Onslow Water Infrastructure Upgrade Project

NORM Risk Assessment at Quick Mud Creek

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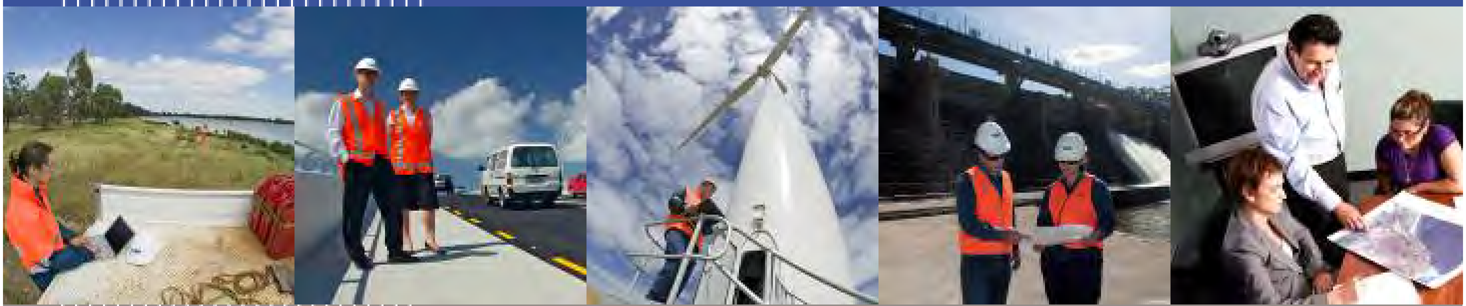

Report

Onslow Water infrastructure Upgrade Project

NORM Risk Assessment at Quick Mud Creek

20 MARCH 2014

Prepared for

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Abbreviations

Abbreviation	Description
ALARA	As Low As Reasonably Achievable
ARI	Average Recurrence Interval
ARPANS	Australian Radiation Protection and Nuclear Safety
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
AR & R	Australian Rainfall & Runoff
Ba	Barium
BJC	Bechtel Jacobs Company
BoM	Bureau of Meteorology
Bq	Becquerel
Bq/L	Becquerel per litre
Ca	Calcium
Cl	Chloride
CEO	Chief Executive Officer
CR	concentration ratios
ERICA	Environmental Risk from Ionising Contaminants Assessment and Management
DoW	Department of Water
^{o}C	degrees Centigrade
FAO	Food and Aquaculture Organisation of the United Nations
FFA	Flood Frequency Analysis
hr	hour
IAEA	International Atomic Energy Agency
ICDD	International Centre for Diffraction Data
ICRP	International Commission on Radiological Protection
IFD	Intensity-Frequency-Duration
Km	Kilometres
L	Litre
LIDAR	Light Detection and Ranging
LNG	Liquefied Natural Gas
MDL	Method Detection Limit
mg	milligram
Mg	Magnesium
ML	Mega litre
mm	millimetre
mrem	Millirem
NATA	National Association of Testing Authorities
NCRP	National Council on Radiation Protection and Measurement (USA)
NHMRC	National Health and Medical Research Council
NRMMC	National Resource Management Ministerial Council
NORM	Naturally Occurring Radioactive Materials
Onslow Salt	Onslow Salt Pty. Ltd
Pb	Lead
PEER	Potential Environmental Effects Reference

Abbreviations

Abbreviation	Description
PEERL	Potential Environmental Effects Reference Level
PPE	personal protective equipment
PSU	Practical Salinity Units
QMC	Quick Mud Creek
Ra	Radium
RAP	Reference Animals and Plants
RMP	Radiation Management Plan
RO	Reverse Osmosis
RSS	Residual Saline Stream
RWMP	Radioactive Waste Management Plan
TDS	Total Dissolved Solids
SRTM	Shuttle Radar Topography Mapping
SIT	specific ion interaction theory
Sr	Strontium
Th	Thorium
TSS	Total Suspended Solids
U	Uranium
WA	Western Australia

Executive Summary

Chevron and the Water Corporation are developing and executing a project that will increase the supply of potable water to the town of Onslow by 2 ML/day with raw water proposed to be sourced from the Birdrong Aquifer. The Reverse Osmosis (RO) treatment of the saline groundwater would produce a Residual Saline Stream (RSS) by-product. This by-product, with salinity 46,418 mg/L TDS and production rate of 857 kL/day, would preferably be disposed to Quick Mud Creek downstream of Wheatstone Road.

The RSS footprint in Quick Mud Creek would extend up to 4.6 km from the release point in dry conditions and the water balance and salt balance would predominantly be influenced by losses due to evaporation. Episodic stream flow events would periodically enable dispersion and dilution of the accumulated RSS and associated crystalline salts, with discharge to the Hooley Creek – Four-Mile Creek tidal embayment. Stream flow may originate from the catchments of Quick Mud Creek and/or flood events in the Ashburton River.

Quick Mud Creek is characterised by supratidal saline flats, clay pans and clayey plains. Each of these landforms accumulates salt and is predominantly barren of vegetation. The lower reaches of the Quick Mud Creek and supratidal saline flats were expected to host comparatively few ecological receptors. It was recognised that mangroves, samphire, bioturbated high tide mud flats and algal mat covered high tide flats within the Hooley Creek – Four-Mile Creek tidal embayment would potentially host the predominant ecological receptors for the disposed RSS.

The RSS contains radium (Ra) and thorium (Th), with measured maximum Ra-226, Ra-228 and Th-228 activities of 13.7, 22.7 and 2.0 Becquerel per litre (Bq/L), respectively. The Ra-226, Ra-228 and Th-228 activities may, however, fluctuate over time as a function of variations within the Birdrong Aquifer source. It is possible that the measured maximum radium and thorium activities may be exceeded in future sampling.

There would be potential accumulation of not previously defined NORM activities above natural concentrations within the Quick Mud Creek setting. In order to characterise the potential radium and thorium activity accumulation and associated risks, this project has:

- Assessed the baseline NORM activities within the Quick Mud Creek setting.
- Developed hydrological models that indicate the frequency of stream flow events that would dispose and transport the RSS footprints from Quick Mud Creek.
- Estimated the reasonable worst-case RSS-derived salt accumulation on the lower reaches of Quick Mud Creek would occur over a period of 2 years during which time there would be an absence of stream flow. The 2-year period of salt accumulation defines the NORM (radium and thorium) source terms used in this study.
- Developed hydrodynamic models that indicate the transport and fate of the RSS once mobilised from Quick Mud Creek by stream flow. These models include the Hooley Creek – Four-Mile Creek tidal embayment and associated roles of seawater in the movement and dilution of NORMs.
- Estimated the NORM activities in the potential receiving environments on Quick Mud Creek to the marine environment and providing context in terms of NORM geochemical modelling, definition of exposure pathways, and radiological dose and risk analyses.
- Assessed the potential regulatory, human and environmental risks of radium and thorium accumulation in Quick Mud Creek due to the RSS disposal and in context to selected regulations and guidelines.

- Selected references and guidelines for NORM management internationally and in Australia include:
  - ICRP *Recommendations of the International Commission on Radiological Protection, 2007.*
  - IAEA *Safety Guide. Application of the Concepts of Exclusion, Exemption and Clearance*, 2004.
  - ARPANSA *National Directory for Radiation Protection*, July 2011.
  - ARPANSA *Safety Guide. Management of Naturally Occurring Material,* 2008.

  The two ARPANSA references capture the regulatory intentions and guidelines regarding general public annual dose limits in Australia.

Once disposed into Quick Mud Creek the radium and thorium would temporarily accumulate during intervals between stream-flow events. Loss of the RSS would predominantly occur by evaporation, producing crystalline salt crusts along the low-flow channel. Groundwater discharges into the pools located in the low-lying areas of Quick Mud Creek. The environmental heads created by the salinity gradient in the underlying aquifers show an upwards vertical flow. In these conditions, the RSS would have limited interaction with the water table; the NORMs would not propagate to the local water table.

The catchment of Quick Mud Creek is characterised by numerous physical features, including incised channel and clay pans, which would attenuate initial flow volumes. Low-volume steam flow events would mobilise the RSS footprint onto the supratidal saline flats. Larger episodic discharge of the RSS and accumulated crystalline salts from Quick Mud Creek to the sea would occur at times when stream flow is generated by rainfall within the sub-regional catchment of the supratidal saline flats (including Quick Mud Creek and Hooley Creek) and\or the Ashburton River. Based on the hydrological characteristics of the catchment, it was recognised that consecutive rainfall events would tend to promote stream flow and discharge; the initial event would tend to inundate the attenuation areas, enabling excess during the subsequent rainfall.

The stream flow discharges from Quick Mud Creek and associated transport and dispersion of the accumulated RSS solutions and salts would originate either from the sub-regional catchments of Quick Mud Creek and\or flooding of the Ashburton River. The stream flow frequency for the sub-regional catchment of Quick Mud Creek that would generate discharge to the sea was expected to occur for a 1- to 2-year ARI event as summarised in the table below. The flood events in the Ashburton River that would contribute to flows in Quick Mud Creek have a similar frequency.

Quick Mud Creek Stream Flow Discharge Event Frequency

Quick Mud Creek Catchment	24-Hour Duration Design Storm			
	1-Year ARI	2-Year ARI	3-Year ARI	5-Year ARI
Sub-regional	Discharge to Sea	Discharge to Sea	Discharge to Sea	Discharge to Sea

When a litre of the RSS solute evaporates, it leaves behind about 46.4 grams of salt that contains 0.83 Bq/g of radium and thorium activity. The stream flow events on Quick Mud Creek would dissolve the accumulated salts, transport and disperse the accumulated RSS. Stream flow from Quick Mud Creek would coalesce with concurrent flows from the supratidal saline flats and Hooley Creek before entering the tidal reaches of West Hooley Creek, East Hooley Creek and Middle Creek. Estimates of the radium and thorium activities for stream flows entering the tidal creeks were informed by the integration of stream flow outputs from predictive MIKE FLOOD HD and TUFLOW models and supported by the geochemical modelling. For these estimates it was assumed that all of the RSS salts accumulated on Quick Mud Creek for a period of 2 years and subsequently were uniformly dissolved and transported in 24-hour stream flow events of varying volumes. As such, the initial NORM activity (in the accumulated salt) was consistent for each stream flow event, with dilution by different volumes. The derived dilute radium and thorium source activities were applied to the hydrodynamic model of the Hooley Creek – Four-Mile Creek tidal embayment as source terms for stream flow entering the tidal reaches of East Hooley Creek.

Based on hydrology analyses for a 2-year ARI event, the Ra-226, Ra-228 and Th-228 activities in the stream flow, derived from 2 years of RSS salt accumulation, would be about 41.6, 68.9 and 6.1 Bq/L, respectively. For selected consecutive rainfall events, the radium and thorium source volumes and activities at the headwaters of the tidal reaches to East Hooley Creek were estimated as follows:

- 1+1-year ARI consecutive events – 1.195 GL at 19.5 Bq/L.
- 1+2-year ARI consecutive events – 1.373 GL at 16.3 Bq/L.
- 1+5-year ARI consecutive events – 3.978 GL at 5.8 Bq/L.
- 1+10-year ARI consecutive events – 11.814 GL at 2.0 Bq/L.

The prediction of the transport and fate of the RSS-derived radium and thorium activities within the Hooley Creek – Four-Mile Creek tidal embayment was assessed using MIKE21HD(FM) hydrodynamic models. The developed models used the available bathymetry data and Beadon Creek tidal records to inform the local tidal forces. Non-reactive solute transport modules of MIKE21HD(FM) were used to determine the radium and thorium source mixing and dilution characteristics associated with the selected range of stream flow events. Findings from the hydrodynamic modelling indicated:

- Periods of 20 to 31 days, typically 25 days, for 100-times dilution of the radium and thorium source terms within the tidal creeks.
- Periods of 4 to 18 days, typically about 14 days, for dilution of the source terms to 1 Bq/L within the entire Hooley Creek – Four-Mile Creek tidal embayment.

The predictive simulations provide indications that the worst-case scenarios are provided by:

- Single comparatively low-flow events that occur over extended periods up to 10 days.
- Consecutive low-flow events where flow occurs over extended period up to 10 days.

The predictions indicate sensitivity to the duration of the stream flow, with longer durations resulting in attenuation of the RSS source before mixing, dilution and transport from the Hooley Creek – Four-Mile Creek tidal embayment.

Based on the assessments of the NORM risk and radiological safety to human receptors, the following conclusions have been interpreted:

- As a general criterion, the analysis was based on restricting the estimated dose rates to less than 1 millisievert per year and\or activity limit to 1 Bq/g. Under these conditions, doses are unlikely to exceed about 1 millisievert per annum (IAEA, 2004).
- Dose for selected scenarios and external radiation, dust inhalation, airborne and ingestion pathways have been estimated from adopted conversion factors. The findings for each scenario are detailed below:

  a. Human receptor at RSS pools on Quick Mud Creek: the maximum dose to a human receptor at the RSS pools on Quick Mud Creek is 0.525 millisievert per year, which is the sum of the external radiation and dust inhalation doses. This conservative analysis demonstrates human receptor doses on Quick Mud Creek are within the recommended limits.

  b. Human receptor at Onslow Salt crystalliser ponds: the calculation for dust inhalation showed a dose of 0.000000699 millisievert per year, which is far below the regulatory general public annual dose limit of 1 millisievert per year.

  c. Limited potential contamination of the produced salt at Onslow Salt by airborne NORM. The limited potential was based on i) the prevailing winds being away from the salt crystalliser ponds; ii) assumptions that the majority airborne NORMs not settle on the salt crystalliser ponds; iii) a limited time salt harvesting cycle limits potentials for NORM accumulation; and iv) the calculation of doses to human receptors.

  d. Consumption of fish by a member of the general public in the tidal zone: calculations indicate a total dose in the range 0.15 to 0.38 millisievert per year. This range is about three to six times below the regulatory general public annual dose limit of 1 millisievert per year.

The findings of the radiological assessments indicate that the proposed RSS disposal to Quick Mud Creek would not expose members of the general public to dose rates that exceed the ARPANSA guideline dose rates and or activity limits of 1 millisievert per year and\or 1 Bq/g, respectively.

The table below present a summary of the dose/risk assessment for human receptors.

Receptors	Dose Limit		Aspect	Exposure (millisievert per year)		
	Millisievert per year	Guidelines		External Radiation	Dust Inhalation	Fish Ingestion
Human	1	ARPANSA, 2011	Human Receptor at RSS Pond	0.525	0.00740	NA
			Human Receptor at Onslow Salt Crystalliser Ponds	NA	0.000000699	NA
			Fish Consumption by the General Public	NA	NA	0.15 – 0.38

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For ecological receptors, the following conclusions regarding dose assessments have been reached:

- As a general criterion, the analysis was based on limiting the dose rate to less than 1 millisievert per year and\or activity to 1 Bq/g. In general terms, the standards in place for the protection of people are believed to offer protection to and limit radiological risk to other species.
- The exposure pathways to the NORMs identified included external radiation. Generally it was recognised that exposures by ingestion would be comparatively low risks given the propensity of the terrestrial habitats formed by Quick Mud Creek and the supratidal saline flats to accumulate salt. Also, both settings are sparsely vegetated.
- The estimated dose limits for selected ecological domains include:

  a. Quick Mud Creek: Potential doses up to 0.525 millisievert per year. The accumulated salt on Quick Mud Creek has residual radium and thorium activities of 0.83 Bq/g irrespective of thickness.

  b. Supratidal Saline Flats: Stream flow and pool potential doses less than 0.525 millisievert per year. The accumulated salt on the supratidal saline flats would have activities less than 0.83 Bq/g.

  c. Tidal Estuary: Radiological exposures were calculated in the range 0.0039 to 0.29 millisievert per year for a number of scenarios with different mixing ratios of stream flow and seawater in the Hooley Creek – Four-Mile Creek tidal embayment. The scenarios considered are expected to address worst-case aspects.

The findings of the radiological assessments indicate that the proposed RSS disposal to Quick Mud Creek would not expose potential ecological receptors to dose rates and activity limits that exceed the ARPANSA guidelines of 1 millisievert per year and 1 Bq/g, respectively.

The table below present a summary of the dose/risk assessment for ecological receptors.

Receptors	Dose and Activity Limits		Aspect	Exposure Pathway External Radiation
	Criteria	Guidelines		
Ecological	1 millisievert per year	ARPANSA, 2011	Receptor on Quick Mud Creek	0.525 millisievert per year
			Receptor on Supratidal Saline Flats	Less than 0.525 millisievert per year
			Receptor in Tidal Estuary	0.0039 to 0.29 millisievert per year
	1 Bq/g		Receptor on Quick Mud Creek	0.83 Bq/g
			Receptor on Supratidal Saline Flats	Less than 0.83 Bq/g

1 Background

1.1 Introduction

Chevron and the Water Corporation are developing and executing a project that will increase the supply of potable water to the town of Onslow by 2 ML/day. The potable water supply involves the Birdrong Aquifer as a source, with Reverse Osmosis (RO) treatment of the saline groundwater prior to distribution. The RO treatment would produce a Residual Saline Stream (RSS) by-product.

The preferred disposal strategy for the RSS is discharge to Quick Mud Creek in the vicinity of the proposed RO plant (downstream of the culvert crossing on Wheatstone Road referred to as PR-1, **Figure 1-1**).

1.2 Predicted RSS Footprint on Quick Mud Creek

MIKE21 grid-version model (DHI, http://www.dhisoftware.com/) was used to predict the footprint for an 857 kL/day rate of RSS disposal to Quick Mud Creek. The proposed discharge point was located downstream of culvert crossing PR-1 on Wheatstone Road. These predictions assumed:

- The creek bed was dry.
- Absence of groundwater storage and through-flow within the water table aquifer.
- The water balance was driven by potential evaporation losses of 2.88 mm/day assuming the RSS salinity was about 45,000 mg/L.
- The predicted RSS footprint extended 4.6 km downstream of the discharge point. The overall wetted footprint was predicted to be about 32 ha.

The RSS discharge for this assessment is assumed to be 857 kL/day for 80 years, with salinity of 46,418 mg/L Total Dissolved Solids (TDS). For this study it is also assumed a maximum RSS production rate of 857 kL/day represents a worst-case scenario with respect to mass load of naturally occurring radioactive material (NORM).

The MIKE21 grid-version model has been re-run using the nominated RSS discharge rate of 857 kL/day. The simulated RSS footprint would extend up to 4.6 km from PR-1 culvert-crossing. The typical baseline setting for Quick Mud Creek and predicted footprint from RSS disposal of 857 kL/day are shown on (**Figure 1-2**).

It was recognised that the majority of the RSS footprint on the dry bed of Quick Mud Creek would, at most times, be contained within the local reaches of the watercourse (**Figure 1-2**). In this setting, the water balance and salt balance would predominantly be influenced by losses due to evaporation. These aspects reflect the baseline environment, with evidence of pools and associated salt accumulation within the low-flow channel.

The RSS footprint on the dry bed of Quick Mud Creek would be temporary. Episodic stream flow events in Quick Mud Creek, and in broader context in the Ashburton River, would periodically enable discharge from the local reaches, with associated dissolution and transport downstream of accumulated RSS and salts. The frequency of the episodic discharge events is irregular and predominantly linked to localised thunderstorms and\or larger cyclonic rainfall systems. Periods of drought would potentially enhance the RSS salt accumulation in Quick Mud Creek. These aspects reflect the need to understand the stream flow frequency in Quick Mud Creek in order to define the RSS salts rates of accumulation and episodic transport and fate downstream.

1.3 RSS Chemistry

Previous studies highlighted the potential accumulation of NORM activities within the Quick Mud Creek setting as a potential impediment to regulatory approval. Stream flow in Quick Mud Creek is ephemeral, with subsequent accumulation of salt in pools residual after seasonal to episodic flow events. Specifications of the expected RSS constituents are provided in **Table 1-1** (WorleyParsons, 2014).

Table 1-1 RSS Quality Data

Parameters	Units	Value
pH	Standard Unit	7.78
Temperature	°C	25
Total Suspended Solids		<1
Total Dissolved Solids	mg/L	46,418
Dissolved Organic Carbon		3.3
Radium-226		13.7[1]
Radium-228	Bq/L	22.7[1]
Thorium-228		2.0[1]
Organic nitrogen -N		3.3
Total Ammonium		29.5
Sodium		15,429
Potassium		484
Calcium		962
Magnesium		653
Barium		8.7
Strontium		28.3
Iron		0
Manganese	mg/L	0
Chloride		26,652
Bromide		89.6
Iodide		5
Sulphate		17.3
Bicarbonate		1,940
Carbon Dioxide		26
Fluoride		3.3
Boron		16.2
Silica		78.9
Note: [1]The estimates are derived from the highest NORM concentrations measured in the Birdrong Aquifer.		

As discussed, the disposed RSS and associated salts would accumulate, temporarily at least, in the low-flow channel of Quick Mud Creek. The thicknesses of accumulated salt would be dependent on the RSS volumes (857 kL/day), area of the low-flow channel and the salt bulk density (1.154 kg/m^3).

Given the RSS volumes and salt contents, and assuming a pool area of about 32 ha, the thicknesses of the accumulated salt crust would be:

- 1 year period – 0.24 m.
- 2 year period – 0.49 m.
- 3 year period – 0.73 m.

A summary of the measured Birdrong Sandstone source activities is provided in **Table 1-2**; the RSS activities have been derived from the source activities by applying a conversion factor of 3.34, due to concentration during reverse osmosis. This study uses the highest measured activities of NORMs throughout.

Table 1-2 Measured Birdrong Sandstone Source Activities

Isotope	Laboratory Measured Birdrong Sandstone Source Activity (Bq/L)		Derived RSS Activity (Bq/L)	
	Highest	Average	Highest	Average
Ra-226	4.1	2.6	13.7	8.7
Ra-228	6.8	5.5	22.7	18.4
Th-228	0.6	0.3	2.0	1.0

The measured NORM activities reflect the local circumstances within the Birdrong Aquifer. The RSS expected maximum Ra-226, Ra-228 and Th-228 activities of 13.7, 22.7 and 2.0 Becquerel per litre (Bq/L), respectively, may however, fluctuate over time and at times be exceeded as a function of variations within the Birdrong Aquifer source. There are no data that inform the range of fluctuations that may occur over the long-term, particularly with limited definition of the NORM sources and understanding that over extended periods of pumping larger areas of the aquifer would contribute to the pumping well. If it is assumed that the NORM sources are remote from the pumping well, then it may be reasonable to assume that the local NORM activities in the Birdrong Aquifer source may reflect a near steady-state condition in which case it would be expected that fluctuations would tend to occur within a limited range.

1.4 Project Objectives

This project looks at disposal of the RSS to the Quick Mud Creek and has objectives that include:

- Characterising the baseline NORM on the local reaches of Quick Mud Creek. The baseline sampling considers:
  - Surface water accumulated in pools.
  - Surface crystalline salts on the perimeter of pools.
  - Soils from the bed of the creek.
  - Shallow groundwater in nearby monitoring bores.

- Development of conceptual hydrological and hydrogeological models, supported by the available data that explains the measured baseline NORM distributions associated with Quick Mud Creek.
- Assessments of the roles of seawater in the movement of NORMs and the possibility of attenuation and accumulation within the Hooley Creek – Four-Mile Creek tidal embayment.
- Development of a MIKE21HD(FM) hydrodynamic model of the Hooley Creek – Four-Mile Creek tidal embayment.
- Use of the hydrodynamic model of the Hooley Creek – Four-Mile Creek tidal embayment to predict the the potential transport and fate of the RSS, including characterisations of transient footprints, concentrations and residence times in the tidal reaches of Hooley Creek after stream flow events in Quick Mud Creek. The intention was to define the reasonable worst-case scenarios in consideration of NORM activities and residence times. The hydrodynamic model would be informed by stream flow hydrographs from flood modelling of Quick Mud Creek and the broader catchment of Hooley Creek.
- Estimate the NORM activities in the potential receiving environments on Quick Mud Creek, including:
  - Reviewing existing data that inform hydrochemical conditions and RSS characteristics.
  - Identification of exposure pathways.
  - Referencing applicable radiological regulations and guidelines.
  - Performing NORM geochemical modelling. This modelling would look at selected Average Recurrence Intervals (ARI) rainfall events that would deliver a range of stream flow mixing and flushing scenarios for the RSS disposed and accumulated on Quick Mud Creek.
- Defining the change in NORM concentrations in the receiving environments due to the RSS disposal to Quick Mud Creek over the 80-year Project life.
- Characterising the potential regulatory, human and environmental risks of NORM accumulation in Quick Mud Creek due to the RSS disposal. This would incorporate a screening level radiological dose/risk assessment and subsequent risk/impediment assessment based on potential changes to the baseline and comparisons to selected regulations and guidelines.

The RSS discharge for this assessment is assumed to be 857 kL/day for 80 years, with salinity of 46,418 mg/L Total Dissolved Solids (TDS).

1.4.1 Methodology

The methodology applied to deliver on the outlined objectives includes:

- Use of the baseline sample results to characterise the NORM surface water and groundwater baseline concentrations of Quick Mud Creek. This sampling predominantly occurred in March 2013, with a subsequent single sample collected in August 2013, and was used to inform the baseline NORM activity in the existing surface water and shallow groundwater environment of Quick Mud Creek. The sampling included:
  - Surface water from residual pools on Quick Mud Creek.
  - Crystalline salt from the fringe of one of the pools.
  - Soils from the bed of Quick Mud Creek.
  - Shallow groundwater from beneath dunes adjacent to Quick Mud Creek.

- Development of a baseline conceptual hydrogeological and hydrological model that was supported by the available data and measured NORM distributions. The conceptual models were used to explore the mechanisms of seasonal natural NORM accumulation and speciation within the pools on Quick Mud Creek.
- Review of the existing data and identify the exposure pathways. The selected references and guidelines for NORM management in Australia include:
  - Australian Radiation Protection and Nuclear Safety Agency (ARPANSA); National Directory for Radiation Protection, July 2011.
  - ARPANSA; Safety Guide. Management of Naturally Occurring Material, 2008.
  - International Commission on Radiological Protection (ICRP); 2007 Recommendations of the International Commission on Radiological Protection.
  - International Atomic Energy Agency (IAEA); Safety Guide. Application of the Concepts of Exclusion, Exemption and Clearance, 2004.
- Determination of the periodic flushing frequency of Quick Mud Creek and fate of accumulated salt. Surface water modelling, using MIKE FLOOD, would provide support to develop the conceptual hydrogeology and hydrology and subsequently inform geochemical modelling across a range of seasonal and episodic ARI rainfall and stream flow events on Quick Mud Creek. Existing surface water numerical hydrodynamic models (URS, December 2010) will be used to enable this task, with further development to understand mixing in residual pools and within lower tidal reaches on Quick Mud Creek. Two models developed in 2010 for the Wheatstone Road design were applied. This task specifically focuses on assessments that include:
  - Modelling and statistical analysis the local events that flush Quick Mud Creek to the saline flats (the supra-tidal saline flats between the burrow pits, Figure 1-1) and to the sea.
  - Modelling of ARI events the Ashburton River breakout flows in the local creeks (including Quick Mud Creek).
  - The probability of drought durations and hence accumulation of salt.
  - A block model describing the system - creeks including Quick Mud Creek, the supratidal saline flats, the tidal area and the sea - to estimate the salt mass in each block for a range of scenarios.
- Simulate the flushing of Quick Mud Creek (and accumulated salt) and the supratidal saline flats by the selected ARI stream flow events that may define worst-case scenarios.
- Determine the conditions under which NORMS can enter the Hooley Creek – Four-Mile Creek tidal embayment. The fluvial model (MIKE FLOOD) and hydrological model (TUFLOW) would be run with a set of low-ARI stream flow scenarios and consecutive stream flow events.
- Use of the MIKE21HD(FM) hydrodynamic model to simulate the interactions, mixing , dilution and transport of stream flow with seawater in the Hooley Creek – Four-Mile Creek tidal embayment. Predictive simulations would include:
  - Characterisation of the transport of NORMs from Quick Mud Creek and the supratidal saline flats during 1- to 2-year ARI stream flow events. These events will transport the salt and associated NORMs to the Hooley Creek – Four-Mile Creek tidal embayment.
  - Use or non-reactive solute transport and particle tracking to identify the transport and fate of salt and NORMs derived from Quick Mud Creek.

- Determine the mixing and dilution of NORMs within the Hooley Creek – Four-Mile Creek tidal embayment for selected scenarios. Both non-reactive solute transport and particle-tracking would be used to characterise potential residence times of the NORMs in the Hooley Creek – Four-Mile Creek tidal embayment.
- Characterisation of the transport of NORMs from the salt pan in Quick Mud Creek during less than 1 to 2-year ARI stream flow events. These events will transport the salt and associated NORMs to the Hooley Creek tidal estuary.

- Characterise the natural mixing, dilution and flushing of stream flow events on Hooley Creek by the tide. The areas where mixing, dilution and flushing are inefficient will be highlighted. The particle tracking would allow areas of salt accumulation to be identified.
- Completion of NORM geochemical modelling for relevant exposure pathways to determine the NORM activities, accumulation and speciation at simulated exposure points. The modelling included equilibrium geochemical speciation of the RSS and receiving waters to determine the NORM species and their solubility. The geochemical modelling was used to simulate the mixing of two waters, such as the RSS and receiving stream, in varying proportions (based on stream flow ARI-based scenarios) and calculate the resulting composition of the mixed waters as well as the speciation, solubility, and precipitation of NORMs in the mixture. Geochemical modelling was also used to simulate the evaporation of waters and predict the resulting mineral precipitates that are likely to occur. The geochemical modelling was performed using PHREEQC. The modelling captures and predicts reasonable worst-case scenarios in regards to the transport, temporary accumulations and fate of NORMs.
- Screening level radiological dose/risk assessments for the disposal of RSS to Quick Mud Creek. The geochemical modelling outputs characterise the likely NORM concentrations in water and soil for use as inputs to general public annual dose calculations. The likely radiological dose/risk scenarios to be evaluated include external, inhalation, and ingestion radiation exposure to radiological-impacted soils and discharge or receiving waters.
- Perform an assessment of the change to the baseline concentrations in order to outline the risk of the alternative in term of regulatory process and potential impediments. Management controls are indicated.

NORM Regulations and Guidelines

The predominant international references that inform the current Australian regulations and guidelines with respect to NORM management are derived from ICRP (1991, 1994 and 2007) and IAEA (1996, 2004 and 2006). Australian regulations (ARPANSA, 2008 and 2011) contain criteria for radiological doses to protect human health and these are predominantly derived from the ICRP recommendations.

The chapters below describe the radiological criteria to which exposures and doses are expected to be regulated and managed in international, Australia and Western Australian settings.

2.1 International Guidelines

2.1.1 Human Dose Limits

The ICRP (2007) sub-divided recommended radiological effective dose limits for humans into three bands. The upper two bands reflect the recommended effective dose limits for deterministic effects (based on case studies) and radiological industry workers, respectively. The lower band, which relates to this study, provides recommended effective dose limits for radiological exposures by the general public from expected and planned exposure situations. The ICRP (2007) effective dose limit for the general public is less than 1 millisievert per year.

2.1.2 ALARA Concept

The ICRP (2008) also framed the As Low As Reasonably Achievable (ALARA) concept to the establishment of protections against likely radiological harm. The ALARA framework seeks to:

- Limit the likelihood of radiological exposures.
- Reduce the numbers of the public that may be exposed.
- Control the magnitude of individual doses.
- Optimise radiological protection after consideration of all relevant factors, including social and financial aspects.

The ALARA approach is an important internationally recognised systematic framework for the assessment of reasonable and practical radiation protection options associated with individual projects and circumstances. Regulatory authorities are key stakeholders in the ALARA assessments.

2.1.3 Non-Human Protection

In regard to environmental protection, the ICRP (1990) indicated that the radiation controls needed to protect the general public would likely limit risks to other species. It was anticipated that the effective dose limit of 1 millisievert per year for planned exposures by the general public might cause harm to other species, but not to the endangerment of the species and\or in changing the balance of species. It was recognised that there was limited case study data to support this position.

Since 1990, the position of ICRP has changed. ARPANSA (2010) describes two approaches for radiological assessment and protection of non-human species. These two approaches are:

- ICRP Framework (ICRP, 2007).
- Environmental Risk from Ionising Contaminants Assessment and Management (ERICA) Framework (Larsson, 2008).

Both frameworks are briefly discussed below.

ICRP Framework

There is (ICRP, 2007) recognition that there is explicit guidance required to enable negligible impacts on the environment and associated non-human species, habitats, communities and ecosystems. A systematic approach to environmental protection of the environment was framed (ICRP, 2009) that provides a consistent framework that parallels that for radiological protection for humans. This system uses reference animals and plants (RAP) as proxies to assess relationships between exposure, dose and harmful effects. The RAP included specific types of animals and plants typical of terrestrial, freshwater and marine temperate ecosystems. The RAP have been generalised to the Family taxonomy, thereby allowing for a large number of species. Preliminary points of reference (based on dose rates, thus analogous to those for humans) for RAPs have been derived based on what is known of the effects of ionising radiation. In particular, the ICRP (2009) framework uses concentration ratios (CR) to estimate the transfer (by various pathways) of radionuclides in the environment. The definitions for CR include:

- For terrestrial biota:

$$CR = \frac{\left(Activity\ concentration\ in\ biota\ whole\ body\ (\frac{Bq}{kg}) fresh\ weigth\right)}{Activity\ concentration\ in\ soil(\frac{Bq}{kg}) dry\ weight}$$

- For Aquatic biota:

$$CR = \frac{\left(Activity\ concentration\ in\ biota\ whole\ body\ (\frac{Bq}{kg})\ fresh\ weigth\right)}{Activity\ concentration\ in\ filtered\ water(\frac{Bq}{L})}$$

The most comprehensive recent review of concentration ratios formed part of the Environmental Risk from Ionising Contaminants Assessment and Management (ERICA) based on reference organisms (Larsson, 2008).

ERICA Framework

The ERICA framework is compatible to the ICRP framework, using reference non-human species for characterising exposures to dose and dose effects based on studies in Europe from 2004 to 2007. This framework also uses CR to inform a methodology for a three-tiered approach (ERICA Integrated Approach; Larsson, 2008) to environmental protection from radiological harm. The three-tiered approach includes:

- Generic screening.
- Detailed screening.
- Site-specific analysis.

The ERICA Integrated Approach incorporates the ERICA Tool software that provides interactive assessments of radiological protection using CR databases for a range of organisms. The ERICA Tool also includes a range of default CR values derived from studies of organisms in temperate to artic European settings. Application of the ERICA framework is typically undertaken assuming equilibrium and\or quasi-equilibrium between the organisms and the environment for planned and existing exposure circumstances. Equilibrium and\or quasi-equilibrium environments may occur where the environment is receiving continuous radiological inputs.

2.2 Australian Guidelines

A review by Jeffries et al. (2011) captures the current regulatory aspects of NORM management in Australia.

