Onslow Water Infrastructure Upgrade Project

Conceptual Design for Injection of the Residual Saline Stream

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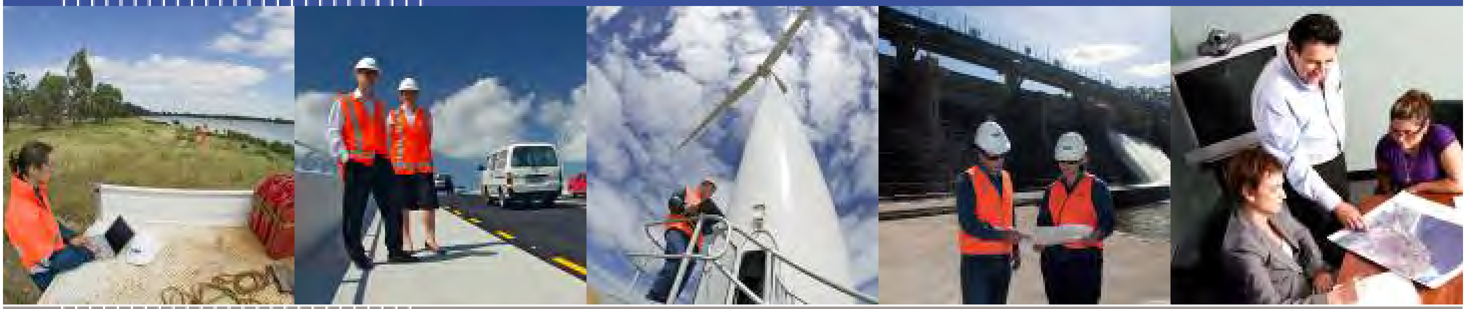

Report

Onslow Water Infrastructure Upgrade Project

Conceptual Design for Injection of the Residual Saline Stream

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Prepared for

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Abbreviations

Abbreviation	Description
BoM	Bureau of Meteorology
C	Celsius
km	kilometre
ha	hectare
OWIUP	Onslow Water Infrastructure Upgrade Project
LiDAR	Light Detection and Ranging
m	metre
mm	millimetre
NORM	naturally occurring radioactive materials
RO	Reverse Osmosis
RSS	Residual Saline Stream
TDS	Total Dissolved Solids

Executive Summary

The Birdrong Sandstone groundwater source for the Onslow Water Infrastructure Upgrade Project (OWIUP) has traces of radium. Therefore radium would be present in the Residual Saline Stream (RSS), a by-product of the Reverse Osmosis (RO) plant. One option for disposal of the RSS is direct discharge into the local Quick Mud Creek; an ephemeral watercourse with a predominantly dry channel and episodic stream flow events typically occurring once or twice each year. In the Quick Mud Creek setting in the interim between flow events, the RSS would pool in the low-flow channel, with propensity for water losses by evaporation leading to accumulation of crystalline salts (with inclusive radium). Flood events on the Ashburton River also spill into Quick Mud Creek with a typical biennial frequency.

There may be circumstances whereby direct disposal of the RSS to Quick Mud Creek is not viable. Under these circumstances, alternative RSS disposal options would need to be considered. One such option in particular has been developed that explores the potential for:

- Shallow groundwater to be abstracted from the local aquifer systems and disposed to Quick Mud Creek.
- Concurrent disposal of RSS by local injection into the shallow groundwater environment.

Beneath Quick Mud Creek and surrounds, the groundwater environment is hosted by a low-transmissivity, low-yield hydrostratigraphy succession that is broadly characterised by:

- Superficial formations – saturated thickness 10 to 20 m and effective transmissivity 10 to 40 m^2/day.
- Ashburton River Delta Clay and Unconformity – saturated thickness 5 to 10 m and effective transmissivity 2 m^2/day.
- Trealla Limestone – saturated thickness 20 to 35 m and effective transmissivity 15 to 20 m^2/day.

The shallow groundwater has no traces of radium, thus its discharge would not lead to the accumulation of radium in Quick Mud Creek.

The potential for success of the proposed groundwater abstraction and concurrent RSS injection concept lies in:

- Characterising the transport and fate of the injected RSS.
- Understanding the cumulative influences of the groundwater abstraction and concurrent injection, such that changes in water table elevations that could impact the environment.

It was recognised from earlier predictive modelling (URS, November 2012) that the injected RSS volumes would mound the water table, promote increased discharge (by evaporation) along Quick Mud Creek and other low-lying areas and, over time progressively displace the groundwater in storage. Therefore, the abstracted groundwater would be characterised by dilute RSS signatures. The dilution would decrease over time.

The concept of concurrent local groundwater abstraction and RSS injection has been investigated using predictive groundwater flow and solute transport models. The initial concept development was informed by:

- RSS production rates that average 400 kL/day, with an operating period of 80 years.
- Injection of the RSS preferably into the Trealla Limestone from facilities located on the peaks of the local longitudinal dunes.
- Abstraction of groundwater from the Ashburton River Delta Alluvium and Trealla Limestone in locations above the 1:100-year ARI flood elevation in Quick Mud Creek.

URS

- Nominally, the production bore yields would be 100 kL/day. There would be a minimum of four production bores.
- There would be increased numbers of injection bores compared to the abstraction bores. Nominal yields for each injection facility would be 50 kL/day. There would be a minimum of eight injection bores.
- A nominal minimum distance of 200 m between individual abstraction and injection facilities to limit interference effects.

The conceptual design injection and abstraction facilities have been interfaced with predictive groundwater flow models to characterise the transport and fate of the disposed RSS. Two predictive models were developed and applied. These models incorporate:

- A preliminary concept design based on:
  - 8 injection facilities aligned on the local longitudinal dune landform.
  - 4 abstraction facilities located on the eastern perimeter of the Quick Mud Creek flood plain.
  - Spacing of the facilities is about 200 m.
- A refined concept design based on :
  - 8 injection facilities aligned on the local longitudinal dune landform, but spaced up to 400 m apart.
  - 5 abstraction facilities located on the eastern perimeter of the Quick Mud Creek flood plain.

The key findings from the predictive models include:

- There are substantial transits periods before the disposed RSS reaches groundwater discharge zones. Transit times for discharge of the disposed RSS to local reaches of Quick Mud Creek may therefore range up to 1,000 years. Further afield transit times to the saline flats of the Hooley Creek – Four Mile Creek tidal embayment may range from 1,800 to 3,000 years.
- The simulated abstraction facilities prevent the occurrence of seepage fronts on Quick Mud Creek but intersect RSS signatures. The maximum RSS signature for radium activity included:
  - Preliminary concept design - ranging up to about 26 Bq/L.
  - Refined concept design - ranging up to about 6 Bq/L.
- The radium activities within the groundwater discharge zones were highest associated with Quick Mud Creek. including:
  - Preliminary concept design - ranging up to about 19 Bq/L. The peak occurred after about 800 years.
  - Refined concept design - ranging up to about 8 Bq/L. The peak occurred after about 849 years.
- Times for transit of peak RSS signatures to the distant groundwater discharge zones ranged up to 2,172 years.
- The refined concept design, based on broader rather than tighter injection and abstraction facility distributions, enables lower radium activities in the receiving environments.
- The water table mounding created by the injection facilities is able to be off-set in part by the concurrent abstraction. The objective was to mitigate potential risks of seepage from the mounded water table to Quick Mud Creek and the simulated concurrent abstraction was successful in this regard.
- The changes in water table elevation beneath potentially sensitive areas are able to be limited. This aspect is a function of the spacing of the injection and abstraction facilities and typical rates of injection and abstraction.

- The maximum NORM activities entering the groundwater discharge zones would typically be significantly lower for the injection and abstraction concepts compared to direct discharge of the RSS to Quick Mud Creek. It is anticipated that the concept designs of the injection and abstraction facilities could be refined to achieve particular set objectives in terms of the NORM activities in the local groundwater discharge zones.

It is expected that the concept designs could be further refined to enable lower radium activities in potentially sensitive areas. This may be achieved by increased broadening of the injection facility distribution.

The potential influence of evaporation concentration effects in groundwater discharge zones on the RSS signature is poorly defined.

There are comparatively limited data that support the model form and parameterisation. There is also recognition that the Trealla Limestone and Ashburton River Delta Alluvium setting is likely to be widely anisotropic. As such, there are uncertainties linked to the likely aquifer behaviours and transport and fates of the injected RSS. The uncertainties include aquifer hydraulics, vertical hydraulic gradients and connectivity of the Trealla Limestone and Ashburton River Delta Alluvium, seasonal and episodic changes in water table elevations, the hydrology of the pools in Quick Mud Creek and potential yields of injection and abstraction facilities.

The data limitations and outlined uncertainties constrain the developed model to a Class 1 classification; this is the lowest classification based on the current (SKM and National Centre for Groundwater Research and Training, June 2012) guidelines. Accordingly, the model findings should be recognised as indicative only, semi-quantitative and semi-qualitative. Furthermore, the simulated transit times of the injected RSS should also be considered in context to climate and landform changes recognising themes of rising sea levels and the Ashburton River Delta being and active accretion landscape subject to both gradual and episodic changes. Despite the Class 1 classification, the predictive model provides reasonable indications of the likely fates of injected RSS and associated NORMs.

Introduction

1.1 Project Description

Chevron proposes to use the Birdrong Aquifer as the raw groundwater source for the Onslow Water Infrastructure Upgrade Project (OWIUP), with reverse osmosis (RO) treatment of the saline groundwater prior to distribution. The RO treatment will produce a residual saline stream (RSS) by-product that includes traces of naturally occurring radioactive materials (NORMS). Disposal strategies for the RSS were previously assessed and document in:

- URS, November 2012: Alternative Assessment of Brine Disposal for Sites A & B. CVX Report No WHSTSTU-WA-RPT-0107.
- URS, December 2012: Definition of Impediments to Residual Saline Stream Disposal for Site B. CVX Report No WHST-STU-WA-RPT-0112.
- URS, September 2013: NORM Risk Assessment at Quick Mud Creek. CVX Report No WHST-STU-WA-RPT-0112.

The injection of the RSS into the local shallow aquifers (Trealla Limestone and Ashburton River Delta Alluvium) was assessed by URS (November 2012). A groundwater model was used to simulate the injection of the RSS. The findings of the predictive modelling indicated that the RSS injection would mound the water table. Further, the lack of available storage due to the shallow water table would result in a propensity for increased groundwater discharge from low-elevation settings, such as Quick Mud Creek and other local watercourses, together with accumulation of NORMS.

In order to offset the predicted lack of storage and RSS discharge to watercourses such as Quick Mud Creek, this project investigates the concurrent abstraction of groundwater and injection of RSS. Groundwater is proposed to be abstracted from the local shallow aquifers, with subsequent discharge to Quick Mud Creek. The RSS would concurrently be injected nearby into the local shallow aquifers. This approach was intended to limit potential impacts understanding that the mounding of the water table due to the RSS injection would be off-set by the nearby groundwater abstraction. Changes in the hydrochemistry would be off-set by mixing and dilution of the RSS in the hypersaline groundwater environment. The abstraction and injection volumes would be compatible to minimise the simulated water table and off-setting the lack of storage mounding to an acceptable level in regards to environmental factors.

This assessment considers one RSS quality and NORM activity signature.

1.2 RSS Reinjection Objectives

The predominant aim of this report is in the development of a practical strategy of RSS injection together with concurrent groundwater abstraction that mitigates human health and environmental risk associated with NORMs. This strategy would provide a balanced approach to RSS injection such that the disposed NORMs would predominantly be stored, at least temporarily, in the local groundwater environment and subsequently diluted in flow paths to discharge zones. The groundwater abstraction would enhance the available storage for the disposed RSS and limit the risks associated with mounding of the water table during injection.

This assessment will assess the feasibility of disposal of the RSS to the local shallow aquifer systems in regard to logistics, storage capacity, environmental impact and NORM risk. The assessment includes:

1 Introduction

- Review and interpret of existing data on the shallow aquifer systems and subsequent use of these data to inform the distributions and hydraulics of the local aquifer systems.
- Development of a number of concepts that explore the abstraction of hypersaline groundwater and injection of the RSS.
- Refine the existing groundwater flow model with reasonable parameterisation in the Project area in order to develop practical abstraction and injection concepts and scenarios. Reasonable calibration of the model would be achieved that reflects the interpreted local setting, including episodic recharge events that contribute to groundwater discharge into pools on Quick Mud Creek.
- Application of the calibrated model to simulate various numbers of pumping bores and injection bores to optimise the RSS disposal and limit associated potential risks.
- Use of particle tracking to predict the fate of the injected RSS.
- Use also of non-reactive solute transport simulations to predict the transient concentrations of the RSS in the receiving aquifers over the 80-year Project life.
- Use of a predictive model to define the wetted footprint from disposal of RSS on Quick Mud Creek and in the surroundings receiving environments.
- Characterising the potential regulatory, human and environmental risks of contaminant and NORM accumulation in the receiving aquifers zones.
- Use of the predictive models to optimise the preferred and practical reinjection concept that mitigates the environmental risks over the 80-year Project life.

Deliverables associated with the conceptual design of the RSS injection system include:

- Develop RSS disposal concepts that involve groundwater abstraction and injection themes.
- Simulate the groundwater abstraction and RSS injection concepts across a range of predictive scenarios.
- Simulate the fate of the RSS injected into the shallow aquifer systems using particle tracking and nonreactive solute transport models.
- Prediction of the RSS footprint, including contaminant and NORM concentrations in the aquifer storage and at groundwater discharge zones.
- Identify exposure pathways and risk associated with the potential contaminants (including NORMs) concentrations.
- Develop a reasonable and practical abstraction and injection concept that delivers a low-risk approach to disposal of the RSS and associated NORM activities.

1.3 Project Area

The Project area is the setting near the intersection of Onslow Road and the access road (Wheatstone Road) to the Wheatstone Project (**Figure 1-1**). This setting includes:

- The OWIUP Project area, a 34 ha site located marginally north of Wheatstone Road and on the eastern perimeter of Quick Mud Creek. This site is the host for production bore MDW4 (Macedon Project, BHP Billiton Pty Limited) that abstracts groundwater from the Birdrong Aquifer.
- Southern and northern perimeter easements to Wheatstone Road.

The Onslow Salt Project and associated crystalliser ponds occurs about 3 km north of the Project area, marginally north of where Quick Mud Creek enters the tidal estuary associated with the Hooley, Middle and Four-Mile creeks.

1.4 RSS Volumes and Quality

The RSS discharge for this assessment is assumed to average 400 kL/day (146 ML/annum) for 80 years, with salinity of 32,356 mg/L Total Dissolved Solids (TDS). The maximum RSS volume derived at periods of peak water supply demand would be 660 kL/day. Specifications of the expected RSS constituents are provided in **Table 1-1** (Chevron, pers. com. 12 July 2013

Table 1-1 RSS Quality Data

Parameters	Units	Value
pH	Standard Unit	7.8
Temperature	^{o}C	14 - 36
Total Suspended Solids	mg/L	0
Total Dissolved Solids		53,662
Dissolved Oxygen Carbon		0
Radium-226	Bq/L	10
Radium-228		33
Organic nitrogen -N	mg/L	4
Total Ammonium		26
Sodium		17,856
Potassium		552
Calcium		1,276
Magnesium		638
Barium		10
Strontium		32
Iron		0
Manganese		0.8
Chloride		30,829
Bromide		111
Iodide		4.8
Sulphate		20
Bicarbonate		2,186
Carbon Dioxide		26
Fluoride		3.9
Boron		15
Silica		91

Background

2.1 Climate

The Pilbara coast climate is arid-tropical, with influences of both tropical maritime air from the Indian Ocean and continental air from the interior. The climate can be generalised into summer (October through April) and winter (May through September) patterns.

Table 2-1 provides a summary of rainfall, evaporation and temperature data from the station Onslow Airport (BoM, July 2013). Summer patterns are characterised by hot daytime temperatures, often exceeding 40°C between November and February, and widely variable rainfall. Winter patterns are characterised by low rainfall and moderate (average daytime 25°C) temperatures.

Table 2-1 Average Monthly Climate Statistics

Statistics	Monthly Aspects												Annual
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Onslow Airport (Station No. 005017; 1940 to 2013)													
Mean Rainfall (mm)	40.9	63.5	71.8	11.9	50.4	47.0	19.3	9.3	1.5	0.9	3.0	3.6	**321.9**
Mean Monthly Pan Evaporation (mm)	351.7	292.3	295.3	232.5	172.1	134.4	145.3	180.7	247.5	319.3	341.3	369.9	**3,082.3**
Decile 1 Maximum Temperature (°C)	35.7	35.6	35.4	33.2	28.9	25.5	24.8	26.5	29.1	31.7	33.8	35.2	**31.3**

Note:
Source BoM, July 2013

The annual rainfall typically ranges from 230 to 350 mm and mainly occurs during cyclonic activity from January through April. Rainfall patterns vary widely due to the influence of tropical cyclones. Rainfall can be irregular and localised due to thunderstorm activity. Typically, rainfall intensity is highest near the coast and decreases inland. Rainfall at a single monitoring site is seldom representative of the entire local or regional catchment.

Evaporation averages about 3,080 mm/annum, measured at Onslow Airport (recorded from 1966 to 1975). Evaporation potentials significantly vary seasonally, with long-term mean monthly pan evaporation rates of 370 mm in December and 135 mm in June.

2.2 Physiography and Topography

Semeniuk (1993) characterised the Pilbara coast as "a riverine coastal plain in a tropical arid setting". The portion of the coast near Onslow is part of the Carnarvon Basin and Ashburton River Delta. The Ashburton River Delta is an accretion sedimentary environment occupying about 9 km of the coastline extending from the mouth of the Ashburton River. The delta is characterised by a complex system of spits, cheniers, tidal flats, channels and coastal dune barriers. The local coastline is dynamic, being characterised by an exposed sandy shore where both depositional and erosional processes prevail. The local hinterland is low-lying with vast areas of high tidal mud flats (bioturbated and samphire) and supratidal salt flats.

The Project area is located on the coastal plain, near the tidal estuary associated with the Hooley, Middle and Four-Mile creeks and, about 17 km southeast of the mouth of the Ashburton River. The local physiography is dominated by wide low-relief alluvial plains that contribute to the river delta and a local watercourse formed by Quick Mud Creek. The topography along Quick Mud Creek varies from 0.40 to 1.0 m AHD. The alluvial plains are interspersed with red dune fields that form coastal and longitudinal dune terrains. Locally, the longitudinal dunes peak at elevations of 11 to 13 m AHD.

The vegetation is open to dense shrub land and spinifex grassland. Occasional trees, including large Eucalypts, occur along the nearby Ashburton River. Within the watercourses and clay pans the vegetation is spare and or absent, perhaps excepting perimeter samphire.

River flows in the Ashburton River are ephemeral. Episodic steam flow events in Quick Mud Creek spill onto the Hooley Creek – Four-Mile Creek tidal embayment.

2.3 Local Landforms

The Project area setting occupies the terrestrial river deltaic environment. Highest elevations occur on longitudinal dunes that form depositional and accretion landscapes. The longitudinal dunes typically have a north-south orientation. At the perimeter of the dunes, the landforms are characterised by low-elevation and low-relief supratidal salt flats, clay pans and clayey plains, saline flats and samphire flats. These landforms host a myriad of drainage lines, including Quick Mud Creek. Several of the drainage lines are linked to the Ashburton River. The local landforms include water retention features such as clay pans and non-perennial pools on watercourses and within intra-dune swales. Typically, these landforms accumulate salt and are barren, with limited vegetation cover.

The low-relief landforms associated with Quick Mud Creek transition from the terrestrial environment to the marine environment (URS, 2010). The transition commences where supratidal salt flats merge with intertidal flats, tidal creeks (such as Hooley Creek) and mangrove swamps of the Hooley Creek – Four-Mile Creek tidal embayment. Landforms within this transition zone reflect the local tidal footprints and include bioturbated high tide mud flats and algal mat covered high tide flats.

The Hooley Creek – Four Mile Creek tidal embayment is a broad tidal flat to the north of the Project area that includes narrow tidal creeks with fringing mangroves and extensive mud flats.

Habitats recognised within the transition zone include bioturbated mud flats with samphire communities and algal mats (URS, 2010). Together with the mangrove habitat, the two mud flat habitats above are considered as Benthic Primary Producer Habitat (BPPH).

The landform mapping in proximity to the Project area is shown on **Figure 2-1**.

2.4 Stratigraphy

The Geological Survey of Western Australia (1975) produced a 1:250 000 geological map and report of the regional area around Onslow as Bulletin 133. These geological data and interpretations were substantially updated in publications by Lasky and Mory (1999) and Lasky et al (2003).

The Project area is located on the Peedamullah Shelf of the Northern Carnarvon Basin. The local superficial formations are about 25 m thick and predominantly comprise silty and sandy alluvium, with occasional sandy palaeochannel deposits, associated with the Ashburton River Delta. Underlying the superficial formations is Tertiary limestone and sandstone (Trealla Limestone), with a variable thickness (maximum about 60 m). Beneath the Trealla Limestone is a thick Early-Cretaceous succession of the Winning Group that includes the Gearle Siltstone, Windalia Radiolarite, Muderong Shale, Mardie Greensand and Birdrong Sandstone.

The shallow stratigraphy beneath the Project area is summarised in **Table 2-2** and described below. The presented data are predominantly informed by a drilling programme undertaken in 2012 that characterises the lithology beneath Quick Mud Creek (Golder Associates, May 2012).

Table 2-2 Stratigraphy beneath Quick Mud Creek

Lithology	Broad Characteristics	Stratigraphic Unit
Quaternary and Recent		
Dune Sands	Sands and gravels with interbedded clayey strata	Dune Sands
Ashburton Red Beds (Soils)	Alluvium and Colluvium: Sandy clay to clayey sand. Sand to sand with some clay.	Ashburton River Delta Alluvium
Ashburton Red Beds (Weak Rock)	Claystone/sands/siltstone	Ashburton River Delta Clay and Unconformity
Tertiary		
Carbonate Rocks	Carbonate rocks typically with a weathered zone towards the top of the unit	Trealla Limestone

2.5 Stream Flow

The two predominant watercourses associated with the Project area are Quick Mud Creek and the Ashburton River. The Ashburton River does not traverse the Project area, but episodic flood events tend to propagate throughout the deltaic setting, including inundation of Quick Mud Creek. Stream flow occurrences in both watercourses are discussed below.

2.5.1 Quick Mud Creek

Local reaches of Quick Mud Creek stretch between Wheatstone Road and the crystalliser ponds of Onslow Salt Pty Ltd (URS, November 2012). The local reaches are approximately 5.5 km in length and characterised by a low-flow channel that is about 70 to 80 m in width.

Wheatstone Road traverses the creek. This traverse at present incorporates culverts to transmit the majority of stream flow events and a floodway for the rarer flow occurrences. It is understood that the road crossing is planned to be upgraded with a bridge in the near future. The hydraulic structures would not impact the flow regime of Quick Mud Creek (URS, December 2010).

Stream flow in Quick Mud Creek is ephemeral; flow commonly occurs after localised and or regional rainfall events. There are commonly long periods of no flow and short, episodic events of comparatively high flow. When in flow, discharge occurs onto the supratidal saline flats and ultimately to the sea.

Episodic rainfall recharge events are interpreted to promote local groundwater discharge into the low-flow channel of Quick Mud Creek. This discharge temporarily sustains pools that form within depressions on the bed of the watercourse (URS, pers. obs.).

2.5.2 Ashburton River

Historical evidence (URS, December 2010) indicates that flood events occur in the Ashburton River Delta when the main channel reaches full capacity. The extents and fate of the flood flows are variable depending on the peak flows in the river channel, the catchment areas contributing to the stream flows and the duration of the flood. Flooding from the Ashburton River may inundate Quick Mud Creek. A regional MIKE FLOOD HD hydrodynamic model (URS, December 2010) showed that all Ashburton River stream flow events less frequent than a 5-year ARI distribute flood waters to the lower reaches of Quick Mud Creek north of Wheatstone Road. Further, the predicted rates of flow enable discharge of Quick Mud Creek to the sea. The outcomes of predictive simulations include:

- The 1-year ARI event does not reach Quick Mud Creek. The main channel of the Ashburton River contains the majority of the flow with limited spill onto the adjoining flood plain.
- The 2-year ARI flood event reaches Quick Mud Creek. The total flow volume is estimated to be 28.7 GL over the flood duration. Quick Mud Creek discharges to the sea.

2.6 Shallow Aquifer Systems

The interpreted shallow aquifer systems beneath the Project area are based on the local lithological profiles intersected during the earlier site investigations (URS, May 2010 and Golder Associates, May 2012) and summarised in **Table 2-3**.

Table 2-3 Interpreted shallow aquifer systems

Aquifer Zone	Aquifer Description		Typical Thickness (m)
	Storage Characteristics	Broad Lithology	
Quaternary/Recent Superficial Formations			
Dune Sands	Unconfined	Sands and Sandstones	10
Ashburton River Delta Alluvium	Unconfined/Semi-Confined	Silty and Sandy Clays	20
Ashburton River Delta Clay and Unconformity	Semi-Confined	Clay and Claystone	5
Tertiary Successions - Carnarvon Basin			
Trealla Limestone	Semi-Confined	Limestone	30

Beneath the Project area, the water table occurs in alluvial successions formed by the superficial formations that are comprised of Dune Sands, Ashburton River Delta Alluvium and Ashburton River Delta Clay. The local superficial formations are about 25 to 30 m in thickness and comprise subordinate dune sands overlying predominantly silty and sandy alluvium. Interspersed within the alluvium are occasional sandy palaeochannel deposits.

2 Background

Locally, the Trealla Limestone is intersected at 25 m and has a thickness from 26 to 60 m (as measured in MDW4 and Jade 1). The local succession consists of three lithological units:

- Upper interbedded soft, puggy claystone and calcilutite and subordinate calcarenite beds.
- A middle hard and brittle calcilutite and variably dolomitic calcarenite bed.
- Lower interbedded soft, sticky claystone, unconsolidated sand and limestone.

The calcilutite and calcarenite beds and lenses may form a fractured rock aquifer. In the Lower Cane River area, yields of up to 300 kL/day have been reported where the limestone is fractured, but most yields are less than 100 kL/day (Skidmore, 1996).

Baseline conditions indicate a shallow water table with brackish, saline to hypersaline groundwater environments. The direction of the local shallow groundwater flow is influenced by the topography. The interpreted water table elevations peak beneath the dunes, with flow lines perpendicular to the dune crests towards lowlands formed by Quick Mud Creek and further north the supratidal, samphire and tidal flats of the Hooley Creek – Four Mile Creek tidal embayment. Groundwater flow is a reflection of the surface water catchments, with the dune systems hosting catchment divides.

In the deeper profiles of the Ashburton River Delta Alluvium and Trealla Limestone, the influence of the local topography is also evident but masked by regional influences and density effects.

Environmental heads indicate vertically upward flow potentials that reflect groundwater discharge from the underlying regional Carnarvon Basin successions into the water table zone. This aspect may reflect that the Project area is predominantly a regional groundwater discharge zone.

Transient records of groundwater level fluctuations show a recharge response to the significant rainfall. For example the amplitude of observed fluctuations includes:

- Beneath the longitudinal dunes landform, the range 0.16 and 0.23 m.
- Beneath the local alluvial/colluvial plains landform, the range 0.20 and 0.25 m.

The Trealla Limestone and Ashburton River Delta Alluvium show similar responses as the alluvial/colluvial plains. **Table 2-4** shows comparative interpretation of typical amplitudes of water table rise due to infiltration of rainfall for a suite of ARI events. Note that there are no data for events with a frequency less than a 5-year ARI.

These interpretations show that even the high frequency small-scale rainfall events provide a recharge response, albeit small in amplitude. Extrapolation of the relationships developed in **Table 2-4** provides indications that a 10-year ARI rainfall event would produce typical rises in the water table of:

- Fringing and coastal dunes – 0.62 m.
- Longitudinal dunes, Ashburton River Delta Alluvium and Trealla Limestone – 0.41 m.

The comparative characteristics of the interpreted water table rises reinforce the controls that the ground surface elevation imposes on the both the water table elevation and amplitudes of water table rise due to rainfall recharge. Further, the similarities of the fluctuations through the superficial formations and Trealla Limestone may reflect the unconfined or semi-confined characteristics of the shallow groundwater deltaic and Tertiary successions.

2 Background

Table 2-4 Typical amplitudes of water table rise following rainfall events

Rainfall event ARI	Interpreted typical amplitude of water table rise (m)			
	Dune Sands		Ashburton River delta alluvium	Trealla limestone
	Fringing and coastal dunes	Longitudinal dunes		
< 1 year	0.10	0.04	0.05 - 0.07	0.04
< 2 year	0.31	0.09	0.12	0.10
< 5 year	0.44	0.20	0.23	0.20

The groundwater salinity and quality is widely varied beneath the Project area and particularly within the sand dunes terrain, with strong contrast both laterally and vertically. In the shallow groundwater environment the measured baseline salinity varies across a range from about 90,000 to 260,000 mg/L Total Dissolved Solids (TDS). A number of samples are characterised by metals concentrations that naturally exceed the ANZECC guideline values and or had high and varied Total Suspended Sediment (TSS) concentrations that provided a variable influence on measured groundwater qualities.

Site Investigations

A number of surface water and groundwater site investigations have been carried out in the vicinity of the Project area. These investigations include:

- Surface Water:
  - Gauges Sites - Flow and Quality.
  - Opportunistic Sampling.
- Groundwater:
  - Geotechnical Drilling at Quick Mud Creek.
  - Birdrong Sandstone Production Bore.
  - Monitoring Bores.
  - Aquifer Tests.
  - Monitoring Programme.

The discrete site investigations are discussed below. A location map comprising all site investigations and associated boreholes is presented on **Figure 3-1**.

3.1 Surface Water Investigations

The monitoring of the surface water baseline commenced in 2009. The episodic nature of the stream flow events contributes to difficulties in the capture of representative surface water samples. Flow gauges have been installed to measure baseline flow and quality. Opportunistic surface water samples have also been collected when practical. **Figure 3-2** shows the locations of the surface water monitoring sites. The monitoring has a quarterly frequency.

3.1.1 Gauged Sites – Flow and Quality

Gauging stations have been situated at selected locations within terrestrial watercourses and settings inundated by high astronomical tides. The gauging stations measure depth of surface water, Electrical Conductivity (EC) and turbidity (URS, 2013). The gauges in proximity to the Project area include FG4 and NFG5. These gauges are located in terrestrial settings on Quick Mud Creek where traversed by Wheatstone Road and downstream of where Quick Mud Creek enters the Hooley Creek – Four Mile Creek tidal embayment, respectively. The FG4 site was abandoned in December 2011 during constr4action of the Wheatstone Road. The gauged data predominantly reflected local catchment responses to comparatively frequent (1 to 5-year ARI) rainfall and stream flow events.

3.1.2 Opportunistic Sampling

Numerous opportunistic samples have been collected within the Project area, from pools on Quick Mud Creek and within the catchment of Quick Mud Creek. The majority of samples were collected in March, April and July 2011 and in March 2013. Site locations are presented in **Table 3-1** and those recently sampled are shown on **Plate 3-1** and **Plate 3-2**.

3 Site Investigations

Table 3-1 Opportunistic Sampling Locations - Quick Mud Creek Catchment

Site	Date	TDS (mg/L)	pH	Turbidity (NTU)	Landform setting
Eastern catchment interfluve					
SW8	Mar-11				Alluvial and colluvial plains on perimeter of the upper Quick Mud Creek watercourse and interfluve to adjoining catchment to the east.
SW9	Mar-11				
SW18	Apr-11				
SW43	Jul-11				
SW44	Jul-11				
SW45	Jul-11				
SW46	Jul-11				
Upper catchment clay pans and saline flats					
SW42	Apr-11				Quick Mud Creek drainage line with nearby clay pans and alluvial and colluvial plains.
SW57	Jul-11				
SW58	Jul-11				
SW59	Jul-11				Clay pan on the Quick Mud Creek drainage line.
Low flow channel - lower reaches					
SW03	Apr-12				Supratidal salt flats, near NFG5 within the eastern estuary.
SW28	Apr-11				Saline flats. On Quick Mud Creek, within the low-flow channel and zones of surface salt.
OSW5	Mar-13				Saline flats. On Quick Mud Creek, within pools and zones of surface salt.
OSW6	Mar-13				
OSW13	Mar-13				

Plate 3-1 Sample site OSW6 on Quick Mud Creek

3 Site Investigations

Plate 3-2 Sample site OSW5 on Quick Mud Creek

3.1.3 NORM Sampling

A specific NORM sampling campaign took place in 18 March 2013 on Quick Mud Creek and nearby environs to determine the concentration of NORMs and its signature in the baseline environment (URS, September 2013) for both soils and water. The type of sampling is described in **Table 3.2** with a combination of NORM analyses, water quality and mineralogy of the bed of Quick Mud Creek. The locations for the NORM sampling sites are described below and on **Figure 3-3**:

- OSW5: the second major pool setting, 1.8 km downstream of Wheatstone Road, within the low-flow channel of Quick Mud Creek. The size of the pool (Plate 3-2) varies depending on local climatic influences.
- Soil Samples in the vicinity of Wheatstone Road, referred as OSW7 and OSW8 on **Figure 3-3**.

Table 3-2 Surface water and salt sampling in Quick Mud Creek

Site	MGA50 Easting	MGA50 Northing	NORMs (liquids)	NORMs (solids)	ALS Suite (limited)	Mineralogy
OSW5	300,856	7591632	X	X	X	
OSW6	300,745	7,591,024			X	
OSW7	301,401	7,590,194		X		X
OSW8	301,365	7,590,223			X	

3.2 Groundwater Investigations

3.2.1 Geotechnical Drilling at Quick Mud Creek

A geotechnical investigation was undertaken to support the engineering design for the bridge structure on the Wheatstone Road at Quick Mud Creek (Golder Associates, 2012). The drilling programme consisted of seven geotechnical boreholes and two potential acid sulphate soil (PASS) boreholes. Lithology and groundwater conditions beneath the local reaches of Quick Mud Creek were interpreted from the borehole data as shown in **Table 3-3** and on cross-section on **Figure 3-4**.

Table 3-3 Geology beneath Quick Mud Creek

Formation[1]	Age	Lithology
Unit 1	Recent	Sand, silty sand and clayey sand.
Unit 2[2]	Recent	Recent marine and alluvial origin, clay, silty clay, clayey silt and silty sand.
Unit 3	Tertiary - Quaternary	Sandy clay, clayey sand, which transitions to a higher strength with depth to material consisting of claystone and sandstone.
Unit 4	Tertiary	Trealla Limestone members of the Cape Range Formation. High carbonate content (calcite and dolomite).

Notes:
1 Golder Associates, 2012.
2 Unit 2 comprising soft silt and clay deposited in an intertidal and supratidal environment is absent beneath Quick Mud Creek.

3.2.2 Birdrong Sandstone Production Bore

The Birdrong Sandstone is a regional confined aquifer in the Carnarvon Basin and is intersected by both artesian and sub-artesian water supply bores. Historically, it has been used to supply brackish (1,000 to 12,000 mg/L TDS) groundwater to pastoral and salt industries (URS, 2010a).

In 2011, BHP Billiton Petroleum Pty Ltd (BHP Billiton) constructed production bore MDW4 for groundwater supply associated with the Macedon Project. MDW4 was drilled to a depth of 401 m and screened between 360 to 390 m (Golder Associates, 2011). The interpreted stratigraphic succession intersected in MDW4 is provided in **Table 3-4**. The Birdrong Aquifer was interpreted to have a 7 m thickness.

Table 3-4 Geological Successions, MDW4

Formation	Age	Lithology	Depth (m)
Superficial	Recent	Clayey sand, gravelly clay, clayey gravel alluvium	0 - 33
Trealla Limestone	Tertiary	Limestone	33 – 59
Upper Gearle Siltstone Lower Gearle Siltstone Windalia Radiolarite Muderong Shale	Cretaceous	Siltstone and claystone	59 - 357
Mardie Greensand	Cretaceous	Sand/interpreted sandstone	357 – 365
Basal claystone unit	Cretaceous	Claystone	365 - 368
Birdrong Sandstone	Cretaceous	Sand/interpreted sandstone	368 - 375
Unconformity		High gamma clayey material	375 - 380
Mungaroo Formation	Triassic	Interbedded sandstone, shale and claystone	380 - 401

Notes:
Referenced from Golder Associates, 2011.

3.2.3 Monitoring Bores

An environmental drilling programme was undertaken between March 2009 and June 2010 (URS, 2010b). A total of 82 monitoring bores, 34 Drive Point Piezometers (DPP) and one production bore were constructed. This programme was focussed at sites located approximately 10 km north-east of the Project area, though included E052FG-S and E052FG-D which are located about 1.1 km west of Quick Mud Creek. About 3 km further to the west, thus in reasonable proximity to the Project area, are E048FG-S, E048FG-I, E049FG-S, E049FG-I, E050FG-S, E050FG-I, E051FG-S, E051FG-I, E051FG-D, E052FG-S and E052FG-D. Of these, however, E048FG-S, E048FG-I, E050FG-S and E050FG-I have been decommissioned.

Monitoring bores E052FG-S and E052FG-D are located on the floodplain of Quick Mud Creek and representative of the underlying groundwater environment associated with the Ashburton River Delta Alluvium, which forms the water table aquifer, and the Trealla Limestone. The monitoring intervals include:

- E052FG-S: 5 m deep and screened the Superficial Aquifer.
- E052FG-D: 36 m deep and screened in the Trealla Limestone.

3.2.4 Aquifer Tests

A summary of aquifer tests conducted in the vicinity of the Project area at Ashburton North and, further afield associated with the Cane and Robe rivers, is provided in **Table 3-5**.

