Well Source Uses and Maximum Pumping Rates

Wellfield	Source	Proposed number of production wells	Recommended potential sustainable (individual) well yield	Simulated maximum (individual) well yield
			(kL/day)	(kL/day)
Western Brackish	Sandy Alluvium	11	130	130
Northern Brackish	Clayey Alluvium and Weathered Granite	13	130	43
Eastern Brackish	Sandy Alluvium and Weathered Granite	6	130	86
Saline	Yeelirrie Palaeochannel	25	260	216
	Sandy Alluvium and Weathered Granite	5	260	216

5.4 Management of Surplus Water from Pit Dewatering - Managed Aquifer Recharge (MAR) system

Pit dewatering flows will exceed water demands during the early stages of the project when the mill operation has not started. In order to conserve groundwater, a Managed Aquifer Recharge (MAR) system is included in the design to manage the variable flows of water from drainage. The MAR concept involves injection of surplus water from pit dewatering into the calcrete for temporary underground storage and subsequent re-extraction. The MAR system would be abandoned once the pit dewatering abstractions drop below the operational water demand.

The conceptual MAR system would be located north of mining block MB#9, in the western part of the resource area (Figure 5.5). Although the design of the MAR system has not been finalized and in practice might be an infiltration canal, in the groundwater model, the system is represented by an injection well, with injection rate as presented in Section 5.6.1.

5.5 Tailings Storage Facility

5.5.1 Hydraulic Parameters

The tailings generated by the milling process will be stored in cells within mined-out blocks. With the progression of mining, the individual mining blocks will be converted into TSF cells sequentially by constructing TSF embankments along the perimeter of the blocks and inside the blocks. This would be followed by tailings deposition, as shown in Figure 5.6. The transition of individual mining blocks to TSF cells was represented in the model by a change of the hydraulic parameters from in-situ values to values representing the tailings, embankments and backfill over time. The change in the hydraulic parameters over time is accomplished in the model by using the Transient Materials Property (TMP) package of MODFLOW-SURFACT.

The Cameco base model uses the same hydraulic properties of the TSF embankments and deposited tailings as used by URS (URS, 2011a). The properties are shown in Table 5.3.

Table 5.3 Hydraulic Parameters of TSF

Material	Hydraulic Conductivity (m/day)		Storage (Dimensionless)	
	Lateral	Vertical	Specific Yield	Porosity
Tailings	3.46×10^{-3}	3.46×10^{-4}	0.10	0.50
TSF Embankments	1.42×10^{-4}	1.42×10^{-4}	0.05	0.45
Non-TSF cell backfill*	4.0×10^{-2}	4.0×10^{-3}	0.05	0.40

*: See Section 6 (closure model) for parameters discussion

5.5.2 Seepage, Recharge and ET Rates

The tailings would be placed into the cells following the planned sequence as shown in Figure 5.6. It is assumed that each TSF cell would be filled with tailings to about 2 m below the original ground level. Subsequently, the deposited, consolidated, tailings would be covered and capped with overburden and topsoil.

During the period of operations, groundwater recharge rate, ET rates and extinction depth outside of the TSF cells are expected to remain the same as baseline condition.

When the tailings slurry is deposited in the TSF cells, some will be recycled, part of water contained in the tailings slurry will evaporate, and part of it will infiltrate into the groundwater below the TSF cells. During TSF placement, the groundwater recharge rate in each element (with a dimension of 50 m by 50 m) is set to 0.08 kL/day (URS, 2011a). After the TSF tailings cover is in place, the recharge rate is reduced to 0.002 kL/day (URS, 2011a).

The ET rates and extinction depth within area covered by the TSF surface are assumed to be the same as baseline conditions.

In summary, the recharge rates within TSF cells are assumed to vary through time as follows:

- Before tailings deposition – recharge rates (i.e., 0.40 mm/year) estimated through calibration process are used;
- During tailings deposition – a uniform recharge rate 0.08 kL/day (equivalent to 11.68 mm/year) is applied; and
- After tailings deposition, with the cover in place, recharge is assumed to be 0.002 kL/day (equivalent to 0.24 mm/year, or 0.00065 mm/day, which is 0.1% of annual average rainfall).

5.6 Modelling Results

5.6.1 Predicted Rates of Dewatering, Groundwater Water Supply and Injection

Predicted rates of dewatering yield, and excess water re-injection rates along with estimated total water demand, minimum volume required from groundwater and actual modelled withdrawals from aquifers are shown in Figure 5.7.

The pit dewatering simulations are based on the proposed pit development schedules. The predicted annual pit dewatering production volumes are summarised in Table 5.5. The volumes obtained from pit dewatering range from 0.04 to 2.73 Gl/a (Mm^3/a) during the project. The total volume of water from dewatering over the project life is 18.9 Gl (Mm^3). Predicted annual daily dewatering rates over the period of the project are shown in Figure 5.9.

Table 5.5 **Predicted annual abstraction from pit dewatering and groundwater supply wells**

Year	Predicted annual dewatering abstraction (Gl/year)	Simulated annual well abstraction (Gl/a)
1	0.85	0.66
2	1.14	0.82
3	2.23	0.82
4	2.73	2.14
5	1.26	2.93
6	0.95	3.18
7	0.79	3.21
8	0.97	3.20
9	1.41	3.20
10	0.80	3.20
11	1.33	3.21
12	0.77	3.20
13	0.66	3.20
14	0.67	3.20
15	0.59	3.21
16	0.55	3.20
17	0.52	3.20
18	0.50	3.20
19	0.04	0.44
20	0.04	0.44
21	0.05	0.44
22	0.05	0.44
Total	**18.90**	**50.72**

In Figure 5.7, both the minimum rates of groundwater production needed to meet the raw water demand and the rates actually used in the modelling are shown.