Radiation protection criteria are based on the Australian Radiation Protection and Nuclear Safety (ARPANS) Act. The national program for radiation safety is administered by ARPANSA, a Commonwealth Government agency that operates under the Australian Radiation Protection and Nuclear Safety Act, 1998 (proclaimed in February 1999). In terms of administration there is a raft of recent APRANSA regulatory guides that may be applicable to this Project, including:

- Regulatory Guide: Applying for a source licence V5 (ARPANSA, August 2012).
- Regulatory Guide: Disposal of controlled apparatus & Controlled Material V3 (ARPANSA, September 2012).
- Regulatory Guide: Plans & Arrangements for Managing Safety V4 (ARPANSA, January 2013).
- Regulatory Guide: Regulation 51 – How to determine When a Change has Significant Implications for Safety V1 (ARPANSA, January 2013).
- Regulatory Guide: Licence Conditions & Practices to be Followed – Extracts from the Act & Regulations V4.1 (ARPANSA, March 2013).
- Safety Guide: Management of Naturally Occurring Material – Radiation Protection Series No 15. (ARPANSA, 2008).

2.2.1 Human Dose Limits

ARPANSA has published a series of reports providing guidelines on radiation protection. The following ARPANSA reports outline the radiation protection standards for general public annual dose limits:

- National Directory for Radiation Protection – Amendment 2 Exclusions and Exemptions (ARPANSA, 2008).
- National Directory for Radiation Protection, Radiation Protection Series No 6 (ARPANSA, July 2011).

This radiation protection standard imposes a general public annual dose limit of 1 millisievert per year. The 1 millisievert per year limit is the allowable dose to general members of the public above the natural background level. Higher dose limits are only allowed for licensed radiation workers. The general public annual dose limit includes the radiological exposure from all sources, including external radiation and the 50-year committed dose from internal NORMs. Sources of internal NORMs include drinking water, food and inhalation of radioactive particles or gases.

The general public annual dose limit of 1 millisievert per year was recommended as an appropriate protective limit by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA, 2011). This recommendation states that a general public annual dose limit of 1 millisievert per year above background from all sources is required to provide adequate protection of public health.

A general public annual dose limit of 1 millisievert per year is also consistent with recommendations of the IAEA. This study uses a dose limit of 1 millisievert per year to judge the risk associated with the proposed disposal of RSS.

There are also guidelines on the radiological characteristics of drinking water (National Health and Medical Research Council (NHMRC) & National Resource Management Ministerial Council (NRMMC), 2011).

2.2.2 Non-Human Protection

ARPANSA (2010, Technical Report No.154) has cited the ICRP (2007) and ERICA (Larsson, 2008) frameworks for radiological assessment and protection of non-human species, though recognises that specific national guidance and research of Australian fauna and flora are required to provide CRs for reference organisms. In particular, ARPANSA (2010) indicates initiatives for use of the ERICA Integrated Approach and the ERICA Tool and associated RAP in Australian contexts.

2.3 In Western Australia

In Western Australia, the radiological regulator is the Radiological Council of Western Australia (Radiological Council). The Radiological Council has a primary role in assisting the Minister for Health to protect public health and to maintain safe practises in the presence of radiation.

The Radiological Council was appointed by the Government of Western Australia as an independent statutory authority under the Radiation Safety Act, 1975. Supplementary legislator includes:

- Radiation Safety (General) Regulations 1983.
- Radiation Safety (Qualifications) 1980.
- Radiation Safety (Transport of Radioactive Substances) Regulations 2002.
- Nuclear Waste Storage and Transportation (Prohibition) Act 1999.

The Radiological Council is not the administrator for the Nuclear Waste Storage and Transportation (Prohibition) Act 1999.

The Radiological Council authority includes the prescription of allowable occupational and general public exposures to radiation in Western Australia. In this regard, the Radiological Council administers Regulation 25A (Schedule 1; Dose Limits and Maximum Permissible Exposure Levels) of the Radiation Safety Act. Based on the Radiation Safety Act, the prescribed general public annual dose limits include:

- An average effective dose of 1 millisievert per year in any period of 5 years.
- An effective dose of 5 millisievert in any 1-year period.

The Radiation Safety act prescribes higher exposure levels for occupational radiation workers:

- An average effective dose of 20 millisievert per year in any period of 5 years.
- An effective dose of 50 millisievert in any 1-year period.

The radiation dose assessments in this report are based on general public annual dose limits and not those for occupational radiation workers. The general public dose limits are applied to both workers in the vicinity of Quick Mud Creek and also the general public in non-work pursuits.

Local Setting

The transport and fate of NORMs disposed and temporarily accumulated within the Quick Mud Creek setting would be influenced by a number physical and socio-economic factors. This chapter provides information on the climate, hydrogeology and the socio-economic and cultural environments of the Project area and surrounds, providing context in terms of both Quick Mud Creek and the proposed disposal of the RSS.

Specifically, the climate would control the recurrence intervals of rainfall and drought events that contribute to the hydrology and watershed characteristics of Quick Mud Creek. The climate would also influence local wind pattern and their associated influences on dispersion of accumulated NORMs from Quick Mud Creek. The hydrogeology of the water table environment would influence the natural water balance and salt balance of Quick Mud Creek and define the opportunities for interactions between the disposed RSS and the shallow groundwater. A brief description of the socio-economic and cultural aspects of the Project area and surrounds provides context regarding RSS disposal to Quick Mud Creek and\or the potential risks to human and environmental receptors linked to the accumulation of NORMs.

3.1 Climate

There are five Bureau of Meteorology (BoM) weather and rainfall stations in the vicinity of the Project area. These stations inform the local climate and include:

- Onslow Town (Station No. 005016).
- Onslow Airport (Station No. 005017).
- Minderoo (Station No. 005013).
- Urala (Station No. 005078).
- Ashburton North.

A review of the rainfall record for four of the rainfall stations has been undertaken (**Appendix A**). The data from Ashburton North has not been used because of its short period of record from 2010 to 2013. The data from both the Onslow Town Station and the Onslow Airport have been collated and assimilated to create a single 107-year (1907 to 2012) record termed Onslow Station. The Onslow Station record was subsequent preferentially used in the design rainfall and hydrology assessments.

3.1.1 Monthly Rainfall, Evaporation and Temperature

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 3-1 provides a summary of rainfall, evaporation and temperature data from the Onslow Airport station (BoM, July 2013). Summer patterns are characterised by hot daytime temperatures, often exceeding 40 ^{o}C between November and February, and widely variable rainfall. Winter patterns are characterised by low rainfall and moderate (average daytime 25 ^{o}C) temperatures.

The annual rainfall typically ranges (decile 2 to decile 8) from 89.2 to 545.9 mm, respectively, with median of median 302.6 mm. Rainfall mainly occurs during January through April, linked to cyclonic activity. Rainfall patterns vary widely due to the influence of tropical cyclones and localised thunderstorm activity.

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.

Table 3-1 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													

3.1.1 Design Rainfall

The BoM (Onslow, 2013) rainfall data used to derive design rainfall Intensity – Frequency – Duration (IFD) data. The derived IFD data are provided in **Table 3-2** and shown in **Plate 3-1**. Assuming a constant intensity for the duration of the storm, then the total depth of rainfall, normalised to 24 hours, can be determined as shown in **Plate 3-2**. The results indicate that the least ARI for a given depth of rainfall occurs for a 24-hour duration storm. The data for the ARI of the 24-hour duration storm can therefore be extracted from the IFD data to identify the probability of the occurrence of a given depth of rainfall. The depths of rainfall for 1-, 2-, 5- and 10-year ARI 24-hour duration storms is shown in **Table 3-3.**

Table 3-2 Intensity-Frequency-Duration Design Rainfall for Onslow

Duration	Rainfall (mm/hour) Selected ARIs						
	1-Year	2-Year	5-Year	10-Year	20-Year	50-Year	100-Year
5 Minutes	74.1	100.0	147.0	178.0	216.0	270.0	313.0
6 Minutes	68.9	93.1	137.0	166.0	202.0	253.0	293.0
10 Minutes	56.0	75.9	113.0	137.0	168.0	211.0	246.0
20 Minutes	41.0	55.9	84.3	103.0	127.0	161.0	188.0
30 Minutes	33.2	45.4	69.1	85.1	105.0	134.0	157.0
1 Hour	21.7	30.0	46.4	57.7	72.0	92.3	109.0
2 Hours	13.3	18.4	29.3	36.9	46.5	60.3	71.7
3 Hours	9.7	13.6	21.9	27.9	35.3	46.2	55.3
6 Hours	5.6	7.9	13.2	17.0	21.9	29.0	35.0
12 Hours	3.3	4.7	8.05	10.5	13.6	18.3	22.3
24 Hours	2.0	2.8	4.9	6.5	8.5	11.6	14.2
48 Hours	1.2	1.7	3.03	4.03	5.31	7.24	8.9
72 Hours	0.8	1.2	2.1	2.9	3.8	5.2	6.5
Notes: Sourced from BoM, July 2013.							

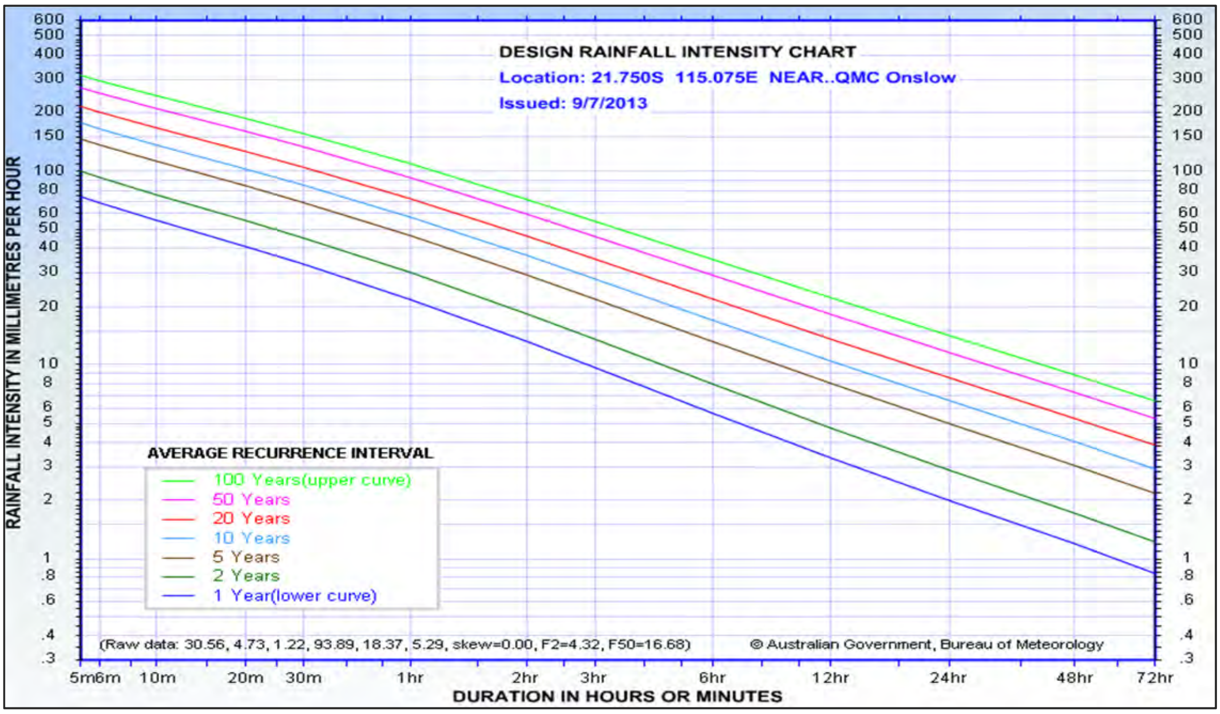


Plate 3-1 Intensity-Frequency-Duration Data for the Project Area

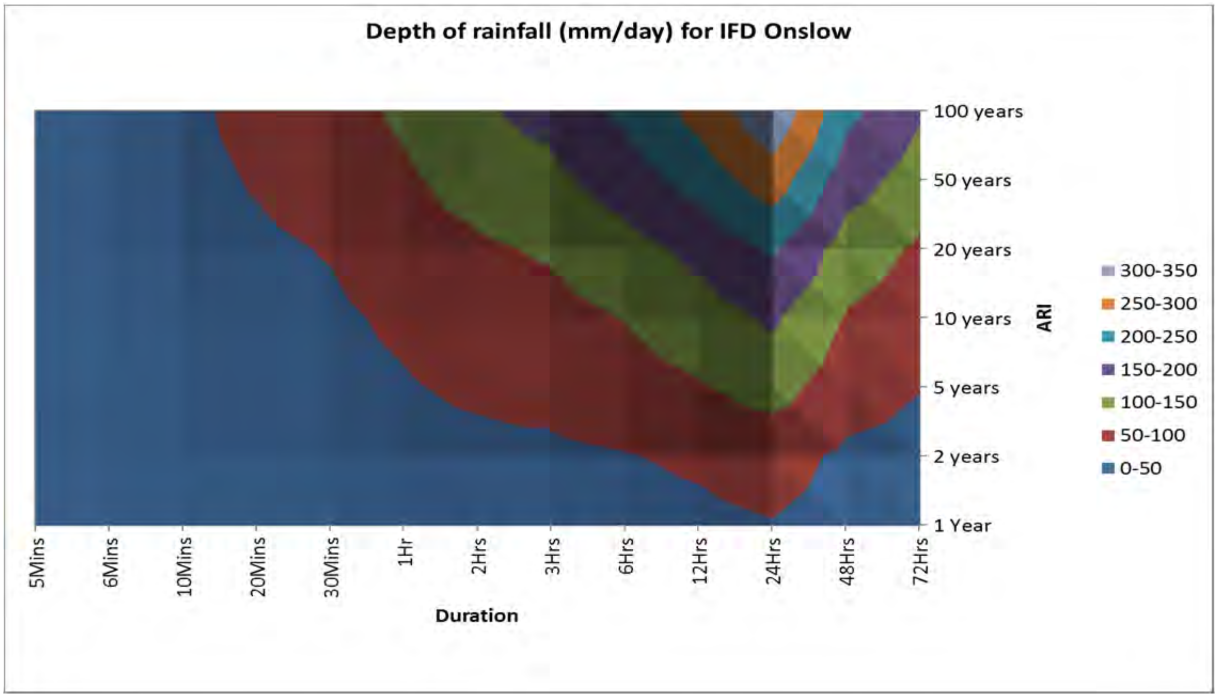


Plate 3-2 Total Rainfall Depth for Storms of Different IFD at Onslow

Table 3-3 Rainfall Depths for Design 24-Hour Storm Durations

ARI	1-Year	2-Year	5-Year	10-Year
Total Rainfall Depth (mm)	48.0	68.9	119.5	157.7

Notes:

Sourced from BoM, July 2013.

3.2 Wind Patterns

Wind data for the Onslow Town (BoM Station 005016) and Onslow Airport (BoM Station 005017) has been obtained from the BoM.

3.2.1 Onslow Town Wind Records

The Onslow Town station recorded wind in the period from January 1957 to July; there is a gap in the data record of approximately four years between October 1971 and March 1975. The wind data recorded derived after March 1975 has been used to produce the wind roses shown on **Plate 3-5**; the predominant wind directions are southerly and westerly to north-westerly.

Wind speeds are rarely above 50 km/h and the average wind speed at 09:00 and 15:00 is 13.6 and 17.7 km/h, respectively.

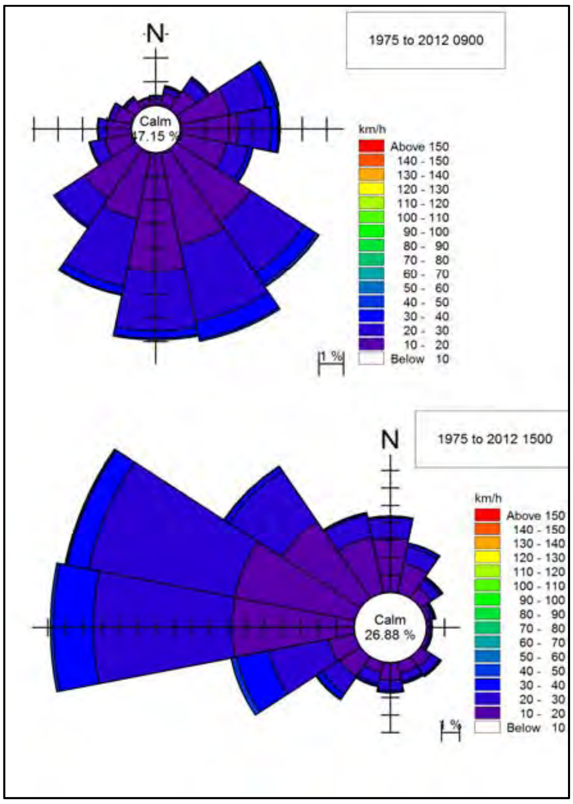


Plate 3-3 Wind Roses for Onslow Town

3.2.2 Onslow Airport Wind Records

The wind records for Onslow Airport (BoM weather station 005017) cover the period from August 1940 to July 2013. The data have a variable time step throughout the observation period and consequently only the records from 1997 to 2013 have been processed to provide hourly values. The wind rose for Onslow Airport is presented in **Plate 3-6**. The rose shows that there are two predominant directions south-westerly and westerly to north-westerly. The average wind speed is 19.5 km/h.

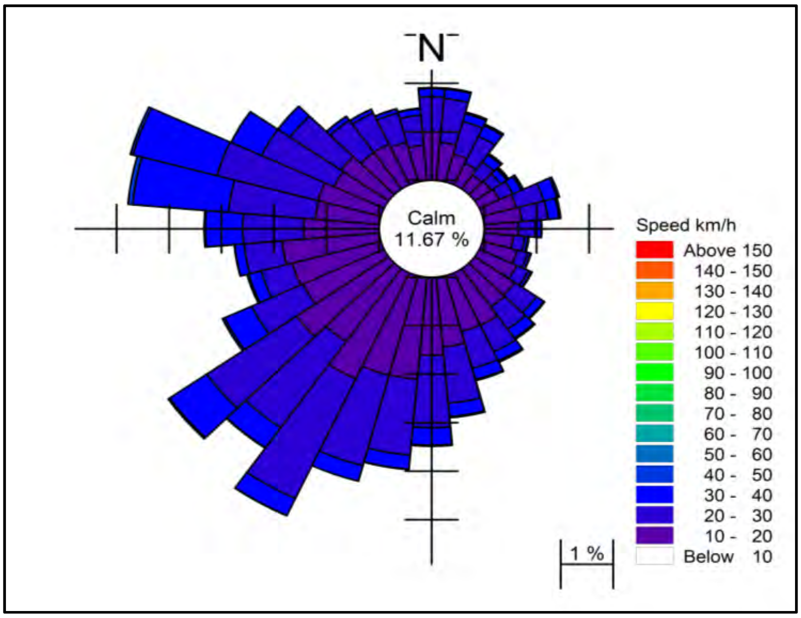


Plate 3-4 Wind Rose for Onslow Airport

3.3 Landform Units and Habitats

The Project area setting occupies the transition zones from a terrestrial watercourse, terrestrial river deltaic environment to a marine environment. The transition commences where supratidal salt flats merge with intertidal flats, tidal creeks (such as Hooley Creek) and mangrove swamps.

Highest elevations occur on foreshore and near-shore sand dunes. The dunes are depositional and accretion landscapes. At the perimeters of the sand dune system, upstream of the tidal range, 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 form a myriad of drainage lines, several of which are linked to the Ashburton River, and surface water retention features. These features include 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. Fringe areas are characterised with clumps of saltbush and samphire.

The low-relief landforms predominantly transition from the terrestrial environment to the marine environment at elevations below the mean low water spring tide elevation of 0.9 m AHD. Landforms within this transition zone reflect the local tidal footprints and include bioturbated high tide mud flats and algal mat covered high tide flats. Mangroves in the vicinity of Ashburton North occupy the section of the intertidal gradient that is approximately between mean sea level (0 m AHD) and an elevation of approximately 0.7 m AHD. The distribution of habitat types within the tidal embayment is a progression from tidal creek – mangroves – samphire and bioturbated high tidal mud flat – algal-mat covered high tidal flat. Two habitat types are recognised within the tidal mud flats, these being bioturbated mud flats with samphire communities and algal mats. Together with the mangrove habitat, the two tidal mud flat habitats are considered as Benthic Primary Producer Habitat (BPPH). The samphire plants and algal mats, like mangrove trees, are primary producers in the strict sense, while the bioturbated mud flats are areas of high secondary production.

Potential environmental receptors were expected to predominantly occur within the tidal embayments and tidal foreshore areas, including mangroves, samphire, bioturbated high tide mud flats and algal mat covered high tide flats. Inundation by seawater during flood tides is the main recharge mechanism that regulates the intertidal zone.

Above the tidal range, the supratidal saline flats, clay pans and clayey plains that extend onto the lower reaches of Quick Mud Creek and Hooley Creek were expected to host comparatively few ecological receptors. For example, the stream flow paths from Quick Mud Creek to the the Hooley Creek – Four-Mile Creek tidal embayment traverse only saline flats and supratidal saline flats; both landforms units accumulate salt and are predominantly barren of vegetation.

3.4 Lithology

A drilling programme undertaken in 2012 provides the local lithology beneath Quick Mud Creek (Golder Associates, May 2012). **Table 3-5** presents the summary of the findings.

Table 3-4 Lithology beneath Quick Mud Creek

Lithology	Broad Characteristics	Aquifer System	Typical Saturated Thickness (m)	Depth to Aquifer System (m)
Alluvium / Colluvium	Sands and gravels with some clayey strata	Dune Sands	3 to 5	-
Ashburton Red Beds (Soils)	Sandy clay to clayey sand. Sand to sand with some clay.	Ashburton River Delta Alluvium	10 to 15	5 - 8
Ashburton Red Beds (Weak Rock)	Claystone/sands/siltstone	Ashburton River Delta Clay and Unconformity	1 to 10	10 - 20
Carbonate Rocks	Carbonate rocks typically with a weathered zone towards the top of the unit	Trealla	26	20

3.5 Quick Mud Creek

The Project area setting occupies the terrestrial river deltaic environment, 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 (**Figure 1-1**). 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 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 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. 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. 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 that form the upper portions of the Hooley Creek – Four-Mile Creek tidal embayment. On Quick Mud Creek, the elevation of the low-flow channel ranges from 0.4 to 1.0 m AHD (**Plate 3-7**) on the reaches downstream of PR-1. The low-flow channel elevation is about 1.0 to 1.1 m AHD near the outflow from Quick Mud Creek, on the saline flats near the Onslow Salt crystalliser ponds. The creek-bed elevations indicate the potential for stream flow on Quick Mud Creek to be attenuated and pool behind barrier bars.

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.

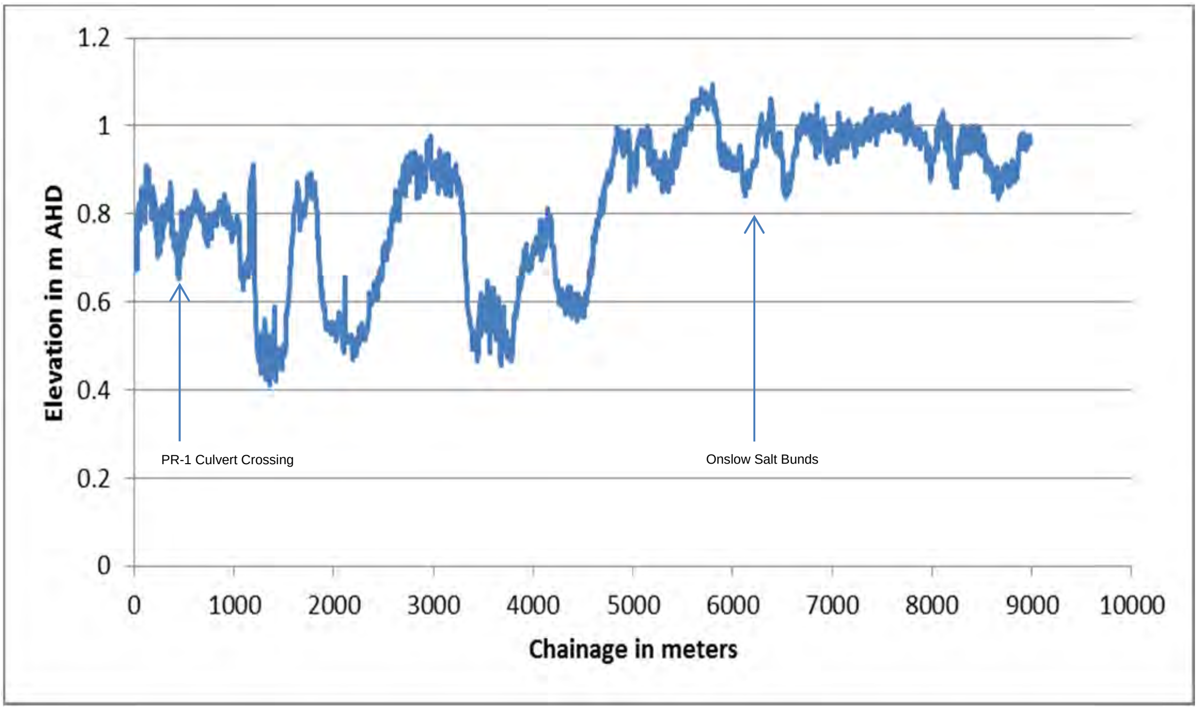


Plate 3-5 Quick Mud Creek Low-Flow Channel Elevation

3.6 Hydrogeology

Groundwater data are limited in the Project area. The nearest monitoring bores (E052FG-S and E052FG-D) are located approximately 1,100 m west of PR-1 **(Figure 1-1)**:

- E052FG-Shallow (E052FG-S): 5 m deep and screened the Ashburton River Delta Alluvium.
- E052FG-Deep (E052FG-D): 36 m deep and screened in the Trealla Limestone.

The monitoring bores are located on the floodplain of Quick Mud Creek and broadly representative of the local groundwater environment associated with the Ashburton River Delta Alluvium that forms the water table aquifer. Monitoring of groundwater levels and salinity in the monitoring bores has been undertaken from October 2011. **Plate 3-8** and **Plate 3-9** presents the data available combined with the rainfall data sourced from the Wheatstone weather station and the Onslow Airport. Groundwater levels in the Ashburton River Delta Alluvium vary seasonally from 2.2 to 1.5 m AHD.

Figure 3-1 presents a conceptual hydrogeology cross-section of Quick Mud Creek broadly characterising the water table setting in context to the dune sands and Ashburton River Delta Alluvium. Interpreted water table elevations derived from data collected in November 2010 are shown on **Figure 3-2**. The mounding of the water table beneath recharge zones associated with the longitudinal dunes generates hydraulic gradients to discharge zones beneath Quick Mud Creek. Groundwater–fed pools may temporarily occur on the local reaches of Quick Mud Creek.

The recharge from rainfall is shown in **Plate 2-8**. Prior to March 2011, significant rainfall events with maximum intensity of 60 mm/day raised the water level in E052FG-S by 0.3 m. The salinity in the Ashburton River Delta Alluvium dropped from just about 93,000 mg/L to 83,000 mg/L. These aspects indicate a direct response of the rainfall recharge on the local water table aquifer. The local shallow groundwater has a widely variable salinity. The dune sands and Ashburton River Delta Alluvium host brackish, saline and hyper saline groundwater. Therefore, the groundwater hydraulics is coupled to density effects that characterise saline and hypersaline groundwater flow dynamics. 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.

The groundwater level elevations in the Trealla Limestone also rose following the rainfall events prior to March 2011. The salinity in the Trealla Limestone Aquifer is considerably higher with hypersaline groundwater ranging 230,000 to 277,000 mg/L TDS.

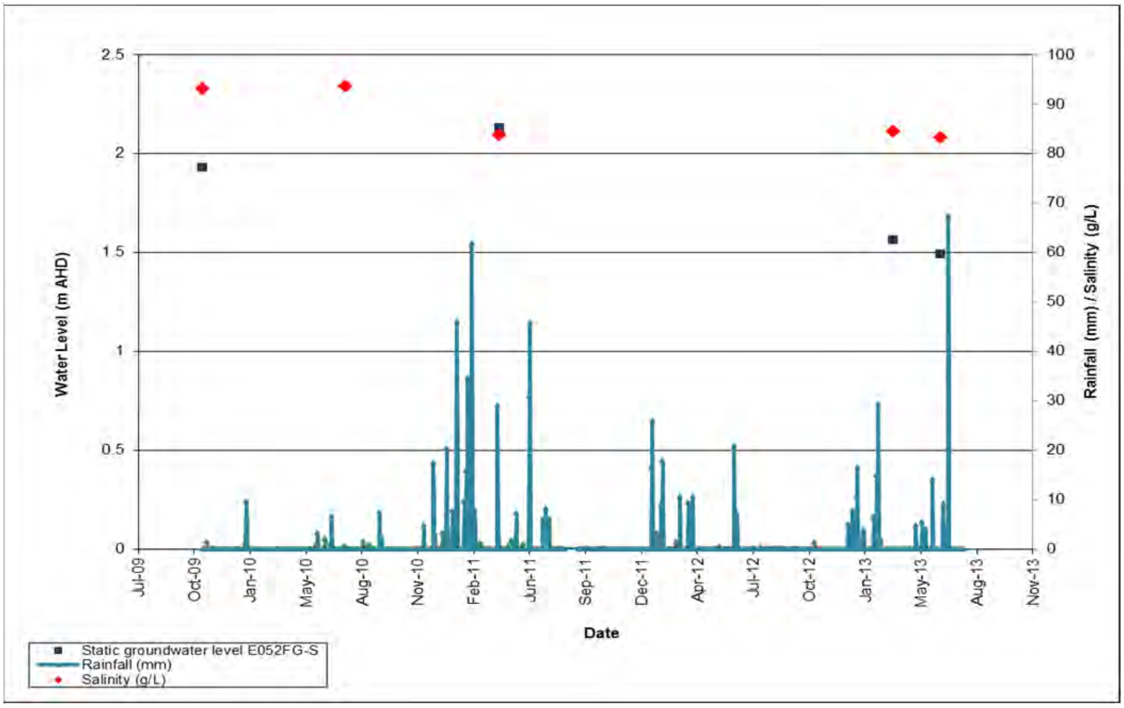


Plate 3-6 Groundwater Levels in EO52FG-S, Ashburton River Delta Alluvium

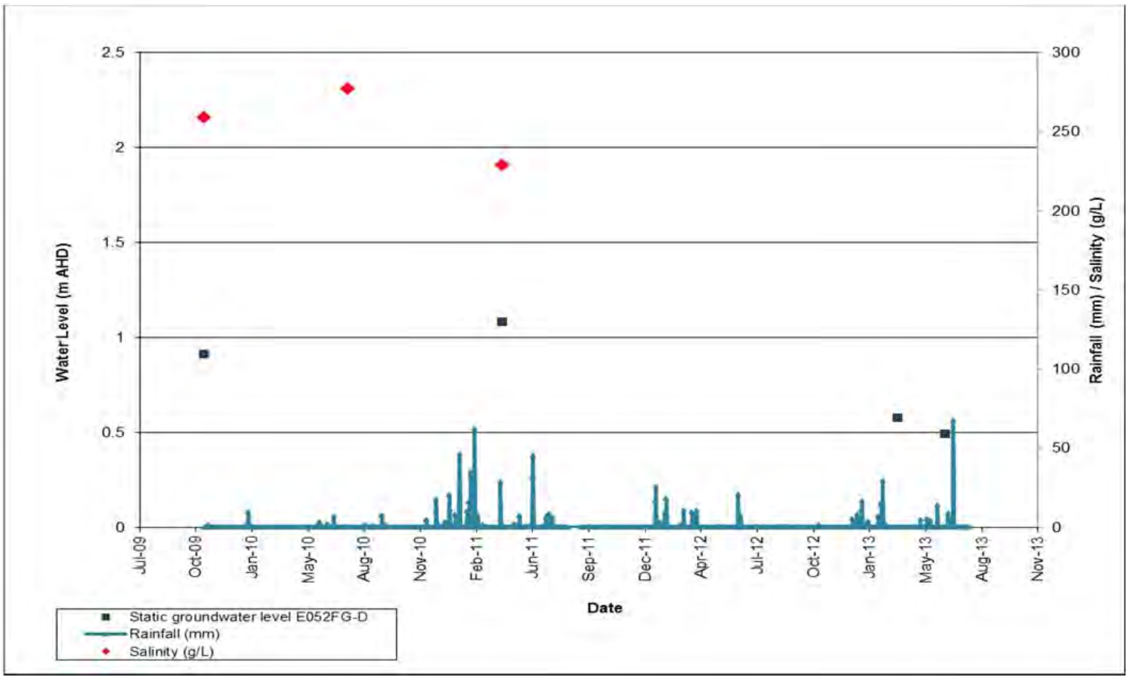


Plate 3-7 Groundwater Levels in EO52FG-D, Trealla Limestone

3.7 Socio-Economic and Cultural Environment

The proximity of the town to the ocean and the Ashburton River attracts visitors in pursuit of recreational coastal activities. Fishing is one of the key recreational activities.

For members of the Aboriginal community, hunting and gathering remains an important recreational and cultural activity. Marine turtles are known to occur seasonally on the shores of Onslow shire (Chevron, July 2010).

In the vicinity of Quick Mud Creek there is potential for socio-economic and cultural activity associated with:

- Onslow Salt Pty. Ltd (Onslow Salt) operations with a succession of salt lakes to the crystalliser pond bunds.
- The Wheatstone accommodation camp which is located 4 km west to PR-1 and hosts workers for the Wheatstone Liquefied Natural Gas (LNG) plant.
- The Macedon Project Plant Site.
- The proposed RO plant is located on dunes on the eastern perimeter of Quick Mud Creek.

Figure 3-2 presents the potential human and environmental receptors in the tidal estuary. It is considered unlikely the local catchment of Quick Mud Creek would be developed for housing during the 80-year Project-life.

Baseline NORM Sampling

There are circumstances where exposures to NORMs occur naturally. An example is exposure to naturally occurring radioactive materials (NORM) in soil and water. Natural NORMs belonging to the uranium and thorium series, as well as potassium-40, are ubiquitous in the earth's crust and are present at varying concentrations in soil and groundwater. Given the natural occurrence of radium and thorium in the Birdrong Sandstone source at depth beneath the Project area, there was consideration that similar occurrence may be evident on the ground surface and in shallow groundwater.

A specific NORM sampling campaign took place in 18th 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 groundwater, surface water, and crystalline salt and soil samples. A further surface water sample was collected on 2nd August 2013. The collected samples were referred to selected laboratories for a suite of analyses that included:

- NORM activities.
- Baseline chemistry, both inorganic and organic (groundwater and surface water samples).
- Mineralogy (crystalline salt and soil samples only).

4.1 Sampling Campaign

The type of sampling is described in **Table 4.1** with a combination of NORM analyses, water quality and mineralogy of the bed of Quick Mud Creek. The locations for the sampling sites are described below and on **Figure 4-1**:

- Monitoring bore E052FG-S. The bore is 5 m deep and screened in the Dune Sand Aquifer of the superficial formations. The lithology log for E052FG-S is presented in **Appendix B**. The intersected lithology varies from silty sandy clay, sand, clayey silty sand, clayey sand and finally silty clayey sand.
- Pool No.1: the first major pool setting, 1.16 km downstream of PR-1, within the low-flow channel of Quick Mud Creek (OSW6 on **Figure 4-1**). The size of the pool (**Plate 4-1**) varies depending on local climatic influences. The samples were analyses for water quality in March 2013 and NORMs in August 2013. Pool No.2 which is the second major pool setting, 1.8 km downstream of PR-1, within the low-flow channel of Quick Mud Creek (OSW5 on **Figure 4-1).** The potential storage for Pool No.2 (**Plate 4-2**) is higher than Pool No.1.
- Soil Samples in the vicinity of PR-1, referred as OSW7 and OSW8 on **Figure 4-2**.