3.2.4.1 Ashburton North

The aquifer testing at Ashburton North has included:

- Step-rare and constant-rate pumping in EO22.
- Short-term pumping and slug tests in monitoring bores and DPP.
- A constant-rate test in BH504a.

A step-drawdown test was conducted at E022 on the Ashburton North site (URS, 2010b). Using the Bierschenk and Wilson method, the well efficiency at E022 was determined to be 80, 84 and 90 per cent at pumping rates of 108, 69 and 35 kL/day, respectively. A 48-hour constant-rate pumping test was also conducted in E022 in September 2009 (URS, 2010b). The aquifer thickness of the dune sands units was interpreted to be 4 m. Short-term pump testing was also conducted in all monitoring bores. Slug testing was conducted in all monitoring bores and DPP, with the exception of shallow and fauna bores.

A 24-hour constant rate pumping test was conducted in pumping well BH504a (Coffey Geotechnics, 2010). The lithology of the aquifer indicated an alternating sequence of fine to coarse sand and clay/silt layers of beach and aeolian deposits. Interpreted hydraulic conductivity for the tested interval was 3 to 4 m/day.

3.2.4.2 Cane River

The Cane River Borefield is located approximately 30 km east of Onslow within alluvial Superficial Aquifer successions and underlying Trealla Limestone. Airlift yields determined during drilling in 1988 ranged between trace and 170 kL/day. The saturated profile is cemented and bore yields were interpreted to be derived from partings in the bedding planes and fractures and joints within the alluvium and underlying limestone (Martin 1996). The highest yielding bore was located where the upper portion of the limestone was layered (Martin 1988). Due to the lateral variations in lithology, it was determined that the yields varied over short distances.

The intersected saturated thickness of the Superficial Aquifer and Trealla Limestone ranged from 7 m to 18 m (Department of Water 2011). An estimated hydraulic conductivity of 10 m/day was determined for these successions.

3.2.4.3 Robe River

Site investigations on the floodplain of the Robe River (Skidmore, 1996) provided information of production bore yields from both alluvium and Trealla Limestone intersections. In saturated profiles that ranged from 6 to 15 m thickness, yields from the alluvium and limestone successions were estimated at 500 and 100 kL/day, respectively. Groundwater storage takes place in the pore spaces of the alluvial sediments and in the fractures within the Trealla Limestone (Skidmore 1996). Specific yields of 0.05 (dimensionless) were estimated in alluvial aquifers where groundwater salinity was greater than 1,000 mg/L. A specific yield of 0.002 (dimensionless) was adopted for Trealla Limestone by Skidmore (1996) following interpretation of an aquifer test along the Robe River.

Table 3-5 Summary of Aquifer Tests

Site	Aquifer Type	Test Performed	Duration (mins)	Discharge Rate (kL/day)	Source
Ashburton North					
Production Bore EO22	Dune sands	Step	30 min each step	35, 69, 108	URS, 2010b
Production Bore EO22	Dune sands	Constant Rate	2,880	86.4	URS, 2010b
3 Production Bore and Observation Bores	Dune sands and Ashburton River Delta Alluvium	Constant Rate	1,440	432	Coffey Geotechnics, 2010
79 Monitoring bores	Dune sands, Ashburton River Delta Alluvium, Unconformity and Trealla Limestone	Constant Rate	6 – 246	4.3 – 8.6	URS, 2010b
38 Monitoring bores	Ashburton River Delta Alluvium, Unconformity and Trealla Limestone	Slug	<10	10 – 15 L	URS, 2010b
19 DPP	Dune sands and Ashburton River Delta Alluvium	Slug	<10	10 – 15 L	URS, 2010b
Ashburton River Alluvial Aquifer					
9 Production bores	Ashburton River and Trealla Limestone	Airlift	-	-	Yesertener and Prangley 1997
Cane River					
3 Production bores	Alluvium and Trealla Limestone	Yield Testing	480	440[1]	Martin, 1988
Robe River					
1 Production Bore	Alluvium and Trealla Limestone	Airlift	-	-	Skidmore, 1996

Notes:
1 Combined yield of three bores.

3.2.5 Sampling of NORMs

NORM sampling of local groundwater took place in 18 March 2013. The location for the sampling was Monitoring bore E052FG-S. The bore is 5 m deep and screened in the Dune Sand Aquifer of the superficial formations. The intersected lithology varies from silty sandy clay, sand, clayey silty sand, clayey sand and finally silty clayey sand.

The sampling is described in **Table 3.6** and the location of E052FG-S shown on **Figure 3-3.**

Table 3-6 Groundwater sampling of NORMs

Site	MGA50 Easting	MGA50 Northing	NORMs (liquids)	NORMs (solids)	ALS Suite (limited)	Mineralogy
E052FG-S	300,321	7,590,244	X		X	

3.2.6 Monitoring Programme

The baseline characteristics of the groundwater flow environments within the Project area have been determined by interpreting monitoring bore and DPP groundwater level and quality data collected since 2009 and translation of these findings to the Project area.

Monitoring of groundwater levels and salinity in local monitoring bores E052FG-S and E052FG-D was undertaken from October 2011.

Baseline Quick Mud Creek Environment

4.1 Catchment Setting

The watersheds for Quick Mud Creek include:

- The catchment area of the immediate flood plain for the 5.5 km reach north of Wheatstone Road is 20 km2.
- The localised upstream catchment covers an area of 52 km2 south Wheatstone Road.
- The regional catchment covers an area of 1,811 km2 extending to Gum Creek 73 km south of Wheatstone Road and draining the eastern floodplain of the Ashburton River.

The low-flow channel is oriented northwards, towards the Onslow Salt crystalliser pond bunds. The flow path follows a low-lying floodplain and then discharge into the supratidal saline flats that form the upper portions of the Hooley Creek – Four Mile Creek tidal embayment. Stream flow in Quick Mud Creek is ephemeral. There are commonly long periods of no flow and short, episodic events of very high flow. Discharge from the creek to the lower supratidal and tidal estuary of the Hooley, Middle and Four-Mile creeks occurs episodically after localised or regional rainfall events that will have different intensity-frequency-duration characteristics.

The Project area setting of Quick Mud Creek why dry is shown on **Figure 4-1**.

4.2 Stream Flow

4.2.1 Episodic Flow Frequency

An existing numerical MIKE FLOOD HD hydrodynamic model and XP-Rafts run-off model (URS, December 2010) have been used to determine the design storm thresholds from which stream flow in Quick Mud Creek would discharge to the Hooley Creek – Four Mile Creek tidal embayment. The model domain includes 190 km^2 of the Ashburton River Delta between the mouth of the Ashburton River and Onslow Road. A range of simulations have been undertaken to determine the hypothetical stream flow events that would discharge from Quick Mud Creek. All of the hypothetical events are based design rainfall for a 24-hour duration storm. The outcomes of the simulations are summarised in **Table 4-1** and footprints of the respective discharges are shown on **Figure 4-2**.

Table 4-1 Characteristics of discharge events in Quick Mud Creek

Stream Flow (m^3/s over 24 hours)	24-Hour Flow Volume (ML)	ARI (years)	Flood Footprint[1] (km^2)	Fate of the Discharge
1	86	1	0.98	Flow does not propagate from Quick Mud Creek. No Discharge
2	172	2	3.7	Flow propagates downstream to supratidal flats. Discharge to Supratidal Flats
5	432	3	12.34	Flow propagates downstream and reaches the sea through Western Hooley Creek. Discharge to Sea
10	864	5	18.64	

4 Baseline Quick Mud Creek Environment

4.2.1 Influence of Ashburton River

A regional MIKE FLOOD HD hydrodynamic model developed in 2010 (URS, December 2010) has been used to determine the minimum ARI threshold event for which the flood flows from the Ashburton River would reach Quick Mud Creek and ultimately the sea. Simulations were completed using 1-year and 2-year ARI flood events at the Nanutarra Bridge, which correspond to peak flows of 312 and 851 m^3/s respectively (URS, December 2010). Initially, the calibrated model was referenced to a flood event in May 1992. This flood from 8 May to 31 May in 1992 is defined as the lowest observed 2-year ARI flood event recorded. The observed peak flow was about 747 m^3/s and flood duration 23 days. This reference provided reasonable confidence for the application of the model to 1- and 2-year ARI events.

The regional hydrodynamic model was subsequently applied to predict peak flow rates and discharge from Quick Mud Creek for selected 1-, 2-, 5- and 10-year ARI events. The predicted Ashburton River and Quick Mud Creek peak flow rates are summarised in **Table 4-2**. Flood footprints for the 1- and 2-year ARI events are shown on **Figure 4-3**.

Table 4-2 Predicted peak discharge rates for Quick Mud Creek

Annual Recurrence Interval (Years)	Ashburton River Designed Peak Flows (m^3/s)	Quick Mud Creek Peak Discharge Flow Rates (m^3/s)
1	312	0
2	851	86
5	2,288	410
10	3,816	773

4.2.2 Quality from Residual Pools on Quick Mud Creek

Pools of hypersaline water are common on Quick Mud Creek. The occurrence of the pools is maintained by run-off and the discharge of groundwater after rainfall recharge events. These aspects indicate that the pools represent the water table. During periods of increased water availability the pools are sustained; conversely the pols would dry after extended period of limited rainfall.

Pools have been observed during site visits since 2010. The pools are generally shallow (about 0.2 m deep) and characterised by a fringe of precipitated crystalline salts. The salinity in April 2011, about 116,000 mg/L TDS, was significantly lower than the other values in the first six months of 2013. Rainfall of 438 mm from January to March 2011 may have significantly diluted the hypersaline pool with fresh water.

An overview of the opportunistic surface water sample data is provided in **Table 4-3**. This overview summarised the typical range of salinity and turbidity of the discretised sub-catchment areas, with definition also of outliers to the typical ranges. Evidently, the opportunistic samples provide a wide range of salinity and turbidity qualities, irrespective of landform and setting within the broader catchment. Notwithstanding, there is evidence of contrast between the typical surface water qualities sampled from upper catchment areas compared with samples collected on saline flats and tidal reaches of the respective catchments.

4 Baseline Quick Mud Creek Environment

Table 4-3 Overview of opportunistic surface water qualities

Sub-catchment setting	Number of samples	Salinity (mg/L, TDS)		Turbidity	
		Typical range	Outliers	Typical range	Outliers
Eastern catchment interfluve	7	46 - 838	69.600	18.6 – 1,780	2,300
Upper catchment clay pans and saline flats	4	77,000 – 97,000	148,000	273 – 2,760	24,400
Low flow channel - lower reaches	2	72,900 – 116,000	-	3.4 - 12	36

The salinity and turbidity measurements taken at these locations indicate:

- The upper areas of Quick Mud Creek are typically characterised by low salinity; the sampled surface water is commonly fresh, with TDS concentrations less than 1,000 mg/L.
- In the upper watersheds of the Quick Mud Creek there are also clay pans and saline flats wherein the surface water accumulates salt. In these settings, the salinity is hypersaline, ranging up to 145,000 mg/L TDS. The salt accumulation may be attributed to dissolution of residual salt and the concentration effects due to evaporation.
- There is a propensity for salt accumulation in the lower catchment areas above the normal tidal range that includes saline flats, samphire flats, supratidal flats and clay pan landforms. The surface water is saline to hypersaline, in the range 40,000 to 140,000 mg/L TDS.
- On Quick Mud Creek, the saline flats are characterised by salinity ranging up to 380 g/L TDS. The salt accumulation may be attributed to dissolution of residual salt and the concentration effects due to evaporation.
- Quick Mud Creek forms a comparatively turbid setting.

There is an expectation of episodic and transient changes in the salinity and turbidity of attenuated surface water pools depending on water availability, pool depths, rainfall, wind action and wave action. There may be significant transient variations within discrete pools and from one pool to another. Infiltration within the higher catchment areas may limit the salt accumulation.

4.2.3 NORM

NORM sampling for radium (Ra) was undertaken during is provided in **Table 4-4**. The details for the NORM results are provided in Appendix A.

Radium (Ra) species were below detection limit in the hypersaline pool on Quick Mud Creek. The total Alpha and Beta particles were also below detection limits. The salt crust and the soil sampled at 0.3 meters below ground level have radium concentrations below detection limits.

Radium-228 was found in the soil samples near Wheatstone Road with concentrations ranging from 31 to 45 mBq/g. The concentrations are just above the detection limits. They likely represent the natural background concentration of Ra-228.

4 Baseline Quick Mud Creek Environment

Table 4-4 Baseline Radium Activities in Surface Water and Salt

Sample Form	Sample ID	Sample Depth	Environment	Ra-226	Ra-228	Ra-226	Ra-228
				mBq/L		mBq/g	
Water	OSW5-S	Pool	Hyper-Saline Pool	<LOR[1]	<LOR		
Solid	OSW5-solid	0.3 m	Hyper-Saline Pool			<LOR	<LOR
	OSW5-salt crust	0.05 m	Hyper-Saline Pool			<LOR	<LOR
	OSW7-solid	0.3 m	Creek Bed			<LOR	31.6 ± 4.5
	OSW8-solid	0.3 m	Creek Bed			<LOR	45.2 ± 5.7

Notes:
[1]The analysis is using the Gamma Spectrometry. LOR refers to Limit of Reporting.

4.3 Shallow Groundwater Environments

4.3.1 Hydrostratigraphy

The shallow stratigraphy beneath Quick Mud Creek is defined by groundwater exploration drilling at E052FG-D (URS, 2010b), drilling to the Birdrong Sandstone at MDW4 (Golder Associates, 2011) and geotechnical investigations (Golder Associates, 2012). The typical profile includes:

- Dune sands with 15 m thickness.
- Clayey sand with 6 m thickness.
- Gravelly sand/ sand gravel with 5 to 10 m thickness.
- Claystone and clay with 5 to 10 m thickness.
- Trealla Limestone with 20 to 35 m typical thickness. This succession may in part form a fractured rock aquifer wherein the predominant flow paths are fractures and or vuggy textures within calcilutite and calcarenite beds rather than intergranular features.

The interpreted hydrostratigraphy to shallow depths beneath Quick Mud Creek and surrounds is shown on **Figure 4-4**.

4.3.2 Water Table Settings

An interpretation of the measured shallow groundwater levels demonstrated that there is topographic control on the water table elevation (URS, 2010a). These interpretations indicated that groundwater flow is a reflection of the surface water catchments, with the dune systems (Dune Sands) hosting catchment divides. In the deeper profiles of the Ashburton River Delta Alluvium and Trealla Limestone, the influence of the local topography remains evident but subdued and increasingly masked by regional influences and density effects with increased depth below the water table.

The interpreted local water table elevations occur in the range of 0.5 to 3.0 m AHD (**Figure 4-5**). Groundwater levels are highest associated with the dunes terrain as shown on **Figure 4-5** and on the cross-section on **Figure 4-6**. The interpreted elevation range reflects the transition from longitudinal dunes to alluvial/colluvial plains and then incision by Quick Mud Creek in the lower landscape. Flow lines propagate perpendicularly from the dune crests towards lowlands form the local reaches of Quick Mud Creek.

On a broader scale, the water table elevation rises in synchronisation with rises in the ground surface elevations. The highest observed water table elevations (2.3 m AHD) occur beneath the Camp Area.

Groundwater levels typically show responses to recharge from rainfall infiltration. The amplitude of the groundwater response is dependent on the amount of rainfall and depths of the monitoring bore. Comparative interpretations of typical amplitudes of water table rise due to infiltration of rainfall for a suite of ARI events in the different hydrostratigraphy units are shown in **Table 4-5**.

Table 4-5 Typical Amplitudes of Water Table Rise after Rainfall Recharge

Rainfall event ARI	Interpreted typical amplitude of water table rise (m)			
	Dune Sands		Ashburton River delta alluvium	Trealla limestone
	Fringing and coastal dunes	Longitudinal dunes		
< 5 year	0.44	0.20	0.23	0.20
< 2 year	0.31	0.09	0.12	0.10
< 1 year	0.10	0.04	0.05 - 0.07	0.04

The water table responses to recharge are episodic. The observed characteristics of the transient fluctuations of the water table reflect the influence of episodic high rainfall events and subsequent decay as recharge and water availability declines in the interim before the next high rainfall event. In the vicinity of the Project area, measured water table elevations were highest in early to mid-2009 and early to mid-2011, following significant tropical-low rainfall events and cyclonic activity in January 2009 (Cyclone Dominic) and in February 2011 (Cyclone Carlos). Subsequent to Cyclone Carlos, the water table elevations show a progressive regressive trend throughout the remainder of 2011 and during 2012. Overall, the water table elevations generally decreased by about 0.9 m from the peak in February 2011 to end-December 2012.

The shallow groundwater environment is also characterised by vertical and lateral stratification. The stratification is driven by:

- Density effects controlled by salinity contrasts. An assessment of environmental heads was undertaken in 2010 (URS, May 2010). The environmental flows are vertically upwards from the Trealla Limestone into the overlying Ashburton River Delta Alluvium successions.
- Upward flow and discharge from the regional early-Cretaceous to Tertiary semi-confined and confined aquifer systems of the Northern Carnarvon Basin. This discharge occurs through the Trealla Limestone and Ashburton River Delta Alluvium.

4.3.3 Groundwater Recharge and Discharge Zones

Recharge zones are focused beneath the dune systems and discharge zones are associated with the low-lying areas of the saline flats of Quick Mud Creek and the Hooley Creek – Four Mile Creek tidal embayment. Within the local setting, the evapotranspiration potentials and consequently discharge would be higher where the depth to the water table is shallow, such as the saline flats, compared to the elevated dune system and to a lesser extent the alluvial/colluvial plains. The interpreted depths to the water table are shown on **Figure 4-7** in context to landforms and topography.

The topography along the Quick Mud Creek varies from 0.40 to 1.0 m AHD and the local water table is marginally higher. Therefore, the low-flow channel of Quick Mud Creek and associated ephemeral pools forms a local groundwater discharge area for the water table aquifer formed locally by the Dune Sands and Ashburton River Alluvium.

4.3.4 Aquifer System Hydraulics

The interpreted aquifer properties are provided in **Table 4-6**. There is limited aquifer testing data within the Project area.

Table 4-6 Summary of Interpreted Aquifer Properties

Test	Transmissivity (m^2/day)	Interpreted Hydraulic Conductivity (m/day)		Storativity (dimensionless)	Saturated Thickness (m)	Specific Yield[1]
		Range	Median			
Dune Sands						
EO22	12 - 24	0.8 - 8	2	1×10^{-3} - 6×10^{-5}	3	-
BH504a	50 - 110	3.5 – 8.8	-	0.5 – 2.3×10^{-4}	14.36	0.12
Ashburton River Delta Alluvium						
Constant-Rate	10	0.2 - 1	0.4	6×10^{-5} – 1×10^{-3}	20	-
Slug	-	0.1 – 7	2	-	20	-
DPP Slug	-	0.01 – 0.2	0.02	-	20	-
Ashburton River Delta Clay and Unconformity						
Constant-Rate	2	0.3	-	-	5	-
Slug	-	1	-	-	5	-
Trealla Limestone						
Constant-Rate[2]	-	0.1 – 10	0.8	-	25[2]	-
Slug	-	0.01 – 7	0.4	-	25	-

Notes:
1 Dimensionless.
2 The monitoring bores do not fully penetrate the Trealla Limestone.

The tabulated parameters provide indications that:

- The aquifer zones are widely anisotropic, with interpreted hydraulic conductivity values varying across tow order of magnitude. This aspect reflects on the range of lithologies from cemented limestone, sand, silt and clay.
- The effective transmissivity of the superficial formations and Trealla Limestone may be in the range 10 to 40 m^2/day. Lower-bound values would be from 1 to 10 m^2/day. Both ranges provide an expectation of low-yield and uncertainty in the likely sustainable yields from individual drill-holes.
- If and or where the Trealla Limestone forms a fractured rock aquifer, or has karst (solution cavity) features the effective transmissivity may be comparatively high.
- There is limited data regarding aquifer storage. The interpreted specific yield of 0.12 (dimensionless) for the Dune Sands is reasonable for sands, but may be overestimation if applied to the silty and clayey successions of the Ashburton River Delta Alluvium.
- The storage characteristics of the Trealla Limestone may vary widely depending on the nature of the calcilutite and calcarenite beds and proportional contents of unconsolidated beds of limestone, sand and claystone. Where the Trealla Limestone predominantly forms a fractured rock aquifer, the expectation would be of comparatively low specific yield in the range 0.01 to 0.001 (dimensionless).

4.3.5 Groundwater Quality

4.3.5.1 Salinity

The dune terrain hosts brackish to hypersaline groundwater. Ashburton River Delta Alluvium and Trealla Limestone typically host hypersaline groundwater. Measured shallow groundwater TDS concentrations in the vicinity of the Project area and surrounds (including the LNG plant pad) range from 3,000 mg/L (E025FG-I) to 277,000 mg/L (E052FG-D), typically being higher in the Trealla Limestone. The measured TDS distributions show vertical salinity stratification. In intervals below 30 m depth, the Trealla Limestone contains hypersaline groundwater (typically 100,000 mg/L to greater than 200,000 mg/L TDS). Within shallower depth settings, the groundwater salinity gradually decreases (typically 50,000 to 150,000 mg/L in the Ashburton River Delta Alluvium and 20,000 to 120,000 mg/L in the Dune Sands.

TDS concentrations measured within the shallow groundwater in close proximity to Quick Mud Creek are within the ranges outlined above. E052FG-S is screened in Ashburton River Delta Alluvium and has a historic TDS range of 83,300 to 104,000 mg/L. E052FG-D is screened in Trealla Limestone and has a historic TDS range of 229,000 to 277,000 mg/L.

4.3.5.2 pH

The measured background groundwater pH range in the vicinity of the Project area (including the LNG plant pad) is 4.1 to 8.5 (median 7.4), varying significantly beneath a wide range of landforms. Historically, the pH ranges in E052FG-S and E052FG-D are 6.92 to 7.56 and 5.91 to 7.04, respectively, indicating the shallow groundwater is slightly acidic to near-neutral.

4.3.5.3 Major Ions

The major ion compositions reflect a sodium-chloride type groundwater which has likely undergone evaporative concentration within the depositional environment and throughflow.

4.3.5.4 *Dissolved metals*

Cadmium, chromium, copper and lead concentrations were detected above LOR in the groundwater sample taken at E052FG-D (2009). Copper concentrations were detected above LOR in the groundwater sample taken at E052FG-S (2009).

Baseline studies have identified elevated metal concentrations in both the soil and groundwater in the vicinity of the Project area. Comparison of these results against an assessment of metals along the Pilbara coastline of similar deltaic systems also reported elevated concentrations of some metals including chromium. The metal concentrations encountered are comparable suggesting that the high background levels are likely a result of the weathering of terrestrial terrains.

Table 4-7 shows the total metals concentrations and physio-chemical parameters recorded in the local groundwater from E052FG-S and E052FG-D.

Table 4-7 Groundwater and RSS Quality Data

Chemistry Parameter	Units	RSS	Trealla Limestone	Superficial Aquifer
pH		7.8	6.64	7.28
TDS	mg/L	53,662	259,000	93,100
Bicarbonate		2,186	126	143
Total Alkalinity		2,186	126	143
Sulphate		20	7,260	2,280
Chloride		30,829	114,000	40,800
Calcium		1,276	1,320	1,670
Magnesium		638	7,790	2,610
Sodium		17,856	46,000	19,800
Potassium		552	1,700	647
Manganese		0.8		
Silica		91		
Fluoride		3.9		
Total Ammonia (NH_4^+-N)		26		
Total Nitrogen		4		
Radium-226	Bq/L	10		
Radium-228		33		
Barium	mg/L	10		
Boron		15		
Bromide		111		
Cadmium			0.0023	<0.0021
Chromium			0.084	<0.021
Copper			0.107	0.054
Lead			0.029	<0.021
Nickel			<0.021	<0.021
Strontium		32		
Zinc			<0.105	<0.105
Mercury			<0.0001	<0.0001

URS

4.3.6 NORMs

An outline of the NORM sampling for radium (Ra) is provided in **Table 4-8**. The details for the NORM results are provided in **Appendix B**.

Table 4-8 Baseline Radium Activities in Groundwater

Sample ID	Sample Depth	Environment	Ra-226	Ra-228
			mBq/L	
E052FG-S	1.22 m	Shallow Aquifer	<LOR[1]	<LOR

Notes:
[1]The analysis is using the Gamma Spectrometry. LOR refers to Limit of Reporting.

Radium (Ra) species were below detection limit in the shallow groundwater from E052FG-S. The total Alpha and Beta particles were also below detection limits.

4.3.7 Conceptual Hydrogeological Model

The Project area is underlain by a shallow water table that hosts predominantly saline to hypersaline groundwater. Local exceptions occur seasonally, when the longitudinal dune terrain intercepts and transmits rainfall recharge. All shallow groundwater intercepted by the site investigations appears to be accumulating salt, thus indicating low rates of net recharge and the predominant occurrence of hypersaline groundwater discharge into the shallow sediments from the underlying Trealla Limestone.

Local groundwater flow is influenced by topography particularly beneath the longitudinal dune terrain. As such, there is lateral flow from dune crests to local watercourses, including Quick Mud Creek, driven in part by seasonal recharge. The local groundwater flow is also influenced by density effects that characterise the flow dynamics of saline and hypersaline groundwater. Environmental groundwater heads support the occurrence of water table mounding beneath the longitudinal dunes, with radial flow lines towards discharge zones on Quick Mud Creek and within the Hooley Creek – Four Mile Creek tidal embayment. The environmental groundwater heads also indicate vertical upward hydraulic gradients from the Trealla Limestone to the Ashburton River Delta Alluvium.

Outside of the local topographical influences the water table has a regional south to north gradient, enabling discharge to the ocean.

The interpreted hydraulic characteristics of the discrete hydrostratigraphy units are summarised in Table 4-9. The vertical hydraulic conductivity values are approximate and indicate potentials for hypersaline groundwater in the Trealla Limestone to discharge into the Ashburton River Delta Alluvium.

The distribution of salinity in the shallow groundwater controls the density-coupled flow dynamics and environmental heads. The salinity distributions within the longitudinal dunes, Ashburton River Delta Alluvium and Trealla Limestone show vertical stratification. The Trealla Limestone contains the highest salinity profiles and there is a progressive vertical reduction towards the water table zones. The longitudinal dunes contain brackish to saline groundwater.

4 Baseline Quick Mud Creek Environment

The shallow groundwater has no traces of radium and therefore is unlike the Birdrong Sandstone source of the RSS.

Table 4-9 Summary of Hydrostratigraphy and Aquifer Characteristics

Hydrostratigraphy	Transmissivity (m^2/day)	Hydraulic Conductivity (m/day)		Specific Storage (1/m)	Specific Yield (dimensionless)	Typical Saturated Thickness (m)
		Horizontal	Vertical[2]			
Superficial Formations[1]	10 - 40	2	0.1	0.002	0.05 – 0.12	10 - 20
Ashburton River Delta Clay and Unconformity	2	0.2	0.02	0.001	0.01	5 – 10
Trealla Limestone	15 - 20	0.6	0.06	0.00001	0.002	20 - 35

Notes:

1 The superficial formations include the longitudinal dunes and Ashburton River Delta Alluvium.

2 The vertical hydraulic conductivity is interpreted based on a 1:10 ratio compared to the horizontal hydraulic conductivity.

Injection and Abstraction Preliminary Conceptual Design

5.1 High-Level Conceptual Design Objectives

The conceptual designs consider high-level objectives for management of the RSS that provide avoidance of environmental and NORM accumulation risks. The proposed approach involves:

- Injection of the RSS, preferably into the Trealla Limestone. Preferably the injection facilities would be located on the peaks of the dunes within the Project area **(Figure 5-1),** thus in groundwater recharge zones and optimising the available storage above the baseline water table. The injected RSS volumes would progressively displace the groundwater in storage and fill the local aquifer profile from bottom to top. The injection would mound the local water table and promote increased discharge (by seepage and evaporation) along local reaches of Quick Mud Creek and other watercourses (**Figure 5-2**). Once the injection system (in a stand-alone situation) attains a steady-state, the injection volumes would be replicated by the increase in the volumes being discharged by evaporation. It is anticipated that the injection facilities would need to be decentralised to avoid situations where the mounded water table intersects the ground surface and provides direct discharge of the injected RSS to Quick Mud Creek.
- Abstraction of groundwater from the Ashburton River Delta Alluvium and Trealla Limestone, with subsequent discharge to Quick Mud Creek. The intentions of the abstraction are avoidance of seepage at the ground surface from the mounded water table, avoidance where practical of the RSS discharge to Quick Mud Creek (and other identified discharge zones) and accumulation of NORMs. This can only be achieved through location of the abstraction facilities is settings whereby:
  - The abstracted groundwater is characterised by a limited RSS signature, up to a threshold defined by NORM activities in crystalline salt that would be below an agreed guideline value. That is, the abstraction facilities intercept a portion of the groundwater flow systems invaded by and transporting the injected RSS, but this proportion is comparatively limited thus enabling control of the NORM concentrations discharged to Quick Mud Creek.
  - Interference effects between the individual injection and abstraction sources off-set the local water table mounding, thus limiting discharge of the RSS and accumulation of NORM activities within the groundwater discharge zones.

  Given the conceptual location of injection facilities on dune crests, then the groundwater abstraction facilities would be located on the lower dune slopes, above a selected flood line on Quick Mud Creek and other watercourses and, in groundwater discharge (by evaporation) zones.
- Rationalisation that there would typically be equivalent volumes of RSS injection and groundwater abstraction. There is recognition, however, that there may be circumstances where the groundwater abstraction volumes are less, due to:
  - The discharge of the abstracted groundwater onto Quick Mud Creek resulting in mounding of the water table and recirculation of a portion of the volumes that infiltrate. This circumstance would occur where the drawdown footprint from the groundwater abstraction propagates beneath reaches of Quick Mud Creek wetted by the groundwater discharge.
  - Identification that the NORM activities in discrete groundwater discharge zones would be sufficiently diluted by mixing of the RSS and groundwater in storage to be below a prescribed threshold.

5.2 Design Inputs

The conceptual design of the injection and abstraction facilities is influenced by a number of considerations. These provide controls, from both technical and practical perspectives, on what can reasonably be achieved in the Project area setting. The concept inputs include:

5 Injection and Abstraction Preliminary Conceptual Design

- The Project area, with preference that the design facilities are constrained to a comparatively small footprint that includes:
  - The 34 ha OWIUP site.
  - Local easements to Wheatstone Road.

  These constraints were proved from various simulation runs not shown in this report to impose limits on the success of the RSS and NORM management. Consequently freedom was applied in seeking solutions without these areal constraints.
- Flood footprints in Quick Mud Creek, with preference to locate all facilities above the 1:100-year ARI flood elevation. The flood extent is provided by earlier models that supported the impact assessment of Wheatstone Road and Plant on local hydrology (URS, 2010c). The model was calibrated to the footprint of a flood event in 1997 and used to support hydraulic infrastructure developments associated with the Wheatstone Project.
- An understanding that local groundwater discharge on Quick Mud Creek is predominantly linked to losses by evaporation. This assumption has been derived from site observations, which indicate salt accumulation in pools on Quick Mud Creek and presence of crystalline salt, and experience in the Pilbara environments.
- The evaporation potentials vary depending on the landform, recognising both depths to the water table and groundwater salinity; including:
  - 3.08 m associated with the dunes terrain corresponding of the potential evaporation rate for fresh water in Onslow as measured by BoM (Section 2.1). The dunes terrain is understood to form the focus of recharge from rainfall infiltration (URS, 2010a and 2013).
  - 2.07 m for the alluvial and colluvial plains and corresponding to the mid-point potential of fresh water and hypersaline water. This potential has not been supported by site measurements.
  - 1.05 m for the saline flats, including Quick Mud Creek. This is the estimated potential for hypersaline water (URS, 2012).
  - It is expected that the expected that the evaporation potentials are overestimated.
- The evaporation potentials extend beneath the ground surface, enabling discharge, albeit at comparatively low potentials, to extinction depths at 3 m below the dune and alluvial/colluvial plains landforms and 1.5 m below Quick Mud Creek. The extinction depths reflect a pint at which there is no evaporation potential; there is a linear interpolation that defined the evaporation potentials from that at the surface and the extinction depth. This crucial parameter is not supported by any field data and was recognised as a calibration variable.
- The RSS production rates that average 400 kL/day and peak at 660 kL/day. The average rate has been preferentially used, though it is understood that the conceptual design facilities would need at times to be able accommodate the peak rate.
- The salinity characteristics of the disposed RSS being 53,700 mg/L TDS.
- The NORM characteristics within the disposed RSS; with radium-226 and radium-228 at activities of 10 and 33 Bq/L, respectively.
- Commonly, injection is inefficient compared to abstraction and there is limited storage in the unsaturated zones above the shallow water table that prevails beneath the Project area. Therefore, it is expected that the injection facilities would be distributed within a broad area and there would be a higher number of injection facilities than abstraction facilities. Furthermore, it is anticipated that the contrasts in salinity between the injected RSS and the groundwater in storage would limit the injection rates. This aspect is based on experience elsewhere in the Pilbara.
- The effective transmissivity of the local superficial formations and Trealla Limestone (estimated range 10 to 40 m^2/day) is comparatively low; with associated expectation of low bore yields. It is

considered that production bore yields in excess of 100 kL/day may be uncommon unless the local Trealla Limestone is vuggy and fractured. From a practical perspective, considering the effective aquifer transmissivity, aquifer anisotropy and interference effects during pumping, a nominal production bore yield of 100 kL/day informs the conceptual design. Accordingly there would be at least four production bores required to abstract 400 kL/day, the average rate of the RSS production. The distances between the production bores would influence interference effects. A nominal minimum distance of 200 m is proposed that provides a spacing of at least twice that of the saturated profile to the base of the Trealla Limestone and sufficient to limit interference effects.

- There would be increased numbers of injection bores compared to the abstraction bores assuming the aggregate volumes of RSS injection and groundwater abstraction are the same. Nominally, there may be at least eight injection facilities, with nominal injection
- Potential each of 50 kL/day. In the absence of site investigations and field trials there are no data that support this nominal injection potential expectation.

5.3 Preliminary Conceptual Design Characteristics

The preliminary conceptual design, informed by the available information, incorporates:

- Eight injection facilities located on the northern portions of the longitudinal dune landform, north of the 34 ha OWIUP site. Each facility provides injection of the RSS into the Trealla Limestone.
- Four groundwater abstraction facilities on the western perimeter slopes of the longitudinal dune landform and east bank of Quick Mud Creek. These facilities abstract groundwater from both the Ashburton River Delta Alluvium and Trealla Limestone.

An outline of the conceptual design for the RSS injection and groundwater abstraction facilities is shown on **Figure 5-3**. Also shown is the 1:100-year ARI flood footprint for the Ashburton River Delta, including Quick Mud Creek. It is evident from the flood footprint that the Project area setting is part of a broad floodplain and that the longitudinal dunes provide the only secure locations. The dune that hosts the OWIUP site is the predominant local feature of higher relief. This aspect forms a significant control on the conceptual design locations of the injection and abstraction facilities.

5.4 Design Sensitivity

The conceptual designs are expected to be sensitive to the majority of the outlined design input parameters. This aspect is enforced by the absence of specific site investigations that closely define the baseline environment and fit the injection and abstraction themes.

The conceptual designs would substantially change if:

- The effective transmissivity of the Ashburton River Delta Alluvium and Trealla Limestone was significantly lower and higher. This aspect would influence the numbers of injection and abstraction facilities, respective distances between individual facilities and, their respective footprints in the management of the RSS volumes.
- The assumptions regarding evaporation potentials and extinction depths were to change.
- The NORMs present within the RSS were to be adsorbed and attenuated on the flow paths form the injection facilities to groundwater discharge zones.
- There was a different benchmark in regard to allowable NORM concentrations within groundwater discharge zones.

5 Injection and Abstraction Preliminary Conceptual Design

Further to these aspects, there is potential for injection rates and abstraction rates in individual facilities to decline over time due to clogging of the well screens and formations. This aspect may influence the RSS management in the long-term. Earlier geochemical modelling (URS, 2012), indicated there is potential for minerals precipitated in the screen slots and adjacent aquifer zones to reduce the injection rates. The modelling indicated, however, that significant mineral precipitation was unlikely due to the pressures and velocities at which injection of the RSS may occur. Another common cause for clogging of injection wells is the concentration of Total Suspended Solids (TSS). The absence of TSS would substantially limit the clogging of the injection wells. The clogging of the injection facilities would need to be regularly assessed during operations; it is expected that periodical re-development would provide advantages in the injection facility performances.

Groundwater Resource Modelling

The conceptual design injection and abstraction facilities have been interfaced with a groundwater flow model to characterise the potential stresses on the groundwater environment together with the transport and fate of the disposed RSS. As such, the predictive model informs the feasibility of the conceptual design injection and abstraction themes. For example, the model enables iterative refinements of the conceptual design that deliver preferred outcomes in regard to the ultimate RSS footprint on the environment.

The model has been developed with conformance to relevant guidelines and practises on a licensed software platform. These aspects are described below.