The estimated total water demand for the project is 53.3 Gl, the total modelled supply (modelled withdrawals from aquifer and estimated volume of water from dewatering, minus the estimated volume re-injected) is estimated to be 63.7 Gl. Overall, the modelled supply exceeds the estimated demand by 26%.

Figure 5.7 shows that during early part of the project, pit dewatering volumes often exceed water demands. The surplus water would be diverted to the MAR system and re-injected into the local calcrete aquifer to conserve water. The predicted rates and volumes of groundwater to be re-injected are summarised in Table 5.6. The total volume estimated to be re-injected total 2.27 Gl during the initial 4 years of operations. Demand is expected to exceed pit dewatering supply beginning in year 4 and extending to the end of the project life.

Table 5.6 Predicted Volume of Dewatering Water to be Re-Injected

Year	Predicted Re-Injection
	Average Rate (Gl/a)
1	0.26
2	0.49
3	1.28
4	0.24
Total Injection (Gl)	**2.27**

After milling has been completed dewatering of mining blocks MB# 8 to 13 and 14/15 will have to continue to allow for safe filling of these blocks with decommissioning materials. It is predicted that an additional total of 0.12 Gl (about 0.03 Gl/a) will be derived from dewatering until the end of the project.

5.6.2 Predicted Groundwater Heads and Drawdown due to Pit Dewatering, Well Abstraction and MAR System

Predicted local hydraulic heads over time within and around the mine pit are illustrated in in Figures 5.9a to 5.9h.

A comparison of the predicted hydraulic head with the mine pit floor elevation in Table 5.1 indicates that, with the exception of a few limited areas, the proposed dewatering plan meets the mine pit dewatering requirements.

In these very limited areas where groundwater levels do not appear to reduce to 1 meter below the average pit floor elevation, operationally, the groundwater level could be further reduced by excavating secondary trenches. Furthermore, evaporation from the pit floor will act as a “pump”, helping the pit floor to be dry.

Predicted regional water table drawdowns for the operational model (pit dewatering, well abstraction and MAR system) at selected points in time are shown in Figures 5.10a to 10e.

Findings of the predictive drawdown simulations include:

- Groundwater re-injection through MAR system causes groundwater mounding around the injection well, with a predicted maximum groundwater level increase of approximately 1 m. The injection ceases at the beginning of year four and the groundwater mound disappears by the end of that year (Figures 5.10a to c).
- Drawdown in the vicinity of the proposed wellfields increases over time and is the greatest at the end of year 18 (end of milling). The typical drawdowns in the Western, Northern and Eastern brackish wellfields are approximately 2, 5 and 3 m, respectively. Around the mine pit the drawdown typically exceeds 7 m.
- Slow expansion of the drawdown cone indicates that the groundwater sources in the proposed wellfields are relatively abundant compared to the extraction rate.
- At the end of project year 18 partial recovery starts as milling has ceased: dewatering trenches corresponding to TSF cells are de-activated, and the demand for water from aquifers is greatly reduced.
- Interference occurs between pit dewatering, the Saline, Eastern and Northern wellfields, which broadens the overall drawdown footprint and increases the magnitude of the associated drawdown.
- The model-predicted water table drawdown cone caused by the proposed saline wellfield has a limited overlap with the water table drawdown cone caused by the Albion Downs wellfield. This slight hydraulic interference starts to occur from project year 12. It is noted that, depending on the future of the Albion Downs wellfield, this interference may not happen.

5.6.3 Predicted Water Table Drawdown due to Pit Dewatering only

The predicted drawdown caused by pit dewatering only are presented in Figure 5.11a and b. Figure 5.11a shows the drawdown at the end of year 18 when milling is finished, and Figure 5.11b shows the drawdown at the end of year 22 when the project is completed.

A comparison of Figures 5.11a and b indicate that:

- Drawdown increases over time but the drawdown cone expansion is slow under continuous abstraction through drains, indicating that the groundwater sources in the vicinity of the mine pit are relatively abundant.
- Drawdown caused by dewatering only could extend up to approximately 3 km beyond the mine pit (0.5 m contour line).
- A comparison of drawdown at year 18 and 22 indicates that groundwater level within the TSF cells starts to recover since drain becomes inactive at year 18, but the drawdown cone extends slightly farther laterally.

5.6.4 Impact on Existing Users

As noted in Section 2.8, the only pastoral well in the vicinity of the deposit that currently is being used is the Big Mill well which provides water to the Yeelirrie Homestead. This well will not be affected by the development (Figure 5.10e).

After project year 12 there is a slight interference between the water table drawdown due to the development and the water table drawdown caused by the operation of the Albion Downs wellfield (Figure 5.10e). It is assumed that the Albion Downs wellfield would continue to be operated indefinitely at historical pumping rates. If this assumption is not valid then there will be no interference between the wellfields.

In Figure 5.12, the predicted water level drawdown in the paleochannel, represented by the drawdown in model layer 7, is shown at the end of milling (project year 18). This figure shows that there is no notable interference between the proposed withdrawals from the paleochannel and the drawdown in the paleochannel due to pumping from the Albion Downs wellfield.

5.7 Barrier Wall – Option Study

An option study was conducted to investigate what impact a barrier wall (bentonite – soil slurry wall) could have on limiting propagation of the drawdown due to dewatering and withdrawals from wellfields.