Table 4-1 Sampling in the Vicinity of Quick Mud Creek (March 2013 and August 2013)

Site	Sampling Date	MGA50 Easting	MGA50 Northing	NORMs (liquids)	NORMs (solids)	Analyte Suite (limited)	Mineralogy
E052FG-S	March 2013	300,321	7,590,244	X		X	
OSW5	March 2013	300,856	7591632	X	X	X	
OSW6	March 2013	300,745	4591024			X	
	August 2013			X			
OSW7	March 2013	301,401	7,590,194		X		X
OSW8	March 2013	301,365	7,590,223			X	

Plate 4-1 Sample Site OSW6 on Pool No 1, Quick Mud Creek

Plate 4-2 Sample Site OSW5 on Pool No 2 Quick Mud Creek

4.1.1 NORM Activity Analyses

The groundwater, surface water, crystalline salt and soil samples dedicated for NORM analyses were submitted to Western Radiation Services; a National Association of Testing Authorities (NATA) accredited (No. 14174) laboratory for compliance with ISO/IEC 17025.

An outline of the NORM sampling for radium (Ra) and thorium (Th) is provided in **Table 4-2**. The details of the NORM analytical methods and laboratory reports are provided in **Appendix D**. The radium and thorium species activities were determined by Gamma Spectrometry Analysis.

Table 4-2 Baseline NORM Activities

<table>
<tr><th rowspan="2">Sample Form</th><th rowspan="2">Sample ID</th><th rowspan="2">Month (2013)</th><th rowspan="2">Sample Depth (m bgl)</th><th rowspan="2">Setting</th><th>Ra-226, Ra-228 and Th-228</th><th>Ra-226</th><th>Ra-228</th><th>Th-228</th></tr>
<tr><th>mBq/L</th><th colspan="3">mBq/g</th></tr>
<tr><td rowspan="3">Liquid</td><td>E052FG-S</td><td>March</td><td>1.51</td><td>Shallow Aquifer</td><td rowspan="3"><MDL[1]</td><td rowspan="3" colspan="3"></td></tr>
<tr><td>OSW5-S</td><td>March</td><td>Pool</td><td>Hypersaline Pool</td></tr>
<tr><td>OSW6</td><td>August</td><td>Pool</td><td>Hypersaline Pool</td></tr>
<tr><td colspan="9"></td></tr>
<tr><td rowspan="4">Solid</td><td>OSW5 - solid</td><td>March</td><td>0.30</td><td>Hypersaline Pool</td><td rowspan="4"></td><td colspan="3"><MDL[2]</td></tr>
<tr><td>OSW5 salt crust</td><td>March</td><td>0.05</td><td>Hypersaline Pool</td><td colspan="3"><MDL[2]</td></tr>
<tr><td>OSW7 - solid</td><td>March</td><td>0.30</td><td>Creek Bed</td><td><MDL[2]</td><td>31.6 ± 4.5[3]</td><td>35.4 ± 4.2[3]</td></tr>
<tr><td>OSW8 - solid</td><td>March</td><td>0.30</td><td>Creek Bed</td><td><MDL[2]</td><td>45.2 ± 5.7[3]</td><td>40.0 ± 4.5[3]</td></tr>
</table>

Notes:

MDL refers to Method Detection Limit.

1 For the liquids, the MDL was 100 mBq/L.

2 For the solids, the MDL was 30 mBq/g.

3 The reported expanded uncertainty of measurement (Western Radiation Services, 9 July 2013) is stated "*as the standard uncertainty of the measurement ± 5.6 per cent, multiplied by the recovery factor k=2, which corresponds to a coverage probability of approximately 95 per cent.*"

Radium and thorium species were below method detection limits in the hypersaline pools on Quick Mud Creek and in the shallow groundwater from E052FG-S. The salt crust and the soil sampled at 0.3 meters below ground level on the fringes of the hypersaline pools were also not found to contain radium above the method detection limits.

Radium-228 and thorium-228 was found in the soil samples from the bed of Quick Mud Creek near PR-1 and the Wheatstone Road, with activities respectively ranging from 31 to 45 and 35 to 40 mBq/g. The concentrations are marginally above the detection limits. They likely represent the natural background concentration of Ra-228 and Th-228.

Analyses of total alpha and beta activities (**Appendix C**) were below the method detection limits. These analyses on the groundwater, surface water, and crystalline salt and soil samples were by

Liquid Scintillation Counting. The method detection limits for alpha and beta activities were 60 and 135 mBq/L, respectively.

4.1.2 Baseline Chemistry Analyses

Shallow groundwater and surface water samples from the residual pools on Quick Mud Creek were provided to ALS Group for selected analyses. The ALS Group has world NATA accreditation for compliance with ISO/IEC 17025 and the quality control on the sample analyses was aligned to National Environmental Protection Measure 1999, Schedule B(3) and ALS QCS3 requirements.

Historical TDS data from sampling of the shallow groundwater and surface water in pools on Quick Mud Creek are presented in **Table 4-3** and on **Figure 4-2.**

The shallow groundwater in monitoring bore EO52FG-S Pool is hypersaline. The measured salinity in March 2013 was 84,400 mg/L TDS; the measured historical range from sampling during 2009 to 2011 was 83,600 to 104,000 mg/L TDS. Fluctuations in the shallow groundwater TDS concentrations may reflect the occurrence of seasonal and\or episodic rainfall recharge events. These events, with associated water table rise, may also change the vertical upward hydraulic gradients, thus changing local flow contributions from deeper aquifer zones.

Pools of hypersaline water appear to be comparatively common on Quick Mud Creek. The occurrence of pools has been observed during site visits since 2010. The pools are generally shallow (about 0.2 m deep) and characterised by a fringe of precipitated salts. Pool No.1 and Pool No.2 on Quick Mud Creek were hypersaline in March 2013, with chloride and TDS concentrations about 170,000 mg/L and 380,000 mg/L, respectively. The salt crust visible during the sampling confirms the natural occurrence of hypersaline surface water.

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 and associated stream flow and groundwater discharge is expected to have significantly diluted the hypersaline pools with low-salinity water. These aspects reflect a widely varied and continually changing baseline environment where the salinity of the surface water is dependent on antecedent conditions and water availability.

Table 4-3 Historical Salinity Data for Pools on Quick Mud Creek

Sampling ID	Pool	Sampling Date	Salinity (mg/L, TDS)	MGA 50 Coordinates	
				Easting	Northing
EO52FG-S	Shallow Groundwater	3/18/2013	84,400	300,290	7,590,244
SW28	Pool No1	4/14/2011	116,000	300,740	7,590,968
OSW6	Pool No1	3/18/2013	380,000	300,745	7,591,024
OSW13	Pool No2	6/16/2013	260,000	300,745	7,591,015
OSW5	Pool No1	3/18/2013	377,000	300,856	7,591,632

The occurrence of the pools is maintained by two assumed mechanisms originating from the run-off/steam flow and local groundwater discharge after seasonal and\or episodic rainfall recharge events.

Evidence of run-off events has been captured following storm events on the 24 and 25 June 2013 (**Plate 4-3**). The photo is taken from the PR-1 culvert crossing. The low-flow channel of Quick Mud Creek is flowing almost full at this time. The water is highly turbid. These types of events have capability to dissolve and transport the crystalline salt precipitated along Quick Mud Creek.

The topography along the Quick Mud Creek varies from 0.40 to 1.0 m AHD and the local water table is marginally higher in elevation. Therefore, the low-flow channel of Quick Mud Creek likely forms an ephemeral groundwater discharge area for the water table aquifer formed locally by the Ashburton River Alluvium. The period of March 2013 coincides with the end of the cyclonic season. Previous months of January and February were reasonably wet with a total rainfall depth of 120 mm (BoM Station 005017). The infiltration of rainfall would have recharged the local water table with sufficient rise to create a temporary discharge zone with groundwater seepage onto the low-elevation areas of the Quick Mud Creek.

Plate 4-3 Quick Mud Creek after Stream Flow Events on 24 and 25 June

4.1.3 Mineralogy

Four crystalline salt and soil samples were submitted to Intertek Genalysis for quantitative x-ray diffraction (XRD) phase analysis. Intertek Genalysis has NATA world recognised accreditation (No.

3244) for compliance to ISO/IEC 17025, including the management requirements of ISO 9001:2000. The local Intertek Genalysis facility is accredited in the field of Chemical Testing.

The samples were provided to the laboratory as wet powders and were subsequently dried at 60 ^{0}C for 12 hours, then coned and quartered to representative 20 g composites. A grab sample was micronized and prepared an un-orientated powder mounts of the total sample. Patterns of sample XRD characteristics were produced on PANalytical Cubix^3 XRD fitted with Copper radiation (operating at 45 kV and 40 mA, scanning a range of 1.3^0 to 65ᶱ2Ɵ. The x-ray bean was diffracted using graphite monochromators. The quantitative analyses of the XRD characteristics were assessed with Bruker Diffrac.EVA 2.1 Search/Match software with the International Centre for Diffraction Data (ICDD) PDF-2 (2011) database.

The details for the mineralogy of the bed can be summarised as follows:

- The salt crust is composed at 96 per cent sodium chloride, as is typical for local waters.
- The bed of Quick Mud Creek is comprised mainly of quartz, illite/muscovite, sodium chloride and subordinate gypsum.

The XRD analytical results are provided in **Appendix D**.

Based on the XRD analytical results it was concluded that the soils on the bed of Quick Mud Creek, at least in the proximity to the pools, are characterised by accumulated salt. The upstream reach near PR-1 has a lower salt concentration because this area is not a groundwater discharge zone. The high ratio of quartz, illite/muscovite in the watercourse bed is interpreted to be due to the stream flow transporting sediments from the inland Pilbara.

Stream Flow Characteristics

5.1 Overview

The Project area is located within the Ashburton River Catchment (**Figure 5-1**). The Ashburton River is one of the major rivers of the Pilbara region, flowing in response to significant local and regional episodic rainfall events. At the mouth of the Ashburton River, the Ashburton River Delta setting is a dynamic fluvial, estuarine and marine environment, with historical evidence indicating both sediment accretion and changes to the river channel within the delta. During a stream flow event in 1921 the channel shifted about 7 km west (Damara, 2009). The estuary between the Onslow Salt crystalliser ponds and the Ashburton River Delta contains creeks and pools, including the Hooley Creek, Middle Creek and Four-Mile Creek estuary, the lower reaches of which are inundated by tides (**Figure 5-1**).

The ephemeral watercourses in the Ashburton River Delta are commonly dry except in tidal reaches. Stream flow occurs in response to both local and regional rainfall events, usually linked to cyclones, and flood events on the Ashburton River.

5.2 Ashburton River Flood Events

The Ashburton River is characterised by:

- A large catchment area. It has a catchment area of approximately 78,777 km^2. Overland flow is channelled in the upstream portion of the catchment, due to greater topographic relief in its upper reaches. At the coast, the river discharges through a network of tributaries and braided flow paths within the Ashburton River Delta.
- Ephemeral flows. Commonly there are long periods of no flow; substantial flows are generated by episodic cyclone events. The maximum observed peak flow estimated at the Nanutarra River Station (Department of Water: Station 706003; Figure 5-1) was about 12,500 m^3/s during 1997.
- Climatic conditions which are characterized by long dry periods and high intensity rainfall events, which generate significant stream flows. The magnitude of stream flow is predominantly determined by the ARI of the rainfall events.

Comparatively major flows occur in the Ashburton River every one to three years.

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 the Ashburton River Delta, including Quick Mud Creek.

Annual flow volumes and maximum flow rates in the lower reaches of the Ashburton River (**Plate 5-1** and **Plate 5-2**, respectively) has been monitored since 1972 through the Department of Water (DoW) Gauging Station at the Nanutarra Bridge, approximately 100 km inland (south) from the river mouth. The station gauges the majority of the Ashburton River Catchment (70,200 km^2 which corresponds to 90 per cent of the total area). The maximum flow rates on the Ashburton River (**Plate 5-2**) were obtained for every year using the average daily maximum stream flow values.

Evidently, the annual flow volumes in the Ashburton River are widely variable, being known to range from 3 GL in 2007 to 4,500 GL in 1997; the average in the period 1973 to 2008 was 840 GL per year.

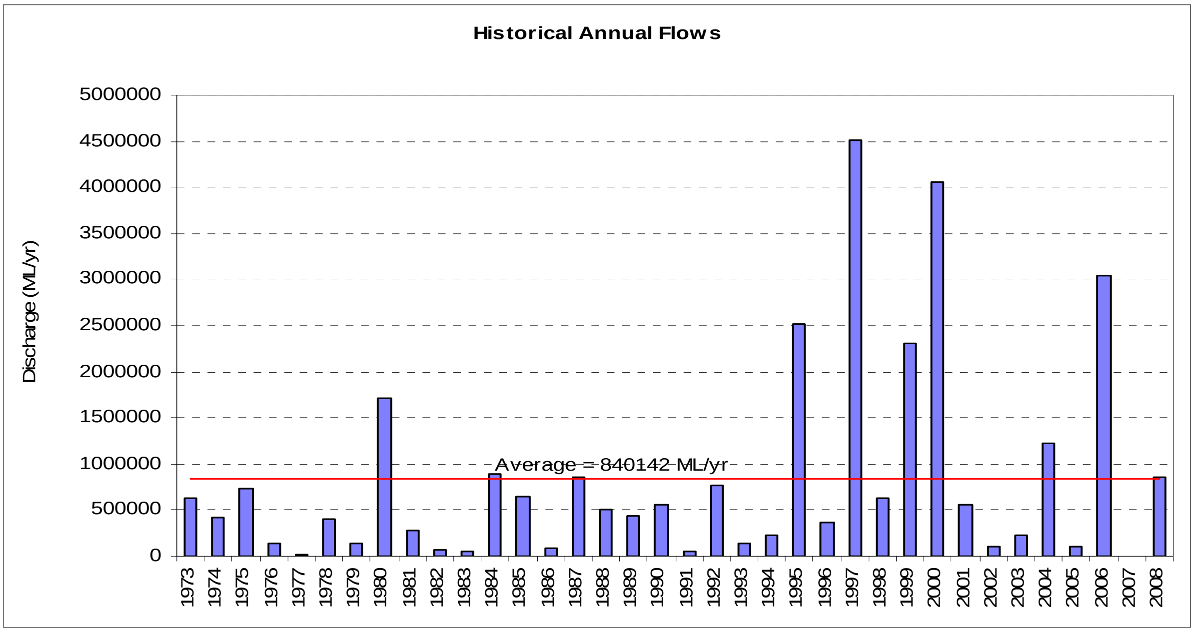


Plate 5-1 Historical Ashburton River Annual Flow Volumes (1973 to 2008)

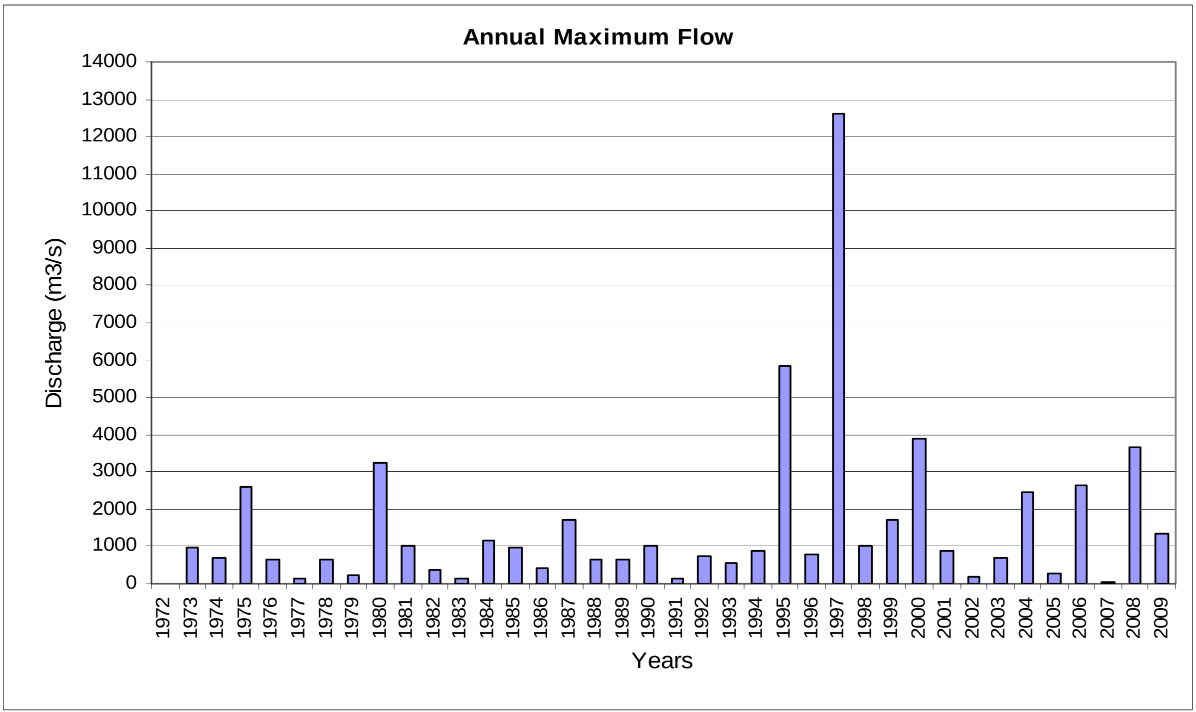


Plate 5-2 Historical Ashburton River Peak Flow Rates (1973 to 2008)

A Frequency Flood Analysis (FFA; URS, December 2010) informs the flow regime of the Ashburton River at the Nanutarra Bridge. A FFA uses statistical analysis to determine the likely frequency of occurrence (recurrence interval) of natural events. The Log Pearson 3 (LP3) statistical method was adopted as the most reliable method given the variability in flood statistics and conforms to the AR & R guidelines (Pilgrim, D.H, 2001). The statistical analysis is based on a record period extending from

1973 to 2009 (URS, December 2010). The results of the Flood Frequency Analysis are summarised in **Table 5-1** and on **Plate 5-3.** The analysis was also conducted with the Generalised Extreme Value (GEV) and the Gumbel distributions for comparison purposes.

Table 5-1 Ashburton River Flood Frequency Analysis at Nanutarra Bridge

Annual Recurrence Interval (Years)	Ashburton River Estimated Peak Flows (m^3/s)
1	312
2	851
5	2,288
10	3,816
20	5,803
50	9,273
100	12,651

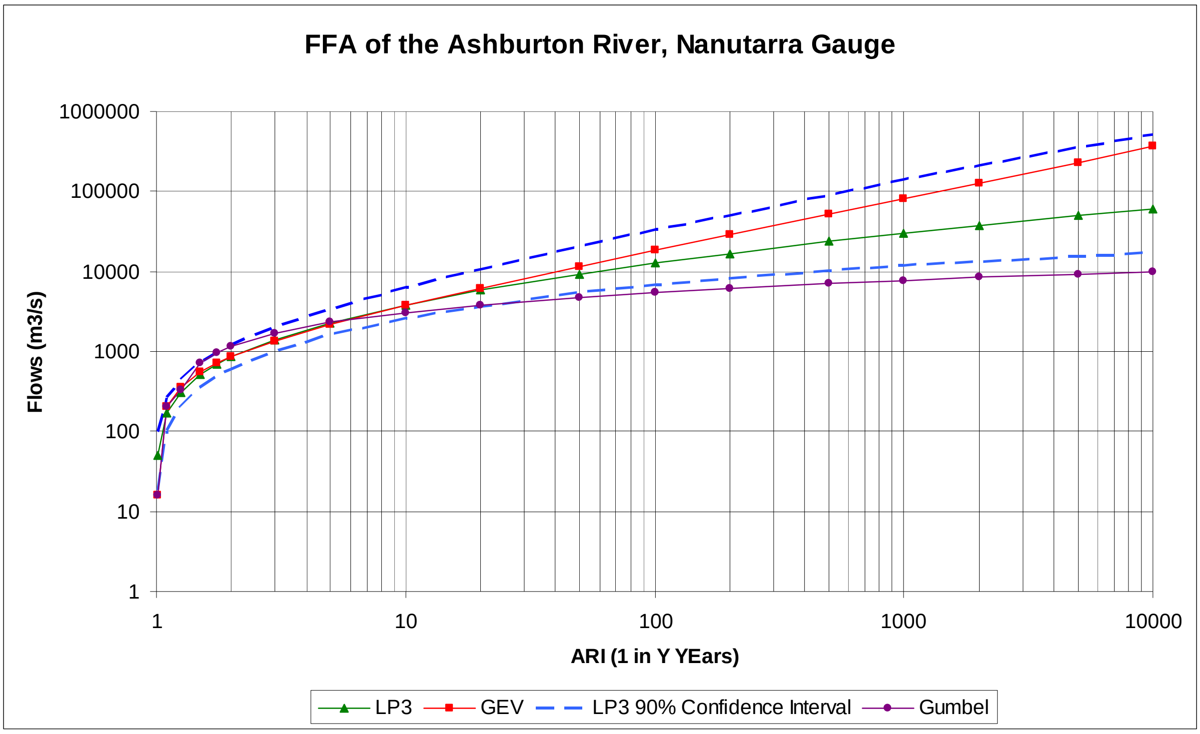


Plate 5-3 Ashburton River FFA at Nanutarra Bridge

Based on the FFA analysis, the observed maximum annual peak flows in the Ashburton River at the Nanutarra Bridge have been classified by ARI, from the lowest to the highest, and presented in **Table 5-2**. There have been 37 flow events, typically representing flow each year during 37-year record.

Table 5-2 ARI for Peak Flows at Nanutarra Bridge

Year	Estimated Peak Flow (m^3/s)	Approximate ARI (year)
1997	12,610	100
1995	5,824	20
2000	3,887	10
2008	3,657	10
1980	3,232	Less than 10
2006	2,660	Greater than 5
1975	2,608	Greater than 5
2004	2,466	5
1987	1,735	2 to 5
1999	1,724	2 to 5
2009	1,350	Less than 2
1984	1,171	Less than 2
1981	1,012	Less than 2
1990	1,003	Less than 2
1985	996	Less than 2
1973	977	Less than 2
1998	998	2
2001	903	2
1994	864	2
1996	800	2
1992	747	2
1974	716	1 to 2
2003	712	1 to 2
1989	651	1 to 2
1978	633	1 to 2
1976	627	1 to 2
1988	628	1 to 2
1993	536	1 to 2
1986	427	1 to 2
1982	373	1
2005	279	Less than 1
1979	228	Less than 1
2002	180	Less than 1
1991	159	Less than 1
1983	153	Less than 1
1977	140	Less than 1
2007	51	Less than 1

Flood flows break out of the main channel of the Ashburton River approximately 40 km north of the Nanutarra gauging station; schematically shown on **Plate 5-4**. The distribution and the likely storage of flood flow volumes for various ARI events have been estimated from a hydrographic survey of the 1997 Ashburton River flood event. The results of this survey (URS, July 2010) indicated that approximately 25 per cent of the stream flow from this 100-year ARI event was diverted to the northeast of the main channel, into the Hooley Creek and Quick Mud Creek watersheds.

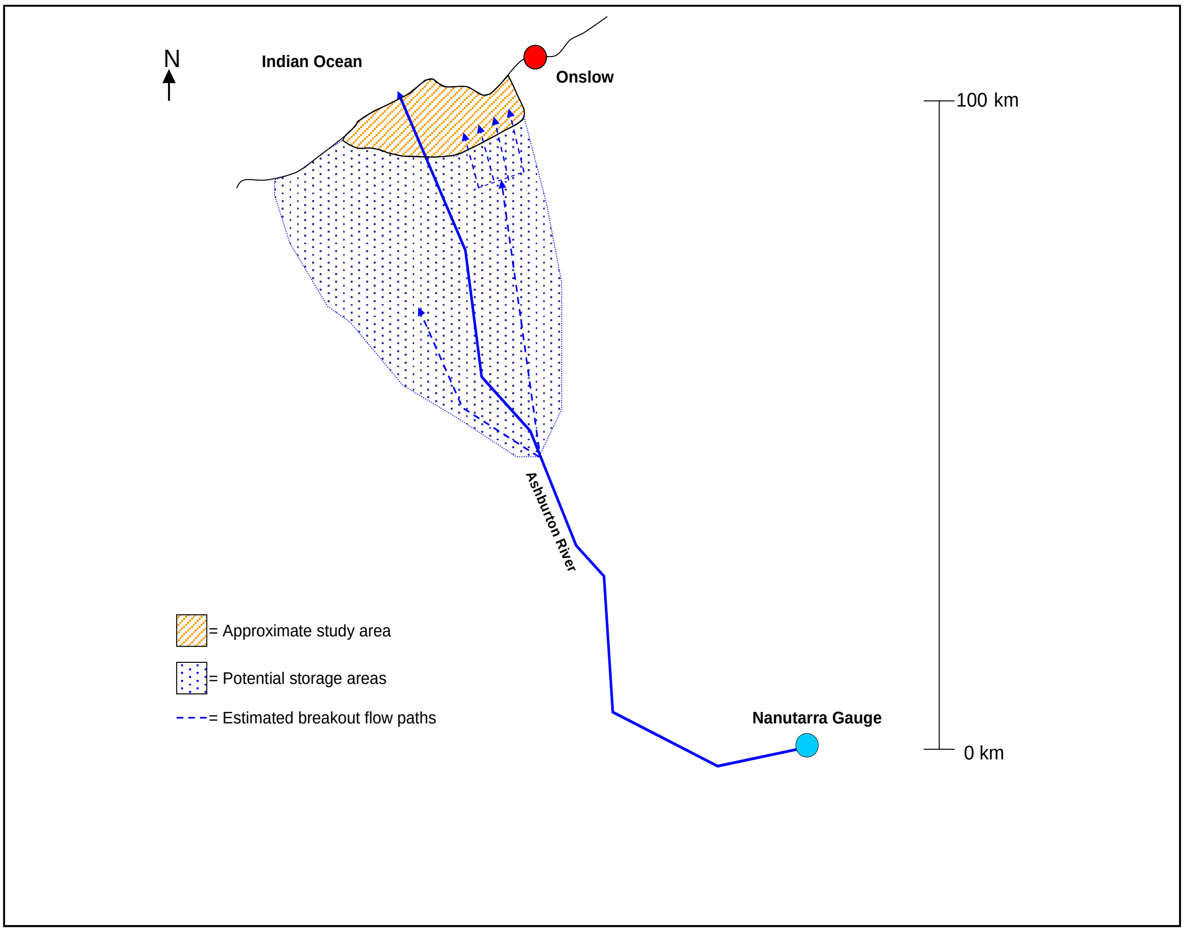


Plate 5-4 Schematic of the Ashburton River North of Nanutarra Bridge

The simulation of a range of ARI events (URS, July 2010) was used to characterise the percentages of the stream flow potentially diverted from the Ashburton River to the Hooley Creek and Quick Mud Creek watersheds. The results are summarised in **Table 5-3**.

Table 5-3 Ashburton River Flood Contributions to Hooley Creek and Quick Mud Creek Watersheds

ARI (years)	Ashburton River Flood Contributions to Quick Mud Creek and Hooley Creek Watersheds (per cent)	
	Minimum	Maximum
5	0	10
10	5	10
25	10	20
50	15	25
100	20	30

Based on these simulations, it might be expected that at times when the Ashburton River is in flood, 5 to 25 per cent of the stream flow volumes may enter the Quick Mud Creek and Hooley Creek watersheds. For a flow event similar to the average annual volume of 840 GL, volumes in the range 42 to 210 GL may be shed through Quick Mud Creek and Hooley Creek.

5.3 Ashburton River Delta

The setting of the Ashburton River Delta is shown on **Figure 5-1**. Within eastern portions of the delta, the predominant watercourses include Hooley Creek (West and East), Middle Creek and Four-Mile Creek estuary. The lower reaches of each creek are inundated by tides. Quick Mud Creek is a tributary to the tidal creeks, with an incised channel upstream of the supratidal saline flats.

The ephemeral watercourses in the Ashburton River Delta are commonly dry except in tidal reaches. Stream flow occurs in response to both local and regional rainfall events, usually linked to cyclones. Pools may prevail on local reaches of the watercourses after significant rainfall events. The water balances of the pools may vary widely and include baseflow contributions linked to local groundwater discharge.

Under seasonal-dry conditions the sub-catchments of the Ashburton River Delta are discrete and the local surface water environments are independent. During and after significant cyclonic rainfall events, however, stream flow typically swells above low-relief catchment divides and connects the individual sub-catchments to form a coastal flood plain. Under these circumstances, the stream flow from the Ashburton River may extend throughout the entire delta, contributing to flows in the sub-catchments of the Hooley, Middle, Four-Mile and Quick Mud creeks.

5.4 Hooley Creek

The Hooley Creek system consists of the drainage lines referred as Hooley Creek West, Hooley Creek East, Middle Creek and Four Mile Creek (**Figure 5-1**). Although Hooley Creek is identified as a discrete catchment, it has low relief and during regional flood events it is hydraulically connected to the Ashburton River and adjoining sub-catchments.

5.5 Quick Mud Creek

5.5.1 Watercourse Setting

Local reaches of Quick Mud Creek stretch between Wheatstone Road and the crystalliser ponds of Onslow Salt Pty Ltd (URS, November 2012). Wheatstone Road, constructed for the Wheatstone Project, traverses the creek. The Wheatstone Road design incorporates culverts to divert frequent 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 significantly the flow regime of Quick Mud Creek (URS, December 2010).

The predominant hydrological characteristics of Quick Mud Creek are derived from earlier reports (URS, November 2012, URS, 2012e and URS 2010c) and include:

- The watersheds for Quick Mud Creek (**Figure 5-1**) include:
  - The local catchment area of the immediate flood plain for the 5.5 km reach north of Wheatstone Road is 20 km^2. This is considered the least watershed area for the generation of stream flow.
  - The sub-regional catchment covers an area of 214 km^2 south of Wheatstone Road culver crossing PR-1. The size of the catchment is still considered localised enough to not apply rainfall reduction factors (Pilgrim, 2001).
  - The regional catchment covers an area of 1,811 km^2 extending to Gum Creek 73 km south of PR-1 and draining the eastern floodplain of the Ashburton River. This catchment is not analysed for the Project given numerous uncertainties in its flow regime.
- The watercourse is not located within the Hooley Creek – Four-Mile Creek tidal embayment, but rare storm surges do inundate the lower reaches.
- The low-flow channel is oriented northwards, towards the Onslow Salt crystalliser pond bunds. The flow path follows a slight low-lying plane and then discharge onto the supratidal saline flats that form the upper portions of the estuary.
- Initial and comparatively small volume stream flows are typically attenuated in the low-flow channel.
- The low-flow channel forms an ephemeral groundwater discharge zone after significant rainfall recharge events. Episodic groundwater discharge occurs to residual pools that form within depressions on the bed of the watercourse (URS, pers. obs. March 2013).
- Stream flow is ephemeral and collects runoff shed from local upstream catchments and\or breakout flows from flooding of the Ashburton River.
- During major floods, the entire floodplain could be inundated.
- Discharge from Quick Mud Creek to the Hooley Creek – Four-Mile Creek tidal embayment occurs episodically after localised or regional rainfall events that will have different intensity-frequency-duration characteristics. Flows form these discharge events may be attenuated on the supratidal saline flats and lower terrestrial reaches of Hooley Creek.
- Stream flow that propagates to the tidal reaches of Hooley Creek appears to preferentially enter the east branch.
- Droughts would influence the water balance of Quick Mud Creek and specifically the frequency of events that would discharge from the creek.

In summary, stream flow in Quick Mud Creek is ephemeral. There are commonly long periods of no flow and short, episodic events of very high flow. Additionally there are events due to localised rainfall that may result in stream flow in local, but not necessarily to the end of the creek which terminates on supratidal saline flats adjacent to the Onslow Salt crystalliser pond bunds.

5.5.2 Contributions from Ashburton River Flood Events

A regional MIKE FLOOD HD hydrodynamic model developed in 2010 (URS, December 2010) to determine the ARI for flooding of the Ashburton River that would contribute to stream flow on Quick Mud Creek. This model originally only considered events less frequent than a 5-year ARI. Predictive outcomes from this model 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 the PR-1 culvert crossing on Wheatstone Road. Further, the predicted rates of flow enable discharge of Quick Mud to the sea.

This numerical model 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 provides 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 5-4**. Flood footprints within the Hooley Creek and Quick Mud Creek watersheds for the 1- and 2-year ARI events on the Ashburton River are shown on **Figure 5-2**.

The outcomes of predictive simulations for the Ashburton River flood events 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 and also inundates the watercourses of Hooley Creek and the supratidal saline flats. The total flow volume is estimated to be 28.7 GL over the flood duration. Quick Mud Creek discharges to the sea during these events.

Table 5-4 Quick Mud Creek Predicted Peak Discharge

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

5.5.3 Determination of Discharge Thresholds for Quick Mud Creek

Discharge events in Quick Mud Creek are characterised by sufficient stream flow volumes and rates that would:

- Overflow the storage volumes formed by the low-flow channel and associated pools.
- Discharge downstream onto the supratidal saline flats.
- Discharge into the Hooley Creek – Four-Mile Creek tidal embayment.

Discharge events may originate from either the local rainfall and\or flooding of the Ashburton River.

Drought periods would reflect extended periods during which there are no discharge events; there may be smaller-scale flow events that do not discharge.

Three approaches have been used to characterise the rainfall and steams flow circumstances that would enable discharge from Quick Mud Creek downstream onto the supratidal saline flats and tidal estuary. These approaches involved:

- Application of the existing MIKE FLOOD HD hydrodynamic model to simulate the footprint of selected stream flow rates.
- Initial rainfall run-off simulations using XP-Rafts to predict the rainfall excess from 1-year and 2-year design 24-hour rainfall events that would contribute to stream flow.
- TUFLOW simulations to predict stream flow hydrographs for selected ARI events, with incorporation of initial and continuing losses and natural attenuation. The TUFLOW simulations captured Quick Mud Creek and other watercourses shedding onto the supratidal saline flats together with the spans of the supratidal saline flats. As such, these predictions enable estimate of the stream flow contributions to the tidal creeks.

The findings of the three approaches are discretely discussed below.

5.5.4 MIKE FLOOD HD Hydrodynamic Model Predictions

The numerical MIKE FLOOD HD hydrodynamic model developed in 2010 has been used to determine the threshold for design storms to generate discharge events (URS, December 2010). The model domain includes 190 km^2 of the Ashburton River Delta between the mouth of the Ashburton River and Onslow Road. The main features of the model include:

- The grid cell size is a 40 by 40 m.
- The creek beds and the supratidal saline flats are dry at the start of the simulations.
- The tidal cycle used in the simulations is based on a standard tidal cycle.
- The model represents the baseline condition at Ashburton North prior to local disturbances.
- The model is calibrated based on the 1997 flood event.

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 simulated discharge rates include 1, 2, 5 and 10 m^3/s and are constant over the 24-hour storm duration. The outcomes of the simulations are summarised in **Table 5-5** and footprints of the respective discharges are shown on **Figure 5-3**.