6.1 Modelling Guidelines and Classifications

The model development process has been aligned and consistent with the themes outlined within the current Australian groundwater modelling guidelines (SKM and National Centre for Groundwater Research and Training, June 2012). It is recognised that the developed model incorporates elements characterised by Class 1, Class 2 and Class 3 confidence levels. It is also assessed that the developed model predominantly fits a Class 1 confidence level classification based on the guidelines. The predominant criteria assessed to inform the Class 1 confidence classification included:

- Spatial and temporal groundwater level observations: It is recognised there are limitations in the number of monitoring bores that define the water table elevations associated with Quick Mud Creek and transient changes linked to episodic rainfall recharge and stream flow events. There is also limited data that characterise the vertical hydraulic gradients and environmental heads between the Trealla Limestone and Ashburton Alluvium. Further, the compatibility between the water table elevation and ground surface topography reflects local-scale recharge and discharge (by evaporation) influences, the potentials of which are uncertain.
- Aquifer test data that define key hydraulic and storage parameters: Aquifer tests in the Ashburton River Delta Alluvium and Trealla Limestone were constrained by distance from the Project area, low-yields, limited pumping durations and point-source characteristics. In particular, the available aquifer test data:
  - Commonly were derived from discrete monitoring standpipes, with associated perspectives that they represent point sources and thus are not representative of the effective local aquifer in the Project area.
  - Prove limited certainty in regard to the effective transmissivity of the Ashburton River Delta Alluvium and Trealla Limestone.
  - May not define the effective aquifer hydraulics.
  - Do not characterise preferred groundwater flow paths that may occur within the Trealla Limestone and Ashburton River Delta Alluvium.
  - Do not characterise the vertical hydraulic conductivity of the local aquifers.
  - Do not stress potential confining beds, formed by the Ashburton River Delta Clay and Unconformity.
- Model parameters consistent with conceptualisation: There is uncertainty in several elements of the conceptual hydrogeology that influence the model outcomes. In particular, the Trealla Limestone may have behaviours typically of a fractured rock aquifer, with preferred flow paths and limited storage, rather than a sedimentary succession. Further, there is limited data that defines vertical hydraulic conductivity throughout the profile and potentials for the Trealla Limestone to be confined and or semi-confined.

Further to these criteria, **Appendix B** provides a table that ranks the model classification in terms of selected criteria (SKM and National Centre for Groundwater Research and Training, June 2012) that include:

- Available Data: These include rainfall and evapotranspiration records, digital elevation model, representative groundwater levels and site investigations that inform aquifer hydraulics.
- Calibration: Including replication of observed and interpreted water table elevations and transient groundwater level trends that reflect episodic rainfall recharge events, replication of vertical groundwater fluxes and absence of model validation aspects.
- Predictive Simulations: Including lengths of the transient predictions in context with the data that inform the calibration time periods and the comparative magnitude of potential stressors in relation to baseline fluctuations.
- Key Indicators: Referring to calibration statistics, accuracy of the predictive simulations and the model review processes.

Overall, the Class 1 classification reflects that the model is derived from a limited data set of relevant site investigations. It is also recognised at a local scale that there are several elements of the Ashburton River Delta Alluvium and Trealla Limestone successions that are not closely mapped. These elements influence the transition from recharge to discharge zones. Further, the modelling has not included validation simulations. There is an absence of relevant data that would support validation of the model.

6.2 Model Objectives and Methodology

The developed groundwater flow and non-reactive solute transport model is intended to provide reasonable and practical representation of the conceptual hydrogeology model, the potential footprint of the injected RSS, and associated changes that may occur to the existing groundwater environment. There are a number of assumptions and uncertainties in regard to the form and parameterisation of the model.

The objectives for the modelling include:

- Representation of the local shallow stratigraphy and aquifer systems, with particular focus on the available storage above the water table and providing reasonable representation of groundwater discharge through evaporation.
- Reasonable calibration in steady-state and transient simulations that reflects the interpreted water table elevations and flow lines to Quick Mud Creek, controlled by the local topography, and groundwater discharge along Quick Mud Creek.
- Optimisation of the injection and abstraction concept by iterative process to provide outcomes of acceptable impacts related to storage and fate of the injected RSS.
- Simulation of the lateral and vertical footprints and the fate of the RSS for a Base-Case injection and abstraction scenario. The Base-Case scenario would represent a reasonable approach to the RSS management based on the conceptual understanding of the Project area hydrogeology. This scenario would provide for limited interferences between the injection and pumping bores to deliver an outcome that provides lower-bound accumulation of NORMs within the groundwater discharge zones of the Project area. Prediction of the transient NORM distributions and concentrations in the receiving aquifers for the Base-Case scenario.
- Sensitivity analysis on the aquifer properties and conceptual model to provide lower-bound and upper-bound scenarios for the RSS management.

The methodology for the modelling comprises:

- Establishment of a model layer form compatible with the interpreted distributions of the Ashburton River Delta Alluvium (inclusive of the Dune Sands), Ashburton River Delta Clay and Unconformity and Trealla Limestone.
- Achievement of steady-state and transient model calibration to the interpreted baseline water table environment. The calibration would be informed by fluxes that control rainfall recharge and groundwater discharge by evaporation.
- Running of iterative injection and abstraction conceptual design scenarios to minimise the footprints and potential environmental impacts of the disposed RSS.
- Use of particle-tracking and non-reactive solute transport simulations to inform the optimisation of the injection and abstraction conceptual designs. These simulations would characterise the RSS solute transport in the groundwater environment, with associated estimates of the dilution and dispersion of the RSS.

6.3 Model Development

6.3.1 Software Platform

The 3-D groundwater flow model was constructed using Visual MODFLOW Version 2000. Visual MODFLOW is a 3D block-centred finite difference code developed by the United States Geological Survey to simulate groundwater flow and is an industrial standard model. The solute transport model was constructed using the MT3DMS interface.

6.3.2 Domain

The model domain incorporates the entire Project area together with the intermediate surroundings within an area of 235 km^2 (**Figure 6-1**). The model boundaries with respect to the OWIUP site are located:

- 8 km south.
- 7.5 km north.

The model incorporates a finite difference grid comprising of 231 rows and 374 columns. The grid imposes a maximum 71 x 163 m cell dimensions over the domain; the grid is refined to 20 m x 20 m cell dimensions within the Project area. The coordinates (in GDA 94, zone 50) of the model corners are shown in **Table 6-1**.

Table 6-1 Model Domain

Easting (m E)	Northing (m N)
294,700	7,598,383
294,700	7,582,116
309,128	7,598,383
309,128	7,582,116

6.3.3 Model Form

The groundwater flow model has been developed with compatibility to the interpreted hydrostratigraphy and conceptual hydrogeological model. The top of the model represents the natural ground surface, interpolated from a 5 m raster dataset. Hydrostratigraphy units are represented in the numerical model as discrete layers.

The model consists of three layers, each representative of a hydrostratigraphy unit. The layer thickness is variable to reflect the influence of topography and the contact with the Gearle Siltstone that underlies the Trealla Limestone:

- Layer 1- Dune sands and Ashburton River Delta Alluvium, with a range in saturated thickness from 10 to 22 m.
- Layer 2 - Ashburton River Delta Clay and Unconformity, with thickness of 5 to 10 m.
- Layer 3 - Trealla Limestone, with thickness commonly of 25 to 35 m.

The bottom elevation of the model follows the interpreted Gearle Siltstone contact, interpreted to locally occur at elevations in the range -30 to -50 m AHD.

Table 6-2 summarises the model layer form.

Table 6-2 Model Layer Form

Layer	Hydrostratigraphy	Typical Thickness (m)
1	Superficial Formations: Dune Sands and Ashburton River Delta Alluvium	10 - 20
2	Ashburton River Delta Clay and Unconformity	5 – 10
3	Trealla Limestone	25 - 35

6.3.4 Boundary Conditions

Boundary conditions are incorporated within several elements of the model form and setup.

The boundary conditions include:

- Constant-head nodes on the southern and northern perimeters of the model. The constant head boundaries have been used to replicate the regional baseline water table gradient from south to north.
- Recharge to the water table.
- Evaporation from the shallow groundwater.

6.3.4.1 Model constant- heads

The southern constant-head boundary in layer 1 defines an interpolated water table elevation of 4 m AHD. The model northern boundary in layer 1 defines a water table elevation of 0.8 m AHD to reflect the environment of the supratidal saline flats landform within upper reaches of the Hooley Creek – Four Mile Creek tidal embayment. The model boundaries to the east and west are approximately aligned along groundwater flow lines and have been assigned no flow boundary conditions.

The simulated constant-head boundaries assigned to Layer 1 of the model are shown on **Figure 6-2**.

6.3.4.2 Recharge domains

Recharge fluxes were used across the model domain to enable simulation of a representative water table. The Project area and surrounds was characterised by different recharge zones associated with discrete landform units, including:

- Dune sands; recharge flux based on 15 per cent of average annual rainfall.
- Alluvial/colluvial plains; recharge flux 5 per cent of average annual rainfall.
- Saline flats, including Quick Mud Creek; recharge flux based on 1 per cent of average annual rainfall.

Portions of the applied recharge fluxes, if not all for the saline flats landform, would be intercepted by the simulated evaporation potentials.

The simulated recharge domains and respective rates are shown on **Figure 6-3**.

6.3.4.3 Evaporation potentials

Groundwater discharge at the land surface and from shallow depths is removed from the model domain via evaporation. The Project area and surrounds is characterised by different evaporation zones associated with the different landform units and depths to the water table. The simulated evaporation potentials included:

- Dune sands: 3.08 m representing 100 per cent of average pan evaporation potentials (fresh to brackish groundwater) and a 3 m extinction depth.
- Alluvial/colluvial plains: 2.07 m representing about 70 per cent of average pan evaporation potentials (brackish and saline groundwater) and a 3 m extinction depth.
- Saline flats, including Quick Mud Creek: 1.05 m representing about 35 per cent of average pan evaporation (hypersaline groundwater) and a 1.5 m extinction depth.

The simulated evaporation domains overlap the recharge domains and shown on **Figure 6-3**.

6.3.5 Parameterisation

The lateral and vertical distribution of the hydrostratigraphy has been represented by using property zones with different hydraulic and storage characteristics. The parameterisation is informed by the conceptual hydrogeology. The simulated hydraulic and storage characteristics of the individual property zones are presented in **Table 6-3** and shown for each model layer in plan-view on **Figure 6-4** and in a cross-section view on **Figure 6-5**.

Table 6-3 Hydraulic and Storage Properties Assigned to Hydrostratigraphy Units

Hydrostratigraphy	Hydraulic Conductivity (m/day)		Specific Storage (1/m)	Specific Yield (dimensionless)
	Horizontal	Vertical		
Superficial Formations	1	0.1	0.002	0.03
Ashburton River Delta Clay and Unconformity	0.2	0.02	0.001	0.01
Trealla Limestone	0.6	0.06	0.00001	0.05

6.4 Model Calibration

The model calibration follows common practise in replication of the conceptual hydrogeological model and providing reasonable representation of the interpreted water table environment using water balance fluxes (rainfall recharge and discharge by evaporation) that conform to average climatic influences.

Aspects of the model calibration are discussed below.

6.4.1 Calibration Objectives

The objectives for the model calibration included:

- Broadly matching the observed, interpreted and simulated water table elevations within the model domain. The observed and interpreted water table elevations were predominantly derived recognising relationships between the water table and topography. These relationships are particularly important in the local settings of Quick Mud Creek and this aspect was the focus of the calibration.
- It was recognised that groundwater discharge by evaporation from the bed of Quick Mud Creek was likely to be significant in context to the transport and fate of the disposed RSS. Therefore this aspect of the model characteristics was integral to the calibration performance.

The calibration is based on observation and interpretation of data from November 2010.There are five monitoring bores in the model domain though the majority of these are not in the vicinity of Quick Mud Creek and consequently not closely representative of the Project area. Therefore, a suite of virtual monitoring bores (**Plate 6-1**) was established to represent the water table elevations beneath the longitudinal dunes and reaches of Quick Mud Creek within the Project area. For the virtual monitoring bores beneath the longitudinal dunes, a reasonable calibration objective was defined as simulated water table elevation being within about 1.0 m of the measured water table. In the low-flow channel setting of Quick Mud Creek, the preference was for the simulated water table elevations to be within about 0.5 m of those interpreted in the virtual monitoring bores.

In terms of model mass balance, the calibration objective was a closure error less than 1 per cent.

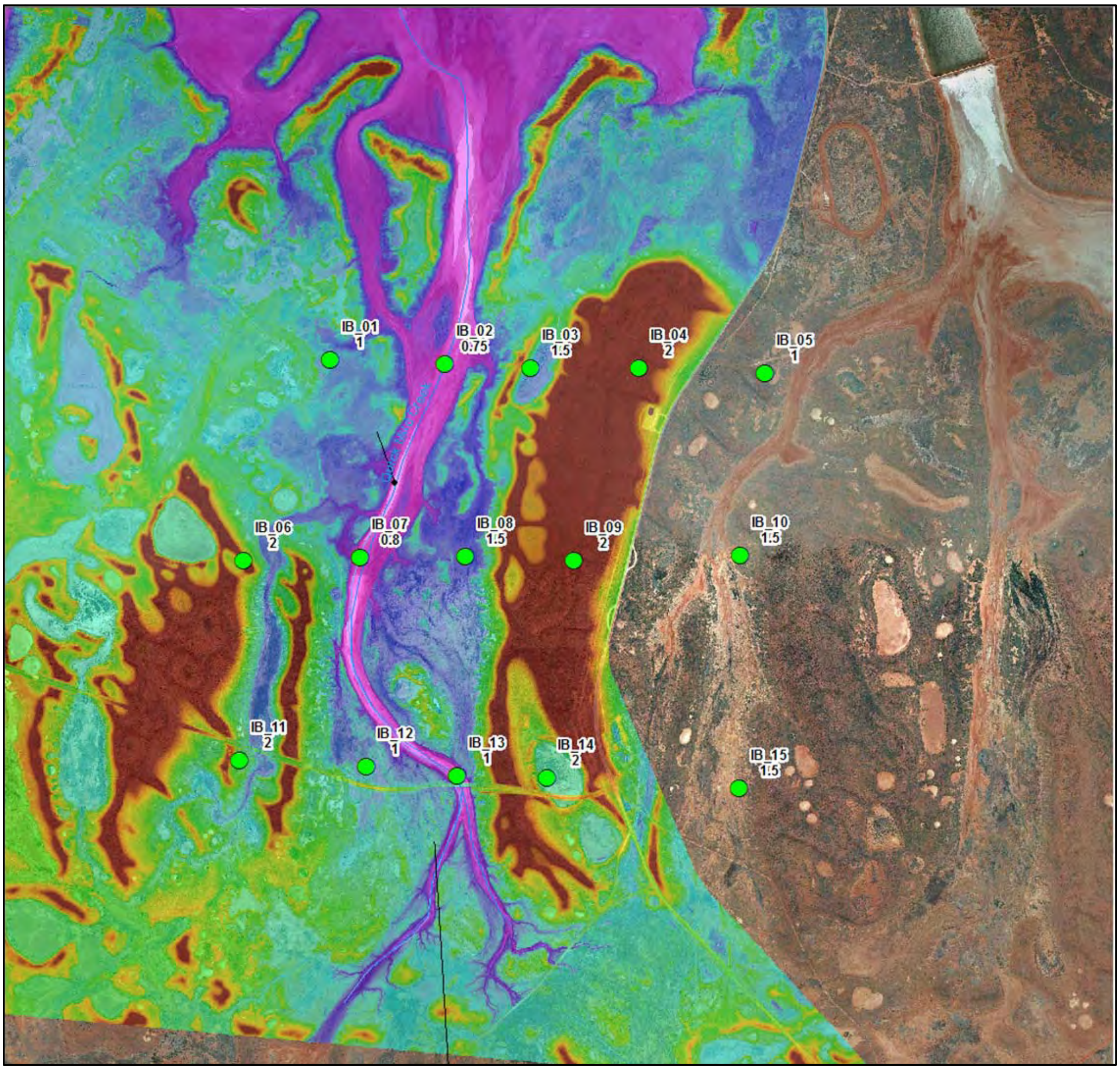

Plate 6-1 Virtual Monitoring Bores for Model Calibration

6.4.2 Calibration Water Table Setting

In steady-state (a flow condition that does not change with time) simulations, the model is calibrated to the interpreted November 2010 water table elevation. Subsequently, the model was run forward 100 years with an annual average transient water balance and time step. The calibration results indicate the developed groundwater flow model is broadly representative of the interpreted local shallow groundwater environment.

The data in **Table 6-4** shows the calibrated model comparisons to the interpreted water table elevations in the virtual monitoring bores and **Figure 6-6** shows the simulated water table, indicating lateral flow from the longitudinal dunes towards Quick Mud Creek and other low-lying areas.

Table 6-4 Calibration Characteristics for Individual Monitoring Bores

Virtual Monitoring Bore	Setting	Water Table Elevation (m AHD)		Offset Simulated and Interpreted (m)
		Interpreted November 2010	Simulated	
E052FG-S	Western Quick Mud Creek floodplain	1.57	1.37	-0.2
IB_01		1	0.18	-0.82
IB_11		2	1.58	-0.42
IB_12		1	0.88	-0.12
IB_06		2	1.03	-0.97
IB_02	Quick Mud Creek low-flow channel	0.75	-0.07	-0.82
IB_07		0.8	0.02	-0.78
IB_13		1	0.78	-0.22
IB_03	Easter Quick Mud Creek floodplain	1.5	0.49	-1.01
IB_08		1.5	0.06	-1.44
IB_04	Longitudinal Dune	2	1.05	-0.95
IB_09		2	1.16	-0.84
IB_14		2	1.27	-0.73
IB_05	Eastern Creek	1	0.6	-0.4
IB_10		1.5	1.01	-0.49
IB_15		1.5	1.48	-0.02

The annual average transient water balance does not enable the simulation of episodic and seasonal climatic aspects that cause fluctuation in the water table elevation.

6.4.3 Calibration Error Profile

The correlation coefficient of the model calibration was 0.71, Root Mean Squared (RMS) error 0.74 m and normalised RMS was 59 per cent. The calibration model provides conservatively low water table elevations. In each of the virtual monitoring bores, the simulated water table is lower than that interpreted. This aspect reflects the dominance of the evaporation potentials in controlling the water table elevations, particularly beneath Quick Mud Creek and associated floodplain. The simulated evaporation potentials and extinction depths are probably overestimated and reducing these would improve the calibration statistics.

Overall, a reasonable calibration result (**Plate 6-2**) is achieved, with replication of the topographical influences on local groundwater flow directions particularly in the vicinity of Quick Mud Creek. It was recognised that the model predictive outcomes would not be particularly sensitive to the simulated evaporation potentials and extinction depths provided the lateral hydraulic gradients were representative.

The overall mass balance error of the transient calibration is 0.02 percent.

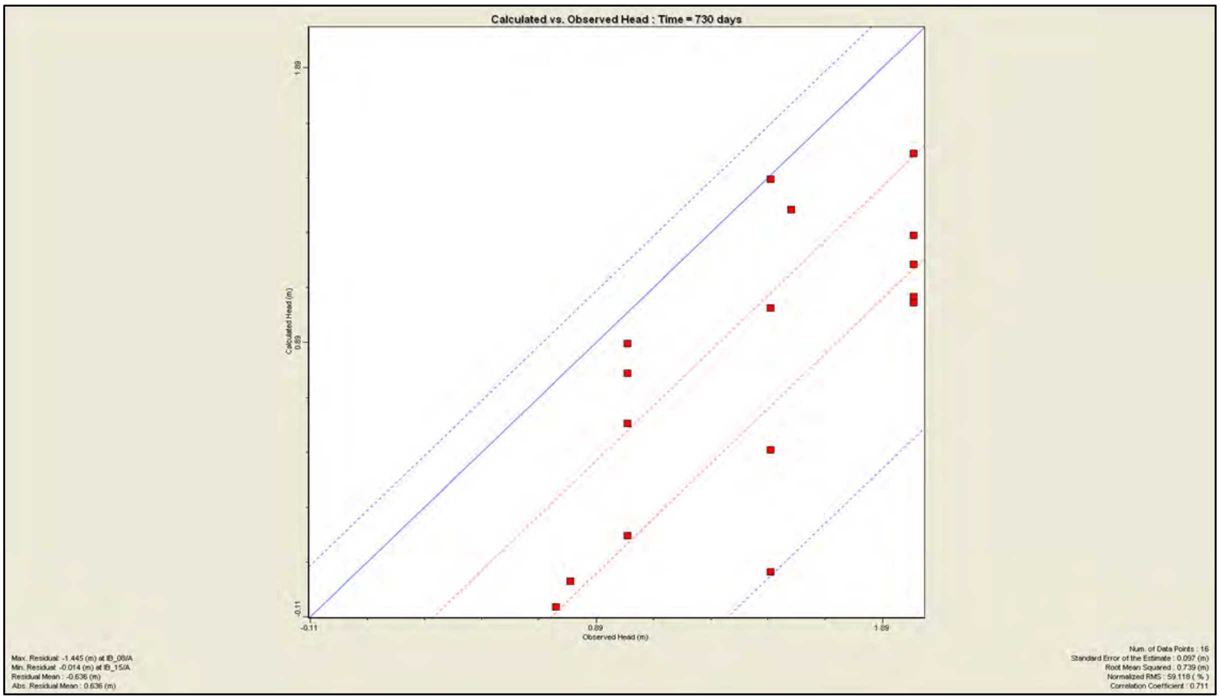

Plate 6-2 Model Calibration - Comparison to Interpreted Heads

6.4.3.1 Sensitivity Analysis

No formal sensitivity analyses have been completed.

It was recognised that the model calibration would be sensitive to many of the preliminary conceptual design inputs and particularly the effective transmissivity, vertical hydraulic conductivity and evaporation potentials. These inputs were, however, not viewed as variables for the model calibration and consequently were fixed.

The predominant variable used in the model calibration was the evaporation extinction depth. The calibration outcomes were sensitive to changes in extinction depths as this factor controlled the simulated water table elevation.

6.4.4 Conformance to Calibration Objectives

The developed model conforms to the conceptual hydrogeological model and simulated water table elevations broadly conform to those observed and interpreted. In particular the, simulated and interpreted water table elevations in the dunes terrain and beneath local reaches of Quick Mud Creek show differences of less than 0.5 m.

The mass-balance closure error was less than 1 per cent.

6.5 Predictive Simulations

The calibrated model was applied to predictive simulations that explored the transport and fate of the disposed RSS. Initially, the inputs to the predictive simulations conformed to the preliminary conceptual design for the abstraction and injection facilities (Chapter 5). The findings of these predictive simulations were subsequently used to develop refined conceptual designs with associated predictions. The two predictive models are referred as:

- Preliminary concept design.
  - There was staged development of this model. The initial stage incorporated only stand-alone injection facilities. Subsequently, this model was upgraded to incorporate the injection and abstraction facilities.
- Refined concept design.

Within the predictive models, well functions were used to simulate the injection and abstraction facilities. These facilities were operated for 80 years and thereafter both the injection and abstraction was ceased. In order to define the predicted transport and fate of the RSS, different predictive models provided:

- Amplitudes of the water table mounding associated with the injection and drawdown associated with the groundwater abstraction.
- Particle-tracking to demonstrate the transport flow paths of the RSS after entry into the Trealla Limestone via the injection bores. The particle-tracking also identifies groundwater discharge zones where the groundwater flow is intercepted by the simulated evaporation potentials.
- Non-reactive solute transport to characterise the mixing and dilution of the disposed RSS within the groundwater environment. A source term equal to the salinity of the RSS was input into the injection wells with the baseline groundwater environment assumed with nil salinity. There was no attenuation of the RSS or any constituents in the model, thus changes to the RSS plume in the groundwater environment reflected only mixing and dilution ratios.

It was anticipated that both the water table mounding and drawdown stressors would attain a steady-state condition over a short period of time and predominantly occur only for the duration of the RSS disposal. Thereafter both footprints would subside and equilibrate to the baseline setting. The particle-tracking and solute transport predictions, however, may not equilibrate and or may equilibrate at different times for different discharge settings. For instance, equilibrium for the particle-tracking and dilute RSS discharge to the groundwater abstraction bores and or Quick Mud Creek (the nearest groundwater discharge zone) may occur comparatively quickly. Where there are longer flow paths to other groundwater discharge zones (to the northern reaches of Quick Mud Creek and in the adjoining catchment to the east), however, the injected RSS may be attenuated in transit for periods that exceed the operating life of the injection and abstraction facilities. Accordingly, the particle-tracking and solute transport simulations were substantially extended after the operating life of the injection and abstraction facilities.

6.5.1 Preliminary Concept Design Predictions

The predictions of the preliminary concept deigns involve eight bores located on the longitudinal dune on the eastern perimeter of Quick Mud Creek injecting the RSS into Trealla Limestone. Concurrently, four production bores abstract groundwater from the western slopes of these dunes, on the eastern perimeter for the floodplain of Quick Mud Creek. The abstraction occurs from both the Ashburton River

Delta Alluvium and Trealla Limestone, with intentions to off-set the water table mounding and increase groundwater discharge to Quick Mud Creek associated with the injection activities. **Figure 5-3** shows the concept design setting.

The findings of the preliminary concept design predictions are described below in context to aquifer hydraulics and associated footprints of the injection and abstraction on the water table, particle-tracking of the RSS solutes and non-reactive solute transport.

6.5.1.1 Footprints on the Water Table

The findings associated with the preliminary concept designs indicate that the stress-fields for the injection and abstractions activities overlap. This aspect was intended to limit direct discharge of the RSS into Quick Mud Creek. Specifically, the footprint of the mounded water table captures the longitudinal dune terrain, propagating distances 1,200 and 1,700 m north and south of the injection borefield, respectively (**Figure 6-7**). To the west, the mounding propagates beneath Quick Mud Creek and the entire 1:100-year ARI floodplain. The predicted drawdown footprint (magnitude greater than 0.1 m) is less extensive and fully captured within the area where the water table is mounded by the injection activities. The drawdown footprint is elongate aligned with the eastern floodplain perimeter of Quick Mud Creek and does not propagate to beneath the low-flow channel (**Figure 6-7**). Given the overlap of the stress-fields, the abstracted groundwater would be expected to intercept the disposed RSS and be characterised by a dilute RSS signature.

6.5.1.2 Particle-Tracking

The particle-tracking demonstrates the flow paths of the RSS from injection sources to groundwater discharge zones. The baseline conceptual hydrogeological model indicates there is groundwater flow from the recharge areas formed by the longitudinal dune landforms to adjacent lowlands (including Quick Mud Creek) that occur to the west, east and north as influenced by the topography. The injection activities would enhance the recharge theme beneath the longitudinal dunes, enhancing the gradients and flow lines to the groundwater discharge zones, similar to the baseline conceptual hydrogeological model.

Particle-tracking predictions for simulations that host stand-alone injection facilities (**Figure 6-8**) show that a period of 232 years transpires before the disposed RSS is transported to the discharge zones underlying Quick Mud Creek. There are substantially longer transit periods before the disposed RSS reaches distant groundwater discharge zone. These simulations show low groundwater flow velocities in the natural groundwater environment. By application of Darcy's Law, the groundwater flow velocity was estimated at about 1 m/annum. The watercourses either side (west (Quick Mud Creek) and east) of the longitudinal dune occur at distances of about 1,000 m from the injection sources. Transit times for discharge of the disposed RSS to local reaches of Quick Mud Creek may therefore range up to 1,000 years or more. Further afield to the north, where discharge would occur beneath the saline flats of the Hooley Creek – Four Mile Creek tidal embayment, the distances from the injection source range from 1,800 to 3,000 m. Transit times to these discharge zones were predicted to range from 1,800 years up to about 3,000 years. The predicted snapshot after 3,000 years is provided on **Figure 6-9** and shows a number of particle-tracks yet to reach the northern discharge zones.

The long transit times indicate that the majority of the injected RSS is retained in storage during the injection period. This aspect is controlled, in part, by the preliminary concept design. Principally the spacing of the injection facilities is important in context to the injection volumes and available local storage volume within the local aquifer systems. Tighter injection facility spacing would enlarge the proportion of the injection volume compared to the available storage in the local aquifer system, leading to more immediate discharge of the RSS signature.

Particle-tracking predictive snapshots after 80 years (**Figure 6-10**) and 3,000 (**Figure 6-9**) years, inclusive, of both injection and abstraction facilities indicate:

- That the groundwater abstraction facilities intercept a portion of the RSS flow lines from the nearby injection facilities. Therefore, over time an increased signature of the disposed RSS would be expected in the abstracted groundwater.
- In particular, the flow lines from the injection facilities converge on the abstraction facilities where the distances separating the two are comparatively limited. The flow lines become comparatively diffuse when the separation is increased.
- The particle-tracking also indicates the presence of RSS flow lines (**Figure 6-9**) that are not drawn directly to and consequently by-pass the groundwater abstraction facilities and discharge by evaporation beneath the floodplain of Quick Mud Creek. Evidently, the simulated local groundwater abstraction does not entirely mitigate the local discharge of the injected RSS to Quick Mud Creek. Therefore, distances between the individual abstraction facilities also provide an influence, with the flow lines increasingly focussed where these facilities are tightly bunched.
- There are accelerated particle velocities towards the abstraction facilities and Quick Mud Creek. Increased particle velocities reflect steeper local hydraulic gradients induced by the groundwater abstraction. The increased particle velocity is demonstrated in that the disposed RSS reaches the groundwater discharge zones associated with Quick Mud Creek within 80 years (**Figure 6-10**).
- Longer-term simulations, over a 3,000-year period, provided sufficient time for the transport of the disposed RSS to the majority of local and distant discharge zones. For the distant groundwater discharge zones, periods up to a possibly exceeding 3,000 years may pass before the RSS signature arrives.

6.5.1.3 RSS Solute Transport

The non-reactive solute transport predictions demonstrate the diffusion, mixing and dilution of the injected RSS within the groundwater environment. In these simulations, the RSS and radium contents are assumed to behave similarly to chloride ions, with transport within the porous media controlled by hydraulics and storage. Accordingly, there is no attenuation of the RSS signature by ionic exchange, adsorption and or precipitation.

The solute transport predictions were informed by the particle-tracking findings and run for periods up to 3,000 years. These predictions were also enhanced by transient measurements of the RSS signature in the individual abstraction facilities and a number of virtual environmental monitoring bores located on the predominant flow paths to local and distant groundwater discharge zones (**Figure 6-11**).

A snapshot of the predicted RSS signature in the groundwater drawn from the abstraction facilities after a period of 80 years is provided in Table 6-5. Transient hydrographs of the RSS signature are provided on **Figure 6-12**. The predicted radium activities were derived from linear interpolation of the predicted TDS concentrations assuming non-reactive solute transport behaviours.

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Table 6-5 Preliminary Concept Design RSS Signatures in Abstracted Groundwater after 80 Years

Aspect	RSS Signatures for TDS and Radium in Abstracted Groundwater			
	PB_01	PB_02	PB_03	PB_04
Abstraction Rate (kL/day)	100	100	100	100
Predicted TDS (mg/L)	28,503	32,379	13,355	6,340
Dilution Ratio to RSS Source TDS[1]	0.53	0.60	0.25	0.12
Predicted Radium[2] (Bq/L)	22.8	25.9	10.7	5.1
Notes:				
1 The RSS source term was 53,700 mg/L TDS and the dilution ratio is the division of the predicted TDS by the source TDS.				
2 The predicted radium was derived from a source term of 43 Bq/L multiplied by the predicted TDS dilution ratio.				

The transient hydrographs of the RSS signature intercepted by the preliminary concept design abstraction facilities (**Figure 6-11 and Figure 6-12**) show:

- Periods from about 14 to 22 years before the disposed RSS is transported to and intercepted by the abstraction facilities.
- The initial RSS signatures are dilute, but progressively increase over time as the footprint of the injected RSS broadens.
- The maximum RSS signature concentrations in the abstraction facilities occur after abstraction has ceased. This aspect reflects transport to the groundwater discharge zones beneath Quick Mud Creek. The maximum TDS concentrations ranged from 21,059 to 32,974 mg/L. Equivalent radium activities would be in the range 17 to 26 Bq/L.
- The RSS signature in the Ashburton River Delta Alluvium beneath the temporary abstraction facilities attains maximum concentrations after periods that range from 103 to 313 years. The shortest periods occur in the southern two abstraction facilities, which are closest to the injection facilities. To the north there is a greater distance between the injection and abstraction facilities, with associated increased transit times.
- The removal of the RSS source was reflected in the RSS signature invaded the abstraction facilities in a pulse; the RSS signatures increase to a maximum, and then progressively decrease because the source is removed.
- The residual RSS signature initially steeply decays but, latter periods of the pulse signature are characterised by an exponential rate of decay. The signature would likely be locally evident for 1,000 to 2,000 years.

It is evident that a comparatively small portion of the disposed RSS would be intercepted by the abstraction facilities. The fates of the remainder of the disposed RSS are indicated by the long-term snapshots of the RSS signature beneath Quick Mud Creek and other groundwater discharge zones. Plan-view and cross-section view snapshots of the predicted RSS signature plume for the preliminary concept design are provided on **Figure 6-13** at times 80 years and 800 years, respectively. These figures illustrate the transport of the RSS signatures from the injection sources to discharge zones.

Evidently, the predominant flow lines would be to discharge zones occur along the local reaches of Quick Mud Creek adjacent to the injection and abstraction facilities. There would be subordinate discharge to the north on entry of Quick Mud Creek to the saline flats of the Hooley Creek – Four Mile Creek tidal embayment. The plan view distribution of the RSS signature after 800 years (**Figure 6-13**) approximates the worst-case snapshot for the preliminary concept design simulations. In this snapshot it is evident that the RSS signature is concentrated in discrete zones beneath Quick Mud Creek. In the model, these zones occur where there is preferential groundwater discharge by evaporation.

The content of transient hydrographs for the selected virtual environmental monitoring bores located within the groundwater discharge zones are summarised in Table 6-6 and shown on Figure 6-11.

Table 6-6 Preliminary Concept Design RSS Signatures in Groundwater Discharge Zones

Aspect	RSS TDS and Radium Signature in Groundwater Discharge Zones			
	Solute_4 Quick mud Creek	Solute_15 Northern Quick Mud Creek	Solute_11 Eastern Watercourse	Solute_12 Northeast Saline Flats
Predicted Maximum TDS (mg/L)	23,600	<1	<1	<1
Time (years)	800	1,149	1,849	2,172
Dilution Ratio to RSS Source TDS[2]	0.44	0.00002	0.00002	0.00002
Predicted Maximum Radium[3] (Bq/L)	19	<0.001	<0.001	<0.001
<u>Notes:</u>				
1 The time at which the RSS signature in the virtual environmental monitoring bore is of the highest concentration.				
2 The RSS source term was 53,700 mg/L TDS and the dilution ratio is the division of the predicted TDS by the source TDS.				
3 The predicted radium was derived from a source term of 43 Bq/L multiplied by the predicted TDS dilution ratio.				

The maximum RSS signature concentrations in the groundwater discharge zones range up to about 24,000 mg/L TDS. The radium activity would about 19 Bq/L.

6.5.2 Refined Concept Design Predictions

The predictions of the refined concept deigns involve eight bores located on the longitudinal dune on the eastern perimeter of Quick Mud Creek injecting the RSS into Trealla Limestone. These injection bores are wider spaced and distributed over a larger area compared to the preliminary concept design. Concurrently, five production bores abstract groundwater from the western slopes of the dunes, on the eastern perimeter for the floodplain of Quick Mud Creek. Again, the production bore locations and intervals have been optimised when compared to the preliminary concept design. These changes were made to reduce the RSS signature in the abstracted groundwater. **Figure 6-14** shows the refined concept design setting.

6.5.2.1 Footprints on the Water Table

The footprints of the mounded water table and drawdown influences are broader within the refined concept design compared to the preliminary concept design (**Figure 6-15**). The enlarged footprint reflects the intentions of the refined concept design in enlargement of the distances between the individual injection facilities and incorporation of five abstraction facilities. The footprints remain elongate aligned with the eastern floodplain perimeter of Quick Mud Creek.

6.5.2.1 Particle-Tracking

Particle-tracking predictive snapshots for the refined concept design are shown on **Figure 6-16** and **Figure 6-17** for 80- and 3,000-year times, respectively. When compared to the preliminary concept design, the particle-tracking simulations indicate a broader set of flow lines. Whilst, the predominant theme of discharge to Quick Mud Creek is evident, there is enhanced transport and diffusion of the RSS towards other groundwater discharge zones, particularly to the north and northeast.

6.5.2.1 RSS Solute Transport

For the refined concept design, a snapshot of the predicted RSS signature in the groundwater drawn from the abstraction facilities after a period of 80 years is provided in Table 6-7. Transient hydrographs of the RSS signature are provided on **Figure 6-12**.

Table 6-7 Refined Concept Design RSS Signatures in Abstracted Groundwater after 80 Years

Aspect	RSS TDS and Radium Signature in Abstracted Groundwater				
	PB_05	PB_06	PB_07	PB_08	PB_09
Abstraction Rate (kL/day)	**80**	**80**	**80**	**80**	**80**
Predicted TDS (mg/L)	2,414	7,586	1,031	547	4,337
Dilution Ratio to RSS Source TDS[1]	0.04	0.14	0.02	0.01	0.08
Predicted Radium[2] (Bq/L)	1.93	6.07	0.83	0.44	3.47

Notes:

1 The RSS source term was 53,700 mg/L TDS and the dilution ratio is the division of the predicted TDS by the source TDS.

2 The predicted radium was derived from a source term of 43 Bq/L multiplied by the predicted TDS dilution ratio.

The transient hydrographs of the RSS signature intercepted by the refined concept design abstraction facilities (**Figure 6-11** and **Figure 6-12**) show:

- Periods from about 19 to 35 years before the disposed RSS is transported to and intercepted by the abstraction facilities.
- The characteristics of the RSS signature pulses are similar to those for the preliminary concept design, though there is increased dilution.
- The maximum TDS concentrations ranged from 3,422 to 14,078 mg/L. Equivalent radium activities would be in the range 2.7 to 11 Bq/L.
- The RSS signature in the Ashburton Alluvium Aquifer beneath the temporary abstraction facilities attains maximum concentrations after periods that range from 220 to 349 years.

Plan-view and cross-section view snapshots of the predicted RSS signature plume for the refined concept design are provided on **Figure 6-18** at times 80 years and 3,000 years, respectively. The content of transient hydrographs for the selected virtual environmental monitoring bores located within the groundwater discharge zones are summarised in Table 6-8 and shown on **Figure 6-11**.