In this option study, the operational model uses the same location and hydraulic properties for the barrier wall as were used in the URS (URS, 2011a) model.

The conceptual location of the wall, at the western end of the open pit, is shown in Figure 5.5. Figure 5.13 illustrates the conceptual design of the wall. The conceptual design of the barrier wall includes:

- a low-hydraulic conductivity soil-bentonite mixture (isotropic hydraulic conductivity of 8.6×10^{-5} m/day);
- a nominal width of 1 m and length of 1,800 m;
- The top of the wall would be placed just above the baseline groundwater table elevation;
- The bottom of the wall would be about 15 m below ground surface (about 10 m below the water table); and
- Above baseline groundwater table elevation (top of the wall), the barrier wall trench would be backfilled with high permeable material to prevent groundwater mounding immediately upstream of the barrier wall. This would effectively allow groundwater potentially mounding on the western side of the wall to "spill" over the wall into the dewatered zone (the wall will act like a weir in the groundwater flow system).

Figure 5.14 shows the representation of the barrier wall in the model.

In the model, the barrier wall is represented by a combination of a wall with relatively low effective hydraulic conductivity and "drain" package located immediately west to the wall. The drain head (elevation bottom of the trench) is set to be as close to the baseline groundwater table elevation as possible to simulate the function of the permeable zone above the barrier wall.

The simulated barrier wall extends through model layers 1 to 5, and was represented by grid cells with a dimension of 50 m by 50 m or 100 m by 50 m. The wall's effective hydraulic conductivity is obtained by scaling the nominal hydraulic conductivity for a 1 m wide wall (with K= 8.6 x 10^{-5} m/day) so that the flux through the 50 m wide wall is equivalent to that through a 1 m wide wall and 49 m wide in-situ geological medium. Similarly, when the wall extends out to 100 m wide cells, the nominal hydraulic conductivity value was scaled from 1 m to 100 m for the same net effect. The effective hydraulic conductivity of the model cells in the wall structure is provided in Table 5.4.

Table 5.7 Effective Model Parameters for the Barrier Wall

Hydraulic conductivity Zone in the model	Stratigraphic Property Zones	Hydraulic Conductivity (x, y, z; m/day)	Specific Storage (1/m)	Specific Yield (Dimensionless)
18	Calcrete, Transition Calcrete, Carbonated Clay Quartz and Sandy Alluvium	0.00864	1.00E-05	0.2
19	Sand/Clay Lower Palaeochannel	0.00849	1.00E-05	0.2
20	Sandy Alluvium	0.00862	1.00E-05	0.2
21	Clayey Alluvium	0.00391	1.00E-05	0.2
22	Clayey Alluvium	0.00712	1.00E-05	0.2
23	Weathered Granite	0.00833	1.00E-05	0.2
24	Calcrete, Transition Calcrete, Carbonated Clay Quartz and Sandy Alluvium	0.00432	1.00E-05	0.2

It is noted that a barrier wall, at the modelled location, is a concept. The need and timing for a wall, its location and design will become apparent during the initial years of dewatering when the development of the drawdown cone can be monitored and compared to modelling results.

5.7.1 Impact of Barrier Wall on Drawdown Propagation

Figures 5.15a to 5.15e show the predicted drawdown over time with a barrier wall in place.

In Figure 5.16, the difference in head between the predicted drawdown without and with a barrier wall is shown. This Figure indicates that in the area west of the wall water levels would have been slightly higher if a wall was present. Conversely, in the area east of the wall, the presence of a wall would have resulted in lower water levels compared to the no wall case. The comparison indicates that a wall, at this particular conceptual location, would have a minor positive impact in limiting westward propagation of the drawdown.

6.0 CLOSURE MODEL

6.1 Introduction

At closure, the mined-out pit will be filled with tailings or other backfill wastes, covered with appropriate materials, and contoured to have a surface profile that minimizes erosion, reduces radon exhalation and provides a revegetated surface. At that time, all water supply abstractions and drainage have ceased.

Due to the change to the in-situ geologic medium, and thus to the groundwater flow field, recharge and discharge rate, the groundwater regime in the proposed development area will be adjusted until it returns to a new state of equilibrium.

Modelling of the closure period was done to simulate the groundwater level recovery process around the mine pit and wellfields to estimate the time required for the groundwater systems to reach a new steady state condition, and to identify any residual change to the groundwater table configuration.

6.2 Model set-up

The closure model settings include:

- The hydraulic conductivity parameters of tailings, backfill and TSF embankments as listed in Table 5.3. Outside the mine pit limits, the hydraulic conductivity distribution in all model layers was unchanged from the calibrated baseline groundwater flow model.
- The model topography was maintained.
- Hydraulic heads predicted at the end of the project were used to define the initial hydraulic heads of the closure model.
- A recharge rate of 0.00065 mm/day (equivalent to 0.2 mm/annum, which is approximately 0.1 percent of the annual average rainfall) was assigned to the TSF cells (URS, 2011a).
- The ET calculation in the closure model used the same extinction depths and potential ET assigned in the base model.
- The closure model is a transient model, with 28 stress periods for a total simulation time of 500 years.
- It is also assumed that Albion Downs wellfield production stops at the end of the Yeelirrie project.

6.3 Modelling Results: Residual Drawdown

The residual drawdown contours at 50, 100, 150, 200, 250, 300, 400 and 500 years after closure are presented in Figure 6.1a to h.