The predictive modelling indicates:

- Stream flow rates of 2 m^3/s over 24-hours enable discharge from Quick Mud Creek onto the supratidal saline flats. Stream flow events below this threshold may enable discontinuous discharge for shorter periods.
- Stream flow rates of 5 m^3/s over 24-hours enable discharge from Quick Mud Creek to be transmitted to the tidal estuary and sea. The low-flow channel from Quick Mud Creek traverses the southern perimeter of the supratidal saline flats then western reaches of Hooley Creek before entering East Hooley Creek.

Table 5-5 MIKE FLOOD HD Predicted Discharge Events in Quick Mud Creek

Stream Flow (m^3/s over 24 hours)	24-Hour Flow Volume (GL)	Flood Footprint[1] (km^2)	Fate of the Discharge	Discharge Status
1	0.09	1.0	Quick Mud Creek storage is full but the discharge does not propagate further downstream.	No Discharge
2	0.17	3.7	Quick Mud Creek storage is full. The flood propagates further downstream to the supratidal saline flats.	Discharge to Supratidal Flats
5	0.43	12.3	The discharge propagates downstream and reaches the sea through western and eastern Hooley Creek.	Discharge to Sea
10	0.86	18.6	The flood propagates further downstream and reaches the sea through Hooley Creek.	Discharge to Sea

Notes:
1 The flood extent refers to the wetted footprint of the maximum flood extent over the catchment.

5.5.5 Simulation of Rainfall Excess from Design Rainfall Events

Rainfall run-off modelling was conducted to determine the watershed characteristics of the local Quick Mud Creek watersheds. XP-Rafts software (XP Solutions, July 2013) was used to predict the rainfall excess from 1-year and 2-year 24-hour design rainfall events. Two catchment sizes define the predicted contribution of Quick Mud Creek to the design rainfall events (**Figure 5-1**):

- The local catchment of 20 km^2 covering the flood plain and the dune sands. This is the minimal size where predictive run-off simulations are made with confidence. The spatial distribution of the rainstorm can be considered as uniform over the entire catchment with limited attenuation due to topographical depressions.

- The sub-regional catchment of 214 km^2 including the flat between the Minderoo rain gauge station to the PR-1 culvert crossing. This catchment contains numerous features (for example clay pans) that attenuate the stream flow. These features would inundate and limit the propagation of stream flow derived from upstream catchment areas.

The design rainfall applied to the models was derived from the IFD relationships outlined in Chapter 3.2.1 (**Table 3-2** and **Plate 3.2**) and rainfall depths determined for 24-hour duration storm events of selected ARI (**Table 3.3**).

An assessment of both initial and continuing losses from the design rainfall was used to generate excess rainfall and subsequent surface runoff in each catchment area. Catchment losses such as infiltration and evaporation used in the modelling were compatible to the Australian Rainfall & Runoff (AR & R) guidelines (Pilgrim, 2001). The estimates of initial and continuing losses are outlined in **Table 5-6.**

Table 5-6 Catchment Losses Based on AR & R Guidelines

Loss Factors	Selected ARI (Years)			
	1	2	5	10
Initial (mm)	17[1]	22	40	52
Continuous (mm)	5	5	5	5

Notes:
1: This initial loss has been extrapolated using a linear regression.

The predicted 1-year and 2-year ARI design storm graphs derived from XP-Rafts are shown on **Plate 5-1** and **Plate 5-2**. Stream flow is only generated when there is excess rainfall (that is the initial and continuing losses have been exceeded).

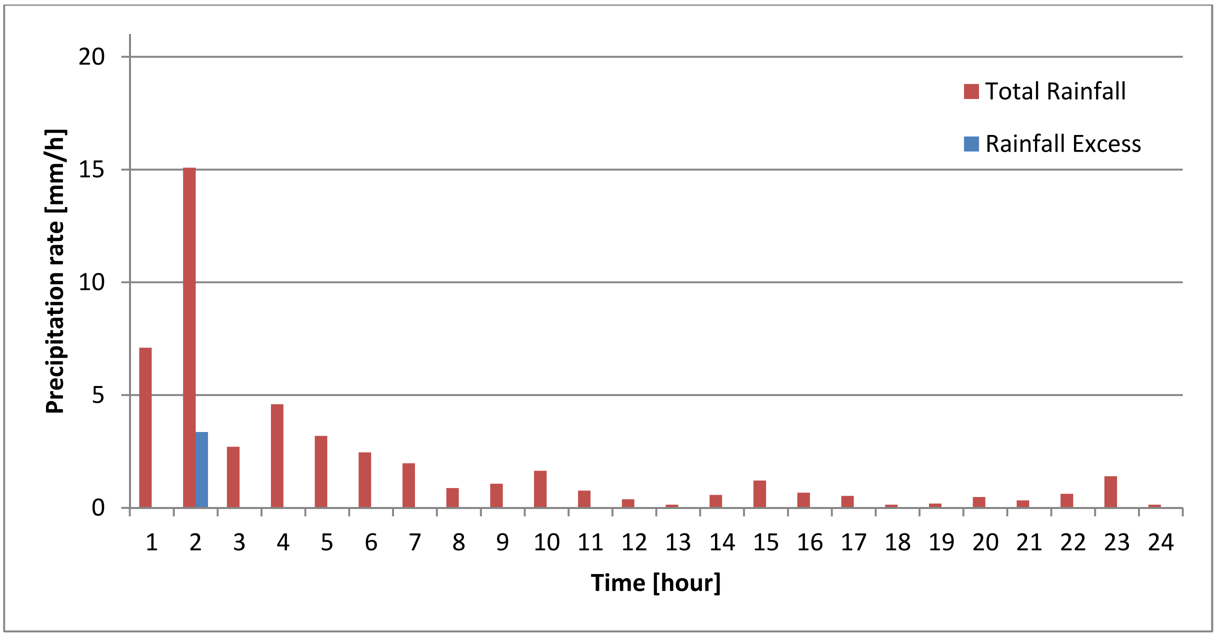


Plate 5-5 1-Year 24-Hour Duration ARI Design Rainfall

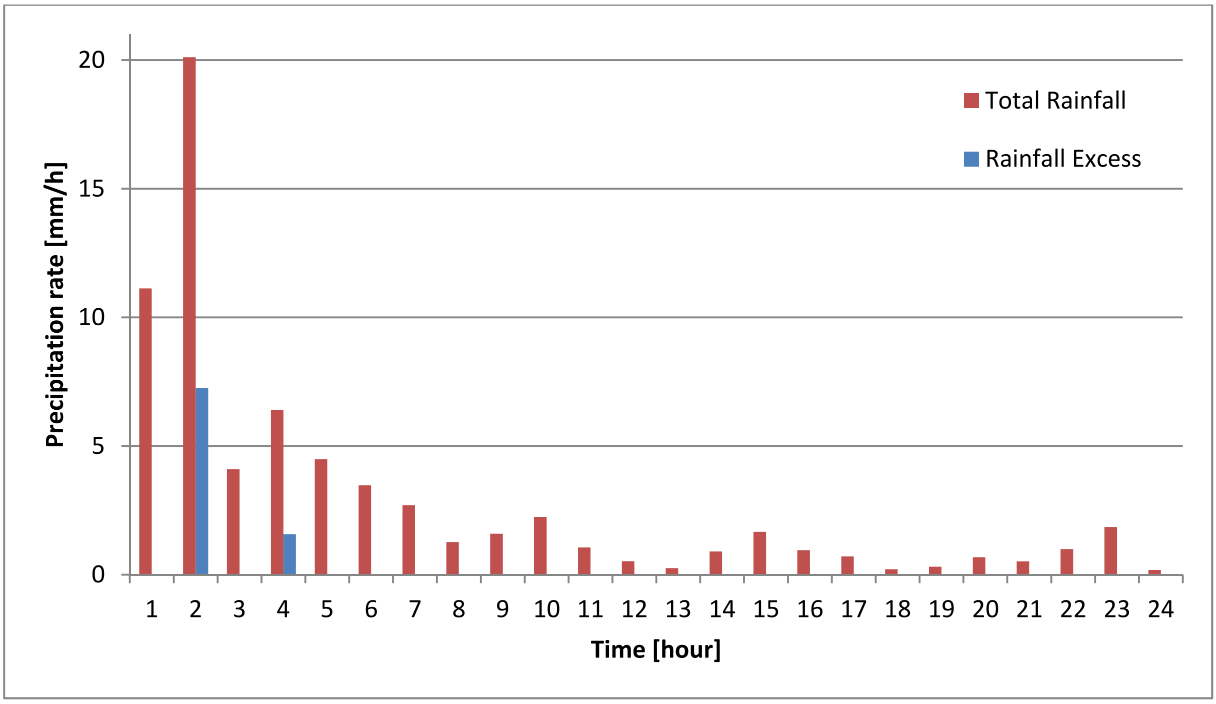


Plate 5-6 2-Year 24-Hour Duration ARI Design Rainfall

5.5.6 TUFLOW Predictions of Stream Flow

The purposes of TUFLOW simulations were based on a “rainfall on grid model and included the development of an understanding regarding watershed of Quick Mud Creek and the supratidal saline flats to the Hooley (west and east) and Middle tidal creeks. It was assumed that rainfall was uniformly distributed over the entire contributing catchment areas.

In this way, the TUFLOW simulations were used to inform:

- Contributing catchments (inflow locations).
- Inflow hydrographs and volumes of water generated by various rainfall events.
- System sensitivity to different loss factors.
- Main flow paths.
- Natural runoff pathways, attenuation and storage areas and volumes within the catchments.

Inputs to the development of the TUFLOW model included:

- A 30 m x 30 m grid.
- Topographic data derived from the following sources:
  - LiDAR 2012.
  - Shuttle Radar Topography Mapping (SRTM) 2000 (where LIDAR data were not available).
- Aerial photographs provided by Chevron Australia Pty Ltd.
- Design rainfall data (AR & R, 87) derived from XP Rafts hydrological model. There was no spatial reduction factor applied to the design rainfall.
- IFD data (BoM, 2013).
- Roughness value of 0.04 Manning’s n.
- Loss factors (AR & R) as per **Table 5-6** for the contributing catchment areas. The loss factors applied to the supratidal saline were assumed based on the understanding that the topography is planar, with very low hydraulic gradients, shallow depths to the underlying water table and comparatively high evaporation potentials. The assumed loss factors are outlined in **Table 5-7**.
- Social infrastructure that includes:
  - Wheatstone Road.
  - Culverts under Wheatstone Road.
  - Expansion of Onslow Salt crystallizer pond which decreases natural storage of Quick Mud Creek. The boundary of the expansion area that propagates onto the lower reaches of Quick Mud Creek was simulated as a glass wall.
- The model was not calibrated since there were no available data. There were a number of sensitivity checks by amending the loss factors.

The present day digital terrain model shows that the reaches of Quick Mud Creek immediately south of the Onslow Salt crystalliser ponds form an attenuation basin (**Figure 5-4**) of approximately 140 ML storage volume. The attenuation characteristics are enhanced on the southeast limits of the supratidal saline flats (onto which Quick Mud Creek discharges) where the topography forms additional, smaller basin on the low-flow channel. Further upstream on Quick Mud Creek there are numerous clay pans and incisions in the landscape that also may attenuate initial stream flow volumes.

Table 5-7 Assumed Losses on the Supratidal Saline Flats

Loss Factors	Selected ARI (Years)			
	1	2	5	10
Initial (mm)	0	0	0	0
Continuous (mm)	0.5	0.5	0.5	0.5

A number of scenarios were explored using the TUFLOW model. These predictive scenarios are outlined in **Table 5-8**.

Table 5-8 TUFLOW Stream Flow Model Scenarios

Scenario Code	Description	Event ARI (years)
TU_X001_04	24-hour rainfall event occurring above the Quick Mud Creek Catchment. Generated flows only on Quick Mud Creek	1
TU_X002_04		2
TU_X005_04		5
TU_X005_08	Consecutive 24-hour rainfall events above Quick Mud Creek and other tributaries contributing to the supratidal saline flats.	1 + 1
TU_X001_08		1 + 2
TU_X002_08		1 + 5
TU_X010_08		1 + 10

Notes:

The likelihood of the respective consecutive events wherein there is a rainfall depth of 1-year ARI on the first day and then y ARI (y= 1,2,3,5 or 10) the second day, include:

- 1 + 1-year – 6.7-year AR1.
- 1 + 2-year; total rainfall of about 110 mm – 9.2-year ARI.
- 1 + 5-year; total rainfall of about 168 mm – 35.2-year ARI.
- 1 + 10-year total rainfall of about 206 mm – 75.7-year ARI.

The likelihood of consecutive events increases under circumstances where the equivalent 24-hour 2-, 5- and 10-year rainfall depths occurs over 2 to 5 days. Under these circumstances, which would produce simular catchment responses, the likelihood becomes 2.5, 3.4, 6.2 and 9.2-year ARI, respectively for the 1+1, 1+2, 1+5 and 1+10-year events. As a further guide to frequency, rainfall of 110, 168 and 206 mm depths accumulated over a period of five days has occurred 7, 5 and 2-times, respectively in the period from 1999 to 2013.

The TUFLOW-model predicted stream flow volumes generated for the Quick Mud Creek catchment areas and the selected 24-hour duration ARI storm events are shown in **Table 5-9**.

Table 5-9 TUFLOW Predicted Stream Flow Volumes on Quick Mud Creek

Event ARI (years)	Event Duration (hours)	Stream Flow Volume (GL)
1	22	0.009
2	30	0.05
5	31	0.16

The TUFLOW-model predicted stream flow volumes for the selected individual ARI events are small compared to those derived from the MIKE FLOOD HD simulations (**Table 5-5**). This aspect is due to the incised features and clay pans within the Quick Mud Creek catchment that attenuate initial runoff. It was anticipated that runoff volumes of these magnitudes would disperse and be lost to evaporation on the supratidal saline flats. Accordingly, it was anticipated that consecutive rainfall events might be required to enable runoff generated on Quick Mud Creek to traverse the supratidal saline flats and discharge into the local tidal creeks. As such, the TUFLOW model was applied to the simulation of 1-year ARI rainfall events with subsequent 1-, 2-, 5- and 10-year ARI events, respectively. In these simulations, the initial 1-year ARI event tends to predominantly fill the clay pans and reaches where the low-flow channel is incised, with the subsequent rainfall shedding as stream flow.

Predicted stream flow contributions for the simulations of consecutive rainfall events that incorporate Quick Mud Creek, other tributaries to the tidal estuary and the supratidal saline flats are summarised in **Table 5-10**. The model domain showing the discretised cross-sections where individual contributions and hydrographs have been simulated is shown on **Figure 5-5**. Further, schematic predictive results of the TUFLOW simulations of the 1 + 1, 1 + 2, 1 + 5 and 1 + 10-year ARI consecutive events are shown on **Figure 5-6** through **Figure 5-9**, inclusive.

For the consecutive 1-year and 2-year ARI events, the stream flow yields from Quick Mud Creek are comparatively low; predicted to be less than 10 per cent contributions to outflows to the tidal creeks. In these simulations, the majority of local flow is generated on the supratidal saline flats. For the less frequent consecutive events, the stream flow volumes increase by an order of magnitude compared to the consecutive 1-year and 2-year ARI events and proportional contributions to the supratidal saline flats from Quick Mud Creek increase to the range 80 to 90 per cent.

Table 5-10 TUFLOW Predicted Stream Flow Contributions to the Tidal Creeks

Event ARI (years)	Stream Flow Contributions (GL)							
	Inflows to Supratidal Saline Flats			Flows on the Supratidal Saline Flats	Outflows to Tidal Creeks			
	Quick Mud Creek	Hooley Creek Tributaries	Total		West Hooley Creek	East Hooley Creek	Middle Creek	Total
1 + 1	0.11	0.10	0.21	0.98	0.68	0.34	0.18	1.195
1 + 2	0.13	0.29	0.42	0.95	0.68	0.43	0.26	1.373
1 + 5	3.06	0.64	3.70	0.28	1.61	1.19	1.18	3.978
1 + 10	11.79	1.38	13.17	(1.35)	4.54	2.87	4.40	11.814
Notes:								
The simulated inflows to the supratidal saline flats were measured at selected points (refer to Figure 5-5).								

The predictive TUFLOW models reflect circumstances whereby accumulated RSS crystalline salt from Quick Mud Creek would tend to be mobilised, in part at least, onto the supratidal saline flats. Over time (between major stream flow events) the RSS salt footprint may propagate onto and traverse the supratidal saline flats. This aspect would depend on the magnitudes of stream flow events together with rates (times) for dissolution of the accumulated crystalline salts and recognition that the tails of the stream flow events would be attenuated on the supratidal saline flats. Subsequent occurrences high-volume stream flow events, including Ashburton River flood events, would tend to mobilise the vast majority of the accumulated salts, with discharge to the sea.

From the predictive hydrology assessments it is concluded that typically:

- Stream flow in Quick Mud Creek, generated by rainfall on the catchments contributing to the supratidal saline flats, would promote an annual to biennial event wherein there is discharge to the sea. The likelihood of discharge to the sea is enhances under circumstances where an antecedent event inundates the majority of the attenuation storages, thus enabling the subsequent event to flow.
- The Ashburton River typically floods once every two years and associated flows spill into Hooley Creek and Quick Mud Creek, enabling discharge to the sea.

Considering all of the analyses of observed events it appears reasonably conservative to assume that Quick Mud Creek would tend to discharge every second year, though probably more frequently. The Ashburton River floods on average once every two years.

5.6 Conceptual Hydrological Model

When the RO plant is operating, Quick Mud Creek would be characterised by:

- A RSS-derived wetted footprint that at a maximum extends about 4.6 km downstream from the release point.
- Attenuation of the RSS footprint in pools within the low-flow channel. The pools would cover about 32 ha and temporarily store a portion of the RSS volume where the depths range from 0.1 to 0.5 m (URS, November 2012).
- Loss of the RSS predominantly by evaporation from the wetted footprint and pools in the low-flow channel. The RSS discharge would, therefore, produce crystalline salt crusts along the low-flow channel.
- Elongation of the RSS footprint and accumulated salts onto the supratidal saline flats by low volume stream flow events.
- Episodic discharge of the RSS and accumulated crystalline salts from Quick Mud Creek would occur at times when stream flow is generated by rainfall within the sub-regional catchment of the supratidal saline flats (including Quick Mud Creek and Hooley Creek) and\or the Ashburton River. Stream flow in Quick Mud Creek would typically promote an annual to biennial event where there is discharge to the sea.
- The Ashburton River typically floods once every two years and associated flows spill into Quick Mud Creek, also enabling discharge to the sea.
- It appears reasonably conservative to assume that Quick Mud Creek would tend to discharge every second year, though probably more frequently.
- The frequency of discharge would be less during periods of low rainfall and associated stream flow. During these periods there would be propensity for increased salt accumulation from the RSS within the low-flow channel of Quick Mud Creek.

It was estimated that the salt on Quick Mud Creek containing the disposed NORMs would accumulate over a maximum period of 2 years. The two-year duration was estimated based on:

- The Ashburton River typically floods once every two years with associated flushing of Quick Mud Creek. It was anticipated that these flood events would enable be of sufficient volumes and durations to entirely dissolve and mobilise the accumulated salt on Quick Mud Creek.

- Local and sub-regional stream flow events derived within the catchment of Quick Mud Creek would partially or entirely dissolve and mobilise the salt crust to the downstream supratidal saline flats. These stream flow events were estimated to occur on a 2-year return period basis.

- Local and sub-regional stream flow events, derived from local thunderstorms and rainfall in the Quick Mud Creek catchment, may be dissociated from regional cyclone-derived stream flow events in the Ashburton River. Cumulative influences of the local, sub-regional and regional stream flow events were estimated to provide an increase the propensity for and frequency of events that would dissolve and mobilise, in part at least, accumulated salt from the lower reaches of Quick Mud Creek.

On the basis of these aspects, it was assumed that the reasonable worst case scenario for salt accumulation would occur over a maximum period of 2 years.

5.7 Dissolution, Dilution and Discharge of the RSS

5.7.1 Dissolution of RSS Accumulated Salts

The MIKE FLOOD HD and TUFLOW models indicate discharge of the ponded RSS and precipitated RSS salts from Quick Mud Creek would occur during periodic stream flow events.

Halite dissolution rates have been estimated vary from about 0.1 to 0.009 moles/m^{2}sec. The dissolution rate depends on the stream flow being under-saturated with respect to halite, the ability to transport the dissolved salt beyond the attention features of Quick Mud Creek system and the rate of stream flow. As the salt is dissolved, the stream flow would increasingly approach saturation with respect to halite, and the dissolution rate decreases exponentially.

Using a median halite dissolution rate of 0.04 moles/m^{2}sec, it would be possible to fully dissolve in about 3.5 days the quantity of accumulated salt (29,059,455 kg) deposited in Quick Mud Creek over a period of 2 years. If the duration of the stream flow event was only 1 day, then only about one third of the salt would dissolve. Under these circumstances, if the stream flow event was longer than 3.5 days, then the latter runoff would not dissolve any salt, but would serve to dilute the concentration of salt attenuated downstream and\or in the tidal estuary. For an upper-bound halite dissolution rate of 0.1 moles/m^{2}sec, about 1.4 days would be required to dissolve salt accumulated over 2 years.

Although complete dissolution and discharge of precipitated RSS salts may not occur during a particular stream flow event, a conservative estimate of the potential radium and thorium activities in stream flow was made by assuming that all of the radium and thorium in the ponded RSS and precipitated RSS salts would be dissolved and transported downstream of Quick Mud Creek during a 24-hour stream flow event. Background radium and thorium activities in the stream flow are assumed to be zero and the highest Ra-226, Ra-228 and Th-228 activities in the RSS and precipitated salt (**Table 1-2**) are 13.7, 22.7 and 2.0 Bq/L, respectively. The Ra-226 and Ra-228 activities in the Hooley Creek – Four-Mile Creek tidal embayment were assumed to be 1.36E-03 and 1.71E-03 Bq/L, respectively, based on radium activities measured in Cockburn Sound, Western Australia (Loveless et al. 2008).

5.7.2 Radium and Thorium Activity in Quick Mud Creek RSS Sources

The radium and thorium activities within the stream flow were calculated using a simple mass balance model. With inputs from the 24-hour stream flow volumes compatible to the MIKE FLOOD HD simulations the mass balance model is based on:

$$Activity_{Stream\ Flow} = \frac{\left(Activity_{Runoff} * Volume_{Runoff}\right) + \left(Activity_{RSS} * Volume_{RSS}\right) + \left(Activity_{Salt} * Volume_{Salt}\right)}{Volume_{Stream\ Flow}}$$

where,

$$Volume_{Stream\ Flow} = Volume_{RSS} + Volume_{Runoff}$$

It was assumed that all of the 2-year accumulated salt volume on Quick Mud Creek was dissolved within the 24-hour period, subsequently transported by the stream flow to the Hooley Creek – Four-Mile Creek tidal embayment and dispersed.

A summary of the predicted radium and thorium concentrations in 24-hour stream flow events on Quick Mud Creek is provided in **Table 5-11**.

Table 5-11 RSS Radium and Thorium Activity in 24-Hour Flow Events on Quick Mud Creek

Stream Flow Discharge Rate (m^3/s)	24-Hour Runoff Volume[1] (m^3)	RSS Steady-State Pool Volume (m^3)	2-Year RSS Precipitated Salt Volume (m^3)	RSS Stream Flow Activity (Bq/L)		
				Ra-226	Ra-228	Th-228
1	86,400	49,926	626,039	67.9	112.6	9.9
2	172,800	49,926	626,039	41.6	68.9	6.1
5	432,000	49,926	626,039	19.2	31.8	2.8
10	864,000	49,926	626,039	10.1	16.8	1.5

Notes:
1 24-hour runoff volume derived from **Table 5-5**.

The total RSS radium and thorium activities for the four events were estimated as follows:

- 1 m^3/sec stream flow discharge rate – 190.4 Bq/L.
- 2 m^3/sec stream flow discharge rate – 116.5 Bq/L.
- 5 m^3/sec stream flow discharge rate – 53.9 Bq/L.
- 10 m^3/sec stream flow discharge rate – 28.4 Bq/L.

5.7.3 TUFLOW-Derived RSS Radium and Thorium Source Activities

The mass balance estimates of radium and thorium activities for the selected stream flow events on Quick Mud Creek (**Table 5-12**) were intergraded with the predicted findings of the TUFLOW models to estimate the RSS radium and thorium source activities at the headwaters of the tidal reaches of the Hooley and Middle creeks. This integration takes into account:

- The relationships between volumes and radium and thorium activities at the Quick Mud Creek source.
- The stream flow volumes that enter onto and are generated on the supratidal saline flats from local catchment areas outside of Quick Mud Creek.
- Predicted total outflows (**Table 5-10**) to the tidal creeks from the consecutive 1 + 1, 1 + 2, 1 + 5 and 1 + 10-year ARI events.

Again it was assumed that all of the accumulated salt on Quick Mud Creek was dissolved and transported in the stream flow.

A summary of the estimated stream flow volumes and associated radium and thorium activities at the headwaters of the Hooley Creek – Four-Mile Creek tidal embayment is provided in **Table 5-12**. The activity balances at the headwaters of the tidal embayment shown in **Table 5-12** are compatible with the dissolution, transport and dilution of the salt sourced from Quick Mud Creek in **Table 5-11**.

Table 5-12 TUFLOW –Derived RSS Radium and Thorium Source Activities at Tidal Embayment

Event ARI (years)	Total Outflows to Tidal Creeks (GL)	RSS Radium and Thorium Source Activity at the Headwater of the Tidal Embayment (Bq/L)
1 + 1	1.195	19.5
1 + 2	1.373	16.3
1 + 5	3.979	5.8
1 + 10	11.814	2.0

The TUFLOW-derived radium and thorium source activities were applied to the hydrodynamic model of the Hooley Creek – Four-Mile Creek tidal embayment as source terms for stream flow entering the tidal reaches of East Hooley Creek.

6 Dynamics of the Tidal Estuary

The Ashburton River and river deltaic environment, that includes the Hooley, Middle and Four-Mile creeks, are tidal. Lower reaches of the Ashburton River and Hooley Creek are daily and temporally inundated by seawater. During a typical high-tide seawater propagates about 7 km upstream of the of the Ashburton River mouth. At the Highest Recorded Tide (HRT; 1.73 m AHD) the tidal influence is estimated to reach about 10 km upstream of the river mouth. During a typical high tide and HRT, the simulated tidal influences on the Hooley Creek – Four-Mile Creek tidal embayment propagate about 2 and 4 km upstream respectively.

Tidal data for the tide gauge at Beadon Creek, Onslow was sourced from the WA Department of Transport and is shown on **Figure 6-1.** Tidal variations have been recorded as follows:

- HRT 1.73 m AHD.
- Lowest Recorded Tide -1.99 m AHD.
- Mean sea level (MSL) of 0.06 m AHD (DPI, 2004).
- The Highest Astronomical Tide (HAT) 1.55 m AHD.
- Lowest Astronomical Tide (LAT) -1.42 m AHD.

The fate of the RSS delivered by stream flow to the Hooley Creek – Four-Mile Creek tidal embayment would be dependent on the mixing and transport processes enabled by tidal forces. These processes are natural functions that include:

- Initial mixing that occurs at the point of entry and is referred to the initial dispersion.
- Advection of the stream flow within the tidal creek embayment.
- Dispersion.

A hydrodynamic model was developed to predict the transport of the RSS within the Hooley Creek – Four-Mile Creek tidal embayment for the selected ARI stream flow events. The predictive simulations were intended to qualitatively inform the mixing, dilution and flushing of the creek system by the local tidal phases.

The numerical hydrodynamic model has been developed using the MIKE21HD(FM) model which is part of the MIKE by DHI suite. Details of the modelling software are available from the DHI website: http://www.dhisoftware.com/Products/CoastAndSea.aspx. This platform is widely used, verified and public domain software. This model also includes a Temperature/Salinity Module, for application in simulations of RSS propagation and dilution within the tidal creeks.

6.1 Hydrodynamic Model Development

6.1.1 Domain and Form

Tidal model domain covers a comparatively relatively large area in order to limit errors within the Hooley Creek – Four-Mile Creek tidal embayment. The western boundary of the tidal model is aligned to North West Cape (Exmouth) and extends about 68 km off-shore to the northwest. The eastern boundary starts at the mouth of the Yanyare River and extends about 118 km off-shore to the northwest. The northern boundary connects two off-shore points.

The western, northern and eastern off-shore boundaries were derived from the global DHI tidal model of 0.125deg resolution. These boundaries provide seawater level time series data in MSL (Coordinated Universal Time) for each model cell. Inland boundaries are open boundaries representing the upper tidal reaches of the Hooley Creek – Four-Mile Creek tidal embayment. These boundaries have been used to release stream flow hydrographs into model domain.

The highest model resolution is within the Hooley Creek – Four-Mile Creek tidal embayment (triangles and quadrangles resolution ranges from 30 to 50 m between mesh centre points). The resolution decreases gradually off-shore to 4 km distances between mesh centre points. The flexible mesh resolution enables reasonable time-frame simulations

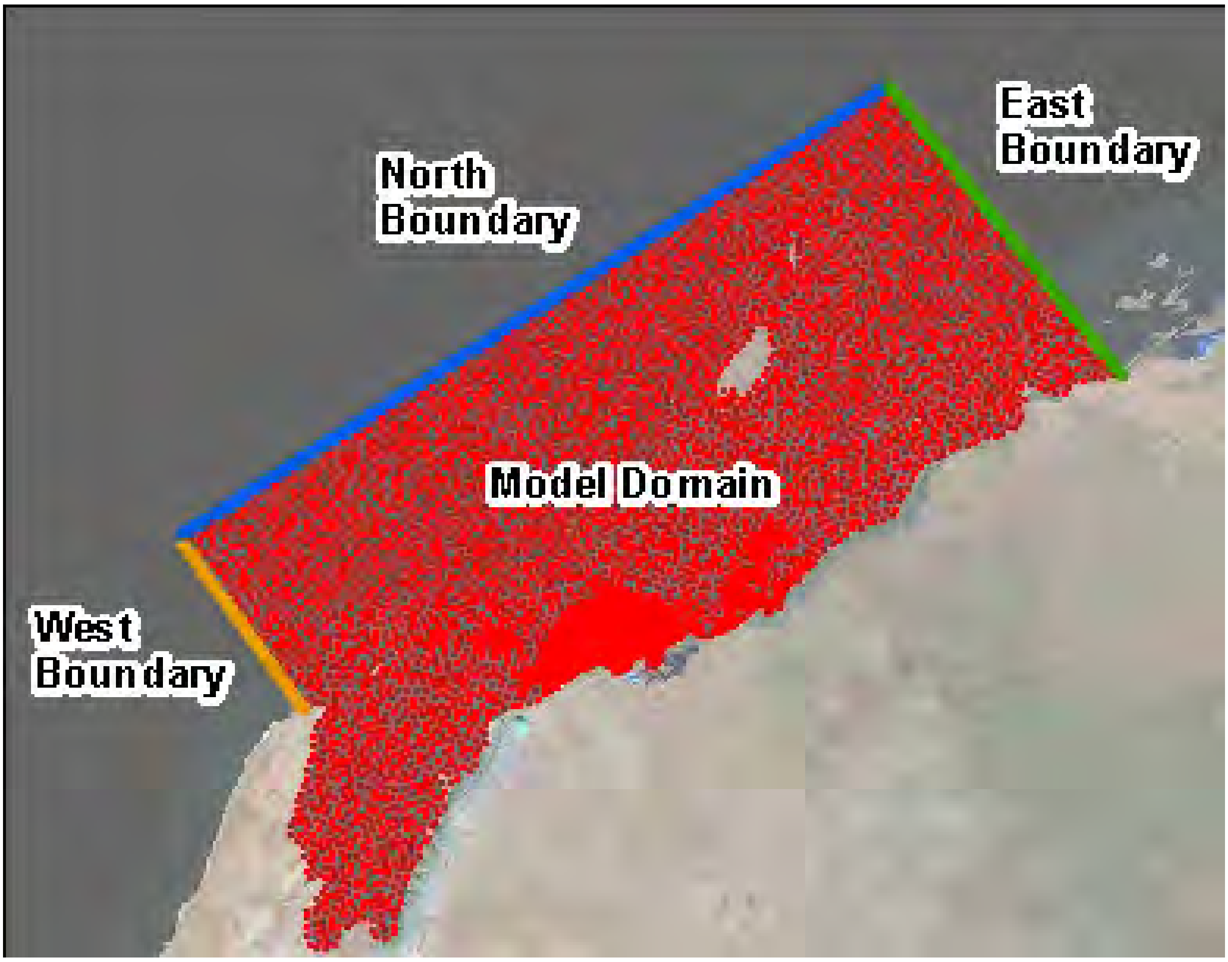


Plate 6-1 Domain of the MIKE21HD(FM) Model

The topography and bathymetry data that inform the model were derived from numerous sources, as described in **Table 6-1**. The simulated volume of the Hooley Creek (west and east) and Middle Creek tidal watercourses was 7,386 ML.

Tidal model bed resistance has been left to default value of 32 Manning's M (0.03125 Manning's n). This is a typical approach for tidal models as bed resistance has minimal impact to the results.

Coriolis forcing was varied with the domain based on the coordinates; this is a standard approach for large-scale tidal models.

Table 6-1 Topography and Bathymetry Data Sources

Data	Year Captured	Source	Priority
Echo sounding of near-shore and tidal creek bathymetry	Unknown	Provided by Chevron	1
Topographic spot survey	Unknown	Provided by Chevron	1
LiDAR	2012	Provided by Chevron	2
SRTM	2000	Geoscience Australia	3
Nautical Charts	Unknown	Australian Hydrographic Service Source date unknown (charts published in 2002)	4
Manually Added Points	Not applicable	Interpolation from the Available data to fill the gaps; mostly within the tidal creeks between surveyed transects.	5

6.1.2 Model Calibration

The hydrodynamic model has been calibrated against several tidal stations within the model domain (**Figure 6-2**). The calibration model was run for one month starting from 03 March 2013. The calibration was mainly based on seawater elevations. The simulated seawater elevations (in MSL) at the calibration points have been compared to seawater elevations at the calibration points generated using AusTides 2012 software (Australian Hydrographic Service 2011). A summary of the calibration results is provided in **Table 6-2**. Calibration Plots provided in the **Appendix D**.

Table 6-2 Summary of MIKE21HD(FM) Hydrodynamic Model Calibration

Domain	Calibration Point	Calibration Accuracy (m)
Area 1	Point Murat Island	Less than 0.08
	Exmouth	Less than 0.10
	Learmonth	Less than 0.12
	Y Island	Less than 0.07
	North Muiron Island	Less than 0.10
Area 2	Roller Island	Less than 0.12
	Onslow – Beadon Creek	Less than 0.12
	Thevenard Island	Less than 0.12
Area 3	Large Island	Less than 0.10
	North Sandy Island	Less than 0.12
Area 4	Barrow Island (W.I.)	Less than 0.12
	Barrow Island (T.M.)	Less than 0.14
	Trimoille Island	Less than 0.08
	North West Island	Less than 0.12

6.2 MIKE21HD(FM) Predictive Scenarios

The calibrated model was applied to selected predictive scenarios compatible to the stream flow outflows from the supratidal saline flats determined by the MIKE FLOOD HD and TUFLOW models. Individual simulations were run for a month, with commencement under neap and spring tide circumstances. This approach enabled the RSS release during:

- Lower tides and associated smaller seawater volumes in the tidal estuary.
- Higher tide extremes and associated larger seawater volumes.