Table 6-8 Refined Concept Design RSS Signatures in Groundwater Discharge Zones

Aspect	RSS TDS and Radium Signature in Groundwater Discharge Zones			
	Solute_4 Quick mud Creek	Solute_15 Northern Quick Mud Creek	Solute_11 Eastern Watercourse	Solute_12 Northeast Saline Flats
Predicted TDS (mg/L)	9,500	366	<1	177
Time (years)	849	1,900	1,200	1,300
Dilution Ratio to RSS Source TDS[1]	0.18	0.007	<0.00002	0.003
Predicted Radium[2] (mg/L)	7.7	0.3	<0.001	0.1
Notes:				
1 The RSS source term was 53,700 mg/L TDS and the dilution ratio is the division of the predicted TDS by the source TDS.				
2 The predicted radium was derived from a source term of 43 Bq/L multiplied by the predicted TDS dilution ratio.				

The maximum RSS signature concentrations in the groundwater discharge zones range up to about 9,500 mg/L TDS, being highest beneath Quick Mud Creek. The peak radium activity would about 8 Bq/L.

6.5.3 Discussion

The predictive models are anticipated to provide reasonable perspectives with regard to the fate and transport of the disposed RSS. The simulations indicate that the disposed RSS signatures would be temporarily hosted in the groundwater environment; the signatures ultimately manifest in the abstraction facilities and thereafter local groundwater discharge zones. Differences between the preliminary concept design and the refined concept design occur in the predicted fates of the RSS signatures and concentrations intercepted by the abstraction facilities and in the groundwater discharge zones. The refined concept designs enable reduced RSS signature concentrations. In comparative terms the differences include:

- Interceptions by the abstraction facilities:
  - Preliminary concept design - radium activities range up to about 26 Bq/L.
  - Refined concept design - radium activities range up to about 6 Bq/L.
- Groundwater discharge zones:
  - Preliminary concept design - radium activities range up to about 19 Bq/L.
  - Refined concept design - radium activities range up to about 8 Bq/L.

The refined concept design, based on broader rather than tighter injection and abstraction facility distributions, enables lower radium activities in the receiving environments. It is expected that the concept designs could be further refined to enable lower radium activities in potentially sensitive areas. This may be achieved by increased broadening of the injection facility distribution.

Evidently, the abstraction facilities intersect only a comparatively small portion of the disposed RSS. This is important given:

- Their roles in reducing seepage of RSS signatures to Quick Mud Creek.
- Enabling discharge to Quick Mud Creek of groundwater that hosts only a dilute RSS signature.

The developed models should be viewed as semi-qualitative. Predictive outcomes are sensitive to a number of model input assumptions, not least being the aquifer hydraulics and storage characteristics.

The actual mechanisms of RSS signature discharge are not closely defined or simulated. Based on the knowledge of the baseline environment there is expectation that the RSS signature would manifest as seepage to discharge zones after episodic rainfall recharge events. The predominant discharge zones maybe the pools on Quick Mud Creek. The potential influence of evaporation concentration effects on the RSS signature, when expressed in shallow water table settings, is poorly defined.

The predicted water table elevations for the baseline environment and three injection and abstraction scenarios are presented on **Figure 6-19** as profiles on a cross-section than spans the local dunes terrain and Quick Mud Creek. The scenarios presented include injection only, and the preliminary and refined concept designs that incorporate both injection and abstraction. The presentation of the injection scenario only enables the influence of the abstraction in the concept design to be characterised.

For this injection only scenario, the mounded water table attains maximum amplitude of 1.8 m beneath the dunes terrain east of Quick Mud Creek. The simulated water table mound does not intersect the ground surface. There are, however, significantly reduced depths to the water table at the foot of the dune terrain and beneath the floodplain of Quick Mud Creek. This outcome is an artefact of the simulated evaporation potentials; this aspect reflects that the model evaporation potentials intercept the water table and control its elevations beneath Quick Mud Creek. It is recognised that the simulated evaporation potentials may be overestimated and or that episodic rainfall recharge events (which are not simulated) are important in the replication of observed water table elevations and pools on Quick Mud Creek.

The potential for the mounded water table to form seepage fronts in groundwater discharge zones is a likely impediment to the regulatory process (**Figure 6-20**). The simulated water table derived from the refined conceptual design injection and abstraction facilities model demonstrated the potential to control the mound heights on the perimeter of Quick Mud Creek, thus mitigating the seepage risks.

Quick Mud Creek Modelling

7.1 Model Objectives

A hydraulic modelling approach was used to simulate stream flow generated by the disposal of abstracted groundwater onto Quick Mud Creek. The objective of the modelling was to predict the potential wetted footprint and fate of the disposed groundwater on Quick Mud Creek.

It was also recognised that the wetted footprint may influence the outcomes of the groundwater abstraction scenarios, with potential for recycling of a portion of the disposed groundwater from settings where drawdown of the water table propagates beneath Quick Mud Creek. In these settings, the wetted footprint would provide a recharge flux, with infiltration potentially off-setting and exceeding the local drawdown influences. The wetted surface water footprint was intended to be interfaced with the groundwater flow predictive models to characterise the associated recharge characteristics.

MIKE 21 HD software was used. This software had been applied for the previous flood models of Quick Mud Creek (URS, April 2013).

7.2 Model Form and Parameterisation

The software used shallow stream flow equations in a 2D environment. The discharge rate simulated was 400 kL/day, representing the average RSS production rate. In the model it was assumed:

- The model domain comprises the local reaches of Quick Mud Creek, from Wheatstone Road north to the Onslow Salt crystalliser ponds.
- The model grid is derived from the LiDAR survey data provided by Chevron in 2009. The LiDAR survey data has a 0.3 m resolution and was derived when the bed of Quick Mud Creek was dry.
- The grid cell size is 5 x 5 m.
- The simulated evaporation rate was 2.88 mm/day on the wetted footprint. This simulated evaporation was derived from the total potential evaporation of 3.08 m/annum or 8.4 mm/day and subsequently altered understanding that the evaporation potentials from hypersaline groundwater would be about 35 per cent of pan potentials. The evaporation was assumed to be steady throughout the year, without seasonal variation.
- No runoff is simulated.
- Infiltration through the bed of Quick Mud Creek to the water table was assumed to be nil. The water table is at shallow depth and the bed of Quick Mud Creek forms a groundwater discharge zone. These aspects reflect the occurrence of limited storage above the water table and limited potential for the underlying aquifer to transmit infiltrates. These assumptions also enable simulation of a reasonable worst-case footprint from the disposed groundwater.
- The simulations were for a dry bed to Quick Mud Creek. Therefore the creek-bed topography enables attenuation of the discharged groundwater and development of pools on pools on the local reaches of Quick Mud Creek.
- The simulated outlet for the discharge of 400 kL/day groundwater is located near Wheatstone Road.
- The period of simulation is one year. The model reaches a steady-state.

7.3 Prediction of Wetted Footprints

The predicted footprints from the discharge of 400 kL/day groundwater are limited the low flow channel of Quick Mud Creek. The groundwater is attenuated in the low-flow channel, forming pools. The footprints remain localised and do not reach the Hooley Creek – Four-Mile Creek tidal

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embayment. **Table 7-1** summarises the output of the model and the predicted footprint is presented on **Figure 7-1.**

Table 7-1 Wetted Footprint from Groundwater Disposal to Quick Mud Creek

Groundwater Disposal Rate (kL/day)	Period to Reach Maximum Footprint (months)	Wetted Footprint (Ha)	Maximum Footprint Length (m)
670	5	27.5	4,950

As discussed, the wetted footprint would tend to infiltrate and saturate the underlying strata and locally mound the water table beneath Quick Mud Creek. The mounded water table height would be of small amplitude; probably in the order of 0.5 m. Under circumstances the wetted footprint would form a local recharge zone. In this zone, if the infiltration rates allow, the recharge would off-set the drawdown linked to the groundwater abstraction facilities, promoting recycling of a small portion of the abstracted groundwater.

The increased availability of groundwater on Quick Mud Creek would tend to promote the accumulation of crystalline salt due to discharge by evaporation.

Conclusions

The Birdrong Sandstone groundwater source for the OWIUP has traces of NORMs, principally radium activity. The radium is to be removed by RO from the potable supply and presents in the RSS by-product as:

- Radium-226: activity of 10 Bq/L.
- Radium-228: activity of 33 Bq/L.

Quick Mud Creek is an ephemeral watercourse and groundwater discharge zone. Predominantly, the channel is dry and stream flow is episodic after significant rainfall events. Stream flow events in Quick Mud Creek tend to occur annually or biennially. Typically with a biennial frequency flood events on the Ashburton River also spill into Quick Mud Creek. Groundwater discharge occurs from shallow water table zones and temporary pools due to water losses by evaporation. The shallow groundwater does not contain NORMs and therefore is unlike the Birdrong Sandstone source of the RSS. In this setting, at times between stream flow events, the RSS disposed directly onto the creek would predominantly pool in the low-flow channel of Quick Mud Creek, with propensity for water losses by evaporation leading to accumulation of crystalline salts (with inclusive radium).

Beneath Quick Mud Creek and surrounds, the groundwater environment is hosted by a hydrostratigraphy succession that is broadly characterised by:

Table 8-1 Hydrostratigraphy Beneath Quick Mud Creek

Hydrostratigraphy	Transmissivity (m^2/day)	Typical Saturated Thickness (m)
Superficial Formations[1]	10 - 40	10 - 20
Ashburton River Delta Clay and Unconformity	2	5 – 10
Trealla Limestone	15 - 20	20 - 35

Notes:
1 The superficial formations include the longitudinal dunes and Ashburton River Delta Alluvium.

A concept has been developed that explores the potential for shallow groundwater to be abstracted from the local aquifer systems (Ashburton River Delta Alluvium and Trealla Limestone) and disposed to Quick Mud Creek whist the RSS is concurrently disposed by injection into the Trealla Limestone. The local shallow groundwater has no NORMs activities, thus its discharge would not lead to the accumulation of radium in Quick Mud Creek. The potential for success of the proposed concept lies in:

- Characterising the transport and fate of the injected RSS.
- Understanding the cumulative influences of the groundwater abstraction and concurrent injection.

It was anticipated from earlier predictive modelling (URS, November 2012) that the injected RSS volumes would progressively displace the groundwater in storage and fill the local aquifer profile from bottom to top. The injection activities would mound the local water table and promote increased discharge (by seepage and evaporation) along local reaches of Quick Mud Creek. Under the concurrent abstraction and injection concept, the potential for increased local groundwater discharge due to water able mounding would be off-set by drawdown linked to the groundwater abstraction. To deliver this outcome there would need to be interference between the footprints imposed by the

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abstraction and injection facilities. That is the drawdown from the groundwater abstraction would need to propagate into the mounded water table zone caused by the RSS injection. In doing so, there is potential that the abstracted groundwater would include dilute RSS signatures.

The concept of concurrent local groundwater abstraction and RSS injection has been investigated using predictive groundwater flow and solute transport models. Initially, the preliminary concept development was informed by:

- RSS production rates that average 400 kL/day, with an operating period of 80 years.
- Injection of the RSS preferably into the Trealla Limestone. Preferably also, the injection facilities would be located on the peaks of the longitudinal dunes within the Project area.
- Abstraction of groundwater from the Ashburton River Delta Alluvium and Trealla Limestone.
- Location of abstraction and injection facilities on higher ground than the 1:100-year ARI flood elevation in Quick Mud Creek.
- The effective transmissivity of the local superficial formations and Trealla Limestone being in the 10 to 40 m^2/day.
- Nominally, the production bore yields would be 100 kL/day. There would be a minimum of four production bores.
- There would be increased numbers of injection bores compared to the abstraction bores. Nominal yields for each would be 50 kL/day. There would be a minimum of eight injection bores.
- A nominal minimum distance of 200 m between individual abstraction and injection facilities to limit interference effects.

The conceptual design injection and abstraction facilities have been interfaced with predictive groundwater flow models to characterise the transport and fate of the disposed RSS. The predictive models informs the feasibility of the conceptual design injection and abstraction themes through the simulation of groundwater flow, particle-tracking and non-reactive solute transport associated with the RSS injection. Model development has been compatible with appropriate guidelines; the models conform to a Class 1 classification.

Two predictive models were developed and applied. These models incorporate:

- A preliminary concept design. This design is based on:
  - 8 injection facilities aligned on the local longitudinal dune landform.
  - 4 abstraction facilities located on the eastern perimeter of the Quick Mud Creek flood plain.
  - Spacing of the facilities is about 200 m.
- A refined concept design. This design is based on :
  - 8 injection facilities aligned on the local longitudinal dune landform, but spaced up to 400 m apart.
  - 5 abstraction facilities located on the eastern perimeter of the Quick Mud Creek flood plain.

The key findings from the predictive models include:

- There are substantial transits periods before the disposed RSS reaches groundwater discharge zones. The simulations indicate that the disposed RSS signatures would be temporarily hosted in the groundwater environment; the signatures ultimately manifest in the abstraction facilities and thereafter local groundwater discharge zones. Transit times for discharge of the disposed RSS to local reaches of Quick Mud Creek may therefore range up to 1,000 years or more. Further afield to the north, where discharge would occur beneath the saline flats of the Hooley Creek – Four Mile Creek tidal embayment, the transit times range from 1,800 to 3,000 years.

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- The simulated abstraction facilities intersect the mounded water table from the injection activities and prevent the occurrence of seepage fronts on Quick Mud Creek. In doing so, the abstraction facilities ultimately intersect RSS signatures. The maximum RSS signature contents for radium activity included:
  - Preliminary concept design - ranging up to about 26 Bq/L.
  - Refined concept design - ranging up to about 6 Bq/L.
- The radium activities within the groundwater discharge zones were highest associated with Quick Mud Creek. Elsewhere, the increased lengths of flow paths enabled mixing and further dilution. The maximum RSS signature contents for radium activity in Quick Mud Creek included:
  - Preliminary concept design - ranging up to about 19 Bq/L. The peak occurred after about 800 years. Times for transit of peak RSS signatures to the distant groundwater discharge zones ranged up to 2,172 years.
  - Refined concept design - ranging up to about 8 Bq/L. The peak occurred after about 849 years. Times for transit of peak RSS signatures to the distant groundwater discharge zones ranged up to 1,900 years.
- The refined concept design, based on broader rather than tighter injection and abstraction facility distributions, enables lower radium activities in the receiving environments.
- During the simulated Project life of 80 years, the abstracted groundwater disposed onto Quick Mud Creek would be characterised with a radium signature. This signature would be substantially dilute compared to the RSS signature.

It is expected that the concept designs could be further refined to enable lower radium activities in potentially sensitive areas. This may be achieved by increased broadening of the injection facility distribution.

The developed models should be viewed as semi-qualitative. Predictive outcomes are sensitive to a number of model input assumptions, not least being the aquifer hydraulics and storage characteristics.

The actual mechanisms of RSS signature discharge are not closely defined. The potential influence of evaporation concentration effects on the RSS signature, when expressed in shallow water table settings, is poorly defined.

There are comparatively limited data that support the model form and parameterisation. There is also recognition that the Trealla Limestone and Ashburton River Delta Alluvium setting is likely to be widely anisotropic. As such, there are uncertainties linked to the likely aquifer behaviours and transport and fates of the injected RSS. The uncertainties include aquifer hydraulics, vertical hydraulic gradients and connectivity of the Trealla Limestone and Ashburton River Delta Alluvium, seasonal and episodic changes in water table elevations, the hydrology of the pools in Quick Mud Creek and potential yields of injection and abstraction facilities.

The data limitations and outlined uncertainties constrain the developed model to a Class 1 classification; this is the lowest classification based on the current (SKM and National Centre for Groundwater Research and Training, June 2012) guidelines. Accordingly, the model findings should be recognised as indicative only, semi-quantitative and semi-qualitative. Furthermore, the simulated transit times of the injected RSS should also be considered in context to climate and landform changes recognising themes of rising sea levels and the Ashburton River Delta being and active accretion landscape subject to both gradual and episodic changes. Despite the Class 1 classification, the predictive model provides reasonable indications of the likely fates of injected RSS and associated NORMs.

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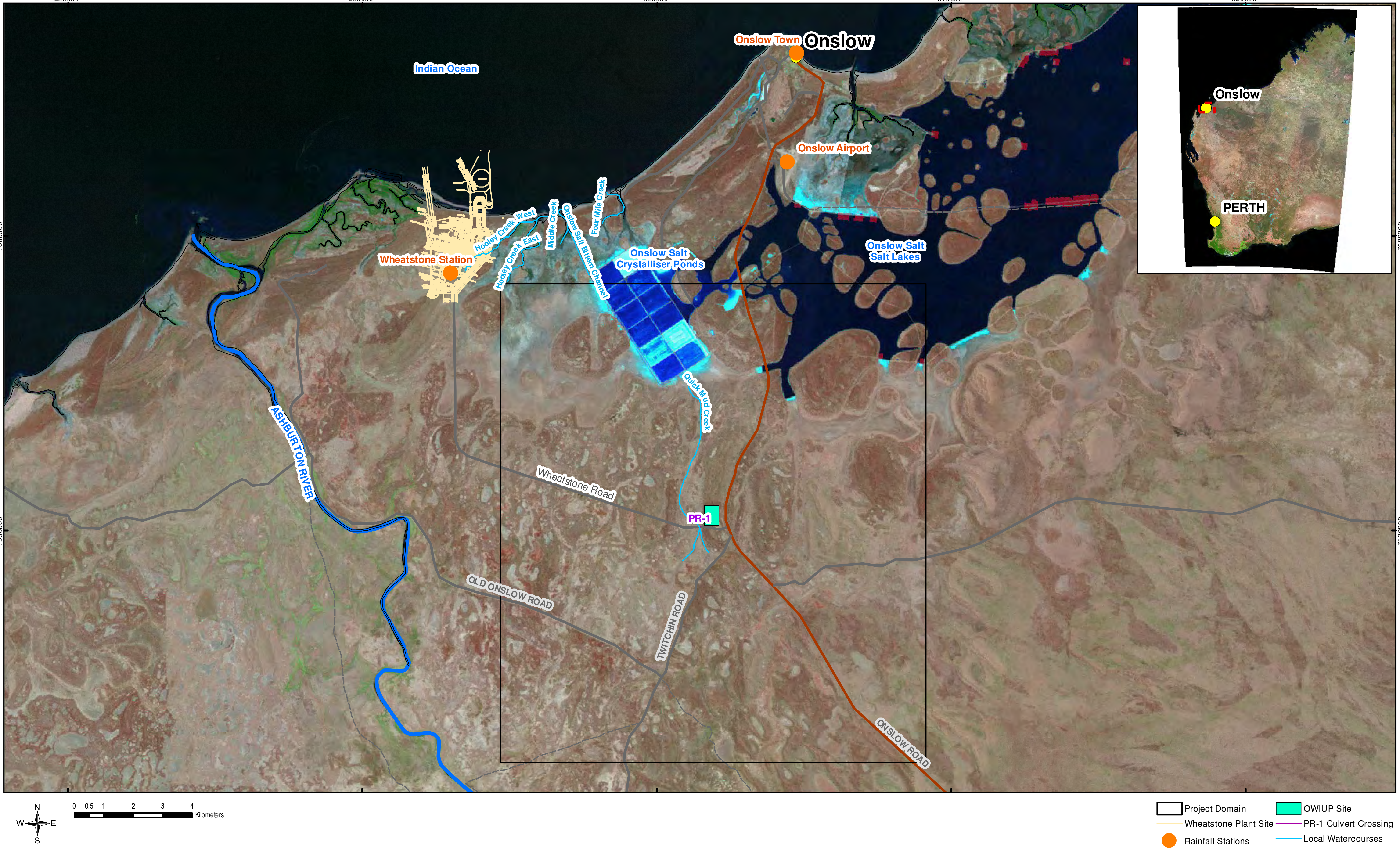
Figures



Coordinate System: GDA 1994 MGA Zone 50

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Chevron

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

PROJECT LOCATION PLAN

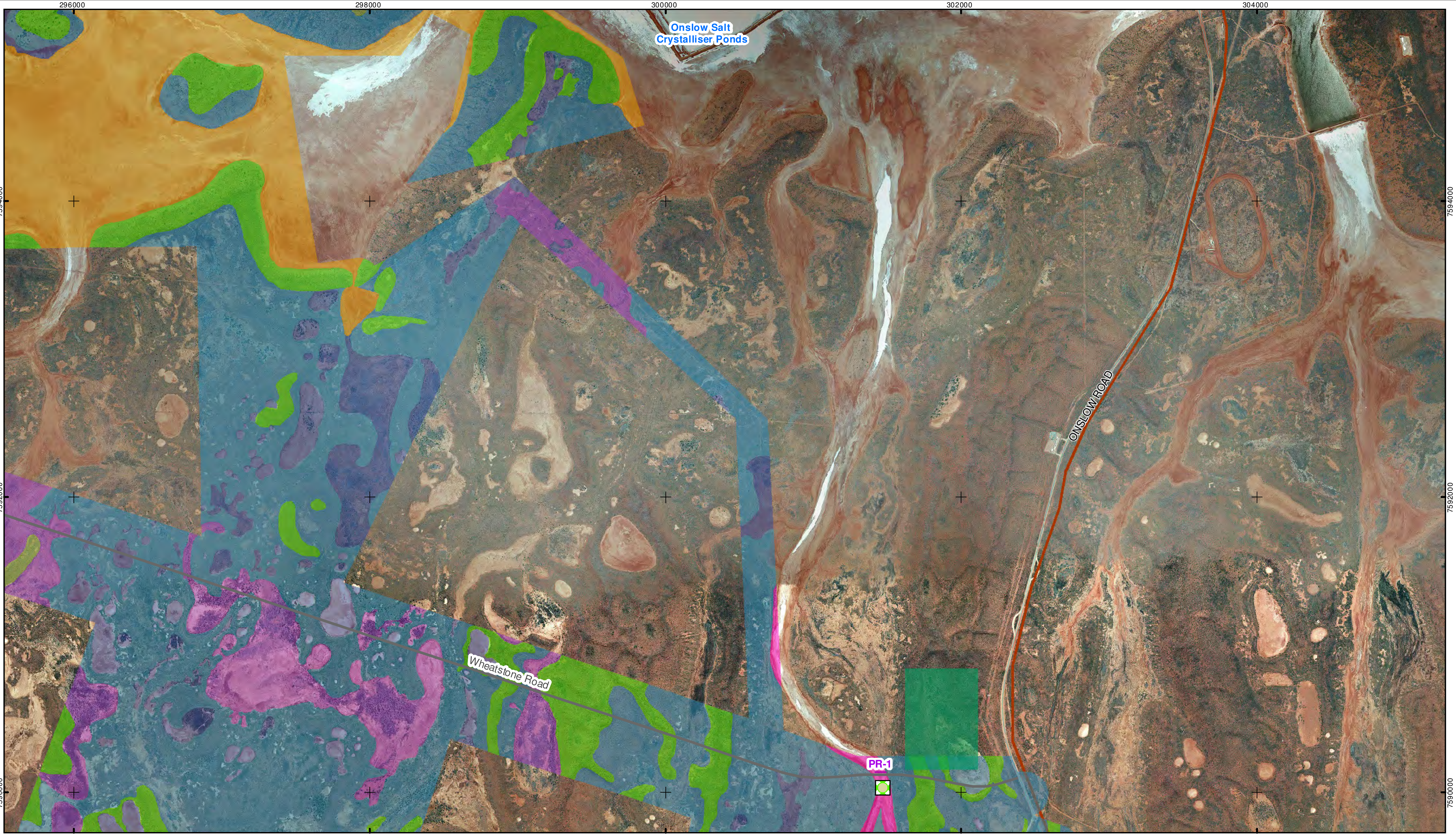
URS

INTRODUCTION

File No: 42908178-WG-055.mxd | Drawn: LS | Approved: IB | Date: 9/25/2013

Figure: 1-1

Rev. A | A3



N W E S

Landform Units

- ALC, Alluvial / Colluvial
- CPB, Claypans and Clay Plains
- DA, Drainage Area
- FCD, Fringing and Coastal Dunes
- LDS, Longitudinal Dunes and Interdunal Swales
- MRD, Mainland Remnant Dunes
- SF, Saline Flats
- SFC, Samphire Flat
- SH, Stony Hills
- SSF, Supratidal Salt Flats
- TCM, Tidal Creek, Mangrove Swamp, Intertidal Flats
- RSS outlet
- PR-1 Culvert Crossing
- OWIUP Site

Scale at A3: 1:25,000
Coordinate System: GDA 1994 MGA Zone 50
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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

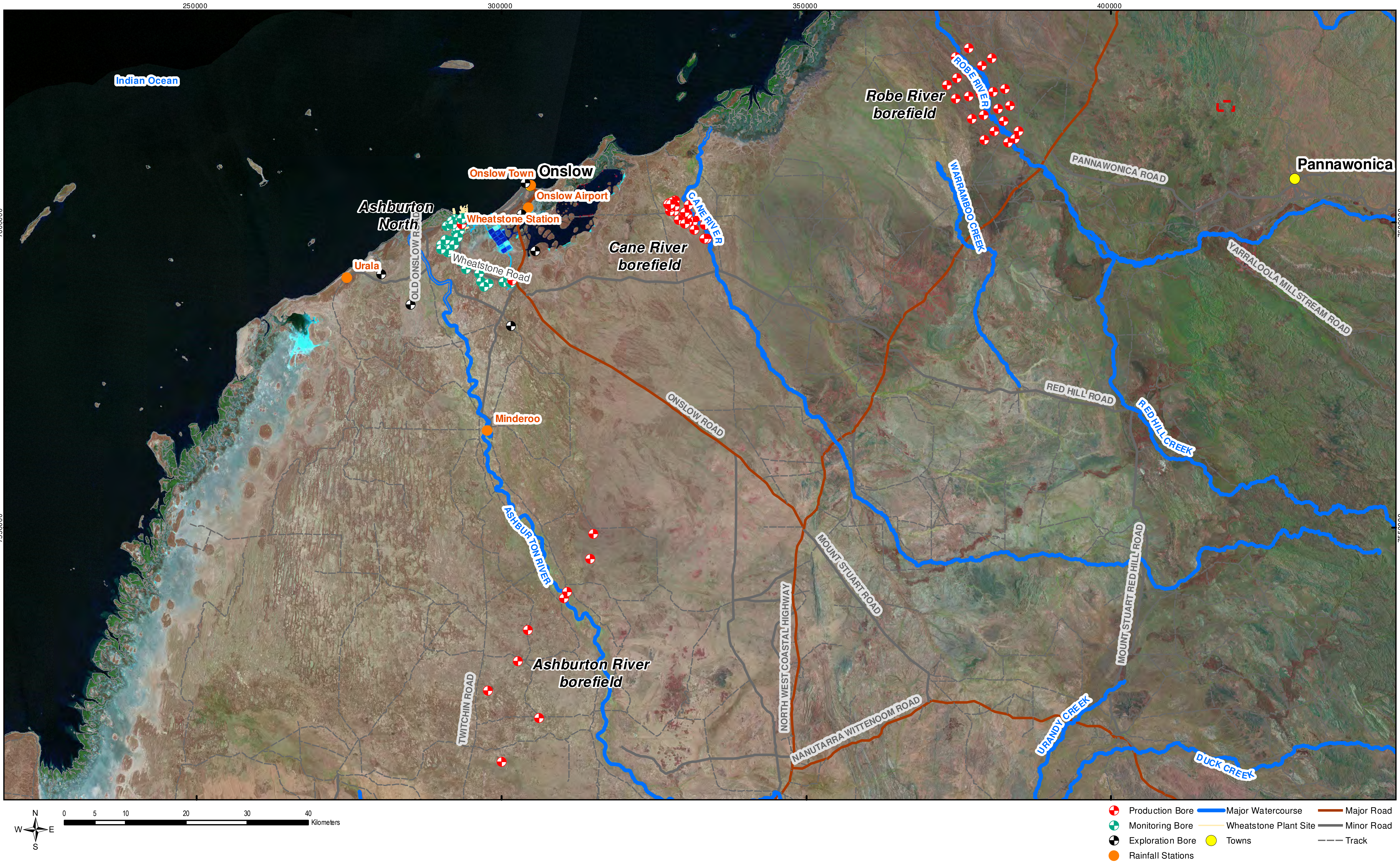
LANDFORM UNITS OF THE PROJECT AREA

URS

BACKGROUND

File No: 42908178-WG-056_RB.mxd Drawn: LS Approved: IB Date: 9/25/2013

Figure: 2-1 Rev. A A3



Coordinate System: GDA 1994 MGA Zone 50

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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

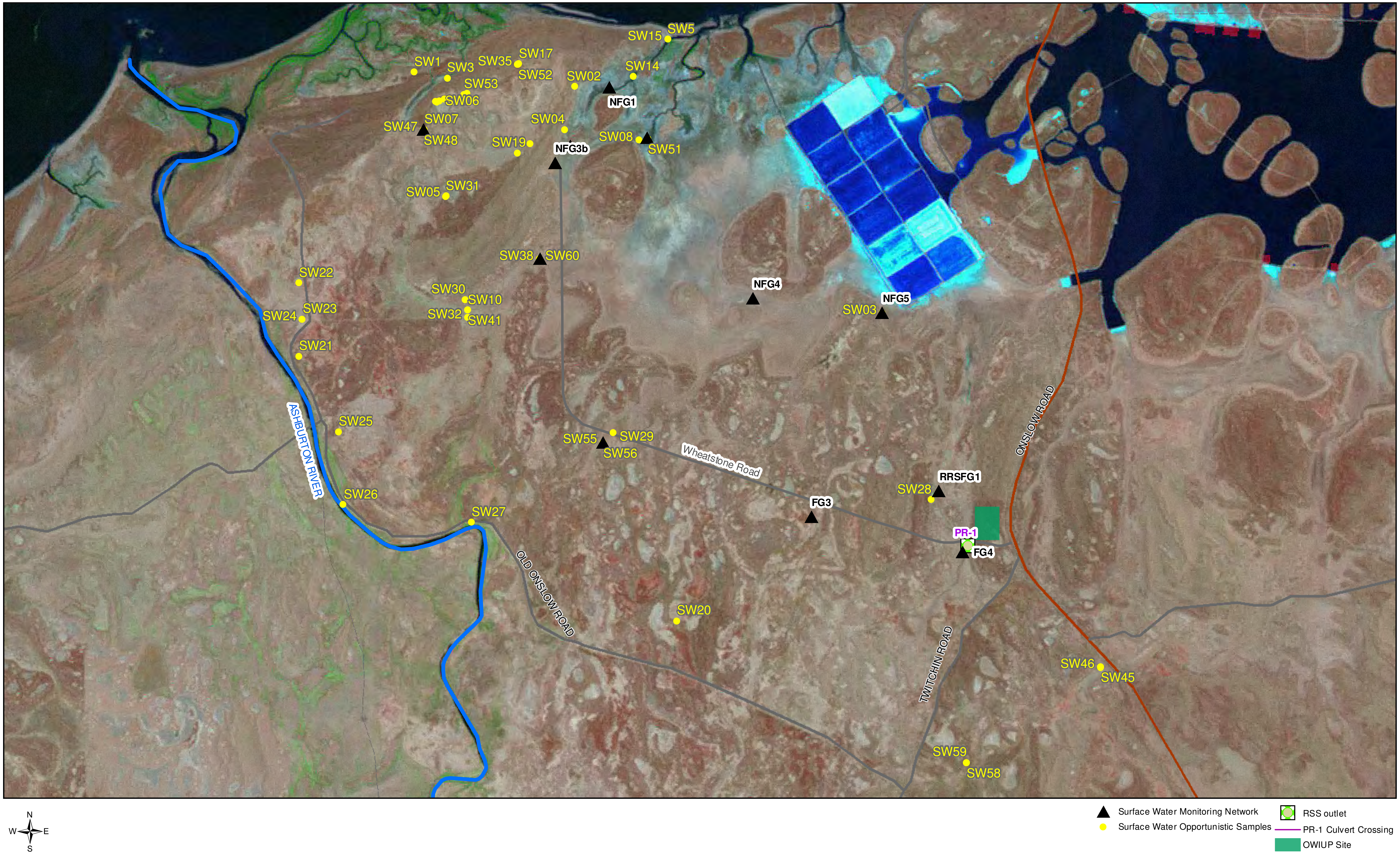
SITE INVESTIGATION LOCATIONS

URS

SITE INVESTIGATIONS

File No: 42908178-WG-057.mxd | Drawn: RM | Approved: IGB | Date: 9/25/2013

Figure: 3-1 | Rev. A | A3



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Scale at A3: 1:73,426
Coordinate System: GDA 1994 MGA Zone 50
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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

SURFACE WATER MONITORING NETWORK

URS

BASELINE QUICK MUD CREEK ENVIRONMENT

Figure: 3-2

File No: 42908178-WG-092.mxd Drawn: LS Approved: IB Date: 9/25/2013 Rev. A A3

Sampling Location in March 2013

EO52FG-S Monitoring Bore

RSS Outlet

OWIUP Site

Scale at A3:

Coordinate System: GDA 1994 MGA Zone 50

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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

RADIONUCLIDE SAMPLE LOCATIONS

URS | SITE INVESTIGATIONS | Figure: 3-3

File No: 42908178-WG-058.mxd | Drawn: LS | Approved: IGB | Date: 9/25/2013 | Rev. A | A3

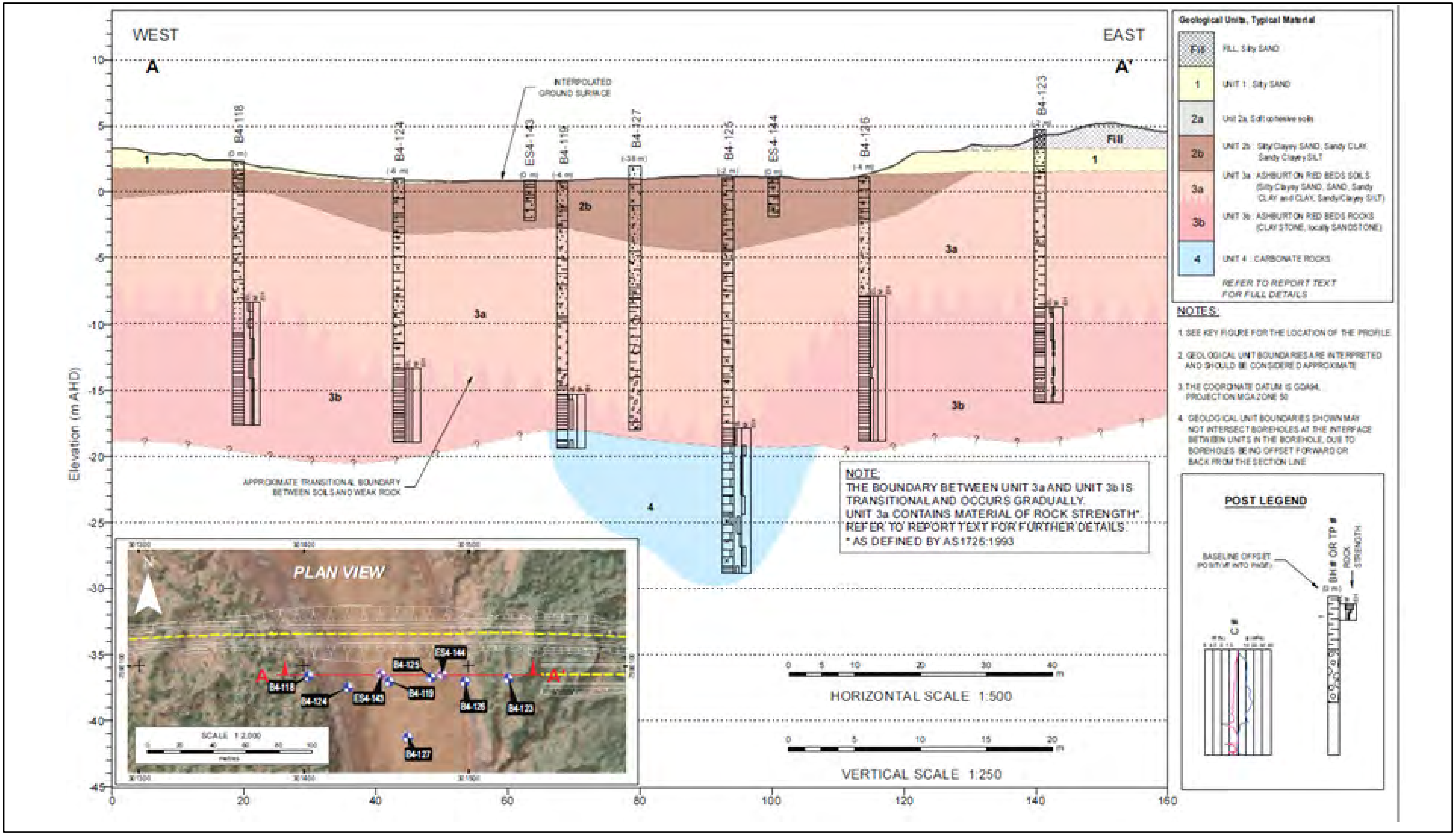


Figure has been supplied by Golder Associates 2013.