The modelling results indicate that:

- Groundwater table recovery is evident in the short-term after cessation of abstraction, with the major part of the recovery to baseline levels occurring over a 50- year period.
- Water table recovery is predicted to occur more quickly beneath the valley floor compared to areas higher upslope. For example, the water table at the pit location is predicted to recover to baseline levels within 100 years, but small residual drawdowns would persist in the area of the nearby northern wellfield for more than 200 years.
- Within the TSF area, the water table recovers to levels about 0.5 m below the baseline elevations. This suggests a new steady state due to the local geologic medium property changes.
- There would be some change in the down-valley groundwater flow path at the local scale in the vicinity of the pit; however, no discernable change in groundwater flow is expected at the catchment scale.

7.0 PREDICTIVE LONG-TERM TRANSPORT MODELLING

7.1 Introduction

The objective of this modelling exercise is to assess the long-term transport of some selected constituents of concern (COCs) in tailings pore water and their potential impact in a post closure environment. Therefore, all COCs in the predicted plume originate from the TSF, and the initial concentrations of COCs in the model are assumed to be "zero" (0).

The base-case transport model set-up is the same as the closure model, except that:

- Transport parameters are included in the transport model; and
- The transport model has 38 stress periods with a total simulation time of 15,000 years.

Sensitivity analyses have been performed to evaluate the impact of the different parameters on transport modelling results. These different parameters include: K_d, COC source terms, recharge rate through tailings cover, and extinction depth within the area of the mine pit.

7.2 Source Terms

Investigations have been conducted to characterize the constituents of concern in the future tailings deposited in the in-pit TSF cells (Cameco, 2015). Table 7.1 shows the estimated concentration and distribution coefficient (K_d) of five COCs: chloride, uranium, vanadium, arsenic, and molybdenum. The COCs chosen represent those expected to be the least retarded in the Yeelirrie environment because they exist as negatively charged species (As and Mo) and uranium and vanadium because they are of particular concern because of the geochemistry of the carnotite deposit. Chloride is included because it is a non-retarding conservative tracer.

Table 7.1 Recommended COC Source Terms and Distribution Coefficients for the Yeelirrie In-pit TSF

Constituent	Cameco Source term (mg/L)	Distribution coefficient, K_d (cm^3g^{-1})	
		loams	clay-quartz
Cl	26,000	0	0
U	180	420	1.1
V	79	480	2.7
As	4.6	350	1.3
Mo	2.1	47	0.67

Source: extracted from Cameco, 2015

7.3 Boundary Conditions for the Transport Model

It is predicted that within the modeling time frame (i.e., 15,000 years), the concentration of COCs in the tailings pore water would remain essentially constant. Therefore, constant concentration boundary conditions are employed to represent the source term in the transport model.

7.4 Transport Processes and Parameters

Mass transport involves the following processes:

- Advection;
- hydrodynamic dispersion (including mechanical dispersion and diffusion); and
- chemical, nuclear, and biological processes.

These transport processes and related parameters are described in this section.

7.4.1 Advection

Advection is mass transport due simply to the flow of the water in which the mass is carried. The direction and rate of transport coincide with that of the groundwater flow.

7.4.2 Hydrodynamic Dispersion

Mechanical dispersion is the process of mechanical mixing that takes place in porous media as a result of the movement of fluids through the pore space. Diffusion is the process whereby constituents move under the influence of their kinetic activity in the direction of their concentration gradient. It is an important transport mechanism in environments with very low groundwater velocities.

The coefficient of hydrodynamic dispersion is expressed as (Freeze and Cherry, 1979):

$$D_l = \alpha_l \bar{v} + D^*$$

where:
D_l = coefficient of hydrodynamic dispersion (m^2/s)
α_l = dynamic dispersivity (dispersivity) (m)
$\bar{v}$ = average linear groundwater velocity (m/s)
D^* = effective molecular diffusion coefficient (m^2/s), equal to $\tau \times D_0$, where D_0 is the aqueous phase molecular diffusion coefficient.

A common ratio of longitudinal to transverse dispersivity is about 10:1 (Freeze and Cherry, 1979). Vertical dispersivity is typically orders of magnitude less than transverse dispersivity. In stratified sedimentary successions, where fine-grained low-conductivity layers limit the vertical component of flows along preferred horizontal flow paths, the vertical dispersivity may be comparatively small. In this modeling exercise, it is assumed that:

- Longitudinal dispersivity: 5 m;
- Transverse dispersivity: 0.5 m; and
- Vertical dispersivity: 0.05 m.

These values are determined based on experience and professional judgment, considering model cell size and hydrostratigraphic characteristics of the Yeelirrie Catchment.

Effective molecular diffusion coefficient is usually very small, and its contribution to the overall transport is insignificant. For simplicity, a value of 8.64×10^{-8} m^2/day (10^{-12} m^2/s) is used for all the COCs in the whole model domain.

7.4.3 Chemical, Nuclear and Biological Processes

The model assumes that, except for the sorption process described by the use of distribution coefficients, there will be no chemical degradation, radioactive decay or any other reactive process involved in the solute transport. This is a conservative assumption meaning that it may cause the model to over-predict the migration distance and concentration for the constituents.

7.4.4 Distribution Coefficients

Sorption is an important attenuation mechanism for many metals and radionuclides. Distribution coefficients (Kd) are commonly used to characterize the sorption processes. The implementation of Kd values does not consider any mechanistic process but is an empirical approach that recognizes the retardation of constituents in solution due to many processes and many solid species.