The simulation start times were 3 March 2013 and 14 March 2013, respectively.

A summary of the hydrodynamic model predictive simulations is shown in **Table 6-3**.

Table 6-3 Summary of MIKE21HD(FM) Hydrodynamic Predictive Model Scenarios

Scenario	Scenario Characteristics	Inflow Volumes to Tidal Creeks[1] (ML)	Duration of RSS Source Release (hours)	Tide at Start of Simulation
MIKE FLOOD HD Derivatives				
AA03	3 x 86 + LT 24-hour	3 x 86[1]	24	Neap
AD03	3 x 864 + LT 24-hour	3 x 864[1]	24	Neap
AE03	3 x 86 + HT 24-hour	3 x 86[1]	24	Spring
AH03	3 x 864 + HT 24-hour	3 x 864[1]	24	Spring
AI04	3 x 86 + LT 240-hour	3 x 86[1]	240	Neap
AL04	3 x 864 + LT 240-hour	3 x 864[1]	240	Neap
AM04	3 x 86 + HT 240-hour	3 x 86[1]	240	Spring
AP04	3 x 864 + HT 240-hour	3 x 864[1]	240	Spring
TUFLOW Derivatives				
AR01	1+1 (250-hour) LT	1,195[2]	240	Neap
AS01	1+2 (250-hour) LT	1,373[2]	240	Neap
AT01	1+5 (250-hour) LT	3,978[2]	240	Neap
AU01	1+10 (250-hour) LT	11,814[2]	240	Neap

Notes:
1 Equal volumes are provides as inflows to West Hooley Creek, East Hooley Creek and Middle Creek. The RSS source terms were only applied to the volumes entering East Hooley Creek.
2 These source volumes were distributed to the West Hooley Creek, East Hooley Creek and Middle Creek based on the proportioning shown in Table 5-10. The RSS source terms were only applied to the volumes entering each creek.

6.3 Predicted Transport and Fates of Radium and Thorium Activities

In each of the MIKE FLOOD HD derivative models, the defined stream flow volumes were applied at uniform rates for the designated periods. Also, the RSS source terms were also applied at a uniform quality (100 Practical Salinity Units (PSU)) only to East Hooley Creek throughout the designated periods. In the TUFLOW derivative models, however, the predicted TUFLOW hydrographs defined the transient stream flow rates and RSS source terms for inputs to the West Hooley Creek, East Hooley Creek and Middle Creek. The background PSU concentration in the models was nil; this approach enabled a ready linear interpolation from PSU to the RSS radium and thorium source terms and assessments of dilution of the RSS source terms within the tidal estuary. The radium and thorium activities have been derived from the PSU concentrations at 17 locations discreetly tracked in each predictive scenario. The 17 locations at which the PSU concentrations were tracked are shown on **Plate 6-2.**

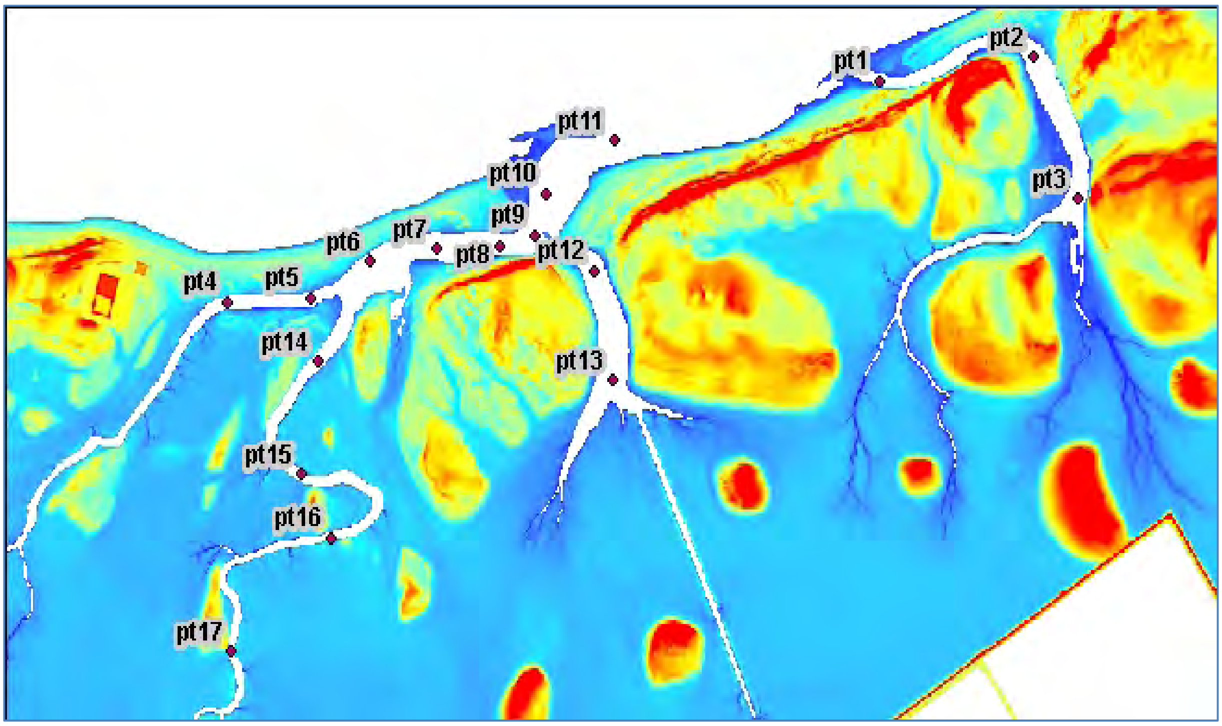


Plate 6-2 Estuarine Locations for Tracking of Predicted Transient PSU

Indications of the predicted transient changes in the PSU concentrations within the Hooley Creek – Four-Mile Creek tidal embayment are shown on **Plate 6-3** for a number of the 17 locations tracked in each model. These PSU hydrographs book-end the predicted responses to the 1+1 (250-hour) stream flow event that represents the worst-case scenario in terms of source concentration and period of retention in the tidal embayment.

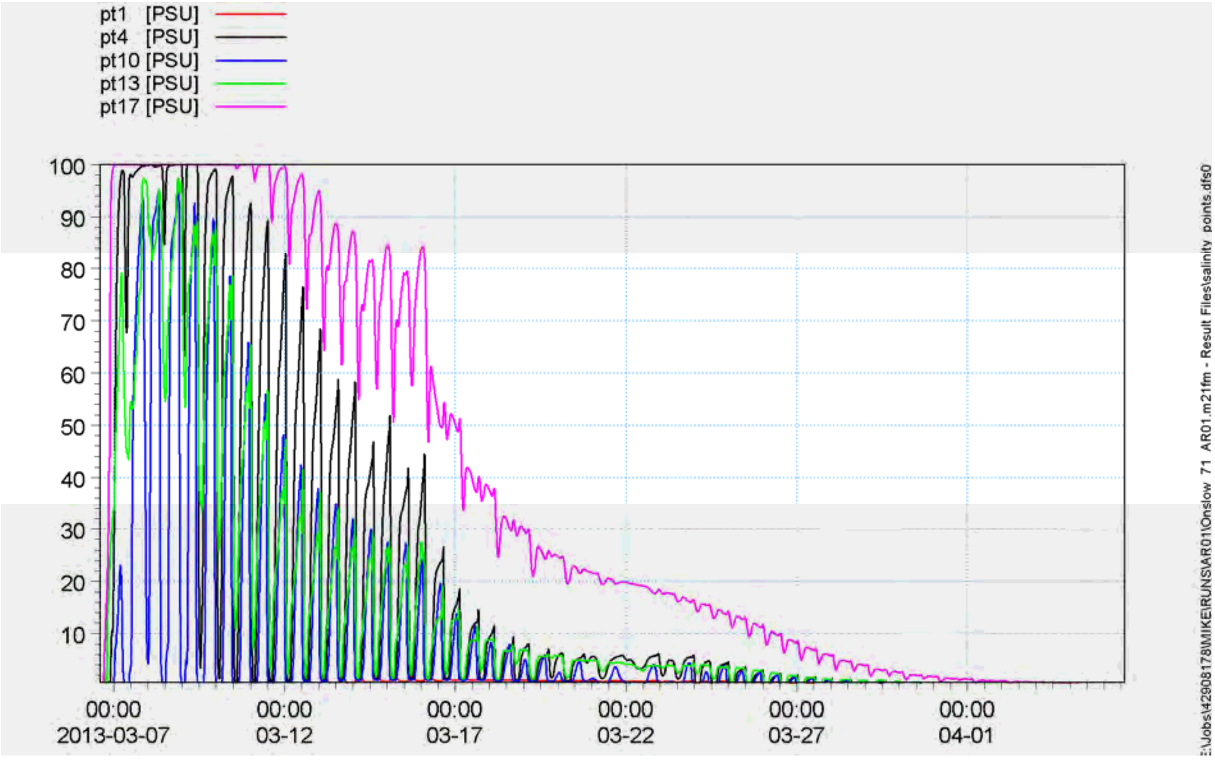


Plate 6-3 Predicted Transient Changes in PSU at Selected Locations

The findings from the predictive MIKE21HD(FM) hydrodynamic models are summarised in **Table 6-4** and **Table 6-5** for the MIKE FLOOD HD and TUFLOW derived scenarios, respectively. The times of source dilution shown in **Table 6-4** and **Table 6-5** reflect when estuary concentrations dropped below 50 (or 2, or 1) across all locations. This approach provides conservatively high estimates of RSS residence times in the tidal estuary.

Table 6-4 MIKE FLOOD HD Derivative RSS Source Transport Predictions

Scenario		Predicted Time of Source Dilution from 100 PSU (days)		
		To 50 PSU	To 2 PSU	To 1 PSU
AH03	3 x 86 + LT 24-hour	4	13	20
AD03	3 x 864 + LT 24-hour	4	17	21
AE03	3 x 86 + HT 24-hour	3	16	18
AH03	3 x 864 + HT 24-hour	4	17	19
AIO4	3 x 86 + LT 240-hour	12	25	27
AL04	3 x 864 + LT 240-hour	14	25	27
AM04	3 x 864 + HT 240-hour	13	22	26
AP04	3 x 864 + HT 240-hour	14	24	27

Table 6-5 TUFLOW-Derivative RSS Source Transport Predictions and Interpolations

Scenario	TUFLOW Outflow Volume (ML)	Estimated Source Activity @ Outflow (Bq/L)[1]	Time of Source Dilution from 100 PSU (days)			Predicted Time to Dilute to 1 Bq/L (days)
			To 50 PSU	To 2 PSU	To 1 PSU	
1+1 (24-hour)[2]	1,195	19.5	4	15	20	10
1+2 (24-hour) [2]	1,373	16.3	4	15	20	10
1+5 (24-hour) [2]	3,978	5.8	4	19	21	5
1+10 (24-hour) [2]	11,814	2.0	4	23	25	4
1+1 (240-hour)[3]	1,195	19.5	13	22	26	18
1+2 (240-hour) [3]	1,373	16.3	13	22	26	18
1+5 (240-hour) [3]	3,978	5.8	14	23	27	16
1+10 (240-hour)[3]	11,814	2.0	18	27	31	18
1+1 (250-hour) LT	1,195	19.5	10	24	26	18
1+2 (250-hour) LT	1,373	16.3	11	24	26	18
1+5 (250-hour) LT	3,978	5.8	12	25	27	14
1+10 (250-hour) LT	11,814	2.0	13	25	28	13

Notes:
1 Derived from TUFLOW-derived dilution algorithms of the RSS source terms for radium and thorium shown in **Table 5-11.**
2 Data derived from interpolation (and extrapolation) of the scenarios results: AA03, AD03, AE03 and AH03.
3 Data derived from interpolation (and extrapolation) of the scenarios results: AI04, AL04, AM04 and AP04.

The typical propagation of the radium and thorium activities within the Hooley Creek – Four-Mile Creek tidal embayment and transient dilution of the source terms is shown on **Figure 6-3**. This figure represents the AR01 scenario (the 1+1 (250-hour) LT scenario shown in **Table 6-5**), but the tabulated results show the transient snapshots provide a reasonable representation of likely outcomes under different stream flow events. The transient snapshots reflect times of 4, 11.5, 24, 74, 149, 249, 455 and 687 hours after the commencement of stream flow entering the tidal embayment. The transient snapshots show the progressive invasion of the West Hooley, East Hooley and Middle creeks by the radium and thorium source during the initial 74 hours. Subsequently, the predictions show significant and progressive mixing and dilution of the plume by seawater due to the tidal forces. Initially, the mixing and dilution is predominant on the seaward reaches of the West Hooley, East Hooley and Middle creeks; a 100-times dilution is typically apparent on the near-coastal reaches of the creeks after about 25 days. Similar mixing and dilution of the upper tidal reaches or the three creeks typically takes up to a month. The longest periods of attenuation occur in East Hooley Creek, reflecting limitations in the tidal forces within the upper reaches of the tidal watercourse.

The predictive simulations provide indications that the worst-case scenarios are provided by:

- Comparatively low-flow events (3 x 86 ML and 3 x 864 ML) that occur over extended periods up to 10 days.
- Consecutive low-flow events (1+1-year ARI) where flow occurs over extended period up to 10 days.

The predictions indicate sensitivity to the duration of the stream flow, with longer durations resulting in attenuation of the RSS source before mixing, dilution and transport from the Hooley Creek – Four-Mile Creek tidal embayment.

Geochemical Modelling

7.1 Introduction

Geochemical modelling was performed to assess the effect of the RSS on Quick Mud Creek, including:

- Evaporation and precipitation of mineral salts during drought periods.
- Subsequent dissolution, dilution and discharge of the accumulated salts from the Quick Mud Creek setting during episodic steam flow events.

It was important to determine the effects of evaporation, mineral precipitation, and subsequent dissolution/discharge on radium concentrations in the RSS and the potential dose to human and environmental receptors.

The concentrations of Ra-226 and Ra-228, naturally-occurring NORM progeny of the U-238 and Th-232 decay series (**Plate 7-1**), respectively, were of particular interest as they are concentrated in the RSS. The geochemistry evaluation was therefore a simple mixing model of the estimated Ra-226 and Ra-228 activities for the various storm events, but did not take decay (or progeny) into account as the storm events were of short duration and the Ra-228 loss would not be significant. This approach was also conservative for radium by not allowing loss of Ra-226 and Ra-228 via decay. With a half-life of 5.75 years, Ra-228 would lose about 11 per cent of its activity in a year. Since the pools on Quick Mud Creek would be continually supplied with incoming RSS, the net reduction is only about 6 per cent in a year. Even with two or three years between flooding events, the Ra-228 decay effect was considered to be of low significance.

The Th-228 was not specifically addressed in the geochemical modelling because it is comparatively insignificant to the radioactivity of the RSS.

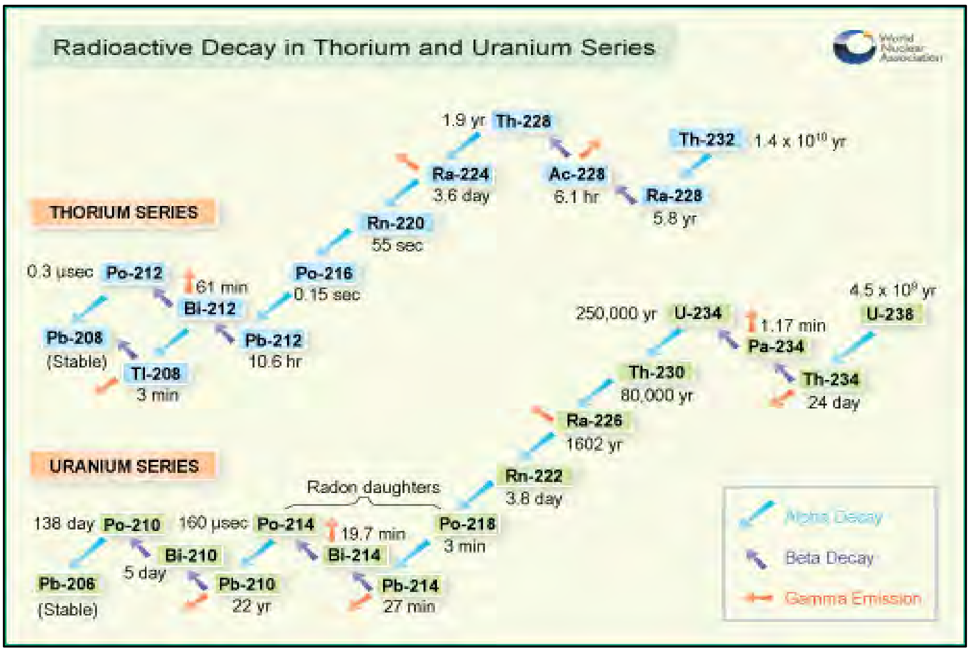


Plate 7-1 Thorium-232 and Uranium-238 Radioactive Decay Series

7.2 Geochemistry of Radium

Radium exists in nature as one of four isotopes, Ra-223, Ra-224, Ra-226, or Ra-228. The naturally occurring radium isotopes are derived from the decay of uranium and thorium which produce a series of radioactive progeny isotopes and ends with the formation of stable (non-radioactive) isotopes of lead (Pb) as shown in **Plate 7-1**. Ra-226, the fifth progeny in the U-238 decay series, and Ra-228, the first progeny in the Th-232 decay series, are generally considered the most important radium isotopes because of their half-lives, 1,602 and 5.8 years, respectively, and the abundance and extremely long half-lives of their parents. Ra-223 and Ra-224 are considered less important because of their short half-lives, 11.4 and 3.6 days, respectively. Ra-223 is a member of the U-235 decay series and, therefore, occurs less frequently at high concentrations in the natural than the other radium isotopes because U-235 only comprises about 0.7 per cent of natural uranium.

Chemically, the radium isotopes behave the same because they have the same electron shell configuration which controls their reactivity. Radium reacts similarly to other divalent alkaline-earth cations (Langmuir and Riese, 1985; Gilkeson and Cowart, 1987), such as calcium (Ca) and strontium (Sr), and is most similar to barium (Ba). Since Ra is closely related to Ca, it has the potential for causing harm by substituting for Ca in bone of humans and animals.

Both Ra and Ba are exclusively divalent dissolved cations (Ra^{2+} and Ba^{2+}) in water and do not undergo reduction-oxidation (redox) transformations. In the pH range of 3 to 9, the uncomplexed Ra^{2+} ion is the dominant dissolved radium species in natural waters. At pH 9 and higher, Ra^{2+} and Ba^{2+} can form neutral to anionic, primarily sulphate aqueous complexes (Langmuir and Riese, 1985). **Plate 7-2** shows an Eh-pH diagram for Ra^{2+} with chloride (Cl^-), bicarbonate (HCO_3^-), and sulphate (SO_4^{2-}) at 25 degrees Centigrade (^oC) and 1 atmosphere of pressure. The diagram was created using the concentrations of radium, chloride, bicarbonate, and sulphate reported for the RSS in **Table 1-1**. Note in **Plate 7-2**, that Ra^{2+} is the predominant aqueous radium species in RSS under most naturally occurring Eh and pH conditions. $RaSO_4^0$, an uncharged aqueous radium sulphate complex, is stable at pH 9.3 and greater.

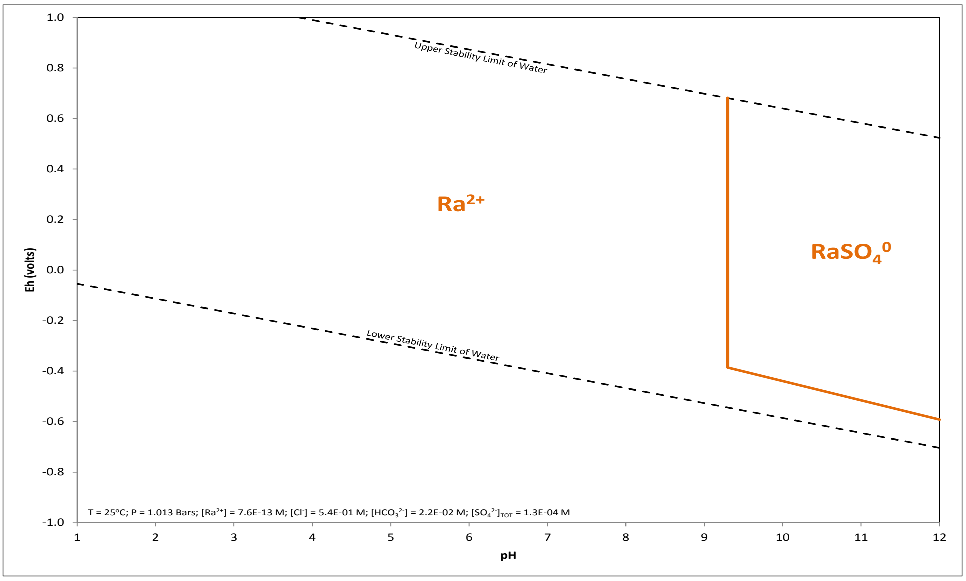


Plate 7-2 Eh-pH Diagram for the Ra^{2+}-Cl^--SO_4^{2-}-HCO_3^--H_2O System at 25 Degrees

Radium can readily co-precipitate with barium minerals, barite ($BaSO_4$) and witherite ($BaCO_3$), or with celestite, a strontium sulphate ($SrSO_4$) mineral, to form solid solution solids [$(Ba,Ra)SO_4$, $(Ba,Ra)CO_3$, or $(Sr,Ra)CO_3$]. Precipitation occurs when the constituents forming these salts are abundant enough in oxidized solutions that they exceed solubility limits (Langmuir and Melchoir, 1985; Martin and Akber 1999; Curti et al., 2010). Under anaerobic sulphate-reducing conditions, bacteria can dissolve sulphate minerals and promote the release of co-precipitated Ra^{2+} (Huck and Anderson, 1990; Pardue and Guo, 1998). Reducing conditions are not, however, expected to develop along Quick Mud Creek where RSS is discharged. Radium is not sufficiently abundant in nature to precipitate radium sulphate salts, even though radium sulphate is relatively insoluble (Langmuir and Melchoir, 1985; Grundl and Cape, 2006). Co-precipitation is likely one of the more important controls on radium solubility, and, thus, transport in natural soil and water systems.

In dilute solutions, radium is chemically reactive and sorbs to clays and iron (Fe) and manganese (Mn) oxyhydroxides via cation exchange or surface complexation. Laboratory studies have shown that Ra^{2+} is readily sorbed by clay minerals (Ames et al., 1983), but is more strongly adsorbed to Fe- and Mn-oxyhydroxide minerals (Moore and Reid 1973; Krishnaswami et al., 1982; Ames et al., 1983; Benes et al., 1984) in low ionic strength solutions. Ra^{2+} may also be strongly sorbed to organic matter (Greeman et al. 1999; Nathwani and Phillips, 1979a and 1979b). Ra^{2+} competes with other alkaline earth cations for sorption sites in soils and sediments (USEPA 2004). Sposito (1989) indicates that the relative ion exchange affinity for these elements on clays is $Ra^{2+} > Ba^{2+} > Sr^{2+} > Ca^{2+} > Mg^{2+}$. Radium distribution coefficient (Kd) values for various soils range from 12 to 950,000 (L/kg), with a geometric mean Kd of 2,500 L/kg (Vandenhove et al., 2009). In saline solutions, such as the RSS or seawater, radium sorption decreases significantly, approaching zero, as ionic strength increases (Vilks, 2011; Vilks et al., 2011).

7.3 Geochemistry of Thorium

Thorium has six natural isotopes, Th-227, Th-228, Th-230, Th-231, Th-232, and Th-234, of which the most abundant and longest-lived is Th-232. Like radium, the naturally-occurring thorium isotopes are derived from the decay of uranium or thorium which produces a series of radioactive progeny isotopes and ends with the formation of stable (non-radioactive) isotopes of lead (Pb) as shown in **Plate 7-1**. Th-227 and Th-231 are not shown on Plate 7-1 because the U-235 decay chain is relatively insignificant as it comprises only about 0.7 percent of natural uranium. Th-227, Th-231, and Th-234 are the shortest lived natural thorium isotopes, with half-lives less than 24 days; whereas Th-228, Th-230, and Th-232 have longer half-lives of 1.9, 80,000, and 1.4E10 years, respectively.

Chemically, the thorium isotopes behave the same because they have the same electron shell configuration, an incomplete 5f shell, which controls their reactivity. Thorium is markedly oxyphile in nature, occurring mainly as oxides, silicates, and phosphates. It also has a biophile tendency and is found in various organisms, and under certain conditions, can be concentrated in organic compounds such as humus, coal, petroleum, bitumen, and pyrobitumen (Mernagh and Miezitis 2008). Three oxidation states are possible for thorium, +2, +3, and +4; however, the tetravalent (+4) state is most important in natural environments, thus, reduction processes are not important in its geochemistry (Boyle 1982).

In natural waters, the concentrations of dissolved thorium are very low. Dissolved thorium forms a variety of aqueous hydroxyl species, and as a small highly charged ion, undergoes extensive chemical interaction with water and most anions. Thorium can form aqueous complexes with dissolved carbonate, fluoride, phosphate, chloride, and nitrate anions (Langmuir and Herman 1980; Boyle 1982; Östhols et al. 1994; Mernagh and Miezitis 2008). The formation of these aqueous complexes increases the concentration of dissolved thorium in soils and waters.

The uncomplexed ion Th^{4+} is the dominant aqueous ion at pH values less than ~3.5. At pH values greater than 3.5, the hydrolysis of thorium is dominated, in order of increasing pH, by the aqueous species $Th(OH)_2^{2+}$, $Th(OH)_3^{+}$, and $Th(OH)_4^{0}(aq)$. The latter two hydrolytic complexes have the widest range of pH stability (USEPA 1999). Recent studies of carbonate complexation of dissolved thorium indicate that the aqueous species may be dominated by mixed thorium carbonate and hydroxyl-carbonate complexes, such as $Th(OH)_3CO_3^{-}$, at pH values greater than 7.5 (Östhols et al. 1994). Thorium hydroxyl-carbonate complexes are the likely aqueous species in RSS. Thorium organic complexes likely predominate over inorganic complexes in organic-rich waters and soils and control the solubility and adsorption of thorium in these media.

Dissolved thorium concentrations in surface water and groundwater are also controlled by adsorption processes. Thorium sorbs strongly to iron oxyhydroxides and humic matter (Nash and Choppin 1980; Hunter et al., 1988; Murphy et al. 1999) and weakly to silica at neutral to basic pH (Öthols 1995). Thorium sorption is sensitive to carbonate alkalinity due to the formation of negatively charged aqueous mixed hydroxy-carbonate complexes (LaFlamme and Murray, 1987); at alkalinities of 100 meq/L, thorium sorption by goethite decreases markedly. Representative Kd values for thorium in crystalline rock that range from 100 to 5,000 mL/g (McKinley and Scholtis 1992) and from 20–300,000 ml/g for low temperature geochemical environments (USEPA 1999).

Thorium sorption at high ionic strength was examined using uranium series disequilibrium techniques by Laul (1992). Laul measured thorium retardation in saline ground waters from the Palo Duro Basin, Texas, and determined sorption Kds of around 2,100 mL/g. Because tetravalent actinides are strongly sorbed by mineral colloids and have a strong tendency to form intrinsic colloids, increases in ionic strength may have more effect on Th^{4+} transport through destabilization and flocculation of colloidal particles (Lieser and Hill, 1992), rather than through changes in the degree of sorption.

7.4 Model Description

An assessment of the aqueous speciation chemistry and mineral saturation state of the RSS prior to disposal and during discharge and evaporation was determined using equilibrium-based geochemical modelling software. PHREEQC Version 3 (Parkhurst and Appelo, 2013), an industry-standard, public-domain code developed by the U.S. Geological Survey was selected for the geochemical modelling. PHREEQC is designed to perform a wide variety of aqueous geochemical calculations. PHREEQC implements several types of aqueous models, including a two ion-association aqueous model, a Pitzer specific-ion-interaction aqueous model, and the specific ion interaction theory (SIT) aqueous model. Using any of these aqueous models, PHREEQC has capabilities for:

- Speciation and saturation-index calculations.
- Batch-reaction and one-dimensional (1D) transport calculations with reversible and irreversible reactions, which include aqueous, mineral, gas, solid-solution, surface-complexation, and ion-exchange equilibria, and specified mole transfers of reactants, kinetically controlled reactions, mixing of solutions, and pressure and temperature changes.
- Inverse modelling, which finds sets of mineral and gas mole transfers that account for differences in composition between waters within specified compositional uncertainty limits.

PHREEQC incorporates several thermodynamic databases to enable flexibility in equilibrium modelling of waters with a range of compositions, including NORMs, and ionic strengths. The SIT model and database were selected to model the elevated ionic strength of the RSS and the higher ionic strengths that develop during evapoconcentration.

7.5 RSS Chemistry Data

The RSS chemistry data used in the geochemical model simulations are listed in **Table 7-1**. The RSS concentrations were indicative based on the Birdrong Sandstone source quality (**Table 1-2**) and preliminary estimates (Worley Parsons September and November 2013) of the RSS radium and thorium activities after treatment.

The RSS Ra-226 and Ra-228 activities were reported in Becquerel per litre (Bq/L). The Ra-226, Ra-228 and Th-228 activities were converted to radium concentrations using the specific activities for each isotope as shown in **Table 7-1.** The sum of the Ra-226 and Ra-228 concentrations (1.66E-07 mg/L) was used as input in the geochemical model.

Table 7-1 RSS Radium and Thorium Activities and Concentrations

Parameter	RSS Activity (Bq/L)	Specific Activity (Bq/mg)	Concentration (mg/L)
Ra-226	9.6	3.66E+07	2.62E-07
Ra-228	15.9	1.01E+10	1.57E-09
Total Radium	25.5	9.66E+07	2.64E-07
Th-228	1.4	8.3E+02	1.69E-03

The major ion composition, ionic strength, and salinity of the RSS are similar to seawater (**Plate 7-3**). The major difference in major ion composition is that RSS has less sulphate and magnesium and more calcium and bicarbonate than seawater. The ionic strength of the RSS is 0.55 moles per litre (mol/L) which is less than the 0.72 mol/L ionic strength of seawater.

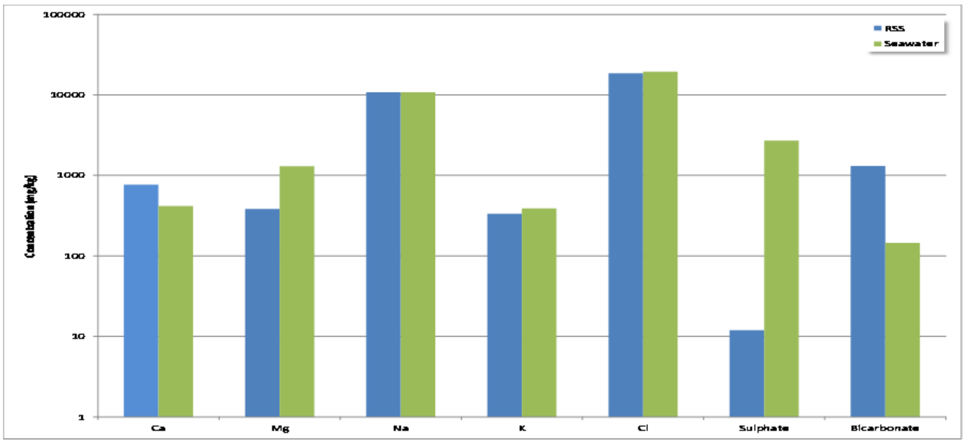


Plate 7-3 Comparison of RSS and Seawater Major Ion Composition

Whilst the TDS concentration of the RSS is similar to seawater, the radium and thorium concentrations in the RSS are significantly greater than the radium and thorium concentrations in seawater. For comparison, the Ra-226 and thorium concentration in seawater is approximately:

- 4E-11 mg/L (1.46E-03 Bq/L; Broecker et al. 1967), 4.3E-11 mg/L (1.57E-3 Bq/L) in the Pacific Ocean (Domanov et al. 2004).
- 4.5E-11 mg/L (1.65E-03 Bq/L) in the Indian Ocean south of Australia (Ku et al. 1970).
- The average Ra-226 and Ra-228 concentrations in Cockburn Sound in Western Australia are 3.70E-11 mg/L (1.36E-03 Bq/L) and 1.69E-13 mg/L (1.71E-03 Bq/L), respectively (Loveless et al. 2008).
- The typical thorium concentration is seawater is 4.0E-07 mg/L (By Dr J Floor Anthoni (2000, 2006); www.seafriends.org.nz/oceano/seawater.htm).

Thus, the RSS radium and thorium concentrations are about 4,000 times greater than the radium concentration in seawater.

7.6 Geochemical Modelling Results

Two geochemical modelling scenarios were simulated that included:

- The speciation and mineral saturation of the RSS before disposal.
- Evaporation of the RSS in Quick Mud Creek.
- Discharge of the RSS from Quick Mud Creek by stream flow. A simple mass balance geochemical model was used to estimate the radium concentrations from the dissolution and dilution of precipitated RSS salts in Quick Mud Creek during episodic rainfall and stream flow events that discharge from Quick Mud Creek.

The results of these simulations are discussed below.

7.6.1 RSS before Discharge

The RSS was initially modelled to assess the aqueous species and saturated minerals that may be present before disposal to Quick Mud Creek. Equilibrium geochemical modelling was performed using the RSS chemistry data and the total radium and thorium concentrations (**Table 7-1**). Redox conditions within the RSS were based on the oxygen gas/water (O^0/O^{2-}) and ammonium/nitrate (N^{3+}/N^{5+}) redox couples.

The results of the RSS speciation modelling are summarised in **Table 7-2**, including the predominant aqueous species and the minerals that are predicted to be near or at saturation (saturation index [SI] greater than -0.1). The predominant radium aqueous species predicted are Ra^{2+}, $RaCl^+$, and $RaCl_2$. Aqueous radium chloride species predominate because of the extremely high chloride concentration and very low sulphate concentration in the RSS. There are no saturated radium or thorium solid phases.