Scale at A3:
Coordinate System:

Chevron

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

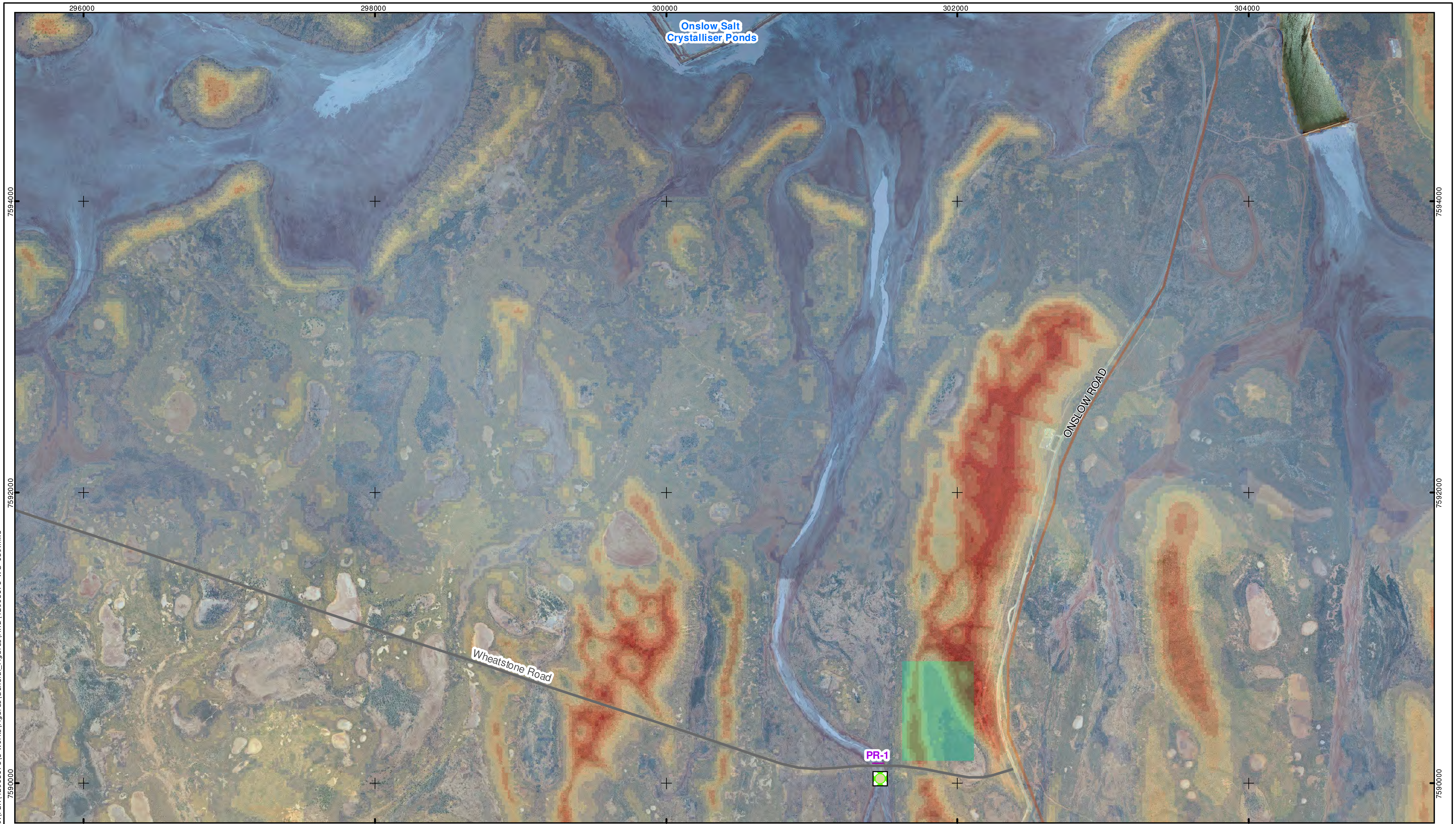
GEOLOGY BENEATH QUICK MUD CREEK

URS

BASELINE QUICK MUD CREEK ENVIRONMENT

Figure: **3-4**

File No: **42908178-WG-089.mxd** Drawn: **LS** Approved: **IB** Date: **9/12/2013** Rev. **A** A3



RSS outlet
Wheatstone Road
PR-1 Culvert Crossing
OWIUP Site

Digital Elevation Model (m AHD)

- Below 2.1
- 2.2 - 3.9
- 4 - 5.5
- 5.6 - 7
- 7.1 - 8.5
- 8.6 - 10
- 11 - 13
- 14 - 16
- 17 - 19
- 20 - 26

N W E S

Scale at A3: 1:25,000
Coordinate System: GDA 1994 MGA Zone 50
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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

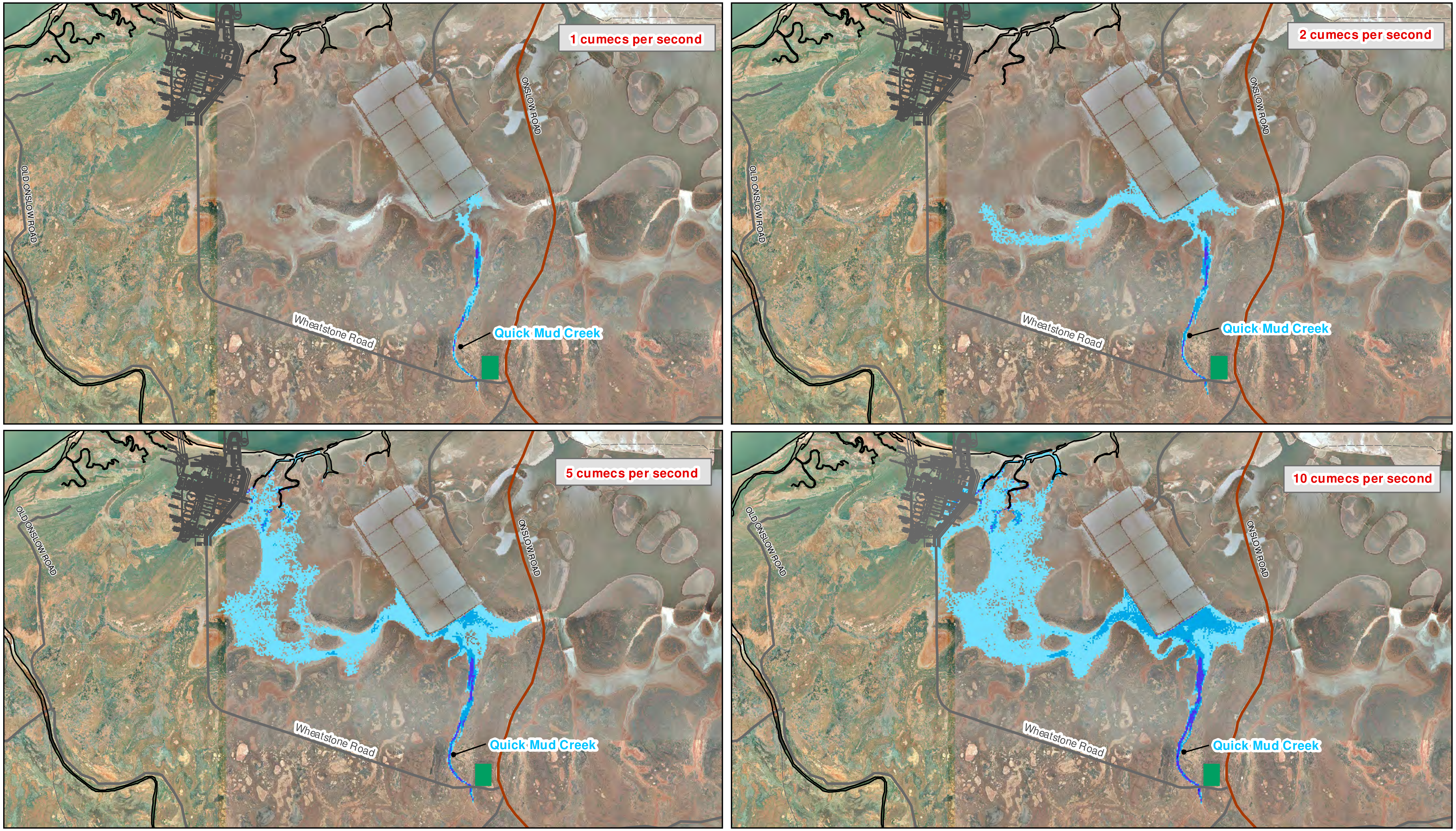
QUICK MUD CREEK BASELINE SETTING

URS

BASELINE QUICK MUD CREEK ENVIRONMENT

Figure: **4-1**

File No: **42908178-WG-059.mxd** Drawn: **LS** Approved: **IB** Date: **9/12/2013** Rev. **A** A3



N W E S

0 0.5 1 2 3 4 Kilometers

Plant Site
Wheatstone Road
Proposed RO Plant

Discharge Event Footprints and Depths
- 0.01 - 0.25 m
- 0.26 - 0.5 m
- 0.51 - 1 m
- > 1 m

Scale at A3: 1:116,960
Coordinate System: GDA 1994 MGA Zone 50
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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

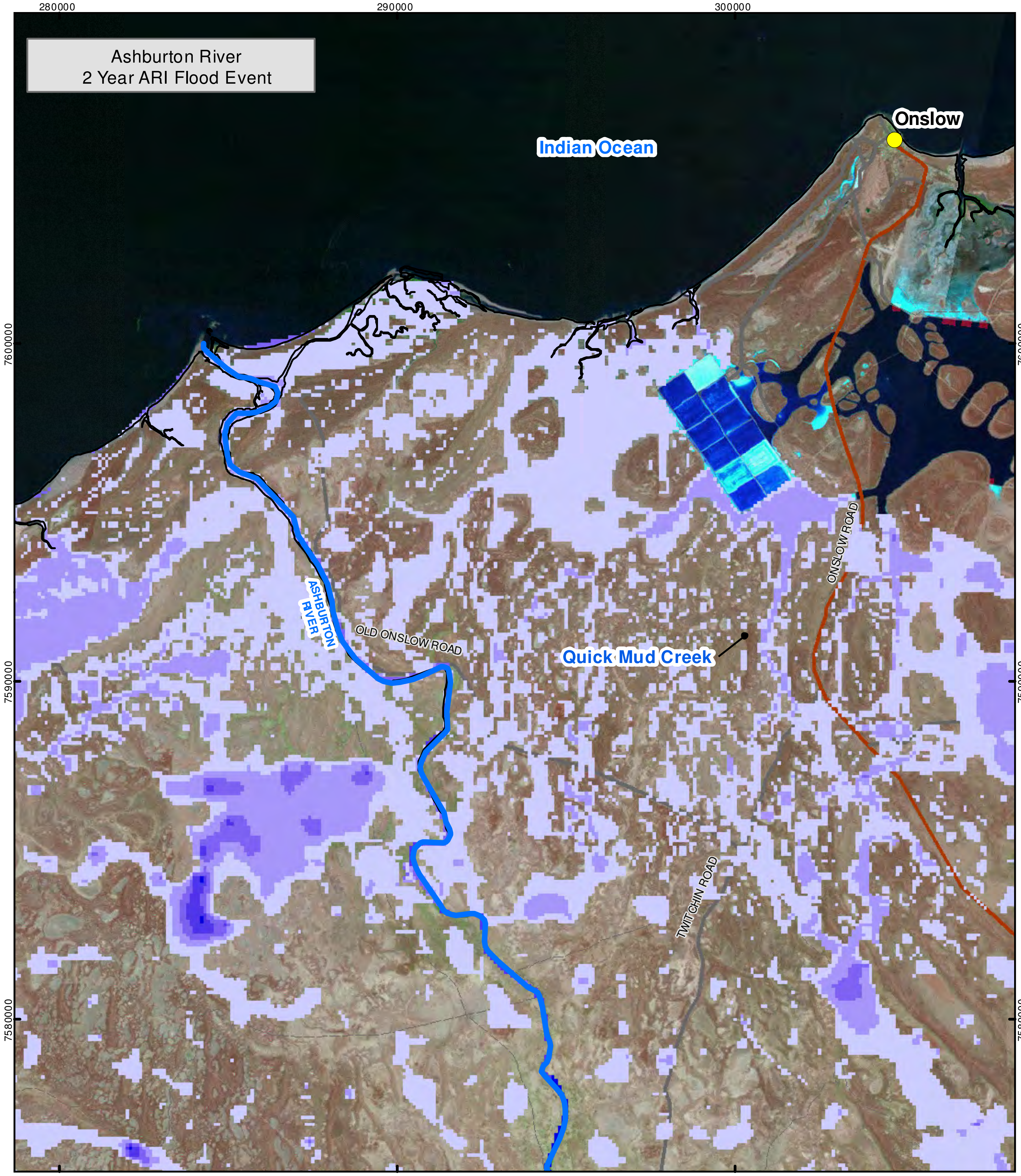
PREDICTED QUICK MUD CREEK FLOOD FOOTPRINT FOR 24-HOUR STORM EVENTS

URS

BASELINE QUICK MUD CREEK ENVIRONMENT

Figure: 4-2

File No: 42908178-WG-060.mxd Drawn: LS Approved: IB Date: 4/09/2013 Rev. A A3



N W E S

0 0.5 1 2 3 4 Kilometers

Scale at A3: 1:154,000

Coordinate System: GDA 1994 MGA Zone 50

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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

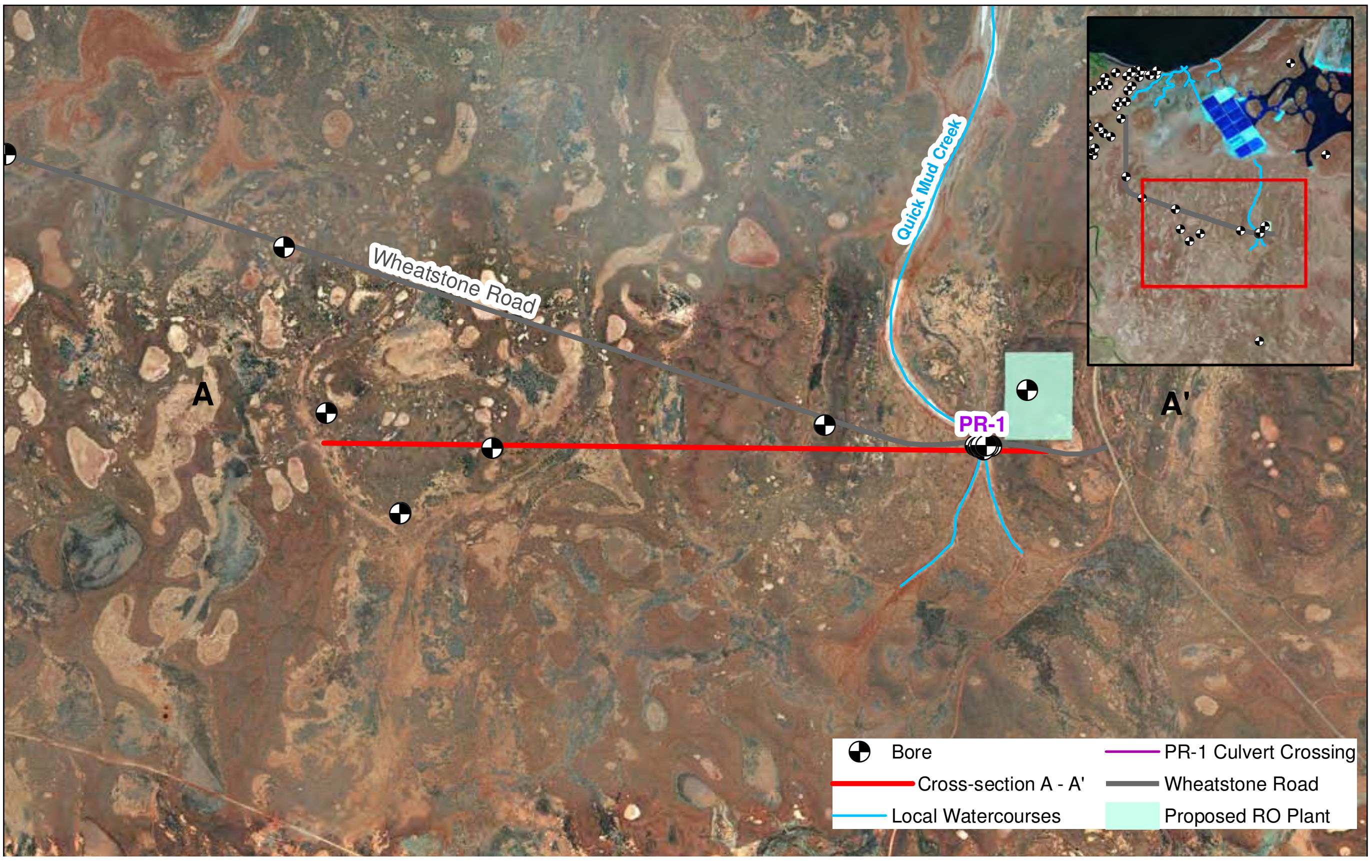
ASHBURTON RIVER FLOOD FOOTPRINTS

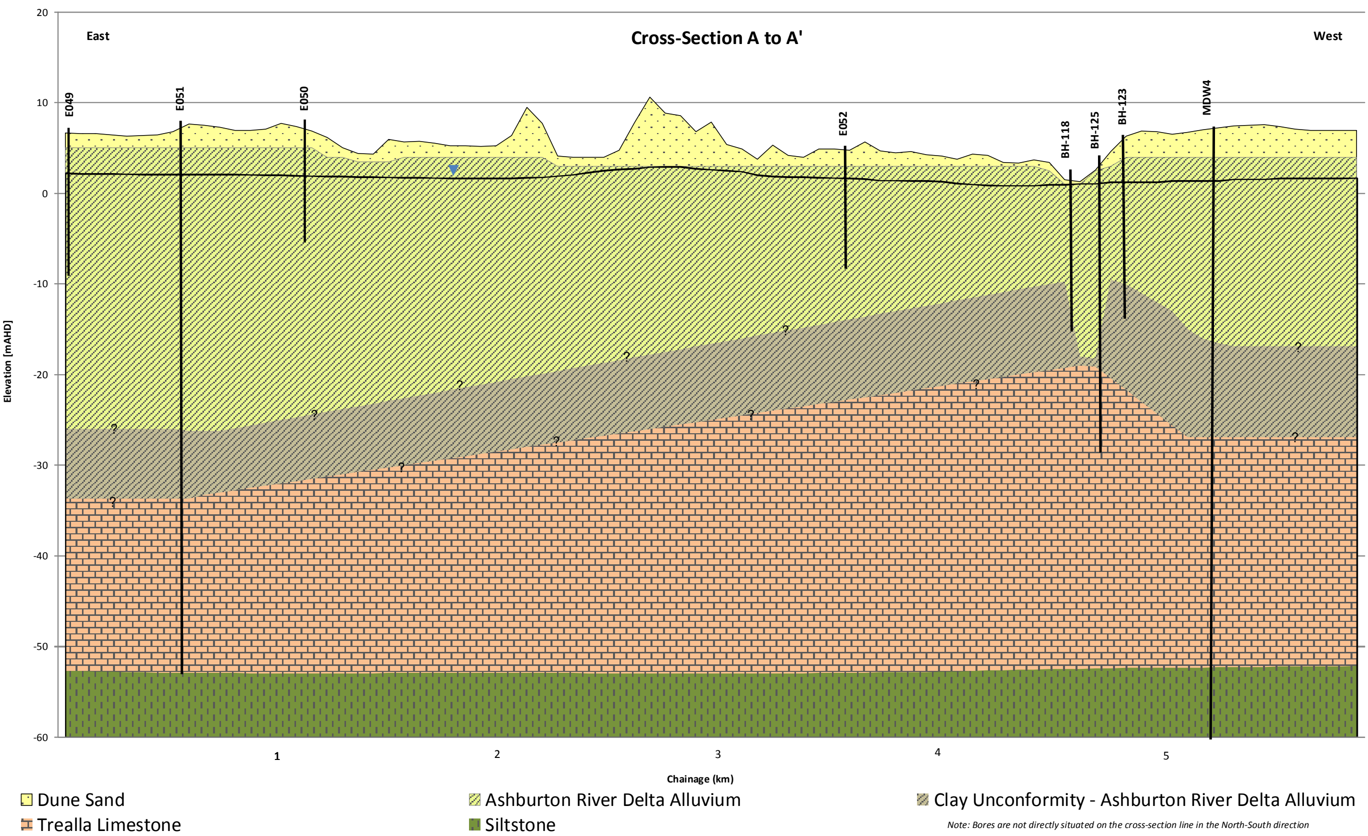
URS

BASELINE QUICK MUD CREEK ENVIRONMENT

Figure: 4-3

File No: 42908178-WG-061.mxd   Drawn: LS   Approved: IB   Date: 4/09/2013   Rev. A   A3





Scale: 1:60,000

0 500 1,000 Meters

N W E S

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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

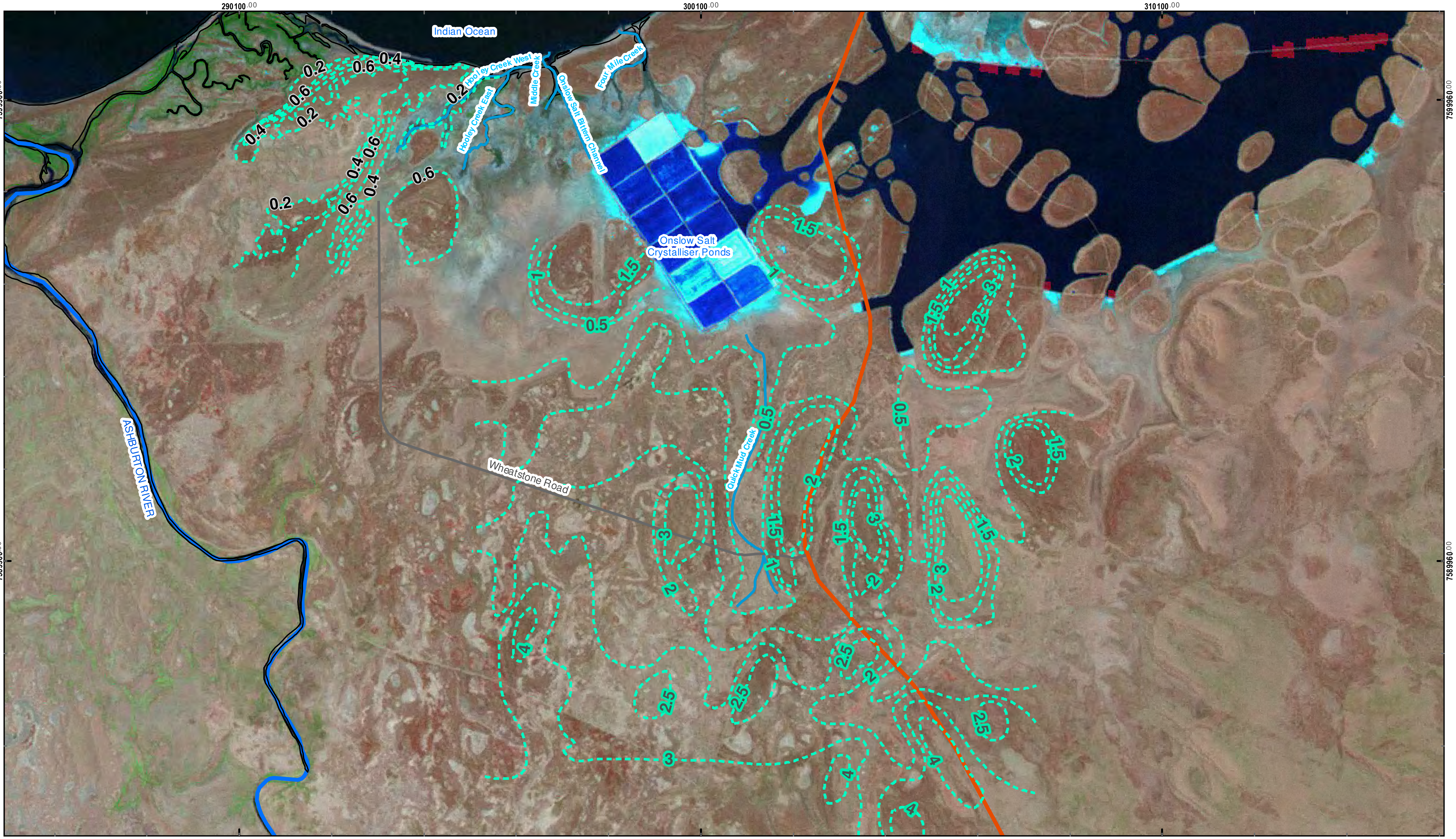
CROSS-SECTION A-A' AND LOCALITY MAP

URS

BASELINE QUICK MUD CREEK ENVIRONMENT

Figure: **4-4**

File No: **42908178-WG-065_RC.mxd** Drawn: **RM** Approved: **IGB** Date: **5/09/2013** Rev. **A** A4



N W E S

0 0.5 1 2 3 4 Kilometers

Interpreted Water Table Elevations (m AHD)
Local Watercourses
coastline

Scale at A3: 1:80,000
Coordinate System: GDA 1994 MGA Zone 50
Based on information provided by and with the permission of the Western Australian Land Information Authority trading as Landgate (2010).

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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

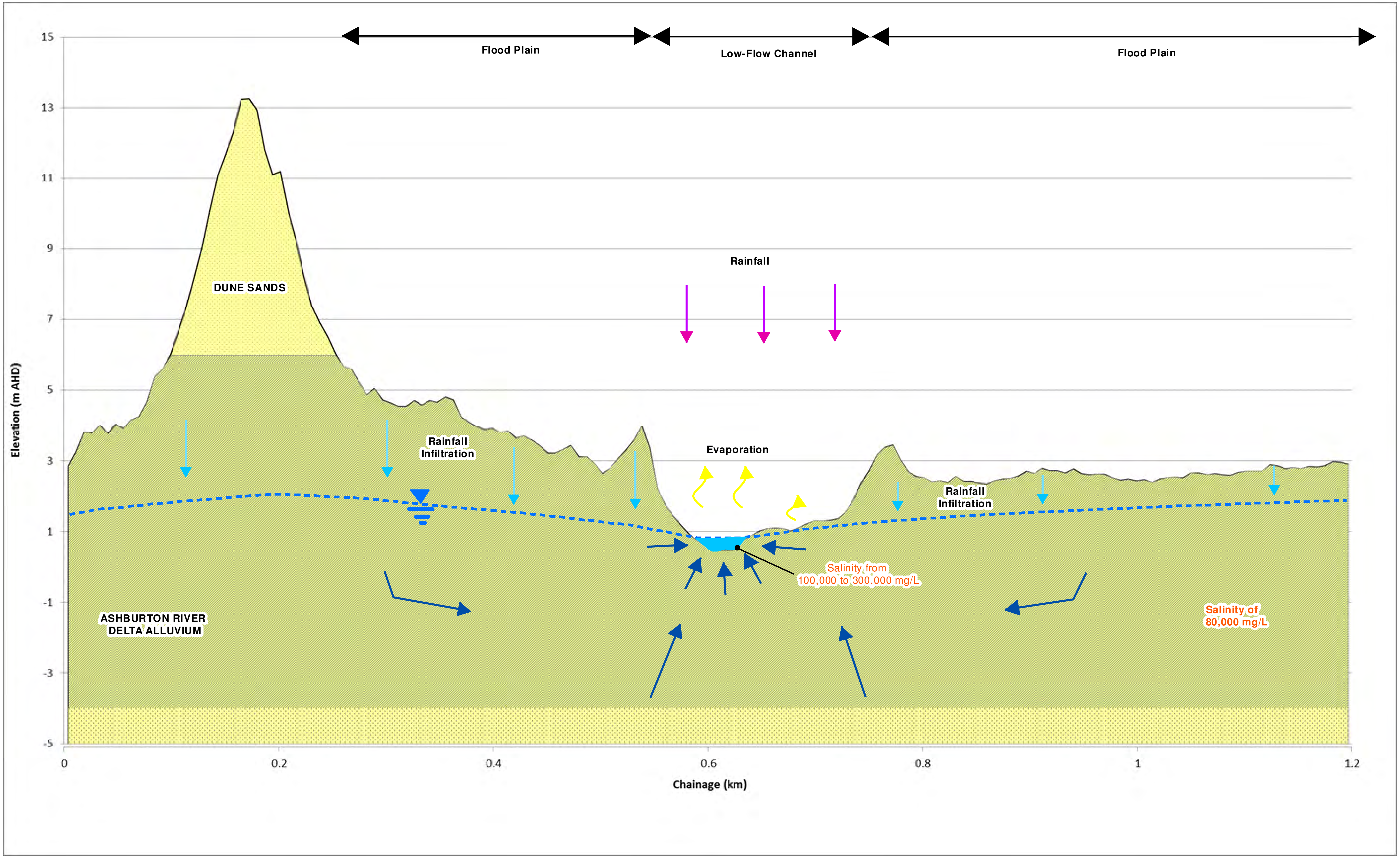
INTERPRETED BASELINE WATER TABLE ELEVATIONS

URS

BASELINE QUICK MUD CREEK ENVIRONMENT

Figure: 4-5

File No: 42908178-WG-062.mxd | Drawn: RM | Approved: IGB | Date: 9/12/2013 | Rev. A | A3



Scale at A3:
Coordinate System:
Based on information provided by and with the permission of the Western Australian Land Information Authority trading as Landgate (2010).

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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

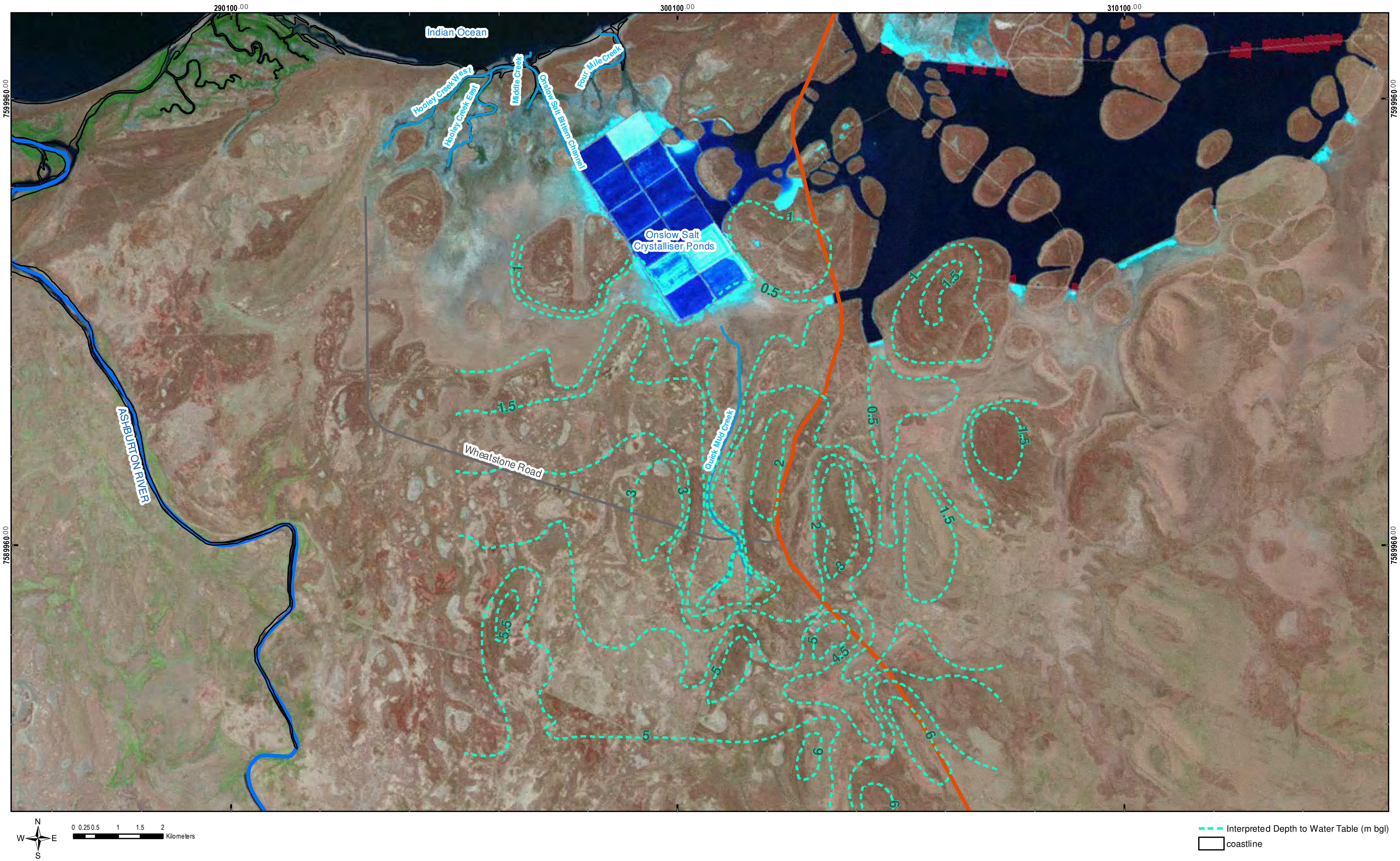
CROSS-SECTION OF QUICK MUD CREEK WATER TABLE SETTING

URS

BASELINE QUICK MUD CREEK ENVIRONMENT

File No: **42908178-WG-063.mxd** Drawn: **LS** Approved: **IGB** Date: **4/09/2013**

Figure: **4-6** Rev. **A** A3



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Coordinate System: GDA 1994 MGA Zone 50

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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

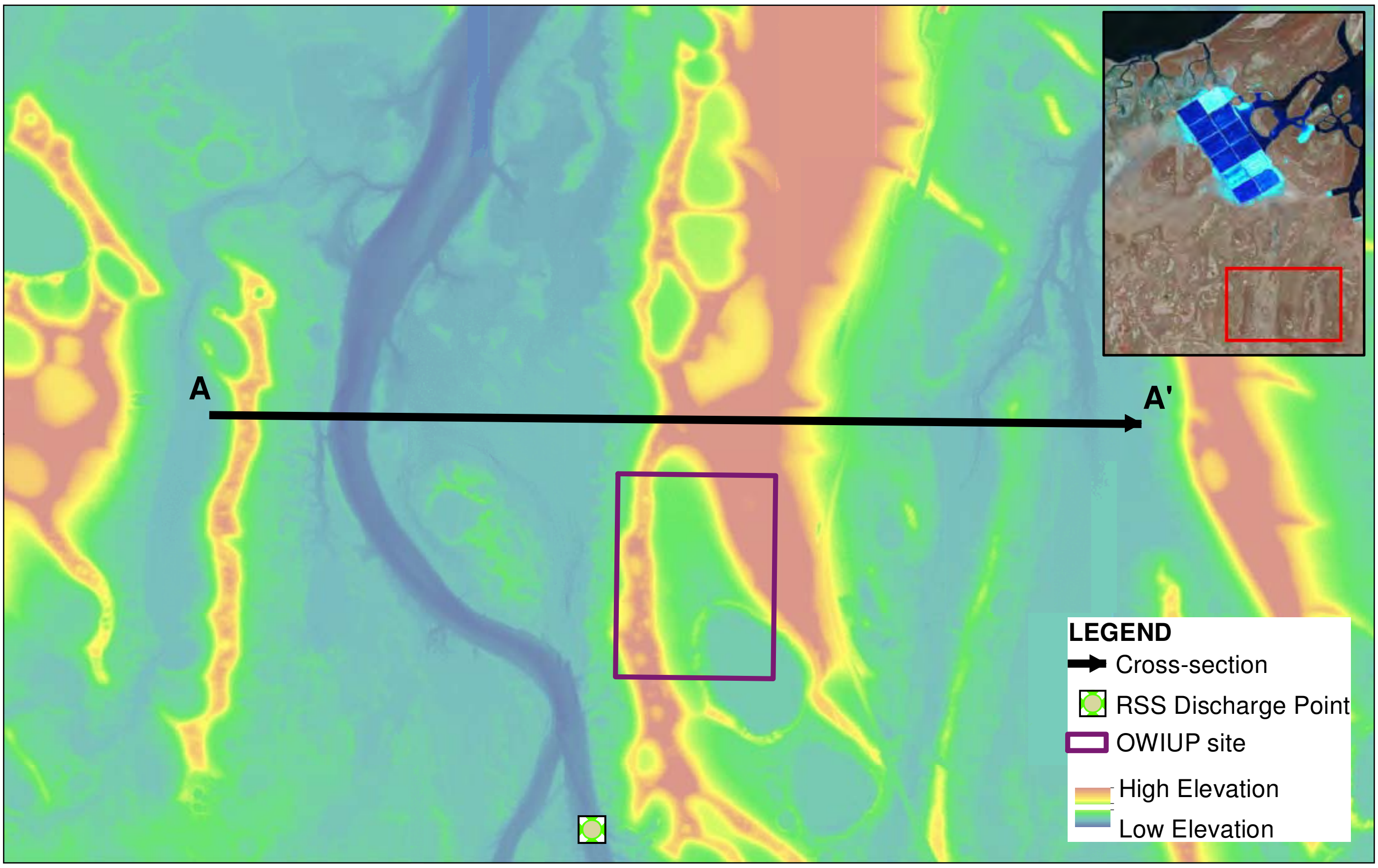
INTERPRETED BASELINE DEPTH TO WATER TABLE