The K_d for loams and clay-quartz is shown in Table 6.1. For solute transport modelling purposes, it is recommended that (Cameco, 2015) the K_d for clay-quartz should be used for the clay-quartz, carbonated clay-quartz, calcrete and transitional calcrete systems; the K_d for loam should be used for the carbonated quartz-rich loam, carbonated loam and loam systems. A K_d of zero has been used for weathered granite and any descriptor including sand. In the present modelling a K_d of zero was used for the palaeochannel sand systems.

Of the five COCs simulated, chloride is geochemically conservative (i.e., its distribution coefficient is zero) and thus is not subject to retardation in groundwater flow systems. Even at comparatively high concentrations, chloride ions remain dissolved in groundwater because these ions do not adsorb onto sediment particles or undergo chemical precipitation reactions with minerals commonly occurring in soils or rocks at uranium mine sites. Therefore, it is a useful indicator parameter for solute migration.

7.4.5 Effective Porosity

The effective porosity value in each model layer was set to the same value as the specific yield (http://web.ead.anl.gov/resrad/datacoll/porosity.htm). This is a conservative assumption for solute transport predictions because effective porosity is typically slightly larger than specific yield for aquifers, and a smaller value of effective porosity would promote solute transport at conservatively high average linear velocities if all other transport parameters are constant. The porosity of the disposed tailings is based on the design porosity values rather than the specific yield values. Table 7.2 presents the assigned storage and effective porosity values.

Table 7.2 Solute Transport Model Parameterisation of Storage and Porosity

Zone	Storage Parameters (dimensionless)		
	Storativity	Specific Yield	Porosity
1	1.00E-08	0.01	0.01
2	1.00E-06	0.1	0.1
3	1.00E-06	0.05	0.05
4	9.00E-06	0.05	0.05
5	2.00E-04	0.2	0.2
6	1.00E-05	0.2	0.2
7	1.00E-04	0.2	0.2
8	1.00E-05	0.1	0.1
9	1.00E-05	0.23	0.23
10	1.00E-05	0.05	0.05
11	1.00E-05	0.1	0.1
12	1.00E-05	0.05	0.05
13	1.00E-05	0.23	0.23
14	1.00E-05	0.2	0.2
15	1.00E-05	0.23	0.23
16	1.00E-05	0.2	0.2
17	1.00E-05	0.1	0.4
18	1.00E-05	0.05	0.5
19	1.00E-05	0.05	0.5
20	1.00E-05	0.1	0.2

7.5 Modelling Results: Base Case

A summary of the predictive findings for each constituent using base case inputs and assumptions is discussed below. It should be noted that all predicted values represent concentrations above (additive to) baseline. Considering that concentrations for COCs vary over several orders of magnitude, concentrations for all COC plumes are presented in the figures with a log scale (for example -1 means 10^{-1} = 0.1 mg/L, 2 means 10^{2} = 100 mg/L).

As shown in Figure 7.1, the mine pit is located in calcrete which has a much higher hydraulic conductivity than its geologic surroundings. After the mine pit is rehabilitated, the low permeable tailings and backfills within the mine pit are laterally bounded by high permeable calcrete. Groundwater in calcrete flows toward and then generally parallel to the TSF cells in an east-west direction (Figure 7.2). In the vertical direction, there is an upward flow in the mine pit zone, mainly due to relative high ET rate (Figure 7.2).

Chloride

The base case predicted chloride plumes in each model layer (with a minimum concentration threshold of 0.01 mg/L) at year 15,000 are illustrated in Figures 7.3a to 7.3h. It is observed that:

- Along the valley, the predicted plume is expected to travel as far as 50 km eastward, with elevated concentrations (>10 mg/L) in very limited local areas, and low concentration (< 10 mg/L) in most areas. Considering the high baseline concentrations of chloride in the Yeelirrie Catchment, the impact of chloride (concentration > 10 mg/L) originating from TSF is limited to approximately 1,000 m east of the TSF. Beyond this distance from the TSF, the increase in chloride concentration is negligible.
- In the north-south direction, chloride migration is minimized due to the large west – east flow component of groundwater in the calcrete alongside the TSF cells. Transport of chloride in the north-south direction would be limited to molecular diffusion. However, it is noted that chloride could migrate farther northward (up to 600 m from the TSF) than southward because of local northward groundwater flow exists in some local locations to the north of the TSF cells.
- The depth to the groundwater table around the mine pit area is approximately 5 m under current conditions. Therefore, tailings in the upper several meters will be unsaturated, and transport of COCs is limited in the unsaturated zone even after the groundwater level recovers about 200 years following TSF rehabilitation (Section 6). Once the COCs travel out of the limited local calcrete zones, the groundwater table becomes shallower, and the transport of COCs becomes faster due to a smaller flow cross-section. Once chloride or other COCs reach the saturated zone, they would be expected to travel faster than in the unsaturated zone. In the saturated zone, many

COCs trend towards smaller source terms due to additional solubility controls from chemical reduction and mixing with natural groundwaters (Cameco, 2015).

- In the vertical direction, the downward transport of chloride is limited to diffusion in the presence of an upward hydraulic upgradient. Therefore, the downward transport is limited, but could reach model layer 8 (weathered granite).

It should be noted that the differences in simulation results between the conservative chloride and other COCs are due to different source concentration and distribution coefficients. The transport characteristics observed for chloride also apply to other COCs; however, the travel distance is reduced due to adsorption along the flow path. In the following description for other COCs, results that are consistent with chloride behaviour will not be discussed.