Table 7-2 Predominant Aqueous Species and Saturated Minerals in the RSS before Disposal

Parameter	Concentration (M)	Predominant Aqueous Species	Saturated Minerals (SI > -0.1)
Cl	5.42E-01	Cl^-, NaCl	-----
Na	4.84E-01	Na^+, NaCl, $NaHCO_3$	-----
C(4)	2.26E-02	HCO_3^-, $NaHCO_3$	-----
Ca	1.98E-02	Ca^{2+}, $CaCl^+$	Calcite, Dolomite
Mg	1.63E-02	Mg^{2+}, $MgCl^+$	Magnesite
K	8.83E-03	K^+, KCl	-----
Si	2.02E-03	H_4SiO_4, NaH_3SiO_4	Chalcedony
B	9.56E-04	BOH_3, $B(OH)_4^-$	-----
N(3)	9.00E-04	NH_4^+, NH_3	-----
Br	8.67E-04	Br^-	-----
Sr	2.24E-04	Sr^{2+}, $SrCl^+$	Strontianite
N(5)	1.77E-04	NO_3^-, $NaNO_3$	-----
S(6)	1.29E-04	SO_4^{2-}, $NaSO_4^-$	-----
F	1.25E-04	F^-, MgF^+	Fluorite
Ba	4.52E-05	Ba^{2+}	Barite
Fe(3)	4.44E-05	$FeCO_3OH$	Ferrihydrite
I	2.36E-05	I^-	-----
Mn	9.41E-06	$MnCO_3$	-----
Fe(2)	1.09E-08	$FeCO_3$	-----
Ra	7.59E-13	Ra^{2+}, $RaCl^+$, $RaCl_2$	-----

7.6.2 Evaporation of the RSS in Quick Mud Creek

Geochemical modelling of the disposal and evaporation of the RSS in Quick Mud Creek was conducted using the RSS chemistry data and the total radium concentration (**Table 7-1**). Evaporation was simulated by incrementally removing water from the disposed RSS until it was desiccated (more than 99 per cent of the water removed), where the only water remaining was present in hydrated minerals that may have precipitated. During evaporation, the RSS was assumed to be in equilibrium with oxygen and carbon dioxide in the atmosphere.

As evaporation proceeds, mineral salts are precipitated when they become so concentrated that they exceed their solubility product constant. Most salts begin to precipitate just before the solution is evaporated to dryness. **Plate 7-4** shows the predicted minerals that precipitate as the RSS evaporates. Halite (NaCl) is most abundant precipitated mineral phase (0.4 moles per litre of RSS [mol/L_{RSS}]), but it does not begin to precipitate until more than 90 per cent of the water has evaporated. Magnesite ($MgCO_3$), calcite ($CaCO_3$), and chalcedony (SiO_2) are the next most abundant precipitated mineral phases, ranging from 2.0E-3 (chalcedony) to 7.2E-3 (magnesite) mol/L_{RSS}. These minerals begin precipitating when approximately 10 per cent or less water has evaporated. Manganese present in the RSS may be precipitated as rhodochrosite, or more likely as kutnohorite, a calcium-manganese carbonate mineral solid solution [(Ca, Mn)CO_3]. Fluorite (CaF_2), barite ($BaSO_4$), and ferrihydrite [$Fe(OH)_3$] also precipitate, but the amounts are small, ranging from 4.4E-5 (ferrihydrite) to 6.2E-5 (fluorite) mol/L_{RSS}. Precipitation of ferrihydrite may tint the precipitating salts a rust orange colour, however, given the very small quantity of ferrihydrite precipitate, the effect may only be noticeable around the disposal outlet.

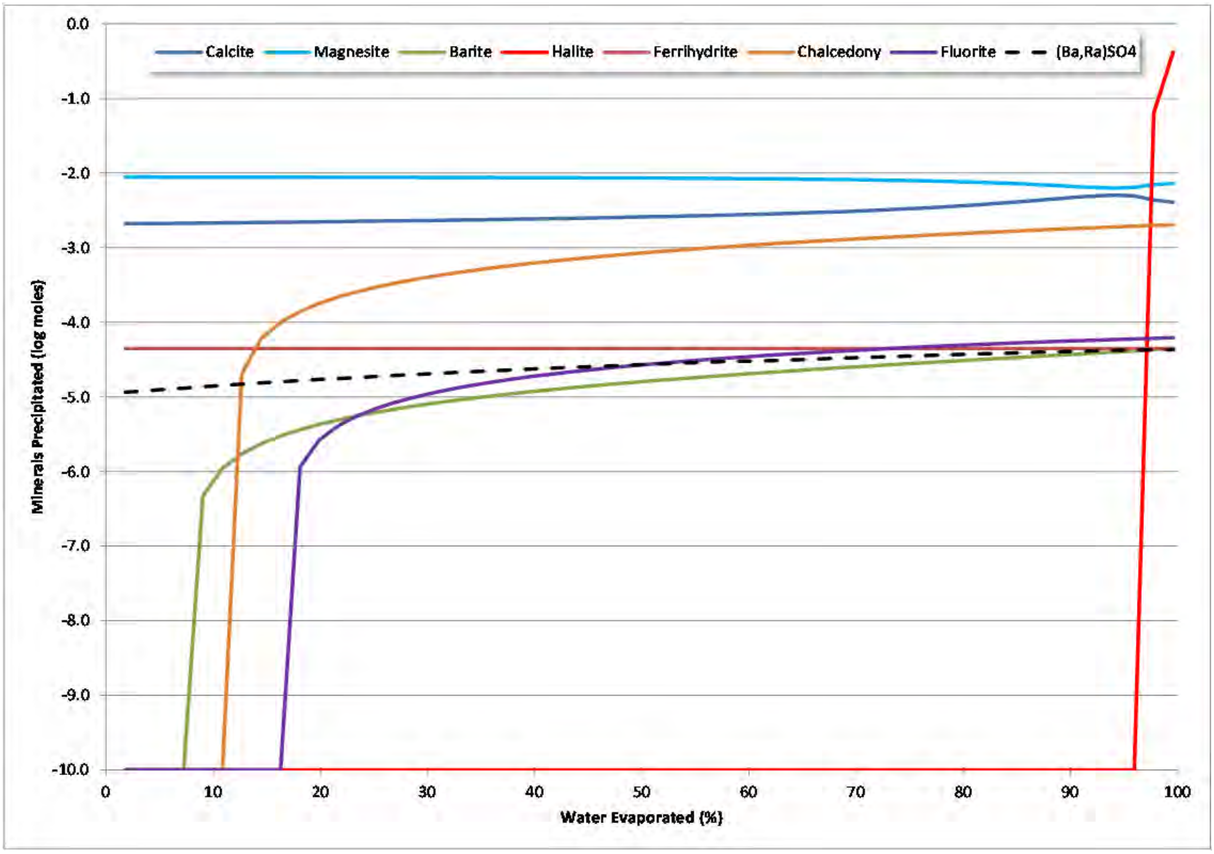


Plate 7-4 Predicted Mineral Precipitates in Evaporating RSS

Plate 7-4 shows that (Ba, Ra)SO_4 (black dashed line) precipitates as the RSS evaporates to dryness in Quick Mud Creek. Radium co-precipitation with barite is the likely radium sequestering mechanism during evaporation of the RSS. The elevated ionic strengths developed during the evaporation of RSS in Quick Mud Creek indicate the radium sorption is not expected to be a significant radium removal mechanism. Once barite is precipitated within the salts in Quick Mud Creek, it may not readily dissolve during stream flow events because of its low solubility. If all of the other salts, mostly halite, are dissolved during a flushing event, barite, if it does not dissolve, may be transported as colloidal particulates.

No manganese oxide minerals are likely to precipitate as they are not near saturation. Manganese may be precipitated as rhodochrosite ($MnCO_3$), a pink carbonate mineral, or incorporated into the calcite ($CaCO_3$) or magnesite ($MgCO_3$) as a solid solution component. The most likely carbonate solid solution mineral created would be kutnohorite [(Ca, Mn)CO_3], which might be whitish pink in color.

No radium solid phases precipitated during evaporation, however, barite with co-precipitated radium [(Ba, Ra)SO_4] is predicted to precipitate at concentrations of 4.3E-5 mol/L_{RSS}. Rosenburg et al. (2013) noted radium co-precipitation with barite in evaporation ponds at a desalination plant in Israel.

RSS Radiological Dose and Risk Assessment

8.1 Dose Analysis

The purpose of the dose analysis is to evaluate the potential radiological doses that could occur to an individual as a consequence of the proposed RSS disposal. The approach for the dose analysis is to postulate how members of the general public could reasonably come in contact with NORMs sourced from the RSS during the normal course of their activities. The dose analysis is based on conservative reasonable assumptions that describe the activities of human receptors at the RSS disposal site, together with individuals at neighbouring sites and members of the general public.

The dose analysis is anticipated to overestimate the potential exposures to NORMs. This approach helps ensure that doses and risks to individuals would not be underestimated. The exposures are based on assumed scenarios that describe likely activities that lead to NORM exposures by members of the general public.

8.1.1 Exposure Scenarios/Pathways for Members of the General Public

Several exposure scenarios are postulated in the dose analysis. These scenarios for general members of the public include:

- Human receptor at the RSS disposal site exposed to external radiation and dust inhalation.
- Human receptor at the Onslow Salt crystalliser ponds, about 5 km from the RSS discharge point.
- Member of the general public fishing in the Hooley Creek tidal estuary.
- Impact to Onslow Salt export product.
- Impact to local fauna/vegetation.

Each scenario includes one or more exposure pathway. The pathways considered (**Table 8-1**) in this analysis include external radiation, contaminated dust inhalation and the ingestion of fish caught in the estuary. Additional scenarios could be developed that include other details and different assumptions, but this set of scenarios is sufficient to capture the maximum likely exposures and serves as a basis for determining whether human health is adequately protected.

Table 8-1 Exposure Scenarios and Pathways

Scenario	Exposure Pathway		
	External Radiation	Dust Inhalation	Fish Ingestion
Human receptor at RSS Pond	✓	✓	
Human receptor at Onslow Salt Crystalliser Ponds		✓	
General Public at Seaside/Estuary		✓	✓

The three scenarios selected for detailed analysis are described below.

8.1.1.1 Human Receptor at RSS Pools on Quick Mud Creek

This scenario describes a human receptor at wetted footprints and pools on Quick Mud Creek where the RSS is accumulated and evaporating. The human receptor is assumed to spend full time (2,000 hours per year) in the vicinity of the wetted footprint on Quick Mud Creek.

There is no operational need for a human receptor to spend this much time near Quick Mud Creek. Therefore, the 2,000 hour per year assumption is an overestimate that provides an upper-bound on the potential dose to a human receptor. The human receptor is exposed to direct external radiation from NORMs in the surface water the crystalline salt crust on the ground surface. The human receptor is also exposed to airborne NORMs in windborne dust from the crystalline salt crust.

8.1.1.2 Human Receptor at Onslow Salt Crystalliser Ponds

This scenario describes human receptors at the Onslow Salt facility about 5 km downstream of the RSS outfall. Human receptors at the facility are assumed to be exposed to RSS-derived airborne dust originating from Quick Mud Creek. The dust is dispersed by downwind transport and is a source of inhalation exposure. The human receptors are assumed to spend fulltime outdoors. This is likely to overestimate the actual exposure times. Dust inhalation is the only exposure pathway for this scenario.

8.1.1.3 Contamination of Produced Salt

Potential contamination of the produced salt at Onslow Salt by airborne NORM was considered. It was estimated that the airborne radionuclide concentrations would be very low (below MDL) at the salt crystalliser ponds. The MDL for Ra-226, Ra-228 and Th-228 activities (**Table 4-2**) are 0.1 Bq/L and 0.03 Bq/g for liquids and solids, respectively. This estimation was based on:

- Understanding that the prevailing winds are south-westerly and westerly to north-westerly, thus away from the salt crystalliser ponds ion context to transportation from Quick Mud Creek.
- An assumption that the majority airborne NORMs would remain airborne and consequently would be transported beyond the salt crystalliser ponds.
- The salt harvesting occurs over a limited time cycle, thus limiting potentials for progressive NORM accumulation from airborne particulates.
- Calculation of doses to human receptors on the crystalliser ponds.

Based on this assessment it was reconciled that there would be limited potential for contamination of the produced salt at Onslow Salt by airborne NORM.

8.1.1.4 Member of the General Public

This scenario describes a member of the general public fishing in the Hooley Creek – Four-Mile Creek tidal embayment. The tidal estuary may contain NORMs following a stream flow event in Quick Mud Creek. The waterborne NORMs enter the estuary and are gradually attenuated by dilution and other natural processes. The fish may contain absorbed NORMs. When the fish are consumed, the individual receives a radiological dose. A stream flow event that transports NORMs to the estuary is assumed to occur at most once per year.

8.2 Doses for each Exposure Scenario

This section presents the results of the dose assessment for each exposure scenario. Doses are shown for each exposure route, as well as the total dose to the individual for each scenario. The doses are compared to regulatory criteria to demonstrate protection of human health. Supporting data on the dose calculations are provided in **Appendix E**.

8.2.1 Human Receptor at RSS Pools on Quick Mud Creek

A human receptor in Quick Mud Creek is assumed to be exposed to external radiation and suspended dust from the accumulated RSS-derived crystalline salt crust. The salt crust contains higher NORM concentrations than the residual liquid RSS.

The salt crust is formed from the suspended solids in the RSS and the dissolved NORMs. When a litre of RSS evaporates, it leaves behind approximately 46.4 grams of salt that contains 0.79 Bq of radium activity and 0.04 Bq of thorium. The NORMs are assumed to be uniformly distributed in the crystalline salt crust. All radioactive decay products of radium and thorium are also assumed to be present in the salt crust. **Table 8-2** shows the RSS properties and NORM concentrations in the salt crust.

It was assumed the NORMs would be uniformly distributed in the salt crust and the salt crust exposed on the ground surface. These are conservative assumptions because, in reality, the salt crust would likely form, in part, beneath the liquid in the ponded RSS and the radiation from the salt crust would be shielded by the water above it. No shielding was assumed in the dose analysis. Whether the NORMs are actually present in the salt crust or the ponded RSS, the assumptions used in the dose analysis were anticipated to provide an upper-bound to the potential dose.

Table 8-2 RSS-Derived Salt Crust Properties

Parameter	Value
Dissolved Solids Concentration	46.4 g/L
RSS Activities Ra-226 Ra-228 Th-228	 13.7 Bq/L 22.7 Bq/L 2.0 Bq/L
Salt Crust Density	1.15 g/cm^3
Salt Crust Activities Ra-226 Ra-228 Th-228	 0.3395 Bq/cm^3 ; 0.30 Bq/g 0.5626 Bq/cm^3 ; 0.49 Bq/g 0.0496 Bq/cm^3 ; 0.04 Bq/g

External radiation dose rates from the salt crust are quantified most simply from the dose conversion factors. The dose conversion factors show the external dose rate to an individual standing on a uniformly contaminated soil surface. The dose conversion factors are expressed as the dose rate (Sievert/s) per unit NORM concentration in the soil (Bq/m^3). The dose conversion factors are based on the recommendations of ICRP (2007).

As the thickness of the RSS-derived salt crust increases, the dose rate also increases. If the salt crust were to reach a thickness of approximately one metre, however, the NORMs at the bottom of the salt crust contribute very little to the dose rate at the surface because the radiation is shielded by the overlying crust. Therefore, as the salt crust thickness increases, the dose rate reaches a maximum above which it becomes independent of the salt crust thickness. For this analysis, the salt crust was assumed to be thick enough to maximise the dose rate, thereby conservatively estimating the maximum possible dose. **Table 8-3** shows the data used in the external dose calculation.

The inhalation dose assumes that the human receptor inhales airborne dust consisting of salt crust material. The ambient dust loading in air was assumed to be 0.1 mg/m^3, which is a conservative estimate of the typical outdoor dust concentration (Healy, 1979; NBS, 1977). The inhalation dose conversion factors are taken from (ICRP, 1994). Data used for dust inhalation calculations are also shown in **Table 8-3.**

The estimated maximum dose to a human receptor at the RSS pools on Quick Mud Creek is 0.525 millisievert per year, which is the sum of the external radiation and dust inhalation doses. This is approximately half of the regulatory general public annual dose limit. This conservative analysis demonstrates that human receptor doses at the RSS pools on Quick Mud Creek would be within the recommended general public annual dose limits.

Table 8-3 Parameters for Dose at Pools on Quick Mud Creek

Parameter	Value
External Dose Conversion Factors[1] Ra-226 Ra-228 Th-228	 5.99E-17 Sievert/s per Bq/m^3 8.66E-17 Sievert/s per Bq/m^3 5.46E-17 Sievert/s per Bq/m^3
Human receptor Exposure Time	2,000 hours/year
External Dose to Human receptor	
Ra-226	0.147 millisievert per year
Ra-228	0.351 millisievert per year
Th-228	0.019 millisievert per year
Total	**0.517 millisievert per year**
Dust Loading in Air	0.1 mg/m^3
Inhalation rate	1.25 m^3/hour
Inhalation Dose Conversion Factors[1] Ra-226 Ra-228 Th-228	 2.02E-05 Sievert/Bq 4.46E-05 Sievert/Bq 4.20E-05 Sievert/Bq
Dust Inhalation Dose	
Ra-226	1.49E-03 millisievert per year
Ra-228	5.45E-03 millisievert per year
Th-228	4.52E-04 millisievert per year
Total	**7.40E-03 millisievert per year**
Total Human Receptor Dose on Quick Mud Creek	**0.525 millisievert per year**

Notes:
(a) Includes all radioactive decay products.

8.2.2 Human Receptor at Onslow Salt Crystalliser Ponds

The Onslow Salt crystalliser ponds would be about 1.5 to 5 km from the RSS-derived salt crusts on Quick Mud Creek. A human receptor at the salt crystalliser ponds could be exposed to airborne dust containing NORMs from the salt crust. An average annual wind speed of 5.4 m/s was used in the analysis, along with a wind frequency of 6 per cent in the south to north direction. This information was taken from the wind rose for the Onslow Airport. The dust source in Quick Mud Creek was conservatively estimated by assuming that the entire wetted footprint of 64,000 m^2 was dry and accumulating crystalline salt. This provides an upper-bound for the amount of dust generated at this source. An atmospheric dispersion factor was calculated for the downwind transport, taking into the account the wind frequency and speed. The atmospheric dispersion parameter (also known as Chi/Q) provides a standard and widely accepted method for estimating downwind concentrations. It is the ratio of the downwind airborne dust concentration (mg/m^3) to the dust source strength (mg/s).

Using the atmospheric dispersion factor and the dust source strength, the ratio of the dust concentration downwind to the dust concentration at the source was calculated. This calculation indicated that the downwind concentration was lower than the source concentration by a factor of 9.45E-05. This factor also represents the ratio of human receptor dose at the downwind Onslow Salt crystalliser pond versus the dose in Quick Mud Creek, because the exposure parameters were the same at both sites (i.e., hours per year exposed and inhalation rate). The calculation showed a dose of 6.99E-07 millisievert per year, which is far below the regulatory dose limit of 1 millisievert per year. Calculation parameters and results are summarised in **Table 8-4.**

The dose calculations assume that typical conditions prevail within the Project area and surrounds. At times, unusual atmospheric conditions may occur that would affect the dose calculation. For example, cyclonic winds and precipitation would have the effect of reducing the doses because of greater wind dispersion leading to lower airborne dust concentrations. Precipitation would also reduce the dust loading in the air. As in the other dose scenarios, the conditions assumed for the dose analysis are expected to result in overestimation of the potential doses.

Table 8-4 Parameters for Dose at Onslow Salt Crystalliser Ponds

Parameter	Value
Distance Downwind to Ponds	5,000 m
Average Wind Speed	5.4 m/s (19.5 km/s)
Wind Frequency from South	6 per cent
Dust Source Area	64,000 m^2
Atmospheric Dispersion Parameter (Chi/Q)	1.75E-08 s/m^3
Ratio of Downwind Dust Concentration to Dust Concentration at Source	9.45E-05
Human Receptor Dose at Salt Ponds	
Ra-226	1.41E-07 millisievert per year
Ra-228	5.16E-07 millisievert per year
Th-228	4.28E-08 millisievert per year
Total Human Receptor Dose at Onslow Salt	**6.99-07 millisievert per year**

8.2.3 Consumption of Fish by a Member of the General Public

This scenario evaluates doses to a member of the general public whom is exposed to NORMs through consumption of fish taken from the Hooley Creek – Four-Mile Creek tidal embayment.

For this analysis, a two-year stream flow frequency was assumed for Quick Mud Creek, which provides the minimum dilution of the RSS for flushing events reaching the sea. Further, it was assumed that salts and NORMs accumulate in the RSS ponded on Quick Mud Creek for two years. After two years of accumulation, a flood event discharges all of the accumulated salt crust and residual liquid RSS to the Hooley Creek – Four-Mile Creek tidal embayment. The stream flow transports the two-year accumulation of salt and radionuclides to the Hooley Creek – Four-Mile Creek tidal embayment. The supratidal saline flats also contribute to the stream flow.

The radium and thorium activities in the Hooley Creek – Four-Mile Creek tidal embayment were derived from the findings of the MIKE21HD(FM) hydrodynamic modelling (**Table 6-5**). If may be estimated that the influence of the RSS in the tidal estuary may prevail for about one month during and after a stream flow event. One month is assumed to represent the time necessary for radium and thorium in the estuary to be diluted to less than 0.5 Bq/L and\or flushed out to sea. The model predictions provide an understanding that radium and thorium activities in tidal reaches exceed 1 Bq/L for periods that range from 4 to 18 days. During these periods, it was assumed that the radium and thorium activities would average about half of the source activity at the outflow into the tidal estuary (**Table 6-5**). For the remaining days in a month it may be reasonably assumed that the sum of the radium and thorium activities averages 0.5 Bq/L. An outline of the interpreted effective radium and thorium activities in the Hooley Creek – Four-Mile Creek tidal embayment derived using this set of assumptions is provided in **Table 8-5**.

The assumed residence time is a conservatively-high worst-case. The assumed residence time limits the potential general public exposure to a fraction of each year.

The quantity of fish consumed from the Hooley Creek – Four-Mile Creek tidal embayment at times when the radium and thorium activities are present is estimated as 2.5 kg/year. This is based on the estimated annual fish consumption of 30 kg/year (FAO, 2006) divided by 12, since the estuary is assumed to contain the RSS for only one month of each year. These estimates are expected to be conservatively high; there is an expectation that fishing in the tidal estuary may preferentially occur at times not concurrent with stream flow.

Table 8-5 Month-Long Radium and Thorium Activities in Hooley Creek - Four-Mile Creek Tidal Embayment

Event	Stream Flow Source Activity @ Outflow (Bq/L)	Time to of Source Dilution to 1 Bq/L (days)	Month-Long Weighted Average Radium and Thorium Activities in Hooley Creek – Four-Mile Creek Tidal Embayment (Bq/L)		
			Ra-226	Ra-228	Th-228
1+1 (24-hour)	19.5	10	1.3	2.1	0.2
1+2 (24-hour)	16.3	10	1.1	1.8	0.2
1+5 (24-hour)	5.8	5	0.3	0.5	0.0
1+10 (24-hour)	2	4	0.2	0.3	0.0
1+1 (240-hour)	19.5	18	2.2	3.6	0.3
1+2 (240-hour)	16.3	18	1.9	3.1	0.3
1+5 (240-hour)	5.8	16	0.7	1.1	0.1
1+10 (240-hour)	2	18	0.3	0.5	0.0
1+1 (250-hour) LT	19.5	18	2.2	3.6	0.3
1+2 (250-hour) LT	16.3	18	1.9	3.1	0.3
1+5 (250-hour) LT	5.8	14	0.6	1.0	0.1
1+10 (250-hour) LT	2	13	0.3	0.4	0.0
Average			**1.1**	**1.8**	**0.2**
Median			0.9	1.4	0.1
Upper-Bound			**2.2**	**3.6**	**0.3**

General public dose assessments from the consumption of fish derived from the Hooley Creek – Four-Mile Creek tidal embayment at times when NORMs are present are shown in **Table 8-6**. In these assessments, a bio-concentration factor of 50 L/kg (ANL, 2001) represents the ratio of the radium and thorium concentration in fish (Bq/kg) divided by the radium and thorium concentration in the water (Bq/L). Also, ingestion dose conversion factors are taken from (ICRP, 1994) and include all radioactive decay products with half-lives less than one year. Longer-lived decay products would not be present in fish following an intake of soluble radium and thorium.

Table 8-6 Parameters for General Public Doses from Fish Consumption

Parameter	Value		
Month-long weighted radium and thorium activity in estuary (Bq/L)	Average	Median	Upper-Bound
Ra-226	1.1	0.9	2.2
Ra-228	1.8	1.4	3.6
Th-228	0.2	0.1	0.3
Quantity of fish consumed	2.5 kg/year (from times when radium and thorium are present)		
Fraction of year water is contaminated	0.083 (one month/year)		
Bioaccumulation factor for radium and thorium in fish	50 L/kg		
Ingestion dose conversion factors (1)	Ra-226: 2.80E-07 Sievert/Bq		
	Ra-228: 6.70E-07 Sievert/Bq		
	Th-228: 7.00E-08 Sievert/Bq		
Doses	Average	Median	Upper-Bound
Ra-226 (millisievert per year)	3.85E-02	3.15E-02	7.71E-02
Ra-228 (millisievert per year)	1.51E-01	1.17E-01	3.02E-01
Th-228 (millisievert per year)	1.75E-03	8.75E-04	2.63E-03
Total (millisievert per year)	**1.91E-01**	**1.50E-01**	**3.81E-01**

Notes:
(1) Includes all radioactive decay products with half-lives less than one year.

The fish ingestion calculations indicate a total potential dose in the range 0.15 to 0.38 millisievert per year. The calculated doses are about three to six times less than the regulatory general public dose limit of 1 millisievert per year.

8.3 Ecological Analysis

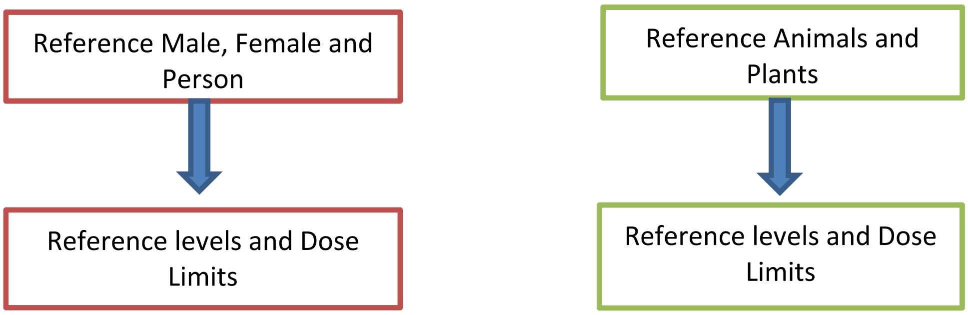
8.3.1 Guidelines

ARPANSA (2010, Technical Report No.154) recognises that research of Australian ecosystems is required in order to develop CRs for reference organisms. Further, ARPANSA (2010) recognises that the ERICA Integrated Approach and the ERICA Tool may provide reasonable prescriptions of provide to limiting harm to the environment.

In 2012 ARPANSA (Dr Rick Tinker) provided an update of radiological protection of the environment in Australia. Important elements of this update reflect that:

- In general terms, the standards in place for the protection of people are believed to offer protection to and limit radiological risk to other species.

- Ultimately, based on the ICRP framework (ICRP, 2009) radiological protection will ultimately be managed on two parallel reference systems; for example:



- The regulations require development in context to specific guidance for protection of non-human species. These regulations would be informed by international guidelines (ICRP).

8.3.2 Ecological Criterion Used

As a general criterion, the ecological analysis was based on limiting the dose rates and\or activity limit to plants and animals to 1 millisievert per year and 1 Bq/g, respectively. These are rates and limits based on the protection of human health. Under these conditions, it can be anticipated that doses to general members of the public are unlikely to exceed about 1 millisievert per annum (IAEA, 2004).

8.3.3 Ecological Dose Assessments

Ecological dose estimates have been undertaken for selected settings. In the dose estimates it was recognised that the likely external dose for direct contact with radium and thorium activity in stream flow would be very small compared to the dose from radium and thorium activity in accumulated RSS salt. In the salt on Quick Mud Creek, the radium and thorium activities were less than 1 Bq/g; in estimated stream flow sources to the tidal creeks they ranged from about 2 to 20 Bq/L. Therefore on a volumetric basis, the external radium and thorium activities in the stream flow were 40 to 250 times less than the salt activities (because 1 L of stream flow would weight about 1,000 grams). Further, the hydrodynamic modelling results (**Table 6-5**) typically show 2, 10 and 100-times dilution in seawater typically after about 10, 22 and 25 days, respectively. Accordingly, for members of the general public, it was recognised that the likely external doses from direct contact with radium and thorium activity in water would be very small compared to the dose from radium and thorium activity in the consumption of fish.

The ecological dose estimates have included setting for:

- Quick Mud Creek.
- Supratidal saline flats
- Tidal estuary.

These assessments are discussed below.

Quick Mud Creek Terrestrial Setting

Dose assessments for the pools on Quick Mud Creek outlined in **Table 8-3** indicate a potential external dose up to 0.525 millisievert per year. This assessment does not include ingestion. Given the characteristics of the local settings, including measured salt concentrations (greater than 84,400 mg/L TDS, **Table 4-3**) in pools on Quick Mud Creek, propensity for salt accumulation and sparse vegetation (**Plate 4-1** through **Plate 4-3**) it was recognised that ingestion was a comparatively low risk.

The accumulated salt on Quick Mud Creek has residual radium and thorium activities of 0.83 Bq/g irrespective of thickness. These activities are below the ecological activity limit criterion of 1 Bq/g. This assessment was based on Ra-226, Ra-228 and Th-228 activities of 13.7, 22.7 and 2.0 Bq/L, respectively and salt in the RSS solution of 46.4 g/L.

Supratidal Saline Flats Terrestrial Setting

Dose assessments for stream flow and residual pools on the supratidal saline flats would be less than those for Quick Mud Creek; that is less than 0.525 millisievert per year. The predictive surface water modelling assessments indicate 8-fold dilution of radium and thorium activities in salt transported by stream flow from Quick Mud Creek. Further, the supratidal saline flats are intrinsically dry; the durations of stream flow events would typically amount to a few tens of days each year.

This assessment also excludes ingestion. There are similarities to the Quick Mud Creek setting, with propensity for salt accumulation and sparse vegetation limiting the injection risks.

The accumulated salt on the supratidal saline flats would have estimated maximum radium and thorium activities of 0.83 Bq/g. Given transport of the salt in steam flow from Quick Mud Creek and mixing with local and Hooley Creek runoff, the radium and thorium activity would typically be less that on Quick Mud Creek.

Tidal Estuary Settings

A summary of potential dose rates for the initial source terms (month-long weighted average, median and upper-bound 20 Bq/L) is provided in **Table 8-7**. These potential doses in the tidal estuary mixes of stream flow and seawater were derived from a dose conversion factor (Sieverts per second per Bq/m^3) for a 0.01 m thick salt crust. The Sieverts per second per Bq/m^3 dose conversions factors included:

- Ra-226 – 1.08E-17.
- Ra-228 – 1.52E-17.
- Th-228 – 9.19E-18.

The assumption regarding use of a 0.01 m thick salt crust seemed a reasonable worst-case, understanding that the thickness of accumulated salt over a two-year period would be 0.61 m and the predicted dilution factors in transportation by stream flow to the headwaters are about 8-fold, with subsequent mixing with seawater exceeding 100-fold dilution over the course of a month. Therefore, the 0.01 m thick salt crust dose conversion factor provides 61-times dilution whereas actual dilution factors would be two to three orders of magnitude.

The assessments in **Table 8-7** indicate that both the annual dose and annualised monthly doses are less than the 1 millisievert per year criteria.

Table 8-7 Estimated Radium and Thorium Source Doses in Tidal Estuary

Radium and Thorium Source Activity (Bq/L)	Source Maximum[1]	Month-long Weighted[2]		
		Average	Median	Upper
	19.5	3.0	2.4	6.1
Ra-226				
Salt Solution (Bq/L)	6.9	1.1	0.9	2.2
Residue Concentration (Bq/g)	0.2156	0.0344	0.0281	0.0688
Residue Concentration (Bq/cm^3)	0.2480	0.0395	0.0323	0.0791
Residue Concentration (Bq/m^3)	247968.75	39531.25	32343.75	79062.5
External Dose (Sievert/s)	2.67E-12	4.26E-13	3.49E-13	8.52E-13
External Dose (millisievert per year)	7.0E-03	1.1E-03	9.2E-04	2.2E-03
Ra-228				
Salt Solution (Bq/L)	11.5	1.8	1.4	3.6
Residue Concentration (Bq/g)	0.3594	0.0563	0.0438	0.1125
Residue Concentration (Bq/cm^3)	0.4133	0.0647	0.0503	0.1294
Residue Concentration (Bq/m^3)	413281.25	64687.5	50312.5	129375
External Dose (Sievert/s)	6.27E-12	9.81E-13	7.63E-13	1.96E-12
External Dose (millisievert per year)	1.6E-02	2.6E-03	2.0E-03	5.2E-03
Th-228				
Salt Solution (Bq/L)	1.0	0.2	0.1	0.3
Residue Concentration (Bq/g)	0.0313	0.0063	0.0031	0.0094
Residue Concentration (Bq/cm^3)	0.0359	0.0072	0.0036	0.0108
Residue Concentration (Bq/m^3)	35937.5	7187.5	3593.8	10781.3
External Dose (Sievert/s)	3.30E-13	6.61E-14	3.30E-14	9.91E-14
External Dose (millisievert per year)	8.7E-04	1.7E-04	8.7E-05	2.6E-04
Total Dose Estimates				
Interpreted Dose (millisievert per year)[3]	2.4E-02	3.9E-03	3.0E-03	7.7E-03
Annualised Monthly Dose (millisievert per year)[4]	2.9E-01	4.6E-02	3.6E-02	9.2E-02

Notes:

1 The source maximum is the highest interpreted stream flow activity prior to entry into the tidal waters.

2 The month-long weighted activities were derived from Table 8.5.

3 The interpreted dose is calculated assuming that the radium and thorium source is present for one month.

4 The interpreted annualised monthly dose is calculated assuming the monthly dose is present for 12 months.

Conclusions

Background

The purpose for the study was to assess the NORM risk imposed by the disposal of a Residual Saline Stream (RSS) on Quick Mud Creek using a flow rate of 857 kL/day.

The Quick Mud Creek occurs in the hinterland of the Hooley Creek – Four-Mile Creek tidal embayment, above the tidal range. The creek is characterised by supratidal saline flats, clay pans and clayey plains. Each of these landforms accumulates salt and is predominantly barren of vegetation. Stream flow paths from Quick Mud Creek to the Hooley Creek – Four-Mile Creek tidal embayment traverse broad expanses of barren supratidal saline flats. Both the lower reaches of the Quick Mud Creek setting and supratidal saline flats were expected to host comparatively few ecological receptors. It was recognised that mangroves, samphire, bioturbated high tide mud flats and algal mat covered high tide flats within the Hooley Creek – Four-Mile Creek tidal embayment would potentially host the predominant ecological receptors for the disposed RSS.

Radium-226, radium-228 and thorium-228 species are expected to be present in the RSS with respective concentrations of 13.7, 22.7 and 2.0 Bq/L. The Birdrong Aquifer source is characterised by maximum Ra-226, Ra-228 and Th-228 activities of 4.1, 6.8 and 0.6 Bq/L, respectively.

Once disposed into Quick Mud Creek the radium and thorium would temporarily accumulate during intervals between stream-flow events. Groundwater discharges into the pools located in the low-lying areas of Quick Mud Creek. The environmental heads created by the salinity gradient in the underlying aquifers show an upwards vertical flow. In these conditions, the RSS would have limited interaction with the water table; the NORMs would not propagate the local water table.

When a litre of the RSS solute evaporates, it leaves behind about 46.4 grams of salt that contains 0.83 Bq of radium and thorium activity. The stream flow events on Quick Mud Creek would transport and disperse the accumulated RSS. The stream flow frequency for Quick Mud Creek that generates discharge to the sea is expected to occur for a 1- to 2-year ARI event. The stream flow discharges from Quick Mud Creek and associated transport and dispersion of the accumulated RSS solutions and salts would originate either from the sub-regional catchments of Quick Mud Creek and\or flooding of the Ashburton River.