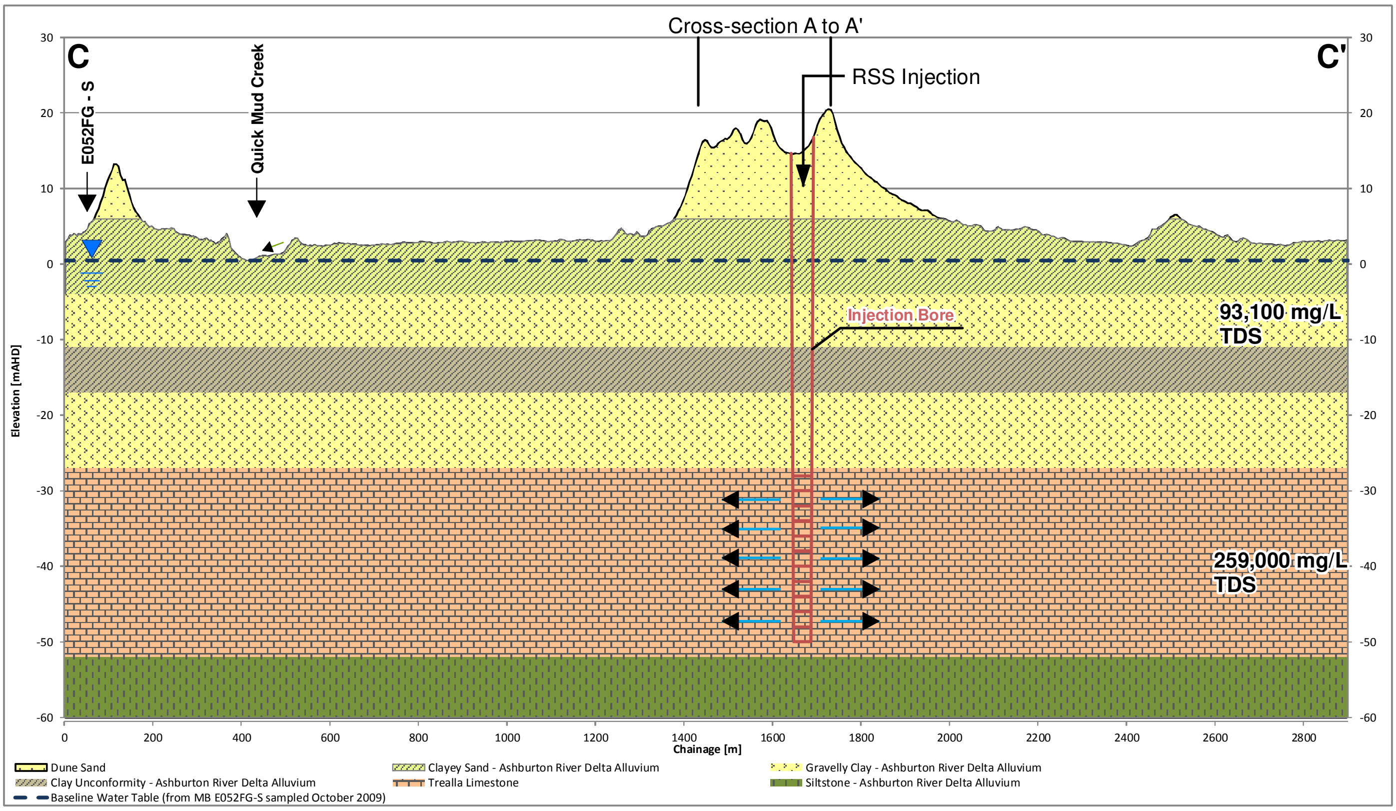
URS

BASELINE QUICK MUD CREEK ENVIRONMENT

Figure: **4-7**

File No: **42908178-WG-064.mxd** Drawn: **RM** Approved: **IGB** Date: **9/12/2013** Rev. **A** A3





N
W E
S

Scale: 1:25,000

0 500 1,000 Meters

Coordinate System: GCS GDA 1994

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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

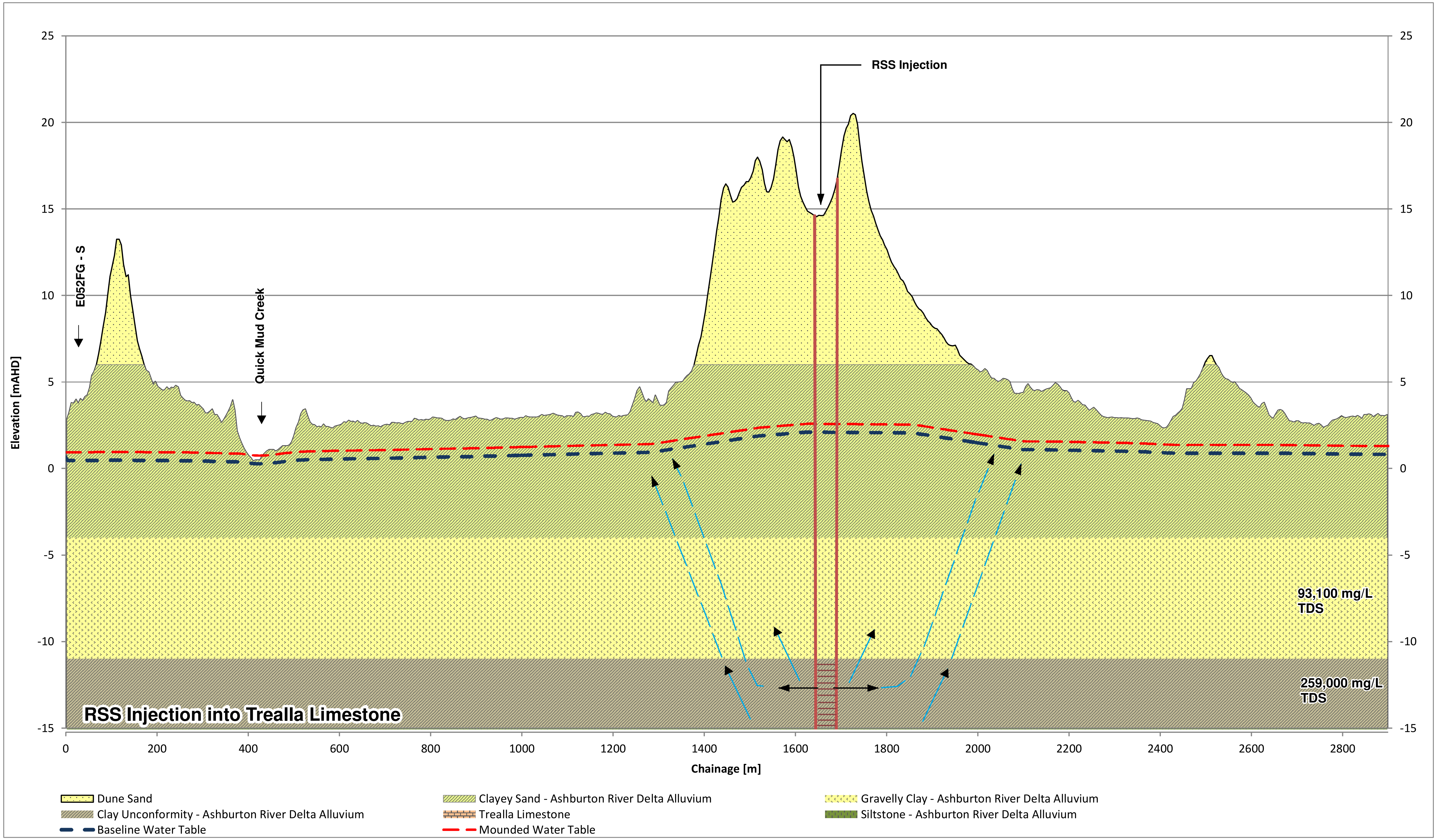
PREFERRED SETTING OF INJECTION FACILITIES

URS

ABSTRACTION AND INJECTION CONCEPT DEVELOPMENT

Figure: **5-1**

File No: **42908178-WG-073.mxd** Drawn: **AV** Approved: **LS** Date: **6/09/2013** Rev. **A** A4



Chevron

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

CROSS-SECTION OF THE RSS INJECTION THEME

URS

ASBTRACTION AND INJECTION CONCEPT DEVELOPMENT

Figure: **5-2**

File No: **42908178-WG-074.mxd** Drawn: **RM** Approved: **IGB** Date: **6/09/2013**

Rev. **A** A3

Scale: 1:23,944
Coordinate System: GDA 1994 MGA Zone 50
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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

PRELIMINARY CONCEPTUAL DESIGN SETTING

URS

INJECTION AND ABSTRACTION PRELIMINARY CONCEPTUAL DESIGN

Figure: **5-3**

File No: **42908178-WG-080.mxd** Drawn: **LS** Approved: **IB** Date: **9/12/2013** Rev. **A** A4

Coordinate System: GCS GDA 1994

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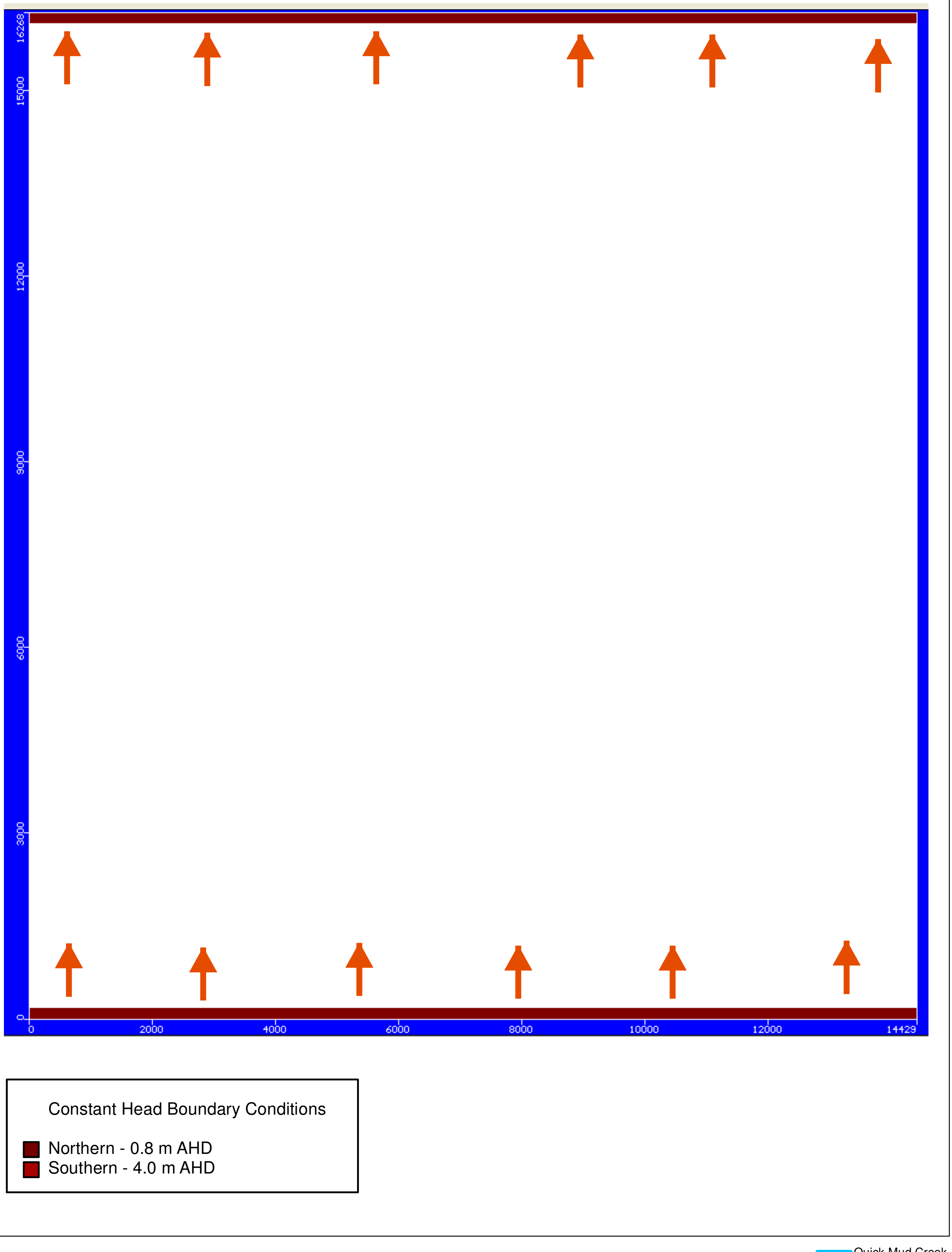
ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

MODEL DOMAIN

URS

GROUNDWATER RESOURCE MODELLING

File No: **42908178-WG-066.mxd**	Drawn: **RM**	Approved: **IGB**	Date: **9/12/2013**	Figure: **6-1** Rev. **A**	A4



Coordinate System: Model Grid

Chevron

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

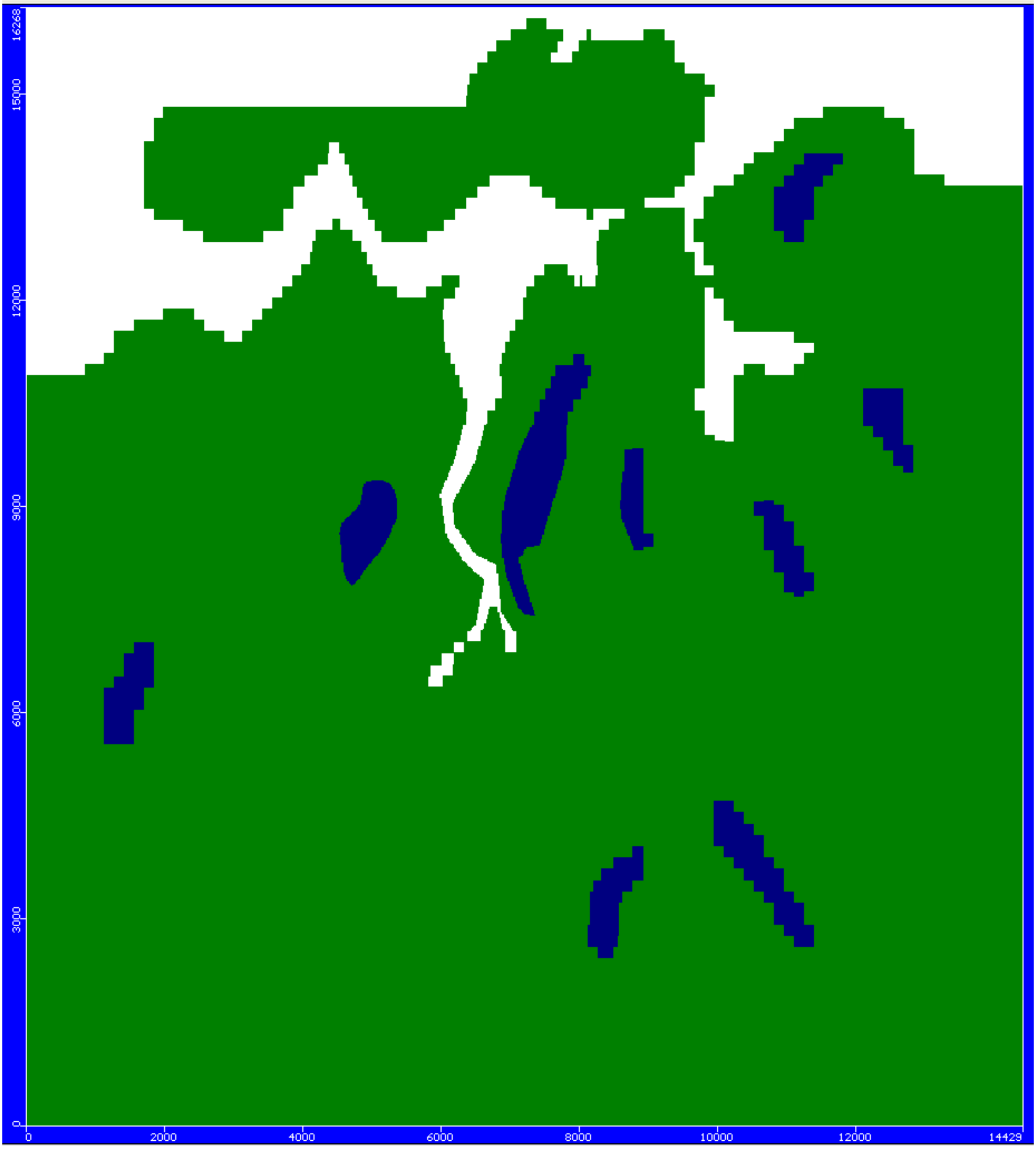
MODEL BOUNDARY CONDITIONS

URS

GROUNDWATER RESOURCE MODELLING

Figure: **6-2**

File No: **42908178-WG-068.mxd** Drawn: **RM** Approved: **IGB** Date: **9/12/2013** Rev. **A** A4



Recharge and Evaporation Distribution in Model Domain

Recharge (mm/annum)	Evaporation (mm/annum)	Extinction Depth (m)
6.46 (2 per cent average annual rainfall)	1051	1.5
16.16 (5 per cent average annual rainfall)	2067	3
48.47 (15 per cent average annual rainfall)	3082	3

Quick Mud Creek
OWIUP site

N W E S

Coordinate System: Model Grid

Chevron

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

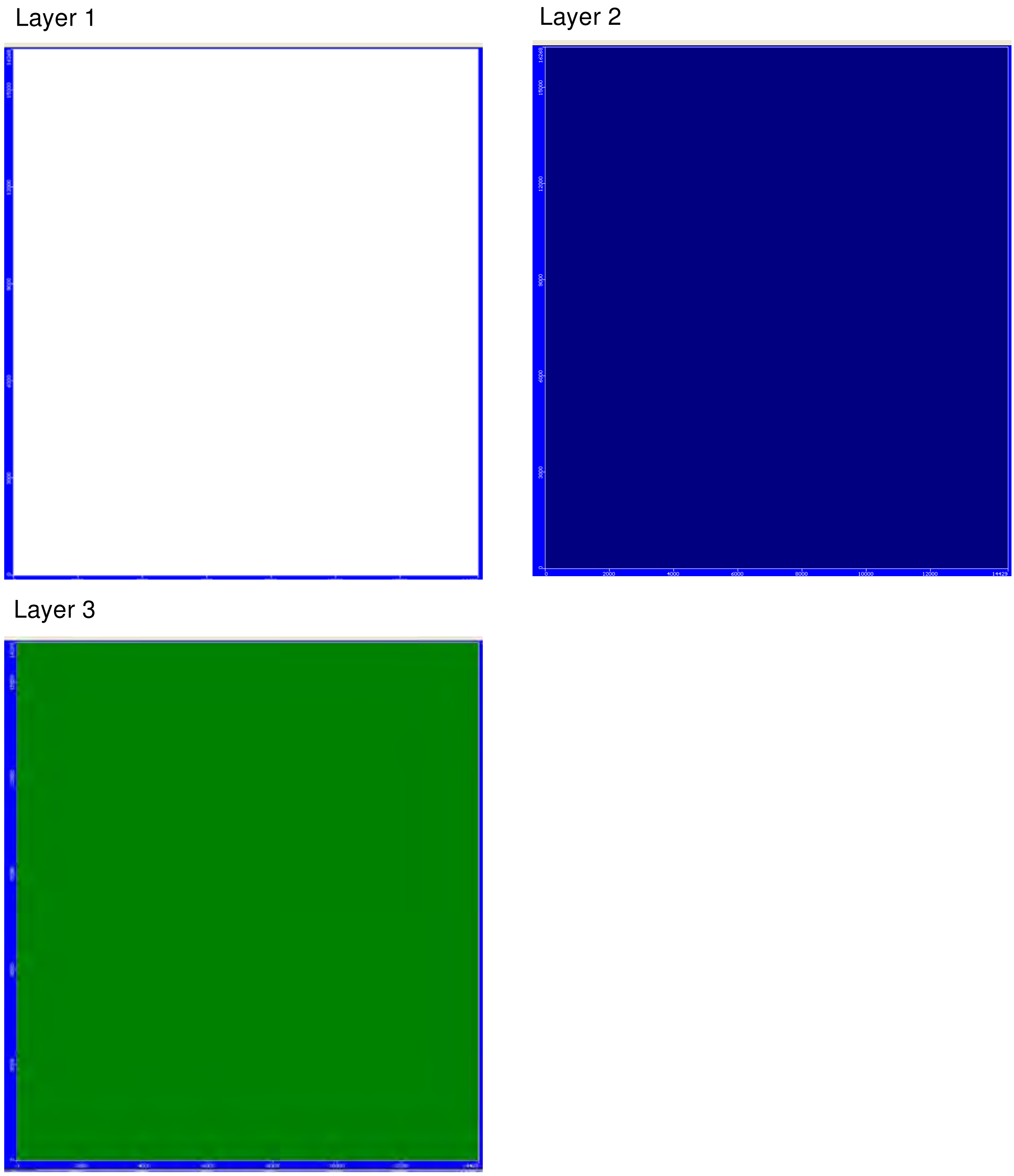
MODEL RECHARGE AND EVAPORATION DOMAINS

URS

GROUNDWATER RESOURCE MODELLING

Figure: **6-3**

File No: **42908178-WG-067.mxd** Drawn: **RM** Approved: **IGB** Date: **9/12/2013** Rev. **A** A4



Hydraulic Conductivity Distributions

Zone		Kx (m/day)	Ky (m/day)	Kz (m/day)
1	Superficial Formations	1	1	0.1
2	Ashburton River Delta Clay and Unconformity	0.2	0.2	0.02
3	Trealla Limestone	0.6	0.6	0.06

N
W E
S

Coordinate System: Model Grid

Chevron

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

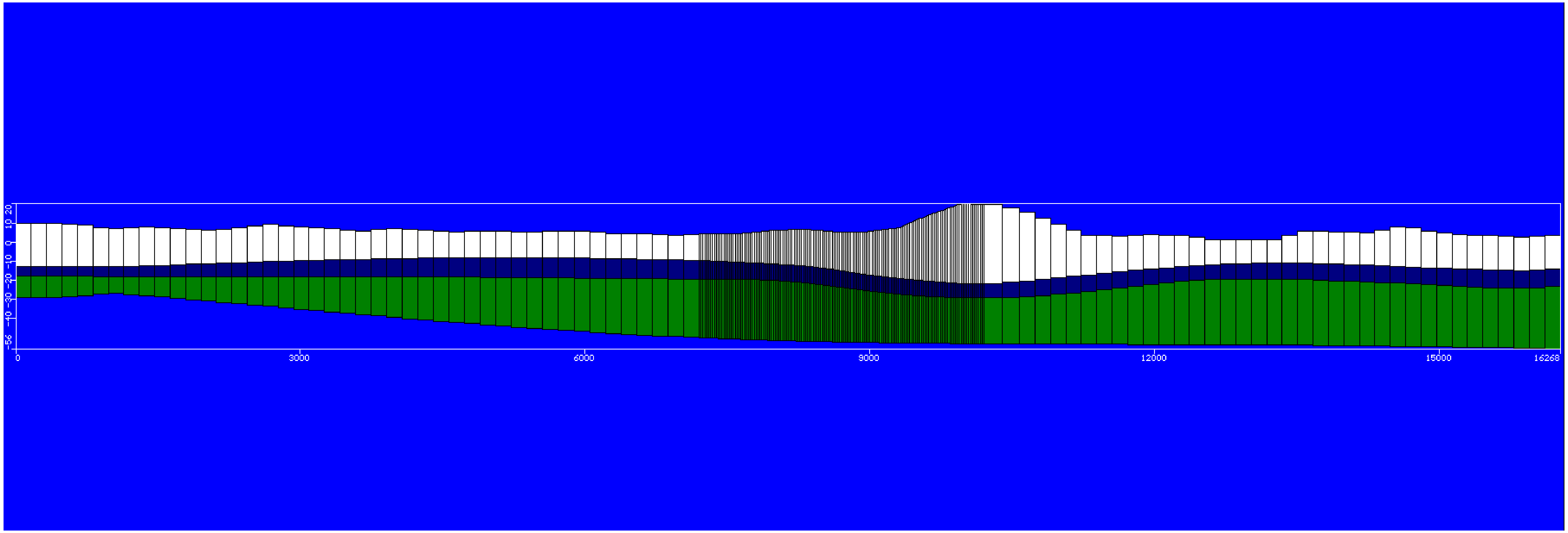
SIMULATED HYDRAULIC CONDUCTIVITY DISTRIBUTION PLAN VIEWS

URS

GROUNDWATER RESOURCE MODELLING

Figure: **6-4**

File No: **42908178-WG-069.mxd** Drawn: **RM** Approved: **IGB** Date: **9/12/2013** Rev. **A** A4



Hydraulic Conductivity Distributions

Zone		Kx (m/day)	Ky (m/day)	Kz (m/day)
1	Superficial Formations	1	1	0.1
2	Ashburton River Delta Clay and Unconformity	0.2	0.2	0.02
3	Trealla Limestone	0.6	0.6	0.06

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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

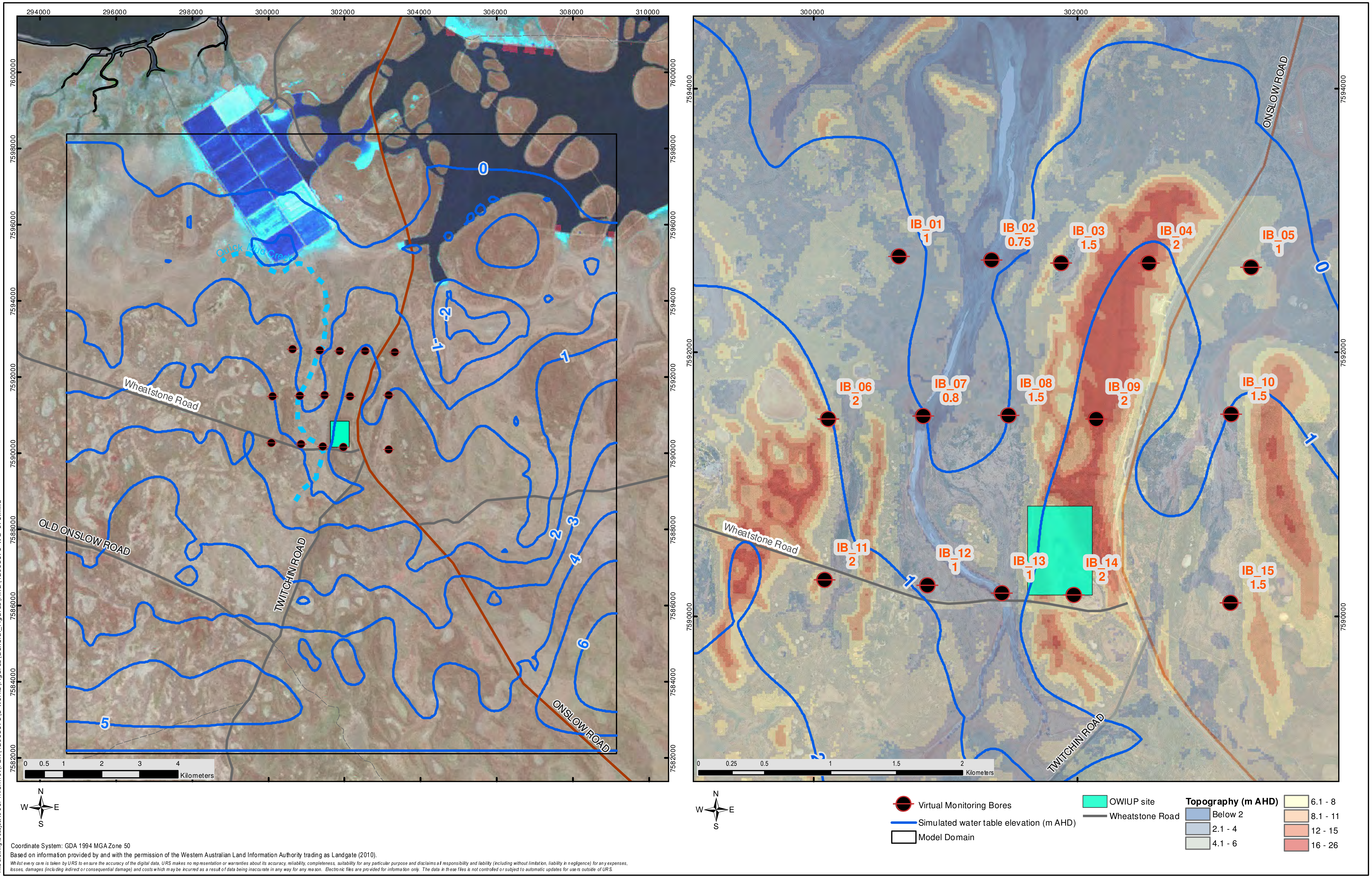
SIMULATED HYDRAULIC CONDUCTIVITY DISTRIBUTION CROSS-SECTION VIEW

URS

GROUNDWATER RESOURCE MODELLING

Figure: **6-5**

File No: **42908178-WG-070.mxd** Drawn: **RM** Approved: **IGB** Date: **6/09/2013** Rev. **A** A3



Coordinate System: GDA 1994 MGA Zone 50

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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

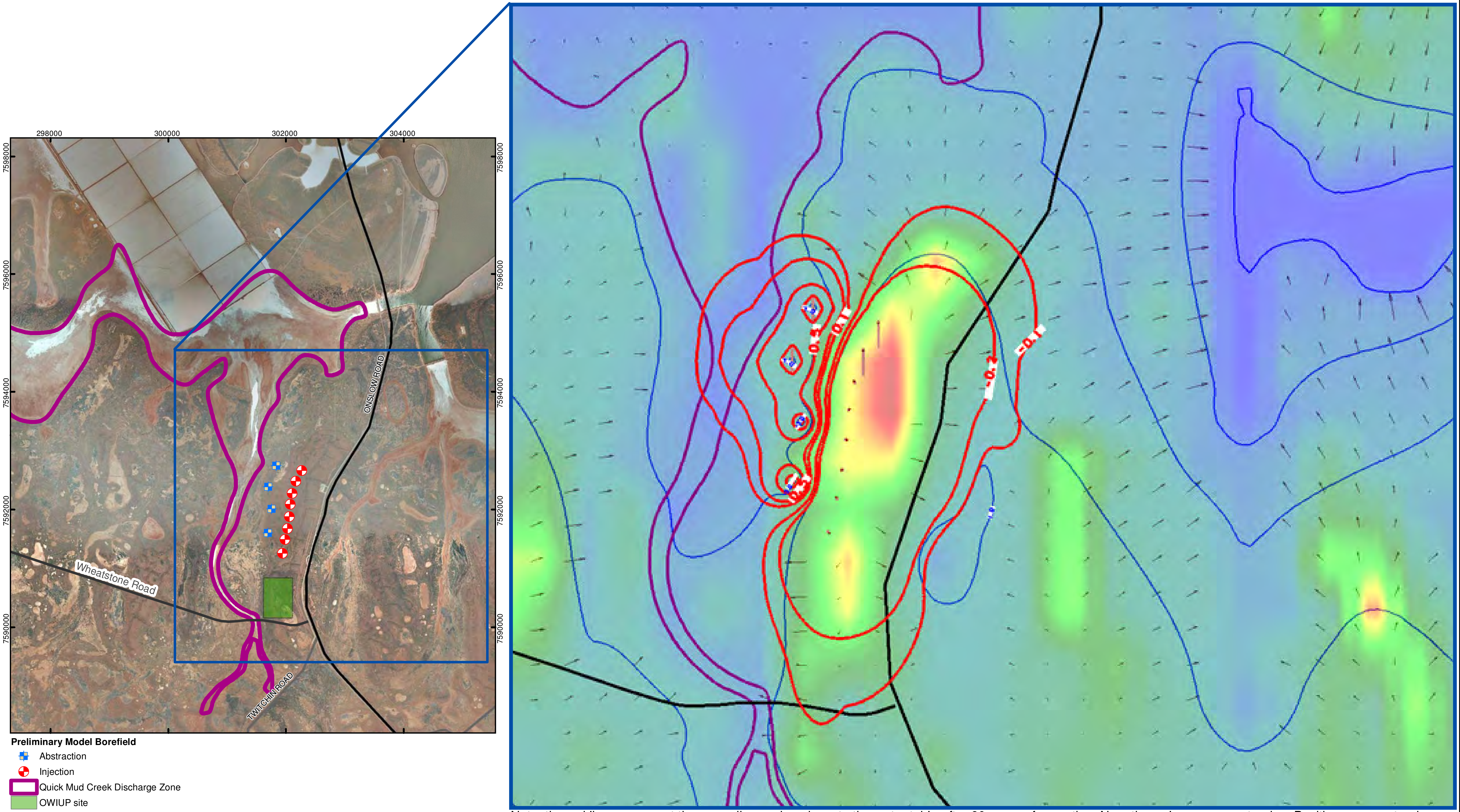
SIMULATED WATER TABLE ELEVATION

URS

GROUNDWATER RESOURCE MODELLING

File No: 42908178-WG-071.mxd Drawn: RM Approved: IGB Date: 9/12/2013

Figure: 6-6 Rev. A A3



Preliminary Model Borefield

- Abstraction
- Injection
- Quick Mud Creek Discharge Zone
- OWIUP site

Note: the red lines represent the mounding or drawdown to the water table after 80 years of operation. Negative values represent a rise. Positive represent a drop.

N W E S

0 0.25 0.5 1 1.5 2 Kilometers

Scale at A3: 1:62,456
Coordinate System: GDA 1994 MGA Zone 50
Based on information provided by and with the permission of the Western Australian Land Information Authority trading as Landgate (2010).