Uranium

The predicted uranium plumes within each model layer (with minimum concentration of 0.01 mg/L) at year 15,000 are illustrated in Figures 7.4a – 7.4h. The red contour line in these figures represents 0.2 mg/L. It is observed that:

- In the east-west direction, the predicted uranium plume front (threshold of 0.2 mg/L) could travel eastward as much as 300 m from the TSF cells. At this travel distance, the plume remains within the mine-waste backfill.
- In the north-south direction, the predicted plume front (0.2 mg/L) could travel northward in the calcrete by as much as approximately 500 m.
- In the vertical direction, the predicted uranium plume could reach model layer 8 (weathered granite).

Vanadium

The predicted uranium plumes within each model layer (with minimum concentration of 0.01 mg/L) at year 15,000 are illustrated in Figures 7.5a to 7.5h. It is observed that:

- In the east-west direction, the predicted vanadium plume front (0.01 mg/L) is predicted to travel eastward by approximately 200 m, still within backfill of the mine pit.
- In the north-south direction, the predicted plume front (0.01 mg/L) could travel northward approximately 600 m, and southward approximately 200 m.
- In the vertical direction, the predicted vanadium plume could reach model layer 8 (weathered granite) in a limited area.

Arsenic

The predicted arsenic plumes with each model layer at year 15,000 are illustrated in Figures 7.6a to 7.6h. It is observed that:

- In the east-west direction, the predicted arsenic plume front (0.01 mg/L) is expected to travel eastward by approximately 200 m, still within backfill of the mine pit.

- In the north-south direction, the predicted arsenic plume front (0.01 mg/L) could travel northward in the calcrete by approximately 600 m.
- In the vertical direction, the predicted arsenic plume could reach model layer 7 (weathered granite, sand/clay lower paleo-channel) in a limited area. Comparing with the vertical travel distance of chloride, this smaller travel distance is due to smaller concentration gradient.

Molybdenum

The predicted molybdenum plumes within each model layer (with minimum concentration of 0.01 mg/L) at year 15,000 are illustrated in Figures 7.7a to 7.7h. It is observed that:

- In the east-west direction, the predicted molybdenum plume front (0.01 mg/L) is expected to travel eastward approximately 300 m, still within backfill of the mine pit.
- In the north-south direction, the predicted plume front (0.01 mg/L) would travel northward in the calcrete by approximately 500 m.
- In the vertical direction, the predicted molybdenum plume front could reach model layer 6 (weathered granite, sand/clay lower paleo-channel) in a limited area. Comparing with the vertical travel distance of chloride, this smaller travel distance is due to smaller concentration gradient.

7.6 Modelling Results: Sensitivity Analyses

Predictive uncertainty can stem from uncertainties related to model parameters, conceptualization and future changes in baseline conditions (Australian Groundwater Modeling Guidelines, 2012). Sensitivity analyses have been conducted to investigate the effect of several parameters (as described below) on the transport of the five COCs:

- **K_d**: K_d values reported in literature are not constants, but vary by up to several orders of magnitude under different geochemical conditions and in different geologic medium (e.g., K_d values for uranium could range by three orders of magnitude, as reported in USEPA (1999). In the sensitivity analysis K_d values for uranium, vanadium, arsenic and molybdenum were reduced by one order of magnitude to investigate the effect on transport. The K_d values used in this analysis are site-specific K_d values determined from leach tests conducted on Yeelirrie geologic materials (Cameco, 2015).
- **Source term**: the source concentrations for the five COCs simulated in this modeling exercise were increased by 20%.
- **Recharge through tailings cover**: During the post closure period, the infiltration rate within the mined-out area is assumed to be 0.1% of average annual rainfall in the base case. Two sensitivity scenarios have been run to investigate the variation of infiltration through tailings cover on solute transport, including:

  - Scenario 1: The infiltration rate is assumed to be the same as baseline conditions before mining (approximately 0.2% of average annual rainfall);
  - Scenario 2: The infiltration rate is assumed to be 2.5% of average annual rainfall.
- **Extinction depth of the tailings and backfill zone:** It is assumed in the base case that the extinction depth is 5 m, the same as in baseline conditions before mining. In the sensitivity analysis, extinction depth is reduced to 3.5 m to investigate its impact on solute transport.

7.6.1 Effect of K_d

The predicted uranium plumes within each model layer (with minimum concentration of 0.01 mg/L) at year 15,000, for a reduced K_d (0.1*base case K_d) are illustrated in Figures 7.8a- 7.8h. The red contour line in the figures represents 0.2 mg/L. It is observed that:

- East-west: the predicted uranium plume front (0.2 mg/L) could travel approximately 1,100 m, in contrast with a travel distance of 300 m in the base case. The predicted concentrations in corresponding areas are higher than those in base case.
- North-south: the predicted plume could travel approximately 500 m, similar to that in base case.
- Vertically: the predicted uranium plume could reach model layer 8 (weathered granite) within a relatively larger area.

The effect of a reduction of K_d on the transport of vanadium, arsenic, and molybdenum is similar to uranium and the predicted plume maps are shown in Appendix A.

7.6.2 Effect of Source Concentration

The predicted chloride plumes within each model layer (with a minimum concentration of 0.01 mg/L) at year 15,000, for a 20% increase in the source concentration, are illustrated in Figures 7.9a to 7.9h. It is observed that, compared to the predicted plume for the base case, the changes in the predicted chloride plumes are very minor in all directions.

The effects of source concentration variation on the transport of uranium, vanadium, arsenic, and molybdenum are also minor. The predicted plume maps are shown in Appendix A.