The RSS salt accumulation in Quick Mud Creek would occur over a maximum period of about 2 years during periods without significant stream flow events. Based on hydrology analyses for a 2-year ARI stream flow event, the Ra-226, Ra-228 and Th-228 activities in the stream flow, derived from 2-years RSS salt accumulation on Quick Mud Creek would be 41.6, 68.9 and 6.1 Bq/L, respectively. For selected consecutive rainfall events, the radium and thorium source volumes and activities at the headwaters of the tidal reaches to East Hooley Creek were estimated as follows:

- 1+1-year ARI consecutive events – 1.195 GL at 19.5 Bq/L.
- 1+2-year ARI consecutive events – 1.373 GL at 16.3 Bq/L.
- 1+5-year ARI consecutive events – 3.978 GL at 5.8 Bq/L.
- 1+10-year ARI consecutive events – 11.814 GL at 2.0 Bq/L.

The prediction of the transport and fate of the RSS-derived radium and thorium activities within the Hooley Creek – Four-Mile Creek tidal embayment was assessed using MIKE21HD(FM) hydrodynamic models. Non-reactive solute transport modules of MIKE21HD(FM) were used to determine the radium and thorium source mixing and dilution characteristics associated with the selected range of stream flow events.

9 Conclusions

Findings from the hydrodynamic modelling indicated:

- Periods of 20 to 31 days, typically about 25 days, for 100-times dilution of the radium and thorium source terms within the tidal creeks.
- Periods of 4 to 18 days, typically about 14 days, for dilution of the source terms to 1 Bq/L within the entire Hooley Creek – Four-Mile Creek tidal embayment.

The predictive simulations provide indications that the worst-case scenarios are provided by:

- Single comparatively low-flow events where flow occurs over extended periods up to 10 days.
- Consecutive low-flow events where flow occurs over extended period up to 10 days.

The predictions indicate sensitivity to the duration of the stream flow, with longer durations resulting in attenuation of the RSS source before mixing, dilution and transport from the Hooley Creek – Four-Mile Creek tidal embayment.

Radiological Risk to Humans

Based on the assessments of the NORM risk and radiological safety to human receptors, the following conclusions have been interpreted:

- As a general criterion, the analysis was based on limiting the dose rates and or activity limits to 1 millisievert per year and 1 Bq/g, respectively. These are doses and limits based on the protection of human health. Under these conditions, it can be anticipated that doses to general members of the public are unlikely to exceed about 1 millisievert per annum (IAEA, 2004).
- The geochemical modelling provides the maximum NORM concentration accumulated in the bed of Quick Mud Creek.
- The exposure pathways to the NORMs identified included external radiation, dust inhalation and ingestion through potential bio-accumulation in the aquatic fauna. The exposure scenarios considered human receptors at the RSS pond or Onslow Salt crystalliser ponds and general public at the estuary along the shore. Dose for each scenario and pathways have been estimated from adopted conversion factors. The findings for each scenario are detailed below:

    a. Human receptor at RSS pools on Quick Mud Creek: the maximum dose to a human receptor at the RSS pools on Quick Mud Creek is 0.525 millisievert per year, which is the sum of the external radiation and dust inhalation doses. This is approximately half of the regulatory general public annual dose limit. This conservative analysis demonstrates that human receptor doses at the RSS pools on Quick Mud Creek are within the recommended limits.

    b. Human receptor at Onslow Salt crystalliser ponds: the calculation for dust inhalation showed a dose of 0.000000699 millisievert per year, which is substantially below the regulatory general public annual dose limit of 1 millisievert per year.

    c. Limited potential contamination of the produced salt at Onslow Salt by airborne NORM. The limited potential was based on i) understanding that the prevailing winds are away from the salt crystalliser ponds in context to transportation from Quick Mud Creek; ii) assumptions that the majority airborne NORMs would remain airborne and not settle on the salt crystalliser ponds; iii) salt harvesting occurs over a limited time cycle, thus limiting potentials for progressive NORM accumulation; and iv) the calculation of doses to human receptors on the crystalliser ponds.

d. Consumption of fish by a member of the general public in the tidal zone: calculations indicate a total dose in the range of 0.15 to 0.38 millisievert per year. This is below the regulatory general public annual dose limit of 1 millisievert per year.

The table below presents a summary of the dose/risk assessment for human receptors.

Receptors	Dose Limit		Aspect	Exposure Pathway		
	millisievert per year	Guidelines		External Radiation	Dust Inhalation	Fish Ingestion
Human	1	ARPANSA, 2011	Human Receptor at RSS Pond	0.525	0.00740	NA
			Human Receptor at Onslow Salt Crystalliser Ponds	NA	0.000000699	NA
			Fish Consumption by the General Public	NA	NA	0.15 – 0.38

Radiological Risks to the Ecology

With regard to ecological receptors, the following conclusions have been interpreted with regard to Norm risk and radiological safety the following conclusions have been reached:

- As a general criterion, the analysis was based on limiting the dose rates and activity limits to 1 millisievert per year and 1 Bq/g, respectively. In general terms, the standards in place for the protection of people are believed to offer protection to and limit radiological risk to other species.
- The exposure pathways to the NORMs identified included external radiation. Generally it was recognised that exposures by ingestion would be comparatively low risks given the propensity of the terrestrial habitats formed by Quick Mud Creek and the supratidal saline flats to accumulate salt. Also, both settings are spare vegetated.
- The estimated dose limits for selected ecological domains include:

  a. Quick Mud Creek: Potential doses up to 0.525 millisievert per year. The accumulated salt on Quick Mud Creek has residual radium and thorium activities of 0.83 Bq/g irrespective of thickness.

  b. Supratidal Saline Flats: Assessments for the stream flow and pools on the supratidal saline flats pools indicate potential doses less than 0.525 millisievert per year. The accumulated salt on the supratidal saline flats would have activities less than 0.83 Bq/g.

  c. Tidal Estuary: Radiological exposures were calculated in the range 0.0039 to 0.29 millisievert per year for a number of scenarios with different mixing ratios of stream flow and seawater in the Hooley Creek – Four-Mile Creek tidal embayment.

The scenarios considered are expected to address worst-case aspects, with an understanding that the attenuation of radiological activities in the tidal estuary would tend to typically occur for a period of one month.

The table below present a summary of the dose/risk assessment for ecological receptors.

Receptors	Dose and Activity Limit		Aspect	Exposure Pathway External Radiation
	Criteria	Guidelines		
Ecological	1 millisievert per year	ARPANSA, 2011	Receptor on Quick Mud Creek	0.525 millisievert per year
			Receptor on Supratidal Saline Flats	Less than 0.525 millisievert per year
			Receptor in Tidal Estuary	0.0039 to 0.29 millisievert per year
	1 Bq/g		Receptor on Quick Mud Creek	0.83 Bq/g
			Receptor on Supratidal Saline Flats	Less than 0.83 Bq/g

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Figures

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) and Chevron Australia (2013).

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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
NORM RISK ASSESSMENT AT QUICK MUD CREEK

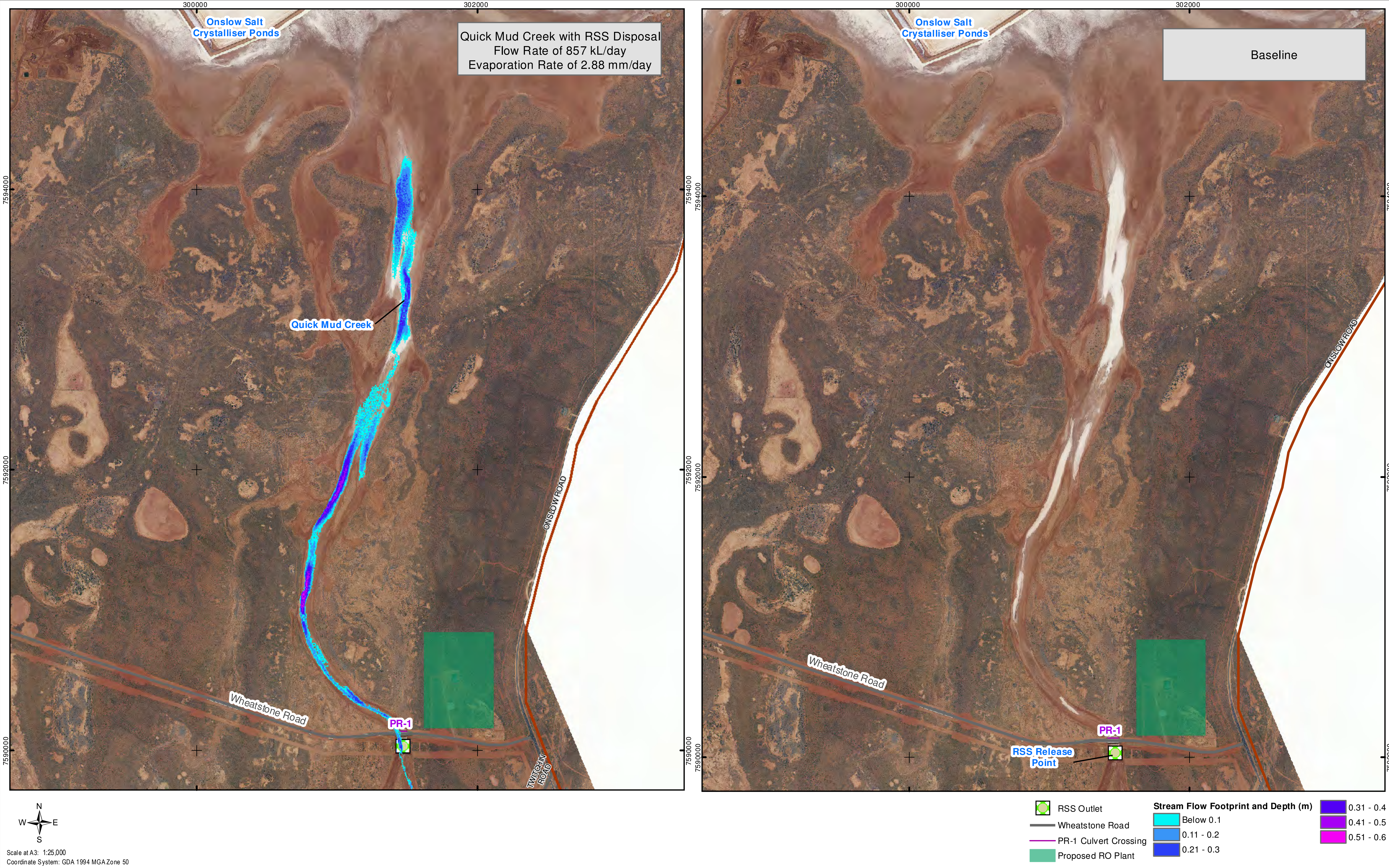
PROJECT AREA LOCATION PLAN

URS

BACKGROUND

File No: 42908178-WG-046.mxd | Drawn: LS | Approved: IB | Date: 25/11/2013

Figure: 1-1 | Rev. A | A3



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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
NORM RISK ASSESSMENT AT QUICK MUD CREEK

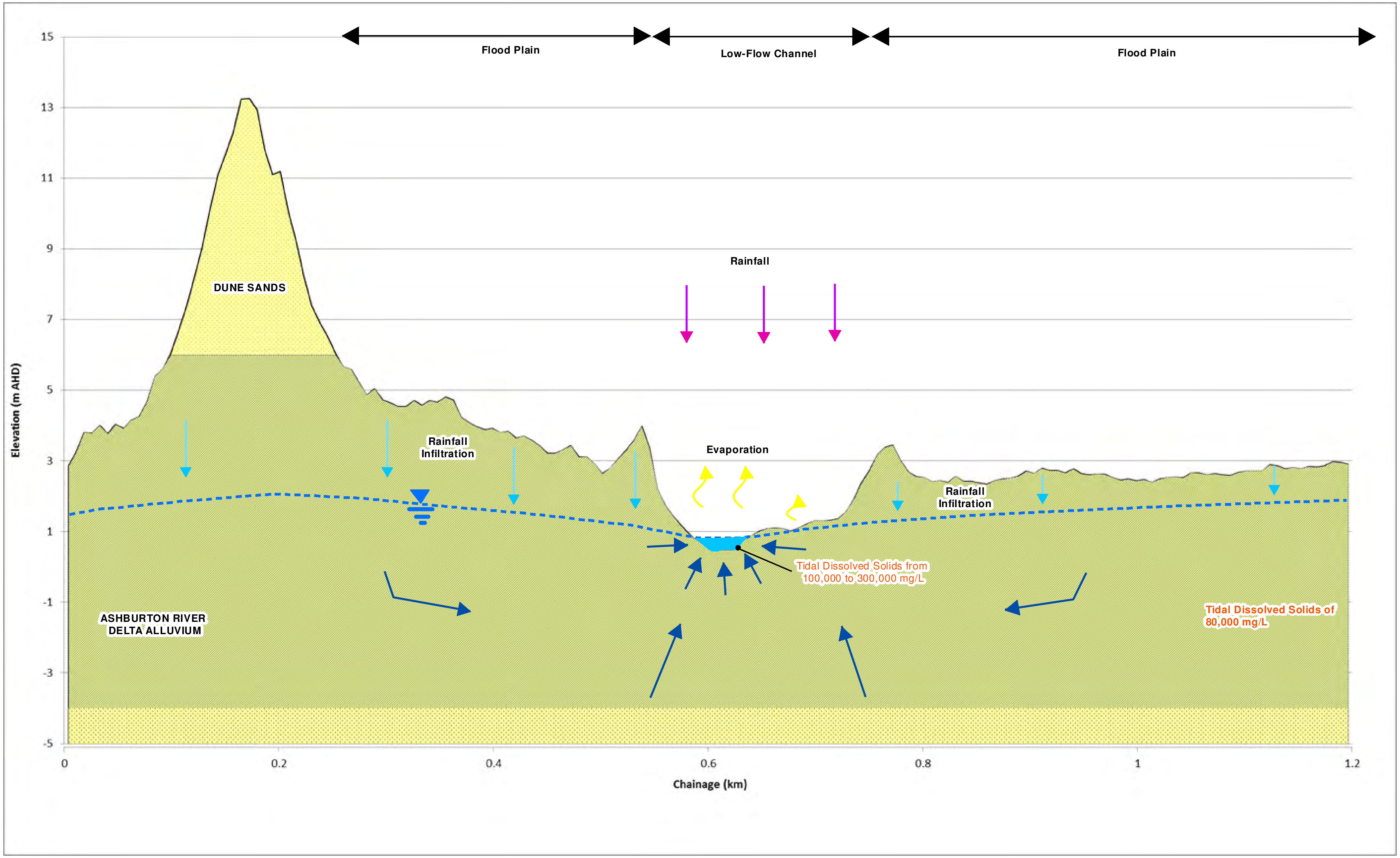
QUICK MUD CREEK SETTING
857 KL/DAY RSS DISPOSAL

URS

BACKGROUND

Figure: 1-2

File No: 42908178-WG-099.mxd | Drawn: LS | Approved: IB | Date: 11/02/2014 | Rev. A | A3



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Coordinate System:
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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
NORM RISK ASSESSMENT AT QUICK MUD CREEK

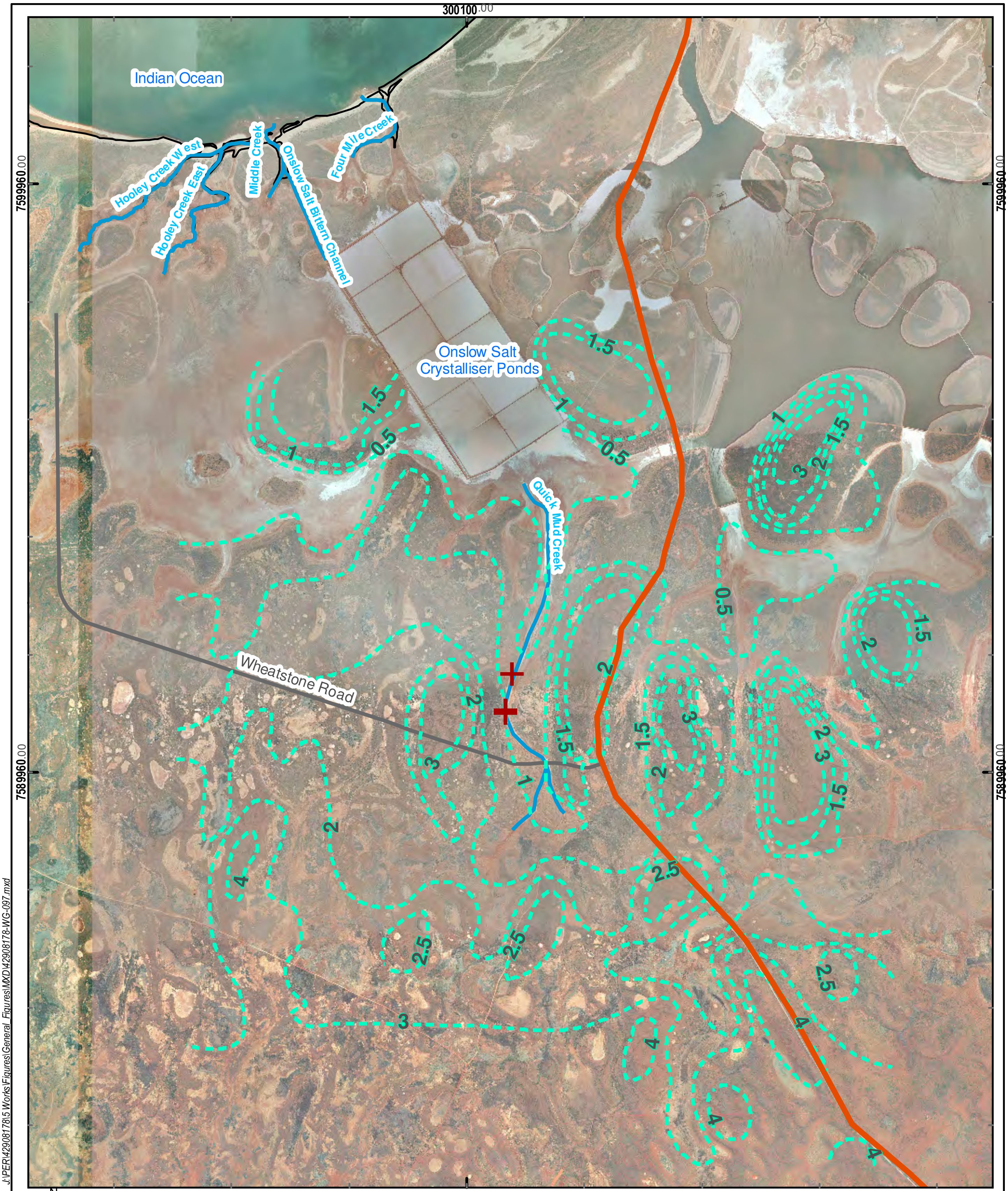
QUICK MUD CREEK
HYDROGEOLOGICAL CROSS-SECTION

URS

LOCAL SETTING

Figure: 3-1

File No: 42908178-WG-053.mxd | Drawn: LS | Approved: IB | Date: 22/11/2013 | Rev. A | A3



Sampling Points of the Pools
Interpreted Water Table Elevations (m AHD)
Local Watercourses
coastline

Scale: 1:130,928

0 2 4 6 8 km

Coordinate System: GCS GDA 1994
Source: 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
NORM RISK ASSESSMENT AT QUICK MUD CREEK

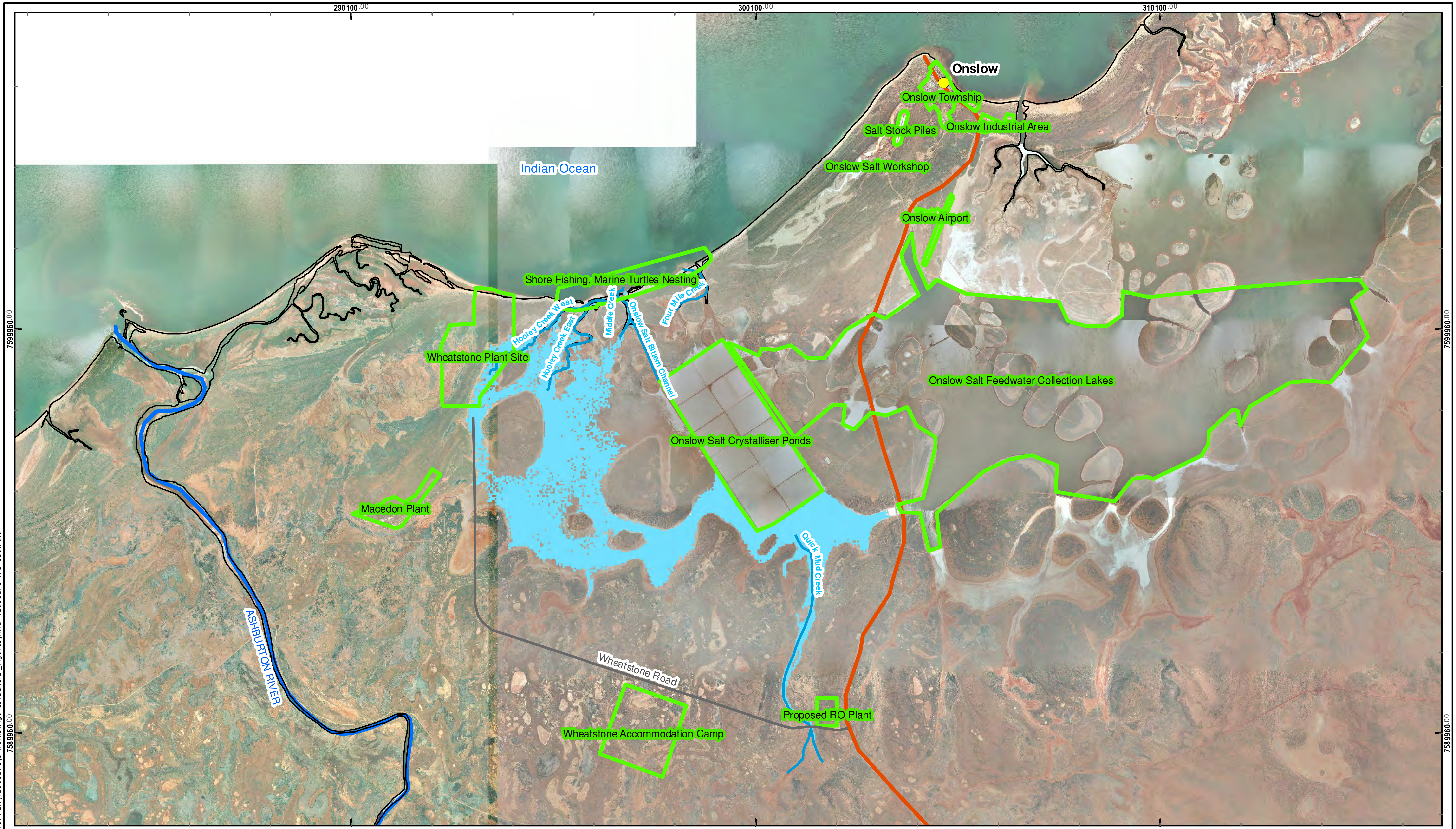
INTERPRETED WATER TABLE ELEVATIONS (NOVEMBER 2010)

URS

LOCAL SETTING

Figure: 3-2

File No: **42908178-WG-097.mxd** Drawn: **XX** Approved: **XX** Date: **28/11/2013** Rev.**A** A4



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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
NORM RISK ASSESSMENT AT QUICK MUD CREEK

SOCIAL INFRASTRUCTURE

LOCAL SETTING

File No: 42908178-WG-039.mxd | Drawn: LS | Approved: IB | Date: 25/11/2013

Figure: 3-3 | Rev. A | A3

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Scale at A3:
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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
NORM RISK ASSESSMENT AT QUICK MUD CREEK

NORM SAMPLE LOCATIONS
ON AND NEARBY QUICK MUD CREEK

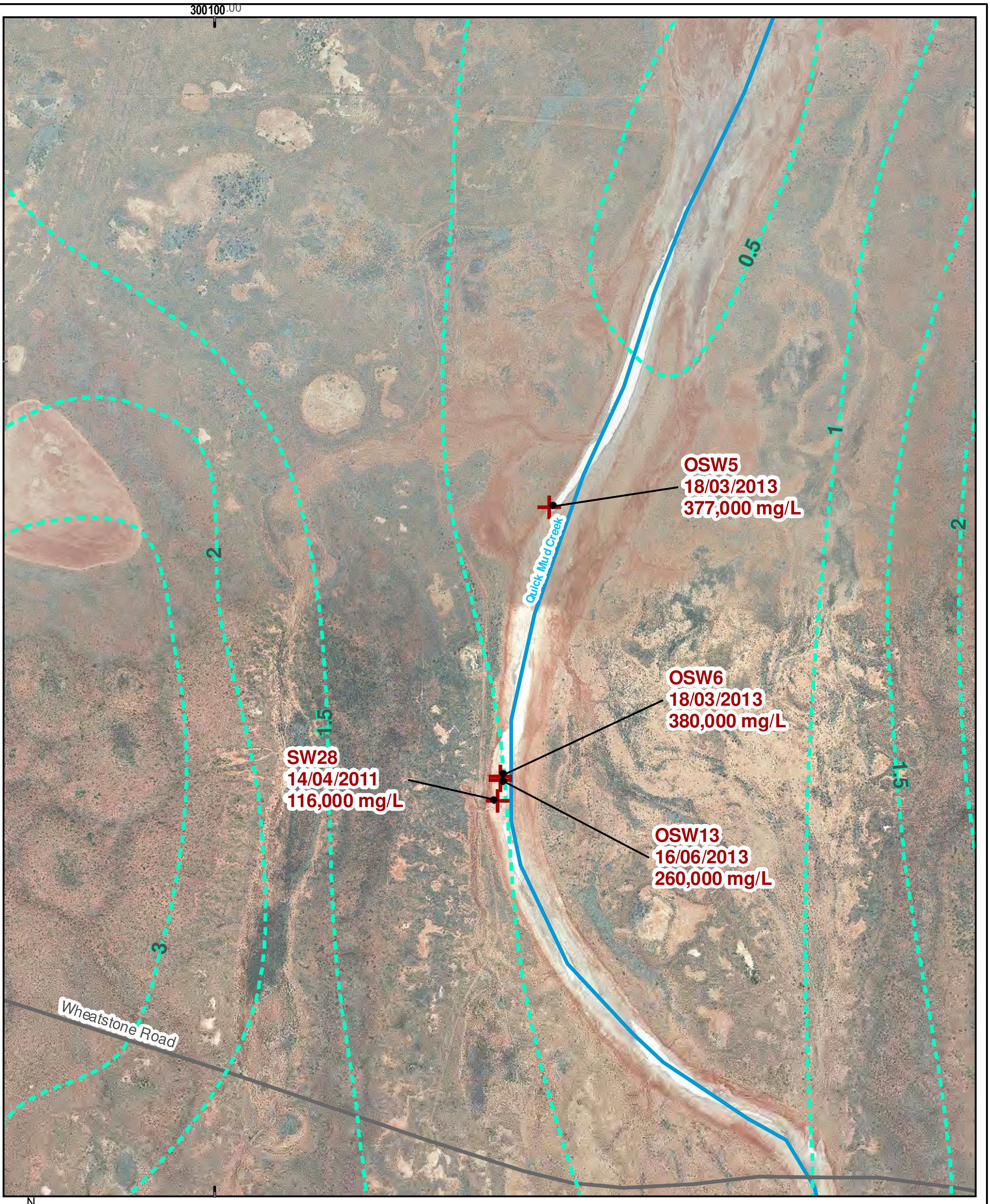
URS

BASELINE NORM SAMPLING

File No: 42908178-WG-036.mxd | Drawn: LS | Approved: CC | Date: 25/11/2013

Figure: 4-1

Rev. A | A3



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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
NORM RISK ASSESSMENT AT QUICK MUD CREEK

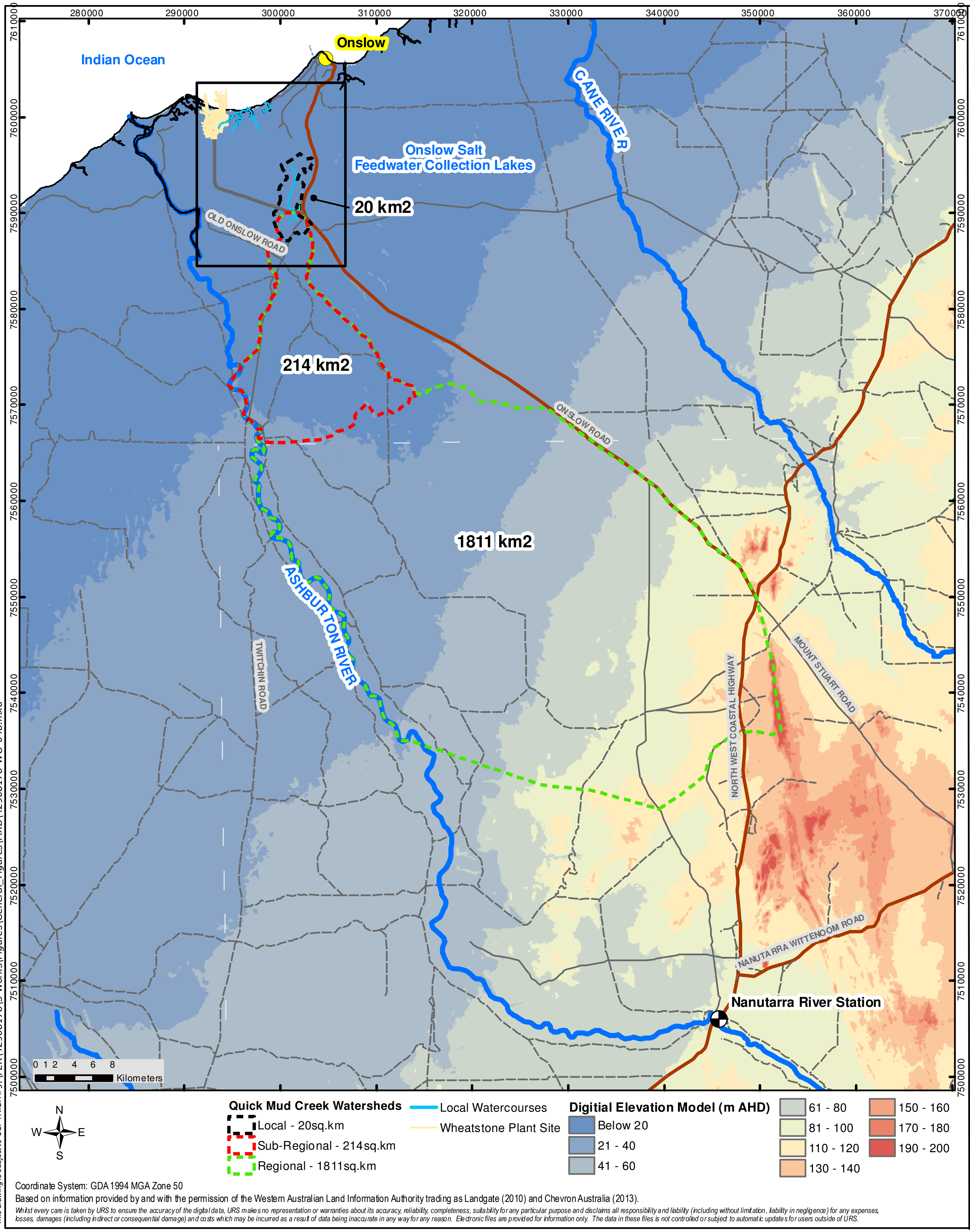
HISTORICAL TDS DATA FROM POOLS ON QUICK MUD CREEK

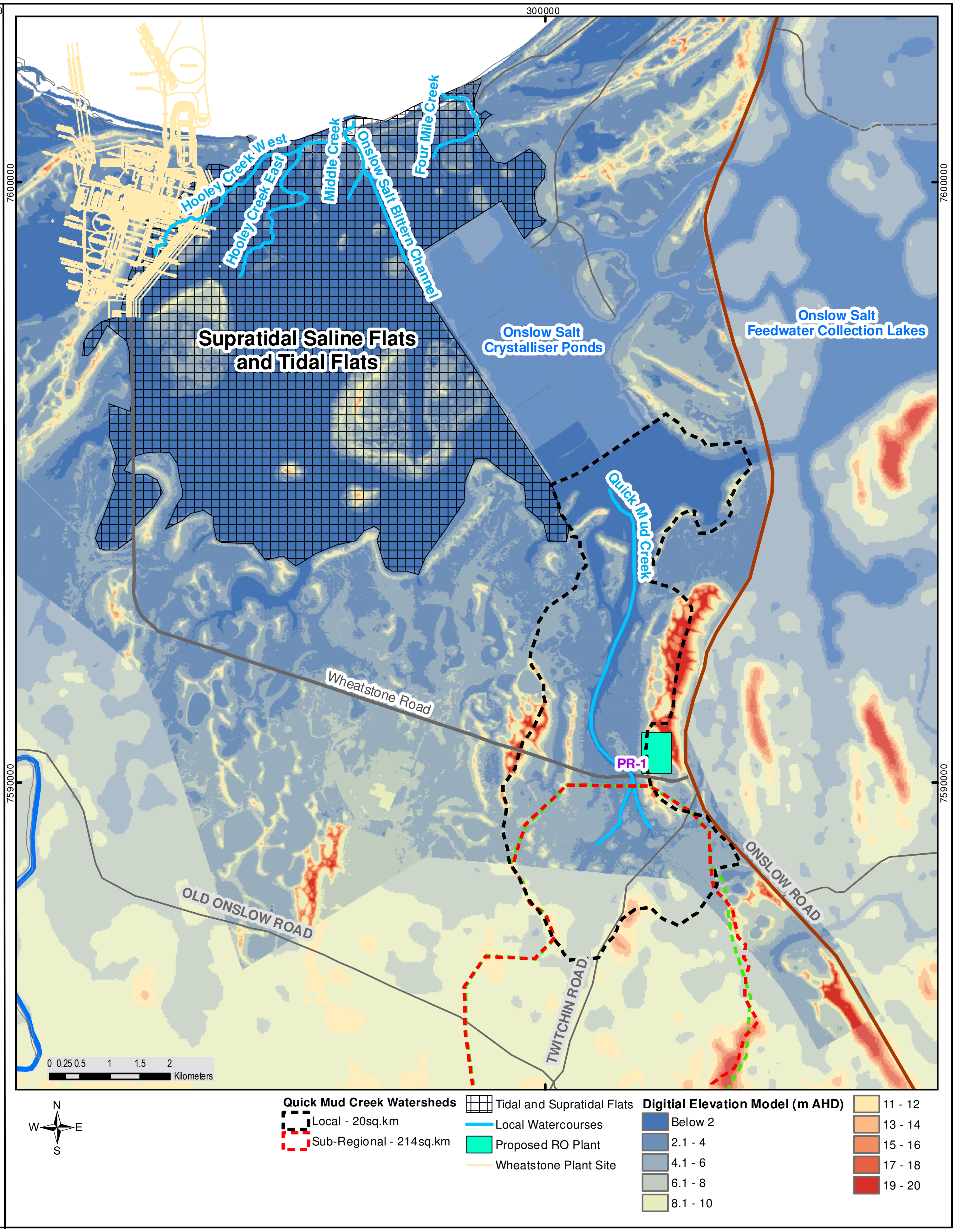
URS

BASELINE NORM SAMPLING

Figure: **4-2**

File No: **42908178-WG-098.mxd** Drawn: **XX** Approved: **XX** Date: **25/11/2013** Rev. **A** A4