Chevron

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

PRELIMINARY CONCEPT DESIGN
INJECTION AND ABSTRACTION
MAXIMUM FOOTPRINTS ON THE WATER TABLE

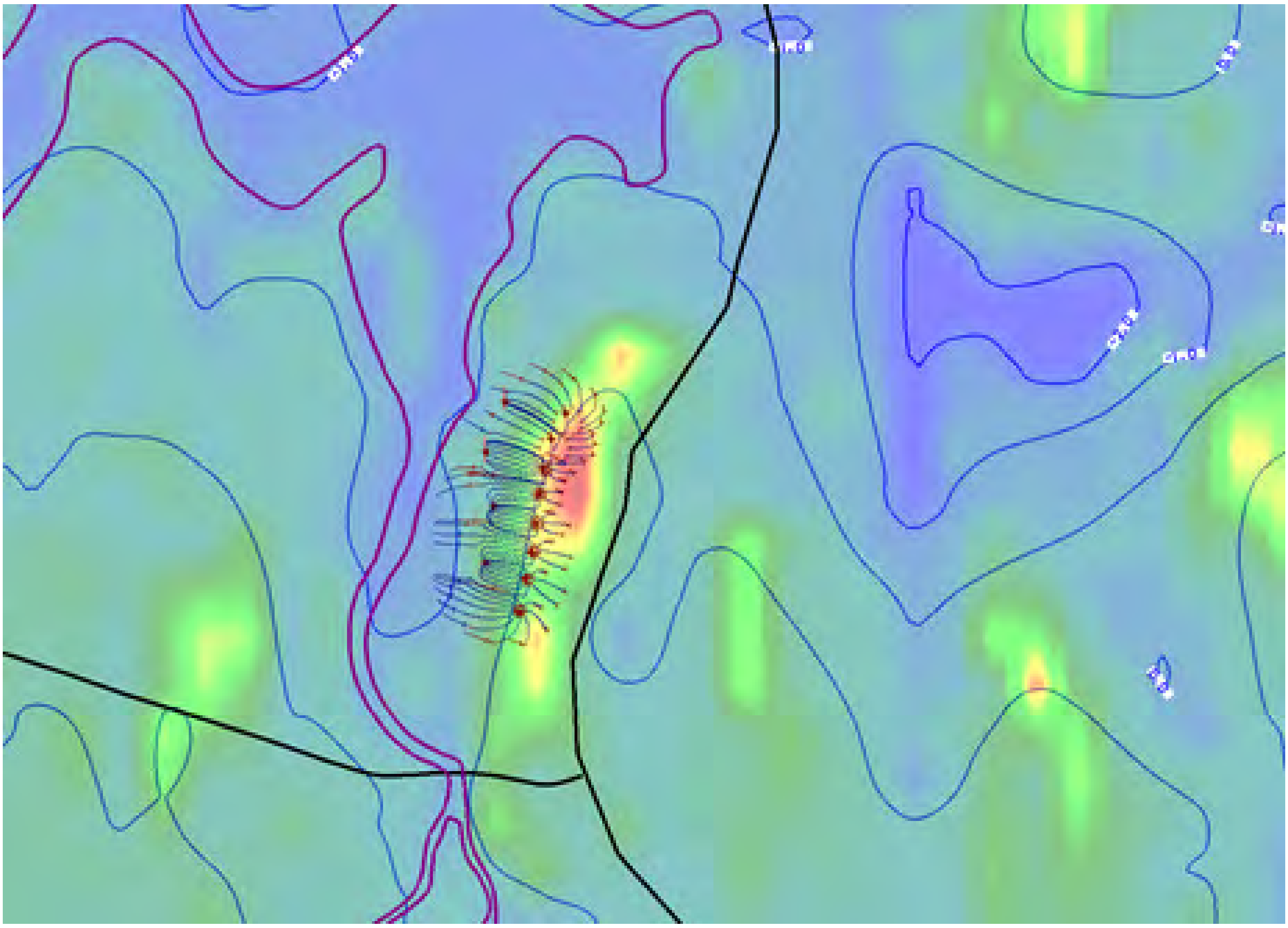
URS

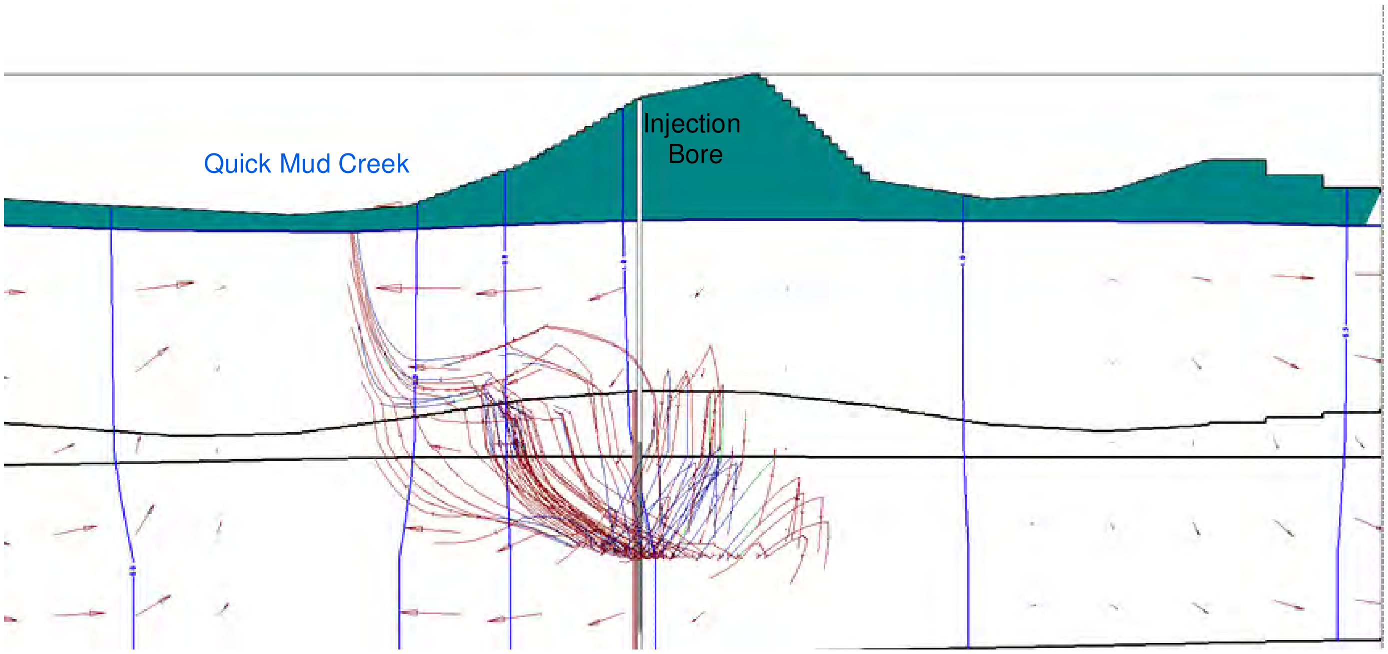
GROUNDWATER RESOURCE MODELLING

File No: **42908178-WG-082.mxd** Drawn: **RM** Approved: **IGB** Date: **9/12/2013**

Figure: **6-7**

Rev. **A** A3





Particle Direction (Cross-section view)

- Inward
- Outward
- In Plane

Based on Modflow modelling outputs (URS, September 2013)

Chevron

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

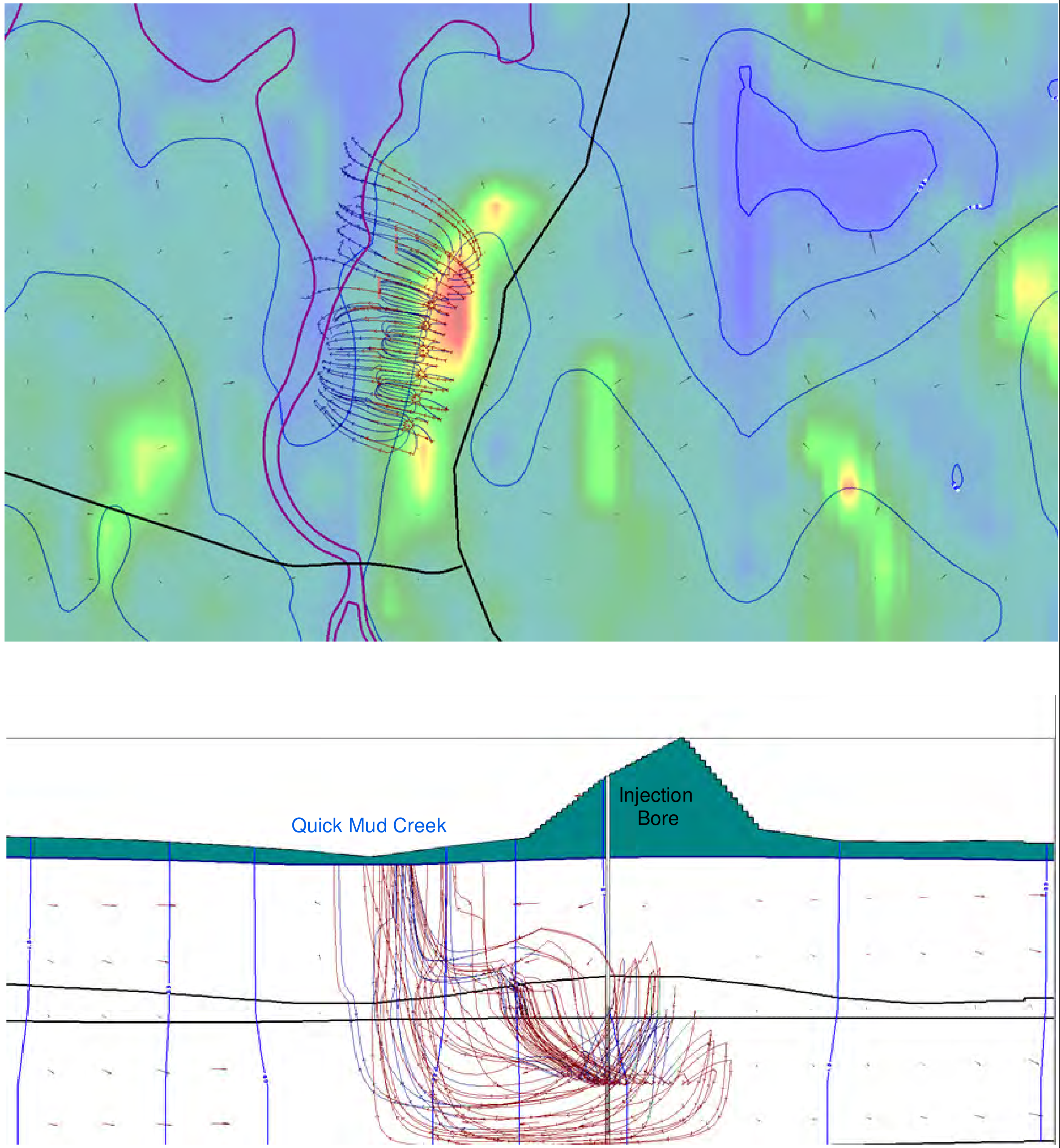
**PRELIMINARY CONCEPT DESIGN
PARTICLE-TRACKING FOOTPRINTS
AFTER 232 YEARS**

URS

GROUNDWATER RESOURCE MODELLING

Figure: **6-8**

File No: **42908178-WG-090.mxd** Drawn: **LS** Approved: **IB** Date: **9/12/2013** Rev. **A** A4



Particle Direction (Cross-section view)

- Inward
- Outward
- In Plane

Based on Modflow modelling outputs (URS, September 2013)

Chevron

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

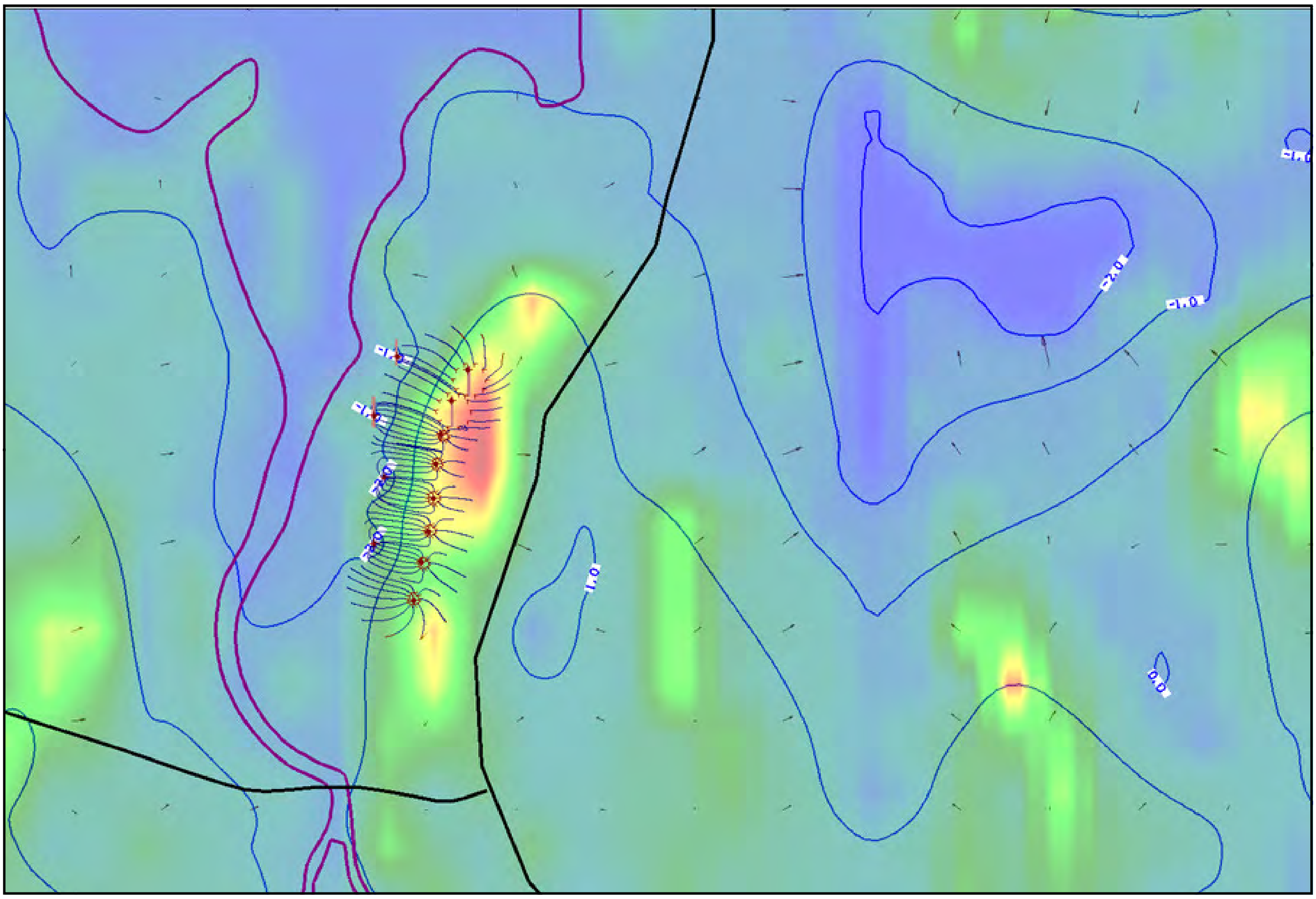
PRELIMINARY CONCEPT DESIGN
PARTICLE-TRACKING FOOTPRINTS
AFTER 3,000 YEARS

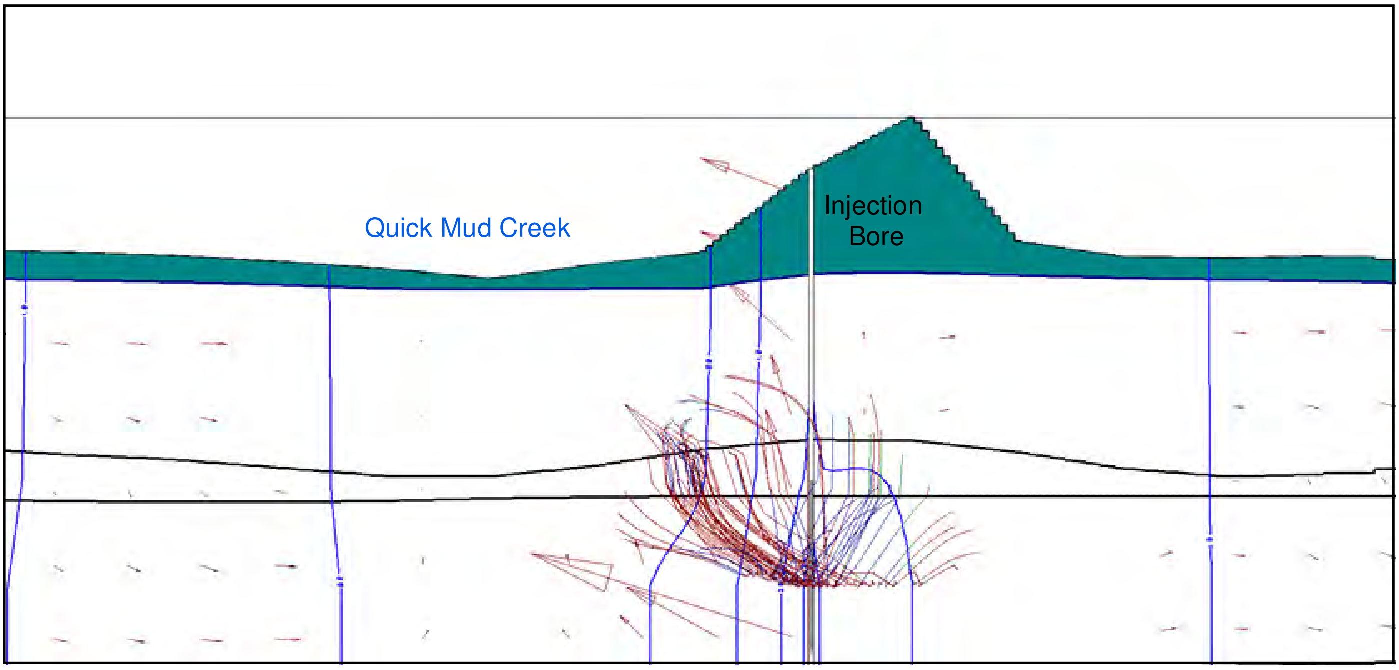
URS

GROUNDWATER RESOURCE MODELLING

Figure: **6-9**

File No: **42908178-WG-086.mxd** Drawn: **LS** Approved: **IB** Date: **9/12/2013** Rev. **A** A4





Particle Direction (Cross-section view)

- Inward
- Outward
- In Plane

Based on Modflow modelling outputs (URS, September 2013)

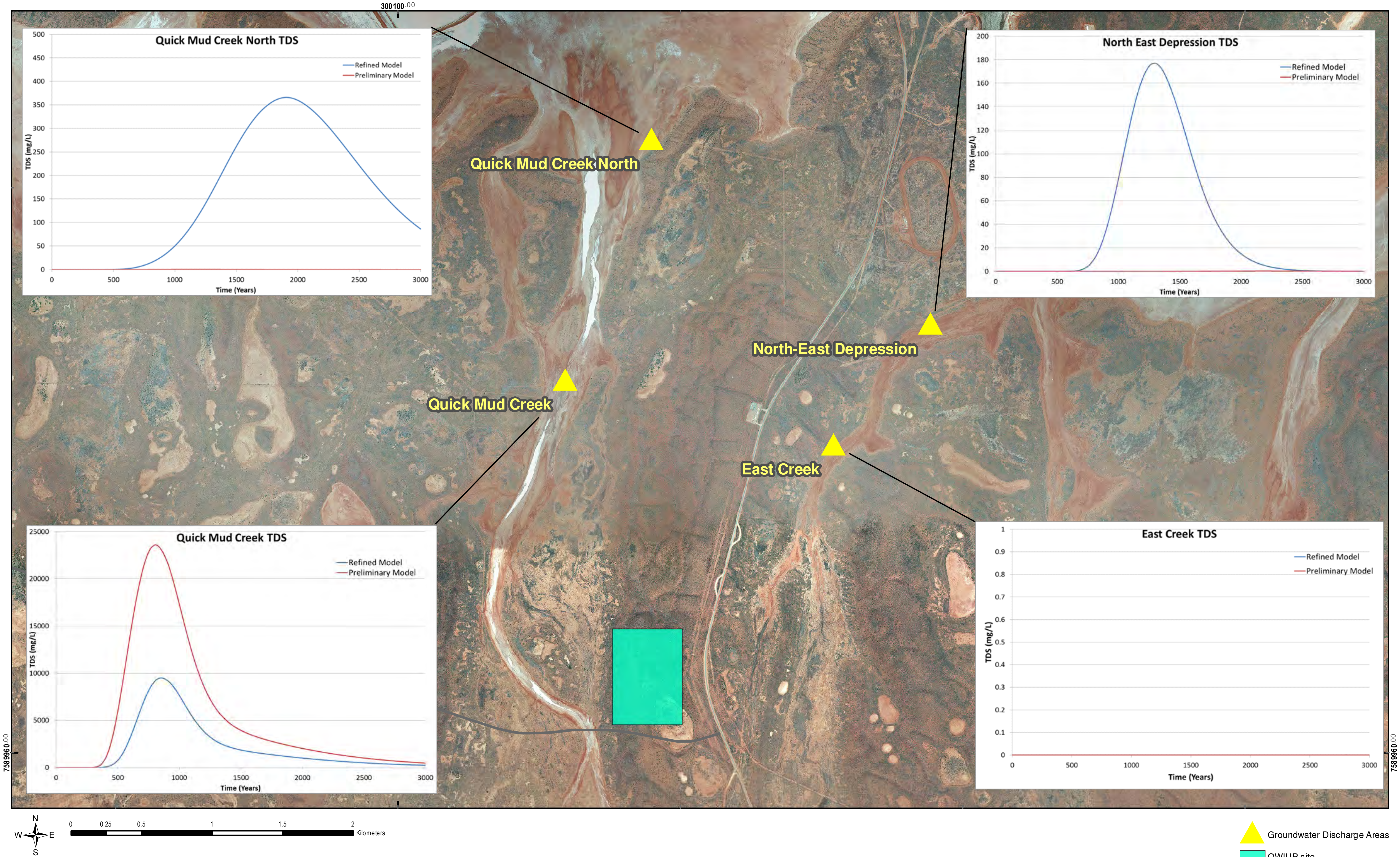
ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

PRELIMINARY CONCEPT DESIGN PARTICLE-TRACKING FOOTPRINTS AFTER 80 YEARS

GROUNDWATER RESOURCE MODELLING

Figure: **6-10**

File No: **42908178-WG-085.mxd** Drawn: **LS** Approved: **IB** Date: **9/12/2013** Rev. **A** A4



Scale at A3: 1:25,293

Coordinate System: GDA 1994 MGA Zone 50

Based on information provided by and with the permission of the Western Australian Land Information Authority trading as Landgate (2010).

Chevron

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

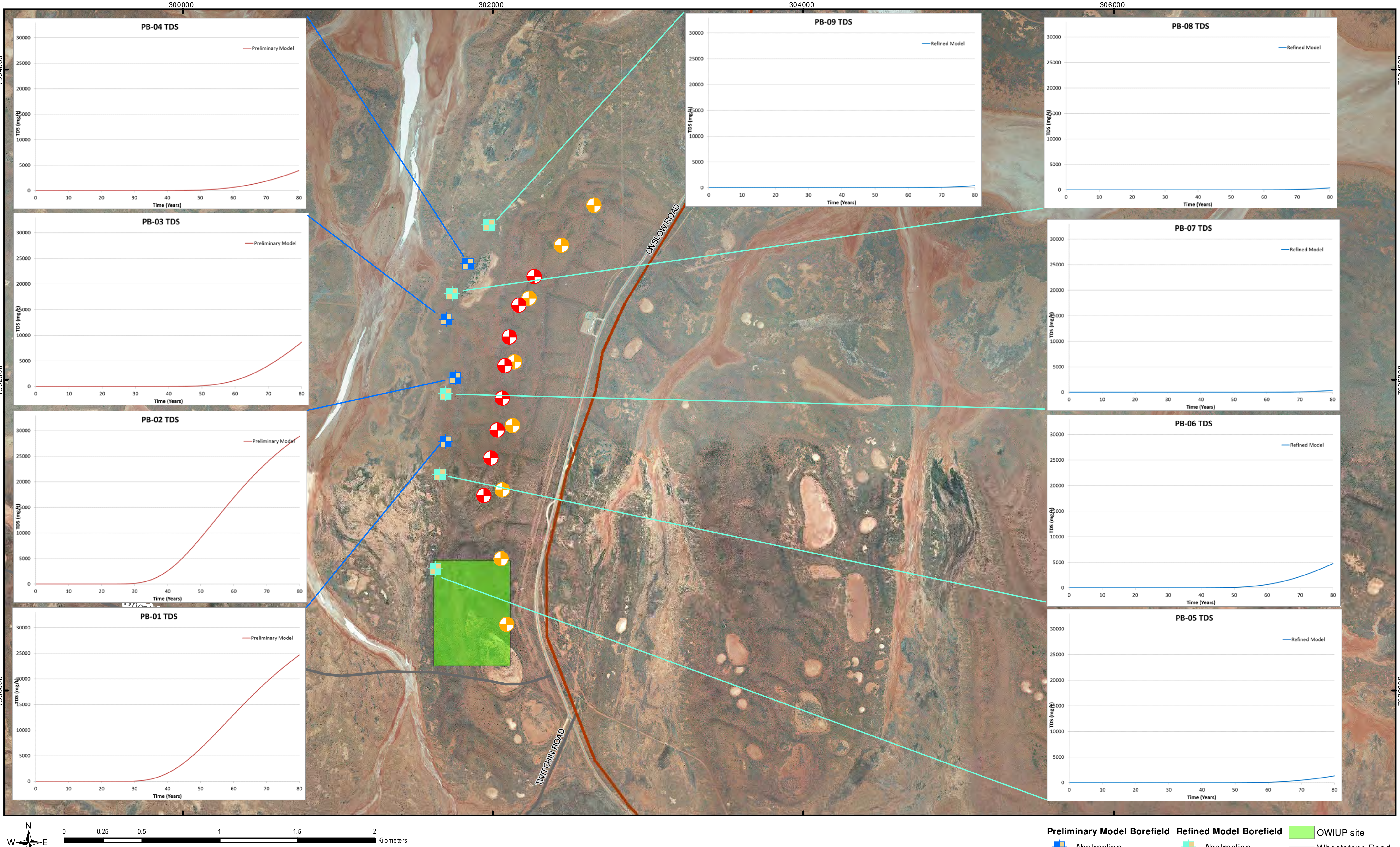
TDS DISCHARGE INTO THE GROUNDWATER DISCHARGE AREAS

URS

GROUNDWATER RESOURCE MODELLING

Figure: 6-11

File No: 42908178-WG-078.mxd | Drawn: LS | Approved: IGB | Date: 9/12/2013 | Rev. A | A3



Scale at A3: 1:23,256

Coordinate System: GDA 1994 MGA Zone 50

Based on information provided by and with the permission of the Western Australian Land Information Authority trading as Landgate (2010).

Chevron

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

TDS PUMPED FROM THE ABSTRACTION BORES

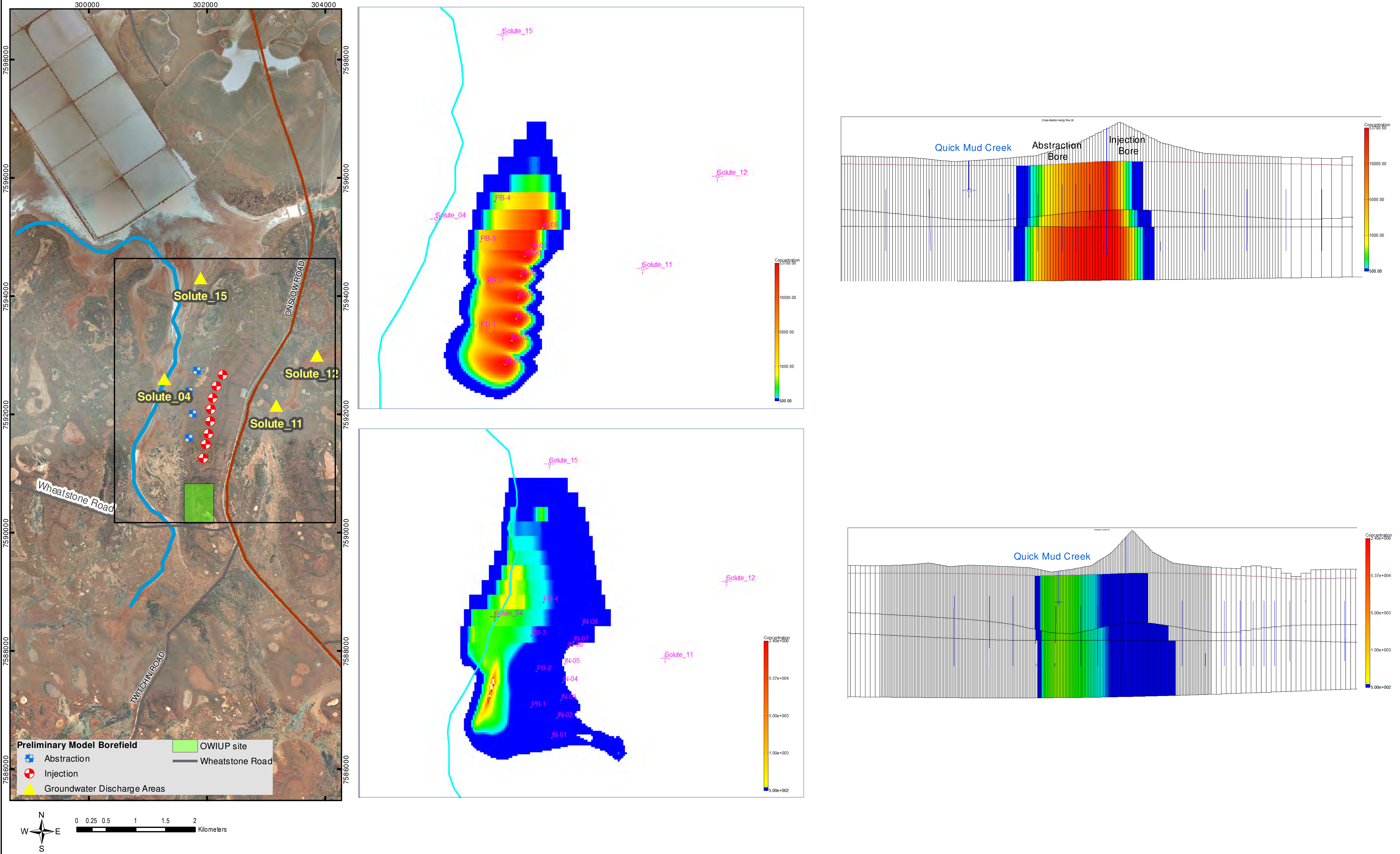
URS

GROUNDWATER RESOURCE MODELLING

File No: 42908178-WG-079.mxd | Drawn: LS | Approved: IGB | Date: 9/12/2013

Figure: 6-12

Rev. A | A3



Scale at A3: 1:60,000

Coordinate System: GDA 1994 MGA Zone 50

Based on information provided by and with the permission of the Western Australian Land Information Authority trading as Landgate (2010).

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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

PRELIMINARY CONCEPT DESIGN
TDS PLUMES AFTER 80 AND 800 YEARS

URS

GROUNDWATER RESOURCE MODELLING

Figure: **6-13**

File No: **42908178-WG-087.mxd** Drawn: **LS** Approved: **IGB** Date: **9/12/2013** Rev. **A** A3

N
W E
S

0 500 1,000 m

Refined Model Borefield
Abstraction
Injection

OWIUP site
Wheatstone Road
1:100 year ARI Flood Footprint

Scale: 1:23,944
Coordinate System: GDA 1994 MGA Zone 50
Based on information provided by and with the permission of the Western Australian Land Information Authority trading as Landgate (2010).

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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

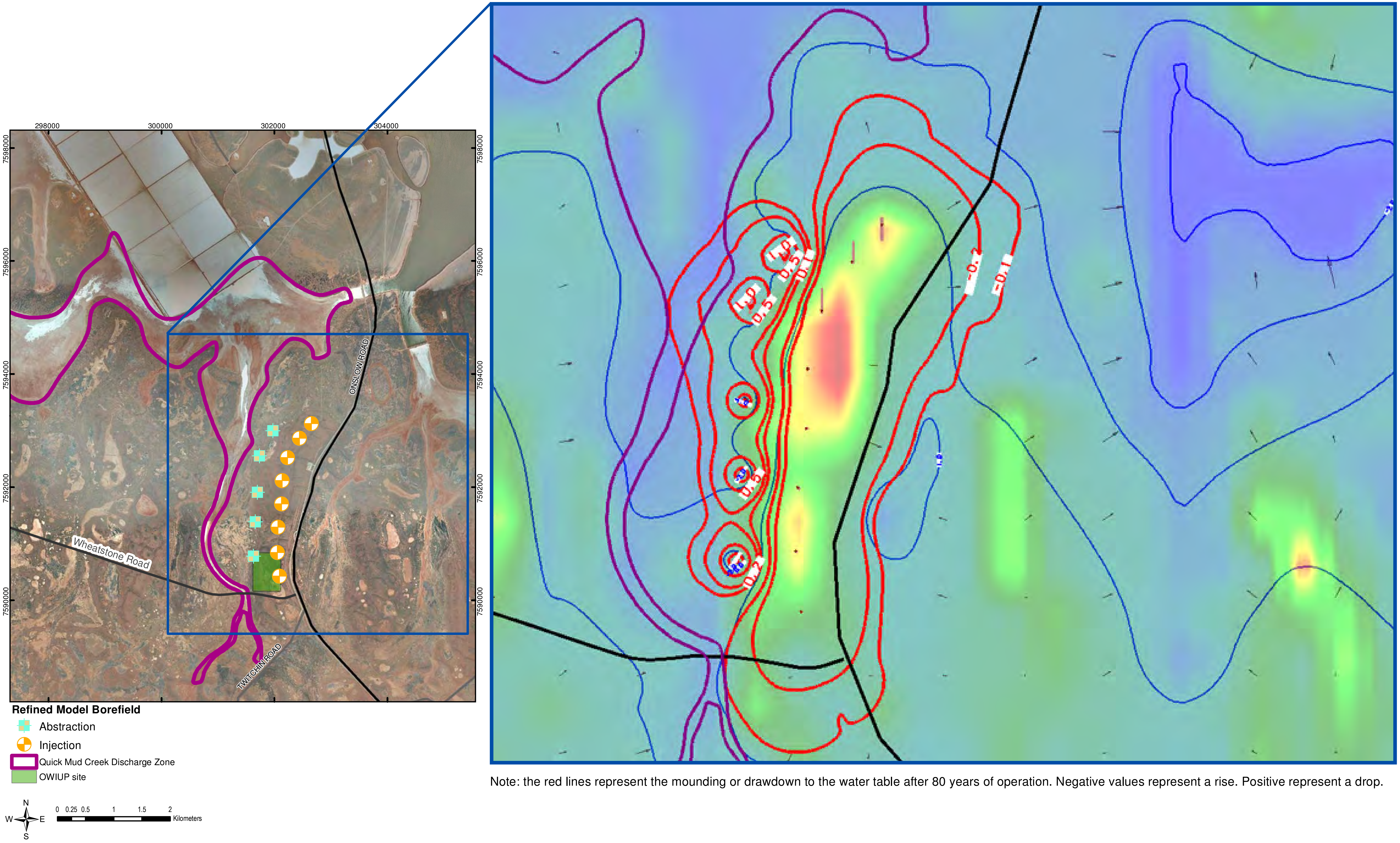
REFINED CONCEPTUAL DESIGN SETTING

URS

INJECTION AND ABSTRACTION PRELIMINARY CONCEPTUAL DESIGN

Figure: **6-14**

File No: **42908178-WG-091.mxd** Drawn: **LS** Approved: **IB** Date: **9/12/2013** Rev. **A** A4



Note: the red lines represent the mounding or drawdown to the water table after 80 years of operation. Negative values represent a rise. Positive represent a drop.

Scale at A3: 1:62,456
Coordinate System: GDA 1994 MGA Zone 50
Based on information provided by and with the permission of the Western Australian Land Information Authority trading as Landgate (2010).

Chevron

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

REFINED CONCEPT DESIGN
INJECTION AND ABSTRACTION
MAXIMUM FOOTPRINTS ON THE WATER TABLE

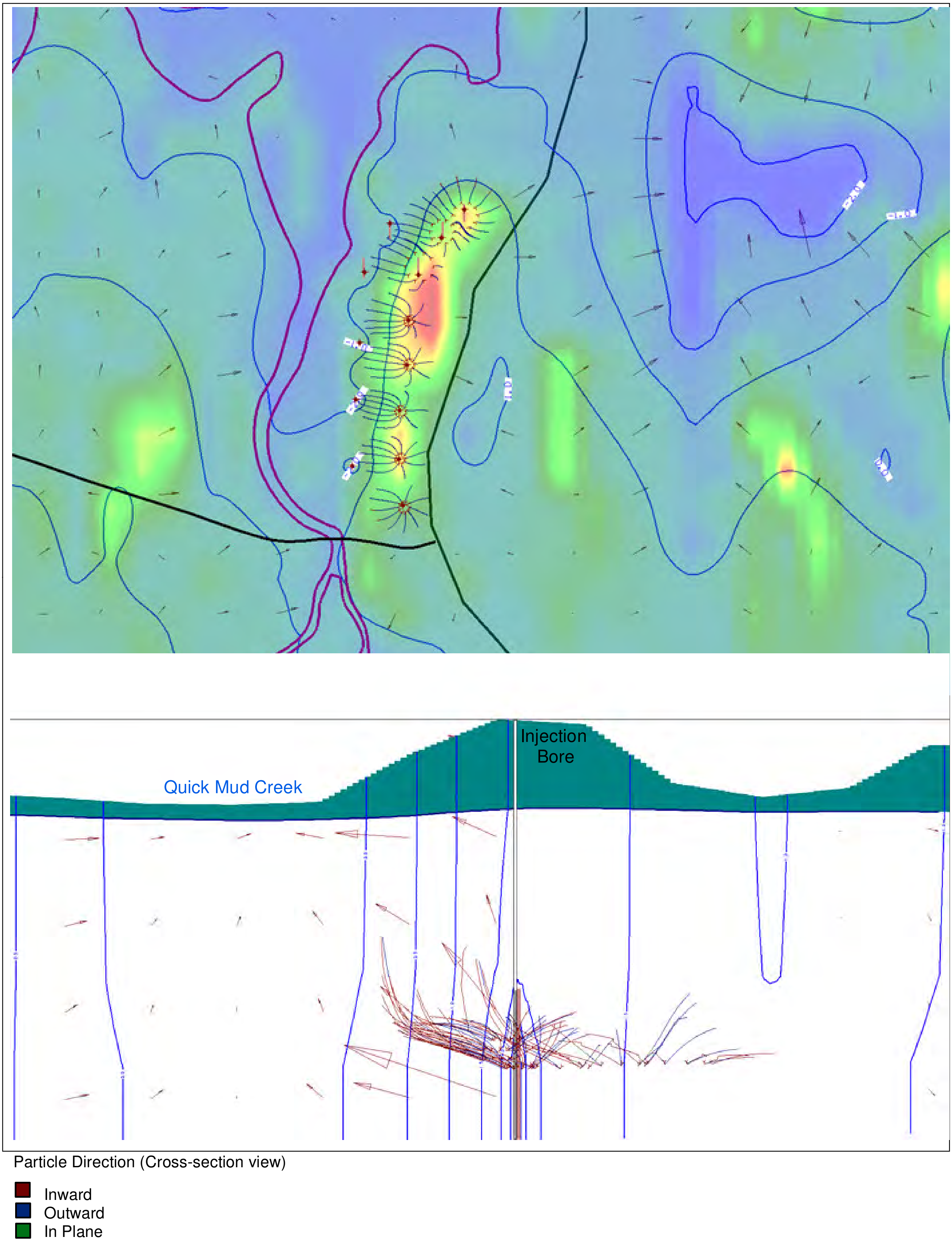
URS

GROUNDWATER RESOURCE MODELLING

File No: 42908178-WG-081.mxd | Drawn: RM | Approved: IGB | Date: 9/12/2013

Figure: 6-15

Rev. A | A3



Based on Modflow modelling outputs (URS, September 2013)

Chevron

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

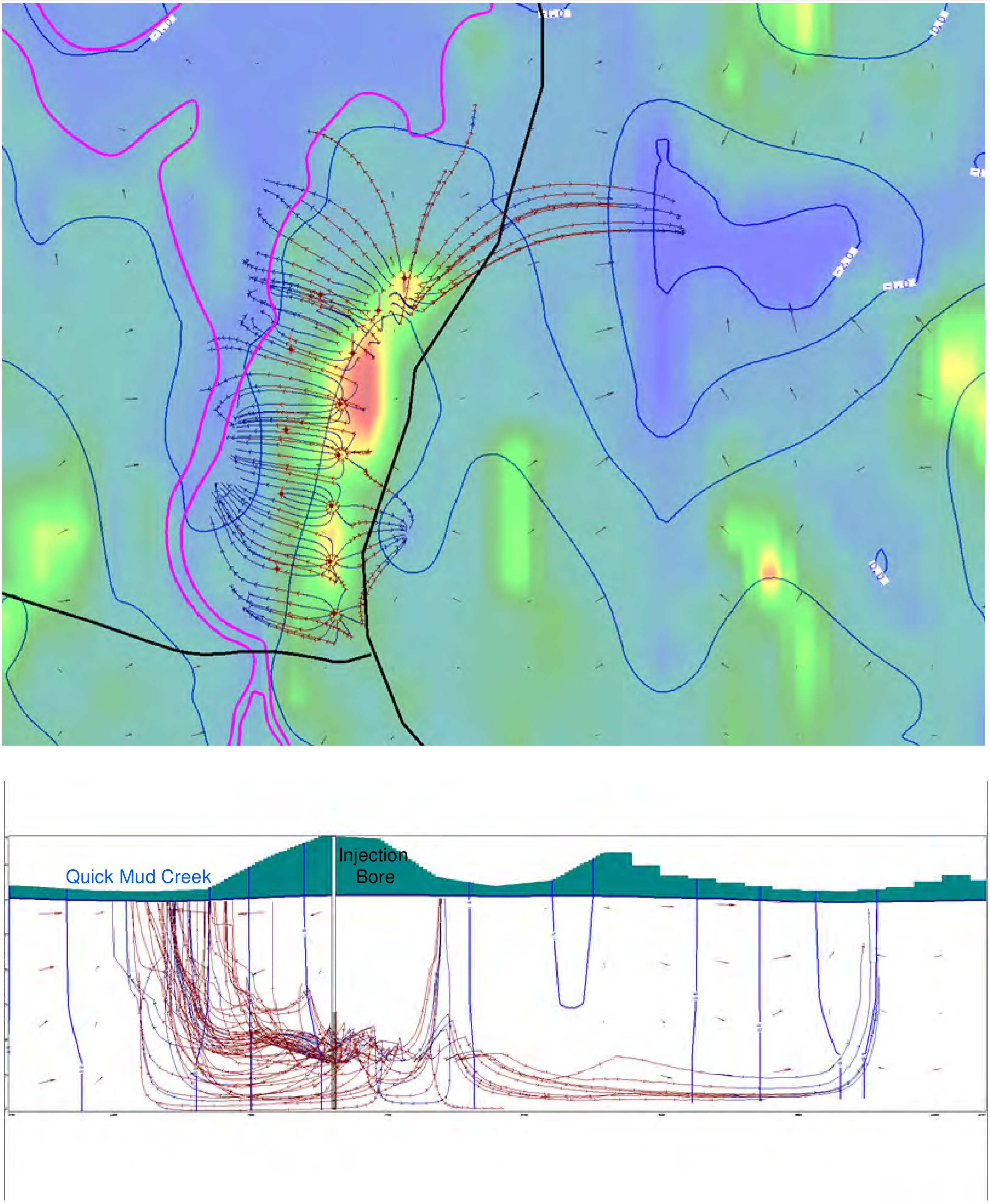
REFINED CONCEPT DESIGN
PARTICLE-TRACKING FOOTPRINTS AFTER 80 YEARS

URS

GROUNDWATER RESOURCE MODELLING

Figure: 6-16

File No: 42908178-WG-083.mxd | Drawn: LS | Approved: IB | Date: 9/12/2013 | Rev. A | A4