7.6.3 Effect of Recharge to Groundwater through Tailings and Backfill Cover

Three sensitivity scenarios have been run to investigate the effect of net infiltration through the tailings cover: base case (0.1% of annual precipitation), scenario 1 (0.2% of annual precipitation), and scenario 2 (2.5% of annual precipitation).

The predicted chloride plumes within each model layer (with minimum concentration of 0.01 mg/L) at year 15,000 are illustrated in Figures 7.10a to 7.10h (scenario 1) and 7.11a to 7.11h (scenario 2). These figures indicate the following:

- When the recharge rate to the groundwater through tailings and backfill cover increases from 0.1% of average annual rainfall to 0.2%, the longitudinal (east-west) travel distance of chloride plume front (0.01 mg/L) does not change noticeably, but the lateral travel distance increases slightly. The areas with concentrations greater than 10 mg/L also show a very minor increase.
- When the recharge rate to the groundwater through tailings cover increases to 2.5% of average annual rainfall, the maximum eastward extent of the chloride plume front (0.01 mg/L) does not change noticeably, but the width of the plume noticeably increases. The downgradient concentrations increased significantly, as have the areas with concentrations larger than 10 mg/L.

The predicted uranium plumes within each model layer (with minimum concentration of 0.01 mg/L) at year 15,000 are illustrated in Figures 7.12a to 7.12h (for Scenario 1) and 7.13a to 7.13h (for Scenario 2). It is observed that:

- When the recharge rate to the groundwater through tailings and backfill cover increases from 0.1% of average annual rainfall to 0.2%, the travel distance of uranium in t does not change noticeably in any direction.
- When the recharge rate to the groundwater through tailings and backfill cover increases to 2.5% of average annual rainfall, the travel distance eastward increases significantly. The downward transport to layer 8 (weathered granite) also increases noticeably.

The effect of recharge to groundwater through tailings cover on the transport of vanadium, arsenic, and molybdenum is similar to that on uranium and the predicted plume maps are shown in Appendix A.

7.6.4 Effect of Extinction Depth

When the extinction depth is reduced from 5 m to 3.5 m within the area covered by the mine pit, the steady-state groundwater table elevation increases, in comparison to the base case.

The predicted chloride plumes within each model layer (with minimum concentration of 0.01 mg/L) at year 15,000 are illustrated in Figures 7.14a to 7.14h. It is observed that:

- When the extinction depth is reduced from 5 m (base case) to 3.5 m, the maximum eastward extent of the chloride plume front (0.01 mg/L) increases only slightly, but the width of the plume becomes wider. The downgradient concentrations within the plume are also increased.

The predicted uranium plumes (with minimum concentration of 0.01 mg/L) at year 15,000 are illustrated in Figures 15a to 7.15h. The red contour line in the figure represents 0.2 mg/L. When the extinction depth is reduced from 5 m (base case) to 3.5 m, it is observed that:

- The eastward travel distance of the uranium plume front (0.2 mg/L) is approximately 1,200 m in contrast with 700 m in base case. A noticeable change is that, when the extinction depth is 3.5 m, uranium is transported preferentially along calcrete south to the mine pit, in contrast to the transport path directly through the backfilled mine pit east to TSF cells in the base case (ET = 5 m).

- Laterally (north-south), the northward transport of uranium does not change noticeably. But uranium travels slightly farther southward, and the uranium concentration in southward direction increases noticeably.
- In vertical direction, uranium concentration in lower layers (i.e. layer 7 and 8) increases noticeably.

The effect of extinction depth on the transport of vanadium, arsenic, and molybdenum is similar to that of uranium and the predicted plume maps are shown in Appendix A.

In summary, COC transport is more sensitive to K_d, infiltration through tailings and backfill cover and the extinction depth rather than source concentration in the respective simulated range of these parameters. This, along with the uncertainty in characterizing K_d, infiltration through tailings cover, extinction depth and source concentration has been taken into account in considering the transport simulation results presented in this report. High site-specific K_d values are supported by field evidence, gamma radiation surveys obtained after the removal of stockpiled materials during rehabilitation activities in 2004 at the Yeelirrie site showed very low readings after removal of the stockpile indicating a very limited release during the stockpiles lifetime (20 to 30 years) (Cameco, 2015).

8.0 SUMMARY AND CONCLUSIONS

The proposed Yeelirrie development occurs entirely within the Yeelirrie Catchment in the Northern Goldfields of Western Australia. Both historical and recent site investigations were used to characterise the catchment hydrogeology and water balance. The known groundwater environment is characterised by a predominance of shallow sandy alluvium, palaeochannel and weathered granite aquifers with minor, but important, discrete occurrences of calcrete. There is local and regionally significant variation in the lithology and hydraulic characteristics of the calcrete, sandy alluvium and Yeelirrie Palaeochannel successions. Based on this evidence, the valley-fill successions and underlying weathered bedrock were interpreted as an anisotropic and leaky multi-layer aquifer system with likely occurrence of preferred flow paths. Aquifer tests confirm that the calcrete forms an important high-transmissivity aquifer and the predominant unconfined groundwater flow path. Typically, however, the calcrete is of limited saturated thickness (typically 0.5 to 3 m) and consequently, has limited water storage.

The hydrogeological model indicates:

- Interpreted groundwater elevations are highest on the catchment margin and lowest beneath valley-floor settings. In broad terms, the groundwater table is a subdued reflection of the ground surface, with shallow groundwater flow towards the valley-floor setting, then longitudinally towards Lake Miranda.
- Groundwater salinity is interpreted to increase along lateral and vertical flow paths from the catchment divide to central valley areas and subsequently in discrete reaches or compartments beneath the valley-floor. The observed salt accumulation in the groundwater environments was intuitively linked to surface water availability and evaporation and transpiration processes that invade the vadose zone and increase the salinity of infiltrates before they percolate to the groundwater table. Salt is accumulated in each compartment and each compartment hosts interpreted shallow water tables at settings within 3 metres of the ground surface.
- Rates of groundwater discharge by evaporation and transpiration are interpreted to typically be less than the recharge rates. The interpreted compartmentalisation of valley-floor recharge and discharge zones indicates that evaporation and transpiration potentials would differ from one valley-floor recharge or discharge zone to another. The interpretations reflect concurrent recharge and discharge processes that accumulate and disperse salt within water table flow paths.

The hydrogeological model was used to inform the development of numerical groundwater flow and solute transport models. Both steady-state and transient models were developed and calibrated. The calibrated models indicate that:

- The model behaviour was strongly influenced by the synchronised influences of the applied recharge and discharge potentials.
- The Yeelirrie Catchment forms a semi-closed, semi-compartmentalised groundwater flow system; the only source input to groundwater is rainfall, and the primary discharge of groundwater is through groundwater ET with a comparatively minor portion (about 11 percent) of groundwater leaving the catchment as through flow to Lake Miranda.

The calibrated numerical models, developed by URS (2011a), were modified to incorporate changes to the groundwater systems due to the proposed development, and predict changes to the groundwater environment that may occur during mining and rehabilitation period. Findings of the predictive operation models include:

- The predicted annual pit dewatering abstraction volumes range from 0.04 to 2.7 GL/annum during the operations period, with a total abstraction of 18.9 GL. The pit dewatering abstractions intercept and include seepage from the TSF cells during the period of mining and rehabilitation.
- The predicted water supply abstractions are from the combined sources of the recommended conceptual wellfields with abstractions of 50.7 GL over the period of operations.
- Water demands can be met by combined groundwater abstraction from the pit dewatering and the proposed wellfields.
- An MAR system is used to divert and conserve excess pit dewatering abstraction volumes of 2.27 GL during the initial four years of operations.
- Drawdown of the groundwater table occurs in response to the pit dewatering and water supply abstraction. The predicted drawdown indicates that:
    - Drawdown in the vicinity of the proposed wellfields increases over time. In the vicinity of individual production wells, water table drawdown at year 18 typically exceeds several metres (typically in the 2 to 5 m).
    - Slow expansion of drawdown cone indicates that the groundwater sources in the proposed wellfields are relatively abundant.
    - Interference occurs between pit dewatering, the Saline, Eastern and Northern wellfields, which broadens the overall drawdown footprint and increases the magnitude of drawdown associated with these abstraction sources.
    - The model-predicted drawdown cone caused by the proposed saline wellfield has a limited overlap with the drawdown cone caused by the Albion Downs wellfield. This slight hydraulic interference starts to occur from year 12.
    - Groundwater re-injection through the MAR system causes groundwater mounding around the injection wells, with a predicted maximum groundwater level increase

of approximately 1 m. Groundwater mounding disappears at the end of year four while re-injection ceases at the beginning of year four.

To simulate the groundwater level recovery process during the post closure period, the operation flow model parameters were modified to represent the future site conditions after mine closure and TSF rehabilitation. Parameter changes reflect the hydraulic characteristics of the tailings material, estimated recharge rates through the final TSF cover soil and cessation of groundwater abstraction. The closure flow model was then run to predict groundwater level changes for 500 years into the future. Findings of the predictive closure models include:

- Groundwater table recovery is evident in the short-term after cessation of abstraction, with recovery to baseline levels predominantly occurring over a 50 year period.
- Water table recovery is predicted to occur at an accelerated rate beneath the valley floor compared to areas higher upslope.
- Within the TSF area, the water table recovers to levels about 0.5 m below the baseline elevations. This may reflect the new steady state the groundwater regime reaches after the local geologic medium property changes.
- There would be some change in the down-valley groundwater flow path at the local scale in the vicinity of the pit; however, no discernable change in groundwater flow is expected at the catchment scale.

The closure model was then converted to a solute transport model to predict the long-term (15,000 years) transport of selected COCs (including chloride, uranium, vanadium, arsenic and molybdenum) in a post closure environment. Findings of the predictive long-term solute transport models include:

- In the east direction, the predicted conservative chloride plume could travel as far as 50 km mainly along the valley, with elevated concentration (>10 mg/L) in very limited local areas, and low concentration (< 10 mg/L) in most areas. Beyond a distance of 1,000 m west of the deposit the increase is negligible compared to the baseline concentrations.
- Other simulated COCs (including uranium, vanadium, arsenic and molybdenum) plume can travel several hundred meters longitudinally along the valley, and traverse the valley, due to sorption of COCs to solid geologic medium.
- Sensitivity analysis indicates that COC transport is more sensitive to Kd, infiltration through tailings and backfill cover and the extinction depth rather than source concentration in the respective simulated range of these parameters.

9.0 MODEL LIMITATIONS

Numerical groundwater flow models are approximate representations of aquifer/aquitard systems (Anderson and Woessner, 2002), and as such have limitations. These limitations are usually associated with:

- the construction of the conceptual hydrogeological model and the understanding of the aquifer/ aquitards systems;
- the quantity and quality of data used to inform parameters in the groundwater flow model; and
- assumptions made during model development.

The numerical simulations as presented in this report are based on the conceptual hydrogeological model and numerical model constructed by URS (URS, 2011a). Data errors and data gaps may be present in the information obtained from previous investigations conducted in the study area.

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