Particle Direction (Cross-section view)

- Inward
- Outward
- In Plane

Based on Modflow modelling outputs (URS, September 2013)

Chevron

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

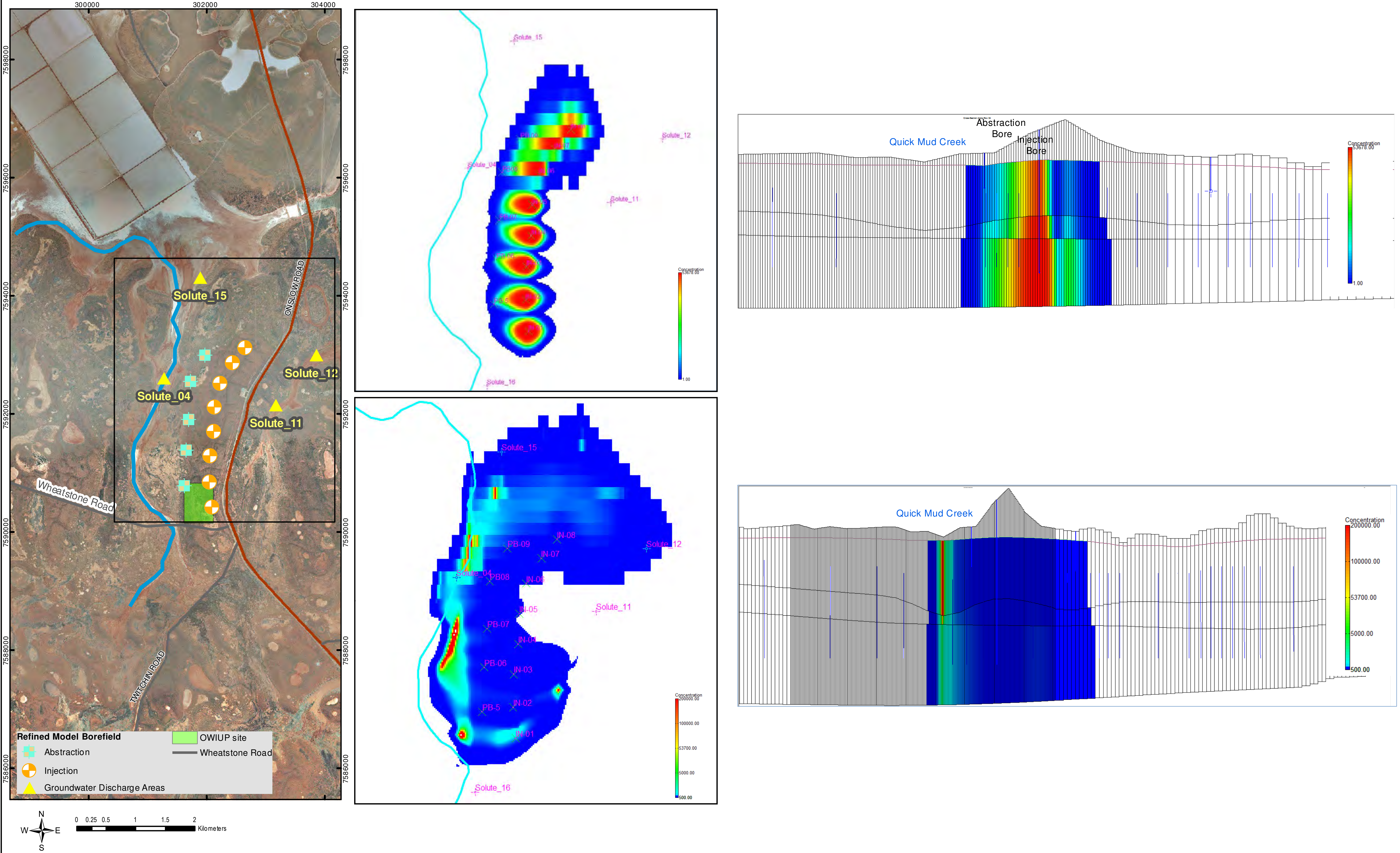
REFINED CONCEPT DESIGN
PARTICLE-TRACKING FOOTPRINTS
AFTER 3,000 YEARS

URS

GROUNDWATER RESOURCE MODELLING

Figure: **6-17**

File No: **42908178-WG-084.mxd** Drawn: **LS** Approved: **IB** Date: **9/12/2013** Rev. **A** A4



This drawing is subject to COPYRIGHT. J:\PER\42908178\5 Works\Figures\General_Figures\MXD\42908178-WG-088.mxd

Scale at A3: 1:60,000
Coordinate System: GDA 1994 MGA Zone 50
Based on information provided by and with the permission of the Western Australian Land Information Authority trading as Landgate (2010).

Chevron

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

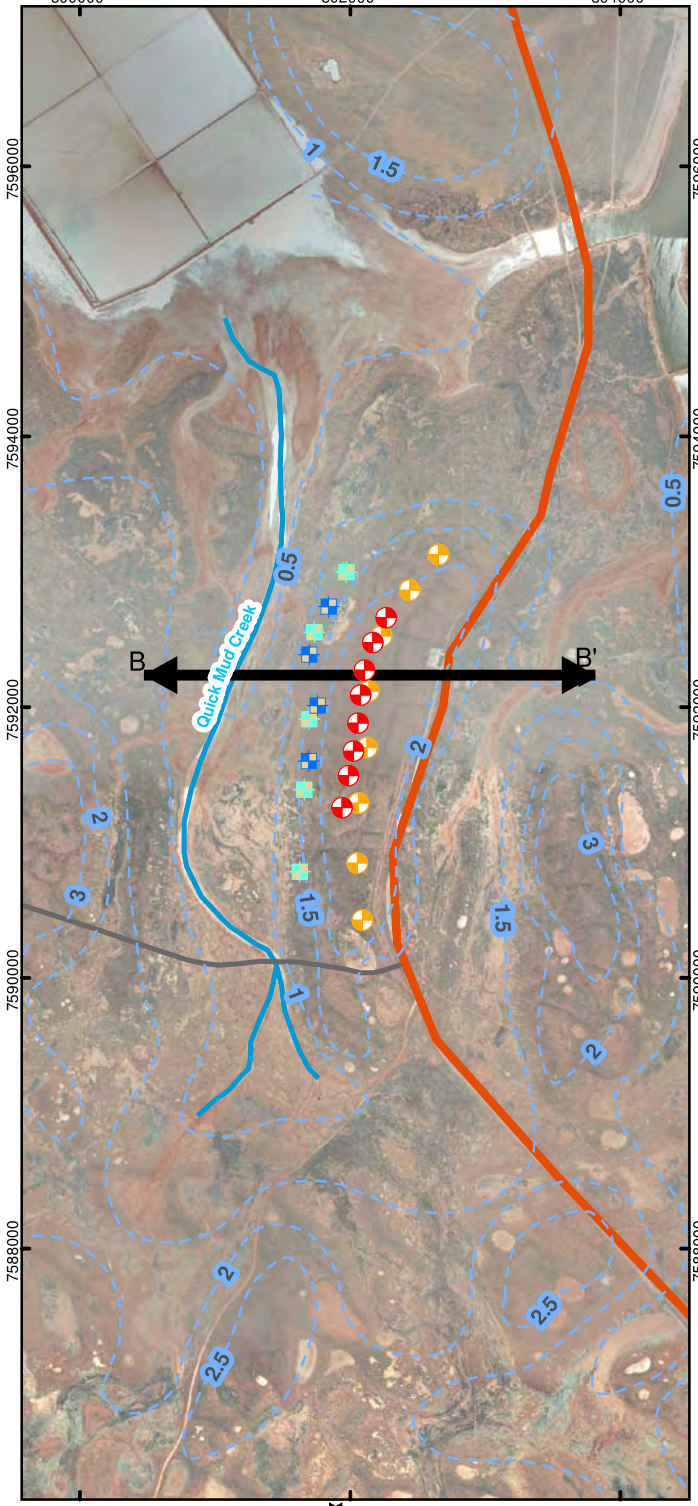
REFINED CONCEPT DESIGN
TDS PLUMES AFTER 80 AND 850 YEARS

URS

GROUNDWATER RESOURCE MODELLING

Figure: **6-18**

File No: **42908178-WG-088.mxd** Drawn: **LS** Approved: **IGB** Date: **9/12/2013** Rev. **A** A3



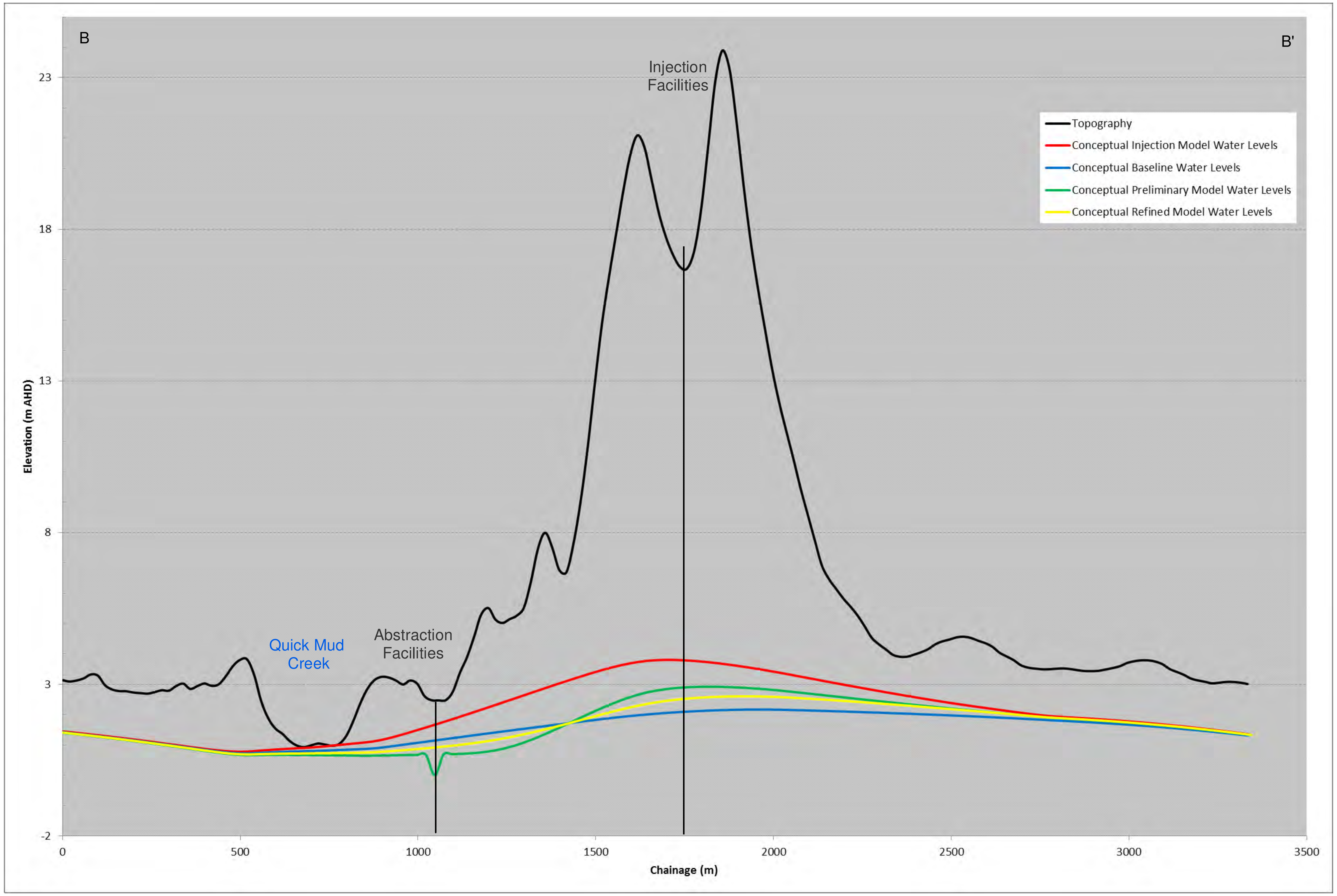
Preliminary Concept Design
- Abstraction
- Injection

Refined Concept Design
- Abstraction
- Injection

Cross-Section B to B'
Interpreted Water Table Elevations (m AHD)

0 0.25 0.5 1 1.5 2 Kilometers

Scale at A3: 1:55,863
Coordinate System: GDA 1994 MGA Zone 50
Based on information provided by and with the permission of the Western Australian Land Information Authority trading as Landgate (2010).



Note:
- Ground elevations extracted from DEM derived from 1 m LiDAR survey (2012) supplied by Chevron.
- The water table elevations are derived from the numerical model with 1.0 m added to all simulated elevations tobetter match the interpreted baseline data.

Chevron

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL SALINE STREAM

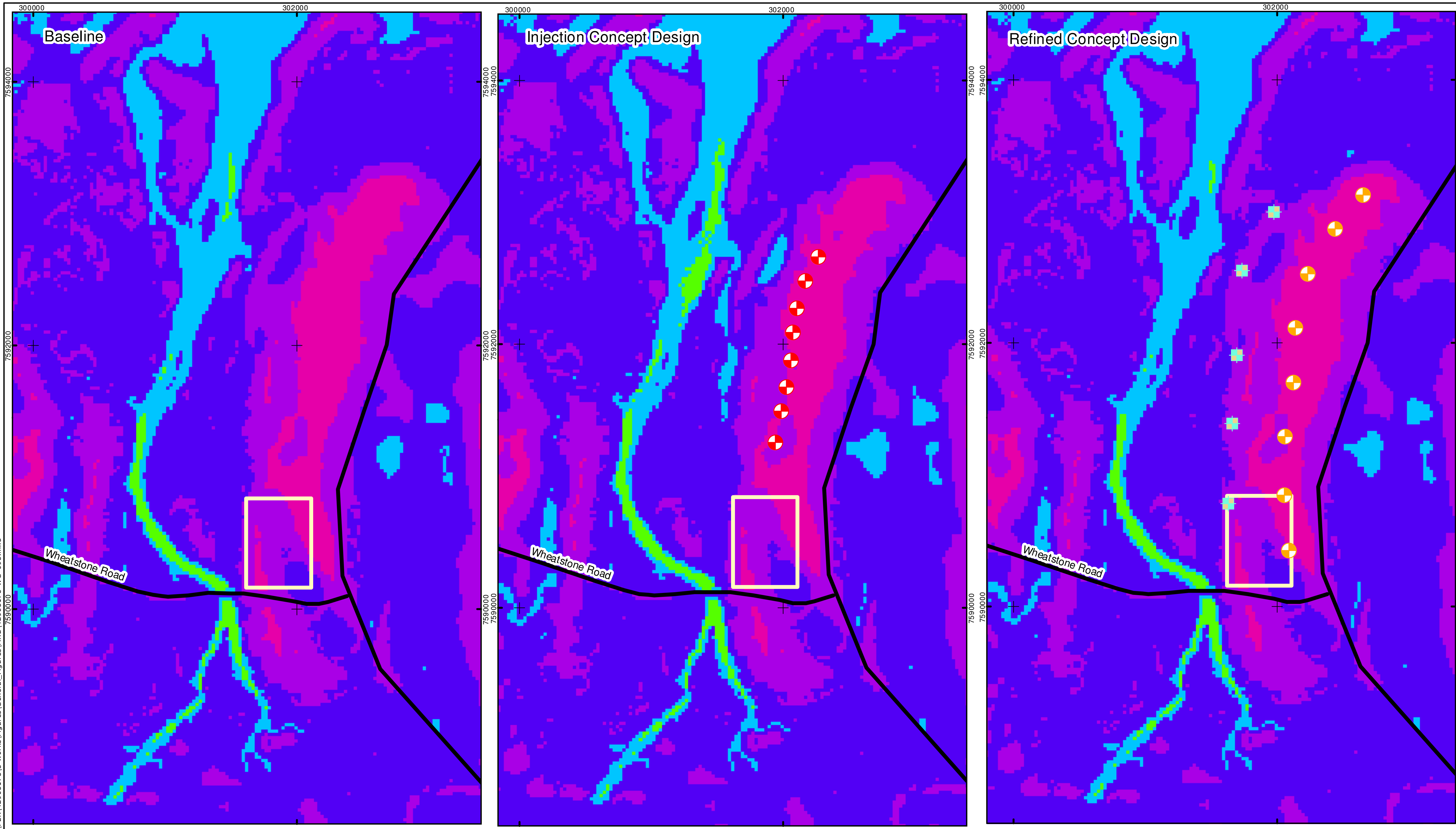
COMPARISONS OF SIMULATED WATER TABLE ELEVATIONS

URS

GROUNDWATER RESOURCE MODELLING

Figure: 6-19

File No: 42908178-WG-093.mxd | Drawn: RM | Approved: IGB | Date: 9/25/2013 | Rev. A | A3



N
W E
S

0 0.1 0.2 0.4 0.6 0.8 1 Kilometers

Note:
- Ground elevations extracted from DEM derived from 1 m LiDAR survey (2012) supplied by Chevron.
- The water table elevations are derived from the numerical model with 1.0 m added to all simulated elevations tobetter match the interpreted baseline data.

Injection Concept Design
- Injection

Refined Concept Design
- Abstraction
- Injection
- OWIUP Site

Depth to Water Table (m below ground level)
- Seepage
- 0.001 - 1
- 1.01 - 3
- 3.01 - 10
- 10.1 - 30

Scale at A3:1:28,000
Coordinate System: GDA 1994 MGA Zone 50
Based on information provided by and with the permission of the Western Australian Land Information Authority trading as Landgate Chevron Australia.

Chevron

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIDUAL STREAM

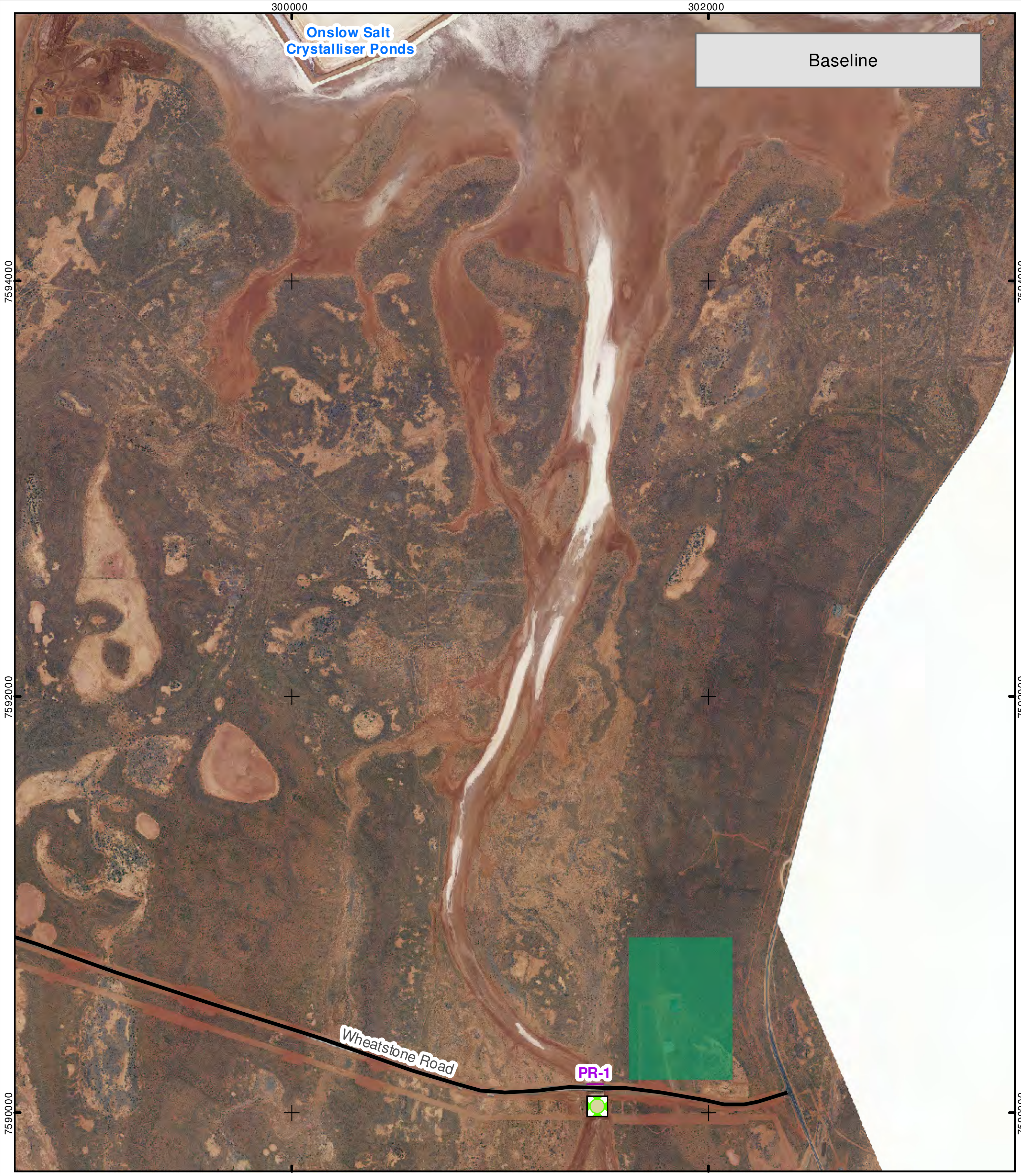
DEPTH TO WATER TABLE AFTER 80 YEARS OF OPERATION

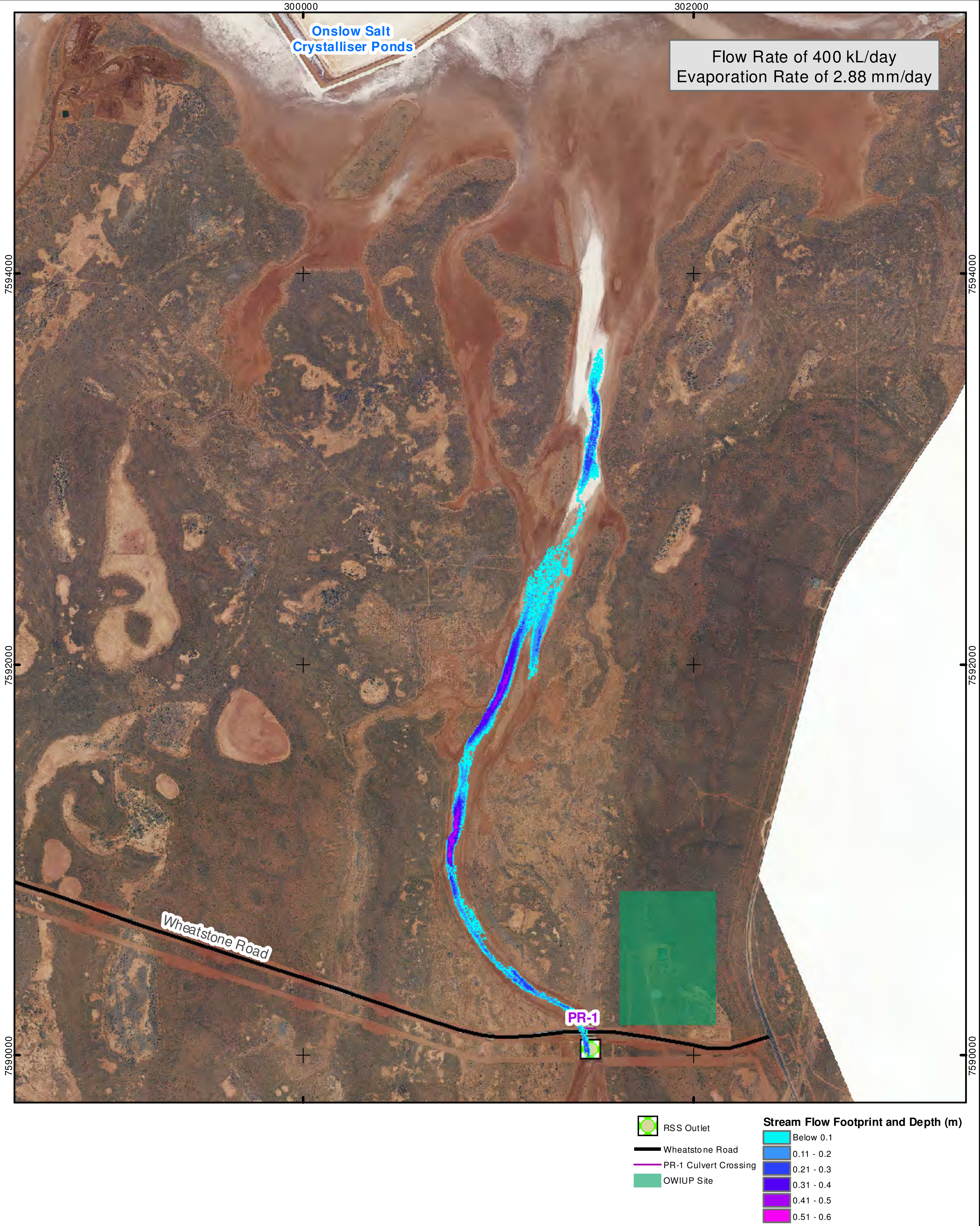
URS

GROUNDWATER RESOURCE MODELLING

Figure: 6-20

File No: 42908178-WG-095.mxd Drawn: LS Approved: IB Date: 9/25/2013 Rev. A A3





Scale at A3: 1:25,000

Coordinate System: GDA 1994 MGA Zone 50

Based on information provided by and with the permission of the Western Australian Land Information Authority trading as Landgate (2010).

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
CONCEPTUAL DESIGN FOR INJECTION OF THE RESIUDAL SALINE STREAM

QUICK MUD CREEK SETTING WITH AND WITHOUT RSS DISPOSAL

QUICK MUD CREEK MODELLING

File No: 42908178-WG-054.mxd | Drawn: LS | Approved: IB | Date: 9/12/2013

Figure: 7-1 | Rev. A | A3

A

Appendix A NORM, Chemistry and Mineralogy Signatures of Quick Mud Creek (18 March and 2 August 2013)

Mineralogy of Quick Mud Creek

		Sample ID	OSW5-SALT CRUST	OSW5-SOIL	OSW7-SOIL	OSW8-SOIL
		Sample Date	3/18/2013	3/18/2013	3/18/2013	3/18/2013
		Sample Type	Primary	Primary	Primary	Primary
		Sample Depth	At ground level	0.3 meter deep	0.3 meter deep	0.3 meter deep
		Environment	Salt Crust of Pool 2	Bed Soil of Pool 2	Bed Soil of QMC (PR-1)	Bed Soil of QMC (PR-1)
		Analysis method	X-ray diffraction	X-ray diffraction	X-ray diffraction	X-ray diffraction
Phase	**Units**					
Amphibole	wt%		1	<1	3	1
Cristobalite	wt%		2	-	-	-
Bassanite	wt%		-	11	-	2
Chlorite	wt%		-	1	6	2
Expanding Clay	wt%		-	<1	-	-
Goethite	wt%		-	2	2	1
Gypsum	wt%		1	13	-	8
Hematite	wt%		-	1	1	2
Illite/Muscovite	wt%		-	19	24	33
Kaolin	wt%		-	1	9	11
Quartz	wt%		1	14	32	18
Sodium Chloride	wt%		96	34	20	20

Legend:
wt% = weight in per cent

Chem_Group	Analyte	Symbol	Units	MDL		LIQUIDS			SOLIDS			
					Sample ID	E052FG-S	OSW5-S	OSW6	OSW5-SOLID	OSW5-SALT CRUST	OSW7-SOLID	OSW8-SOLID
					Sample Date	3/18/2013	3/18/2013	3/18/2013	3/18/2013	3/18/2013	3/18/2013	3/18/2013
					Sample Type	Primary	Primary	Primary	Primary	Primary	Primary	Primary
					Sample Depth	1.22 m below ground level	Surface of pool	Surface of pool	0.3 m	0.05 m	0.3 m	0.3 m
					Environment	Shallow Aquifer	Hyper-Saline Pool	Hyper-Saline Pool	Hyper-Saline Pool	Hyper-Saline Pool		
					Analysis method (Radionuclides)	Gamma Spectrometry (1)	Gamma Spectrometry (1)		Gamma Spectrometry (1)	Gamma Spectrometry (1)	Gamma Spectrometry (1)	Gamma Spectrometry (1)
						Liquid Scintillation Counting (2)	Liquid Scintillation Counting (2)		Liquid Scintillation Counting (2)	Liquid Scintillation Counting (2)	Liquid Scintillation Counting (2)	Liquid Scintillation Counting (2)
						ICPMS Data (3)	ICPMS Data (3)		ICPMS Data (3)	ICPMS Data (3)	ICPMS Data (3)	ICPMS Data (3)
					Lab Batch (Radionuclides)	7347-1	7347-2		7347-3	7347-4	7347-5	7347-6
Chem_Group	**Analyte**	**Symbol**	**Units**	**MDL**								
Radionuclides	Radium - 226	Ra-226	mBq/L	100		<100	<100					
	Radium - 228	Ra-228	mBq/L	100		<100	<100					
	Thorium - 228	Th-228	mBq/L	100		<100	<100					
	Lead - 210	Pb-210	mBq/L	100		<100	<100					
	Alpha		mBq/L	60		<60	<60					
	Beta		mBq/L	135		<135	<135					
	Potassium	K	mg/L			550	6,500					
	Total Uranium		mBq/L			<MDL	<MDL					
	Total Thorium		mBq/L			<MDL	<MDL					
	Radium - 226	Ra-226	mBq/g	30					<30	<30	<30	<30
	Radium - 228	Ra-228	mBq/g	30					<30	<30	31.6 ± 4.5	45.2 ± 5.7
	Thorium - 228	Th-228	mBq/g	30					<30	<30	35.4 ± 4.2	40.0 ± 4.5
	Lead - 210	Pb-210	mBq/g	30					<30	<30	<30	<30
	Lead - 212	Pb-212	mBq/g	30					<30	<30	32.8 ± 2.7	40.3 ± 3.2
	Lead - 214	Pb-214	mBq/g	30					<30	<30	<30	32.3 ± 3.9
	Bismuth - 212	Bi-212	mBq/g	30					<30	<30	39.2 ± 19.8	<30
	Bismuth - 214	Bi-214	mBq/g	30					<30	<30	<30	<30
	Thalium - 208	Tl-208	mBq/g	30					<30	<30	35.4 ± 4.2	40.0 ± 4.5
	Potassium	K-40	mBq/g	30					273 ± 25	34.4 ± 5.2	430 ± 36	495 ± 41
Alkalinity	Bicarbonate Alkalinity as CaCO3	CaCo3	mg/L	1		131	361	353				
	Carbonate Alkalinity as CaCO3	CaCo3	mg/L	1		<1	<1	<1				
	Hydroxide Alkalinity as CaCO3	CaCo3	mg/L	1		<1	<1	<1				
	Total Alkalinity as CaCO3	CaCo3	mg/L	1		131	361	353				
Major Ions	Chloride	Cl	mg/L	1		40,400	179,000	187,000				
	Calcium (Dissolved)	CaCo3	mg/L	0.2		1,470	361	407				
	Magnesium (Dissolved)	Mg	mg/L	0.1		2,480	29,200	25,700				
	Potassium (Dissolved)	K	mg/L	0.1		749	8,790	7,700				
	Sodium (Dissolved)	Na	mg/L	0.5		20,000	79,600	76,600				
	Sulphur (as S) (Total)	S	mg/L	1		822	8,530	7,780				
	Sulphur (as S) (Dissolved)	S	mg/L	0.5		770	8,830	7,680				
	Sulphate (as SO4-) (Filtered)	$SO4^{-}$	mg/L	1		2450	21,100	8520				
	Total Anions		meq/L	0.01		1,190	5,510	5,720				
	Total Cations		meq/L	0.01		1,170	6,110	5,660				
	Ionic Balance		%	0.01		1.14	5.1	0.51				
Ferrous/Ferric Iron	Ferrous Iron	Fe	mg/L	0.05		0.05	<0.05	-				
Total Dissolved Solids	Total Dissolved Solids	TDS	mg/L	10		84,400	377,000	380,000				
Inorganics	Electrical conductivity (lab)	EC	µS/cm	1		95,500	211,000	219,000				
	pH (Lab)		pH Units	0.01		7.18	7.2	7.23				
	Total Suspended Solids		mg/L	5		-	60	187				
	Turbidity		NTU	0.1		-	2.7	11.7				

Legend:
mg/L = milligrams per litre
µg/L = micrograms per litre
mBq/g =

(1) include the disclaimer

B

Appendix B Groundwater Model Level Classification Criteria Assessment

URS

GROUNDWATER MODEL LEVEL CLASSIFICATION CRITERIA ASSESSMENT

Data Aspects	Comments	Calibration Aspects	URS Comments	Prediction Aspects	Comments	Key indicator Aspects	Comments
		· Validation is either not undertaken or is not demonstrated for the full model domain.	Level 2. The simulated water table fits broadly the conceptual model with better validation in the sensitive areas.	· Length of predictive model is not excessive compared to length of calibration period.	Level 1. The calibration is based on a snapshot. The predicitive simulations period is 100 years. The aspect is not relevant to the exercise.	· Key calibration statistics are acceptable and meet agreed targets.	
· Spatial distribution of bore logs and associated stratigraphic interpretations that define aquifer geometry.	Level 1. Few or poorly distributed existing wells from whick to obtian reliable groundwater and geological informations within the model domain. Reasonnable data coverage along Quick Mud Creek.	· Calibration statistics are generally reasonable but may suggest significant errors in parts of the model domain(s).	Level 2. Calibration is very good for the few bores in the superficial aquifer. The simulated water table map doesn't not match in the entire model domain the interpreted water level map.	· Temporal discretisation used in the predictive model is consistent with the transient calibration.	Level 1. There are no transient calibration in such.	· Model predictive time frame is less than 3 times the duration of transient calibration.	
· Metered groundwater-extraction data may be available but spatial and temporal coverage may not be extensive.	Not relevant to the exercise because no existing abstraction in the model domain.	· Long-term trends are adequately replicated where these are important.	Level 1. A detailed long-term could not been informed because of limited data on trends. Long-term trends are not crucial for the head-boundaries.	· Level and type of stresses included in the predictive model are within the range of those used in the transient calibration.	Level 1. There are no transient calibration in such.	· Stresses are not more than 2 times greater than those included in calibration.	
· Rainfall and evaporation data is available.	Level 3. There is good understanding of the rainfall pattern and the evaporation rates based on the Bureau of Meteorology weather stations within the model domain or nearby.	· Seasonal fluctuations are adequately replicated where these are important.	Level 2. The model includes the wet and the dry seasons aspect using the rainfall data.			· Temporal discretisation in predictive model is the same as that used in calibration.	
· Aquifer-testing data to define key parameters.	Level 1. Good coverage of aquifer testings are available on the north-west of the Project. Very little data in the Quick Mud Creek area.	· Transient calibration is current, i.e. uses recent data.	Level 1. The model has limited calibration bores. The evaportation rate in the model seems too low compared to the obsvered potential EVT.			· Mass balance closure error is less than 0.5% of total.	
· Stream flow and stage measurements are available with reliable baseflow estimates at a number of points.	Not relevant to the exercise.	· Model is calibrated to heads and fluxes.	Level 1. The model has limited calibration bores. The fit is very good for the bores but uncertainity is high where calibration data are absent.			· Model parameters consistent with conceptualisation.	
· Reliable land-use and soil-mapping data available.	Level 3. Surface geology and soil mapping data are available in the model domain. The level of detail required is low.					· Appropriate computational methods used with appropriate spatial discretisation to model the problem.	
· Reliable irrigation application data (where relevant) is available.	Not relevant to the exercise.					· The model has been reviewed and deemed fit for purpose by an experienced, independent hydrogeologist with modelling experience.	Level 1. The model has been reviewed internally.
· Good quality and adequate spatial coverage of digital elevation model to define ground surface elevation.	Level 3. The digital elevation model generated for the model is high resolution, especially in the interpreted groundwater discharge areas.						

Notes:

Green	Class 3
Blue	Class 2
Orange	Class 1
White	Not relevant to the exercise.

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