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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
NORM RISK ASSESSMENT AT QUICK MUD CREEK

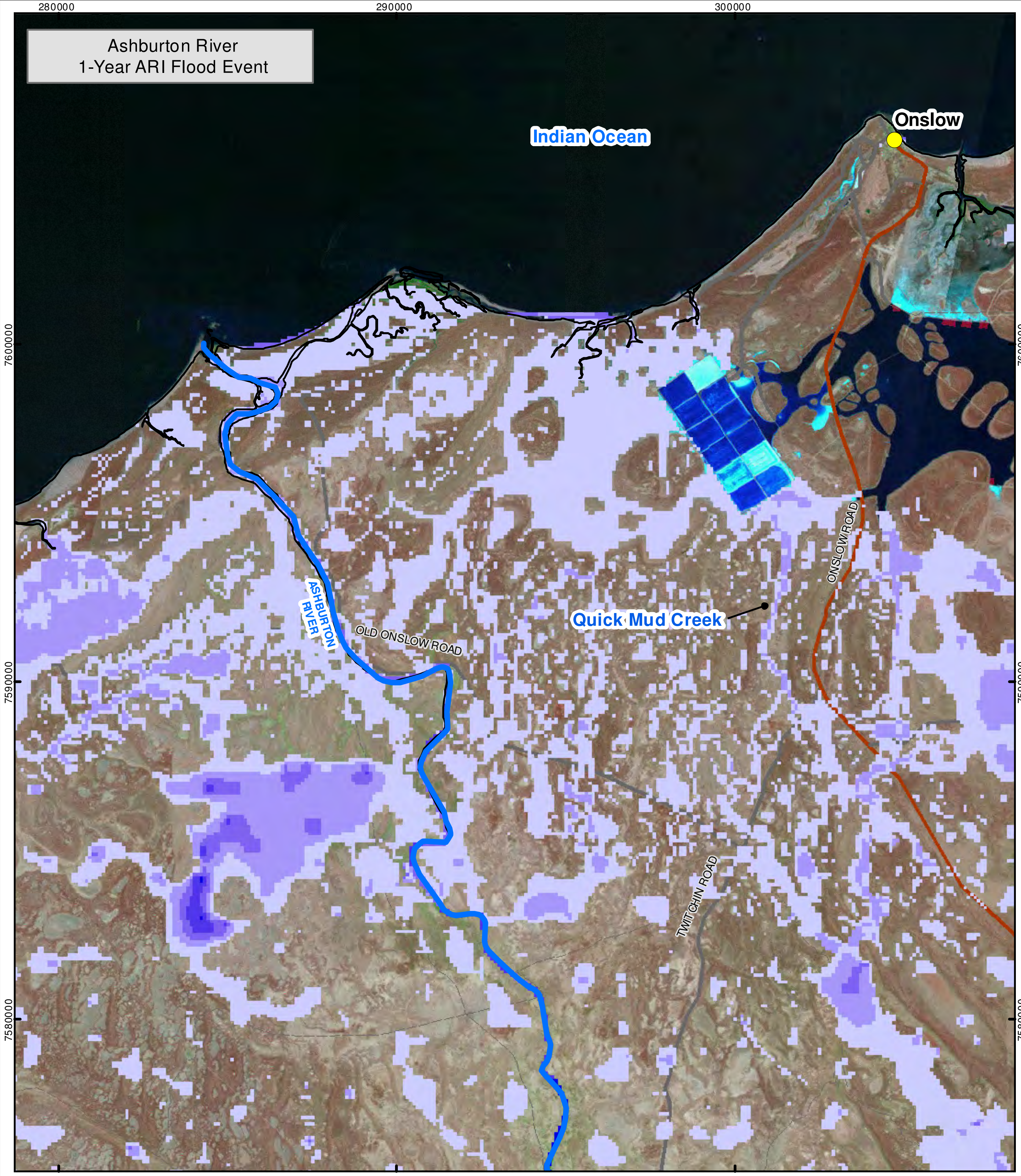
ASBURTON RIVER SETTING AND QUICK MUD CREEK CATCHMENTS

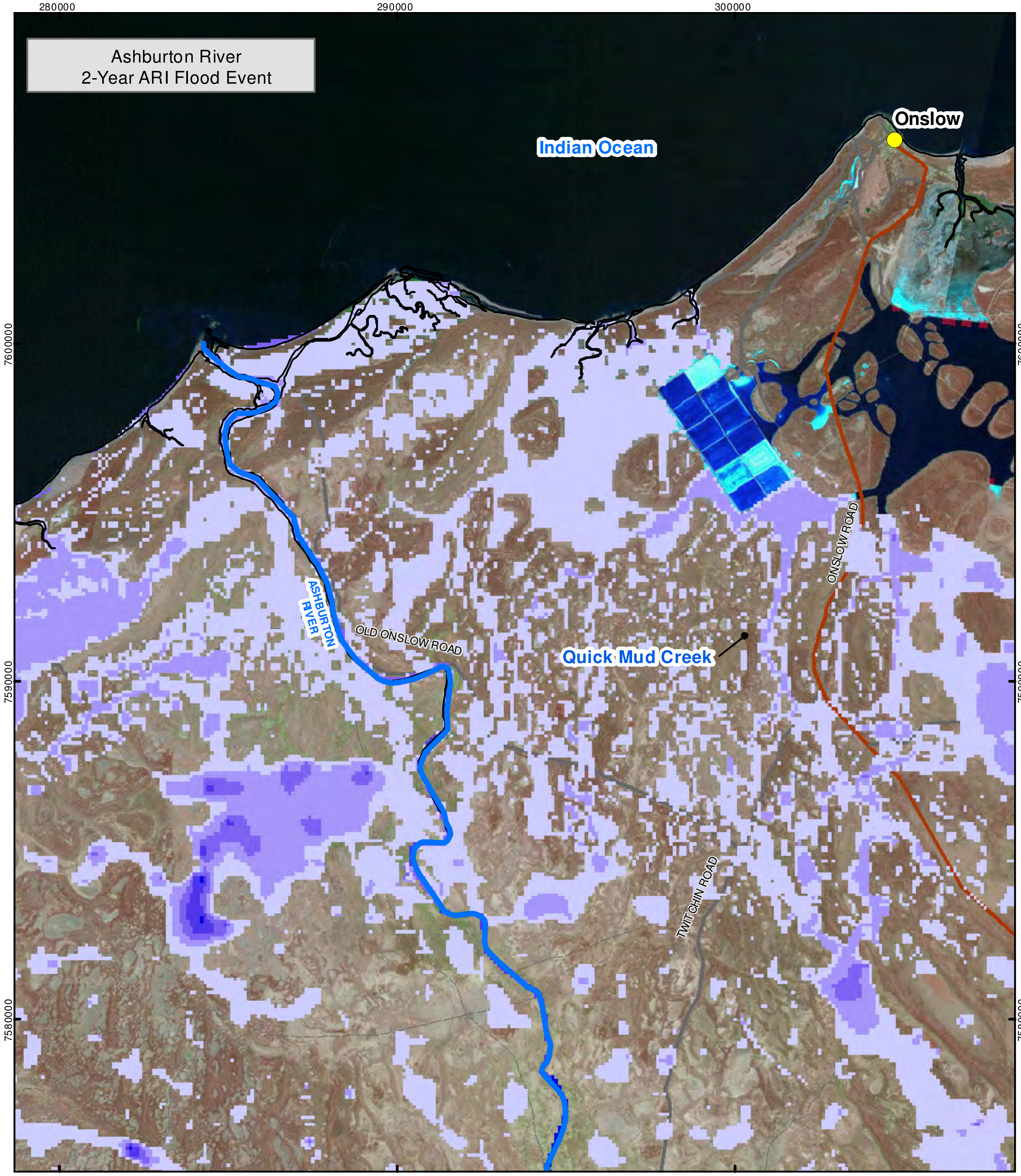
URS

STREAM FLOW CHARACTERISTICS

Figure: 5-1

File No: 42908178-WG-048.mxd | Drawn: LS | Approved: IB | Date: 28/11/2013 | Rev. A | A3





N
W E
S
0 0.5 1 2 3 4 Kilometers

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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
NORM RISK ASSESSMENT AT QUICK MUD CREEK

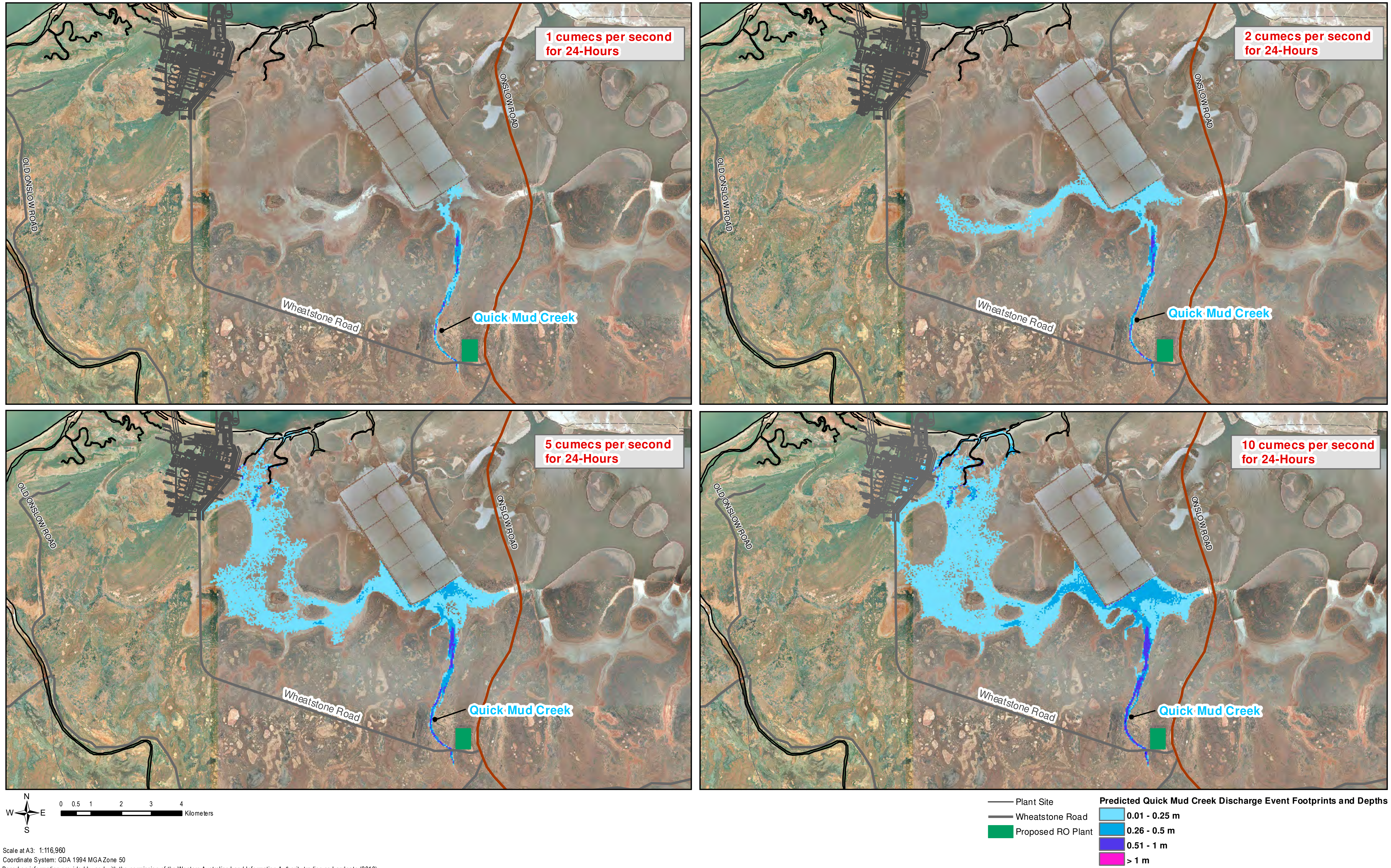
ASHBURTON RIVER FLOOD FOOTPRINTS

URS

STREAM FLOW CHARACTERISTICS

Figure: 5-2

File No: 42908178-WG-049.mxd Drawn: LS Approved: IB Date: 28/11/2013 Rev. A A3



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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
NORM RISK ASSESSMENT AT QUICK MUD CREEK

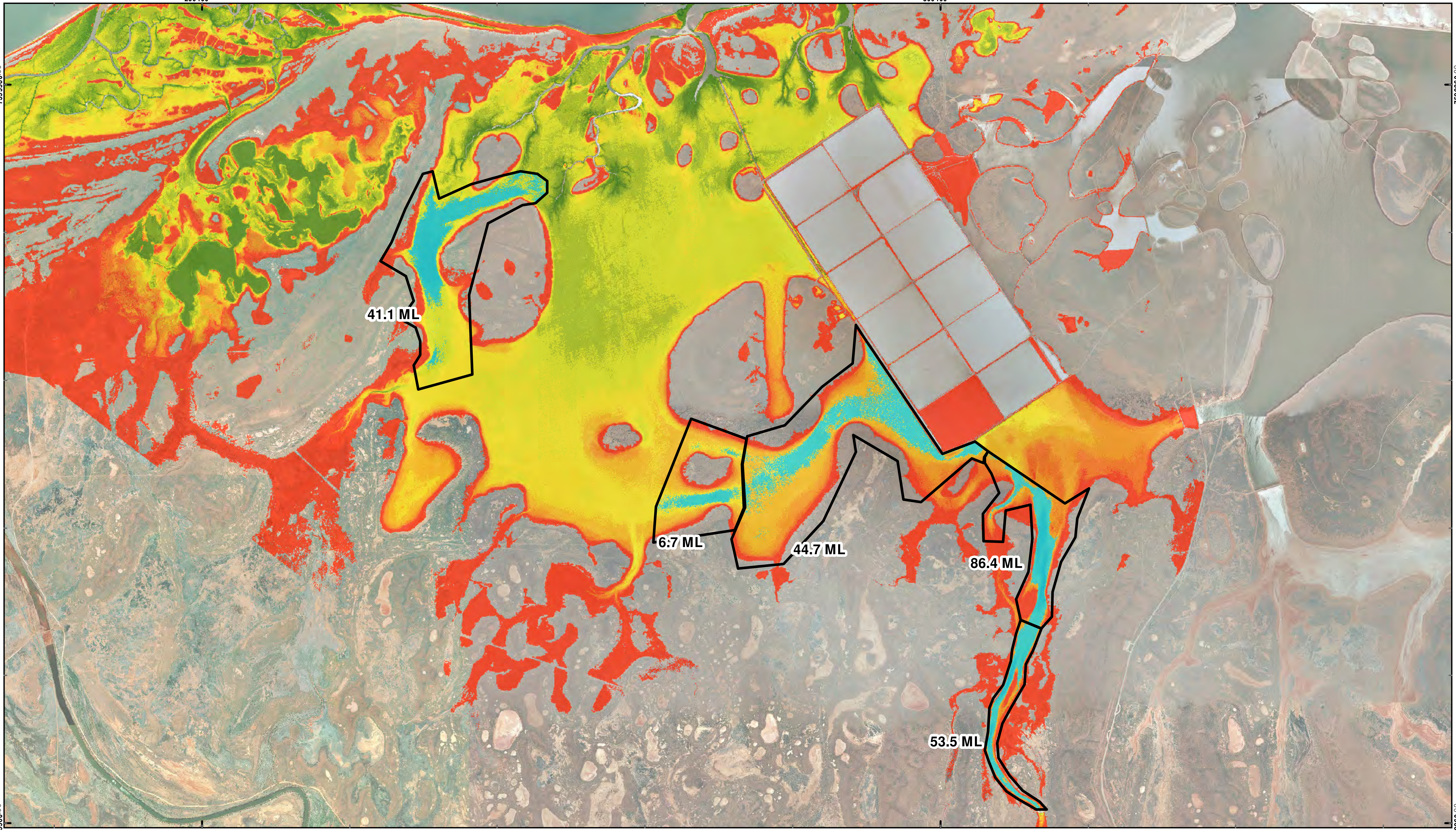
PREDICTED QUICK MUD CREEK FOOTPRINTS FOR 24-HOUR DURATION STORM EVENTS

URS

STREAM FLOW CHARACTERISTICS

Figure: 5-3

File No: 42908178-WG-042.mxd | Drawn: LS | Approved: IB | Date: 28/11/2013 | Rev. A | A3



N
W E
S
0 0.5 1 2 3 4 Kilometers

Storage boundaries

Attenuating Areas (natural storage)

Topography (LIDAR 2012) [mAHD]

< 0	1.01 - 1.1
0.01 - 0.8	1.11 - 1.2
0.81 - 0.9	1.21 - 1.3
0.91 - 1	1.31 - 1.4
	1.41 - 1.5
	1.51 - 1.6

Scale at A3: 1:50,000
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
NORM RISK ASSESSMENT AT QUICK MUD CREEK

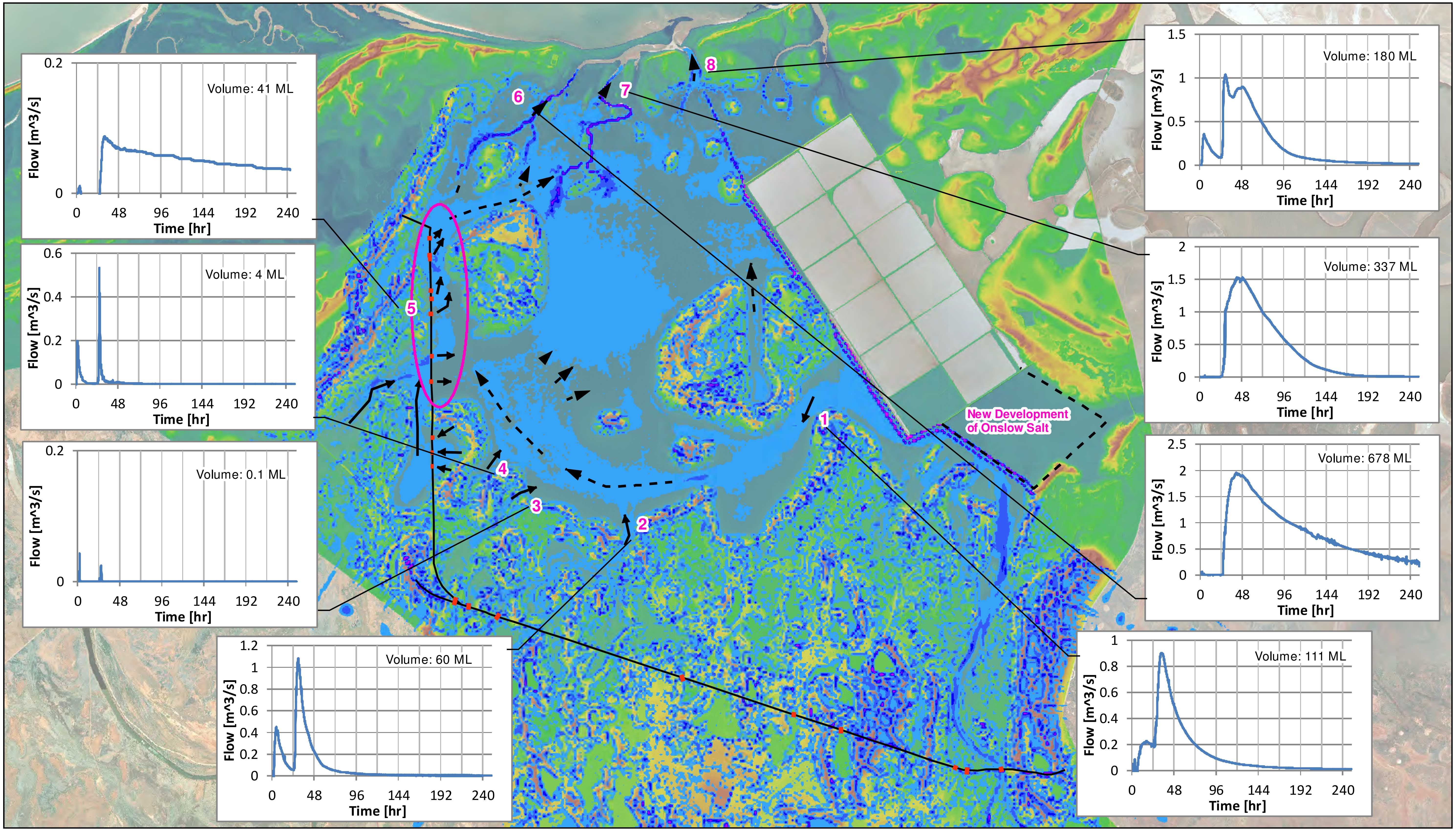
AREAS OF STREAM FLOW ATTENUATING IN HOOLEY AND QUICK MUD CREEKS WATERSHEDS

URS

STREAM FLOW CHARACTERISTICS

Figure: 5-4

File No: 42908178-AV-004.mxd Drawn: AV Approved: IB Date: 28/11/2013 Rev. A A3



N
W E
S

0 0.5 1 2 3 4 Kilometers

Main Flow Path Direction
Culverts
New Access Road

Topography (LIDAR 2012)
High : 27.91
Low : -0.25

1+1-year ARI Event Maximum Water Depth [m]
0.10 - 0.25
0.26 - 0.5
0.51 - 0.75
0.76 - 1
1.01 - 2
> 2

Scale at A3: 1:54,000
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
NORM RISK ASSESSMENT AT QUICK MUD CREEK

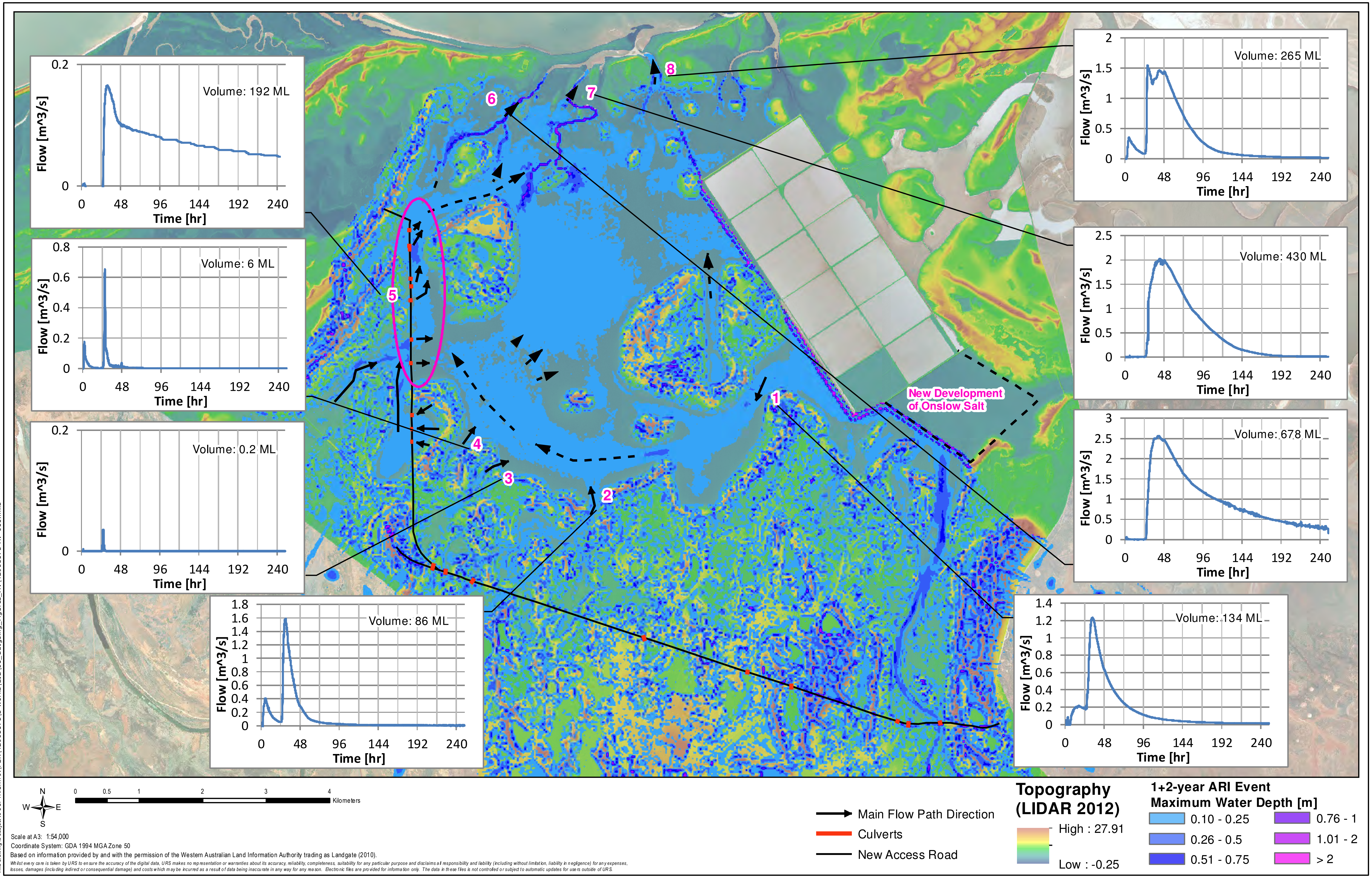
DISCRETISED STREAM FLOW PATHS AND VOLUMES - 1 + 1-YEAR ARI EVENT

URS

STREAM FLOW CHARACTERISTICS

File No: 42908178-AV-006.mxd Drawn: AV Approved: IB Date: 25/11/2013

Figure: 5-5 Rev. A A3



Chevron

ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
NORM RISK ASSESSMENT AT QUICK MUD CREEK

DISCRETISED STREAM FLOW PATHS AND VOLUMES - 1 + 2-YEAR ARI EVENT

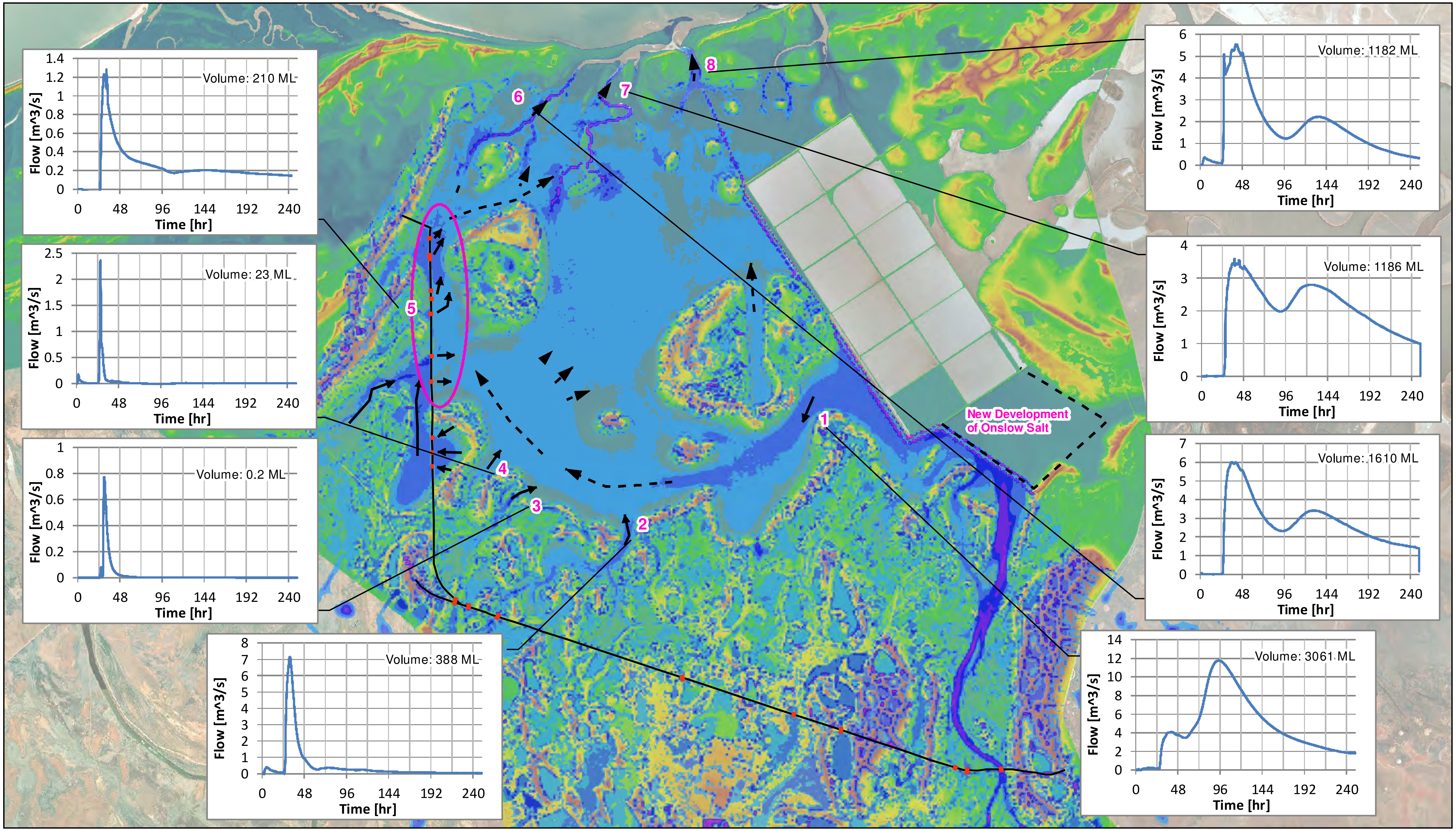
URS

STREAM FLOW CHARACTERISTICS

File No: 42908178-AV-011.mxd Drawn: AV Approved: IB Date: 25/11/2013

Figure: 5-6

Rev. A A3



N W E S

0 0.5 1 2 3 4 Kilometers

Scale at A3: 1:54,000

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).

- Main Flow Path Direction
- Culverts
- New Access Road

Topography (LIDAR 2012)

High : 27.91

Low : -0.25

1+5-year ARI Event Maximum Water Depth [m]

- 0.10 - 0.25
- 0.26 - 0.5
- 0.51 - 0.75
- 0.76 - 1
- 1.01 - 2
- > 2

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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
NORM RISK ASSESSMENT AT QUICK MUD CREEK

DISCRETISED STREAM FLOW PATHS AND VOLUMES - 1 + 5-YEAR ARI EVENT

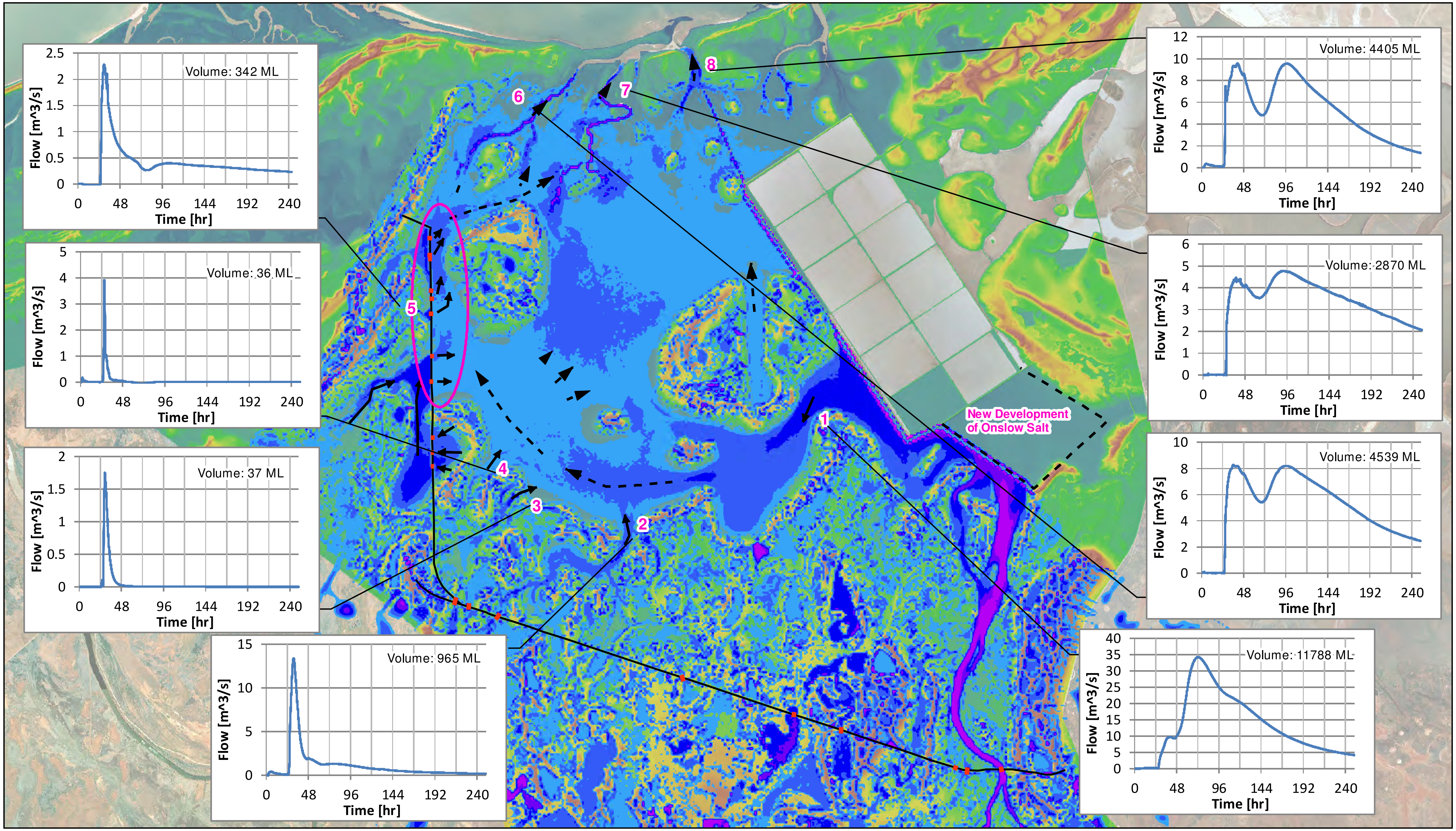
URS

STREAM FLOW CHARACTERISTICS

File No: 42908178-AV-012.mxd Drawn: AV Approved: IB Date: 25/11/2013

Figure: 5-7

Rev. A A3



N W E S

0 0.5 1 2 3 4 Kilometers

Scale at A3: 1:54,000
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).

Main Flow Path Direction
Culverts
New Access Road

Topography (LIDAR 2012)
High : 27.91
Low : -0.25

1+10-year ARI Event Maximum Water Depth [m]
0.10 - 0.25
0.26 - 0.5
0.51 - 0.75
0.76 - 1
1.01 - 2
> 2

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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
NORM RISK ASSESSMENT AT QUICK MUD CREEK

DISCRETISED STREAM FLOW PATHS AND VOLUMES - 1 + 10-YEAR ARI EVENT

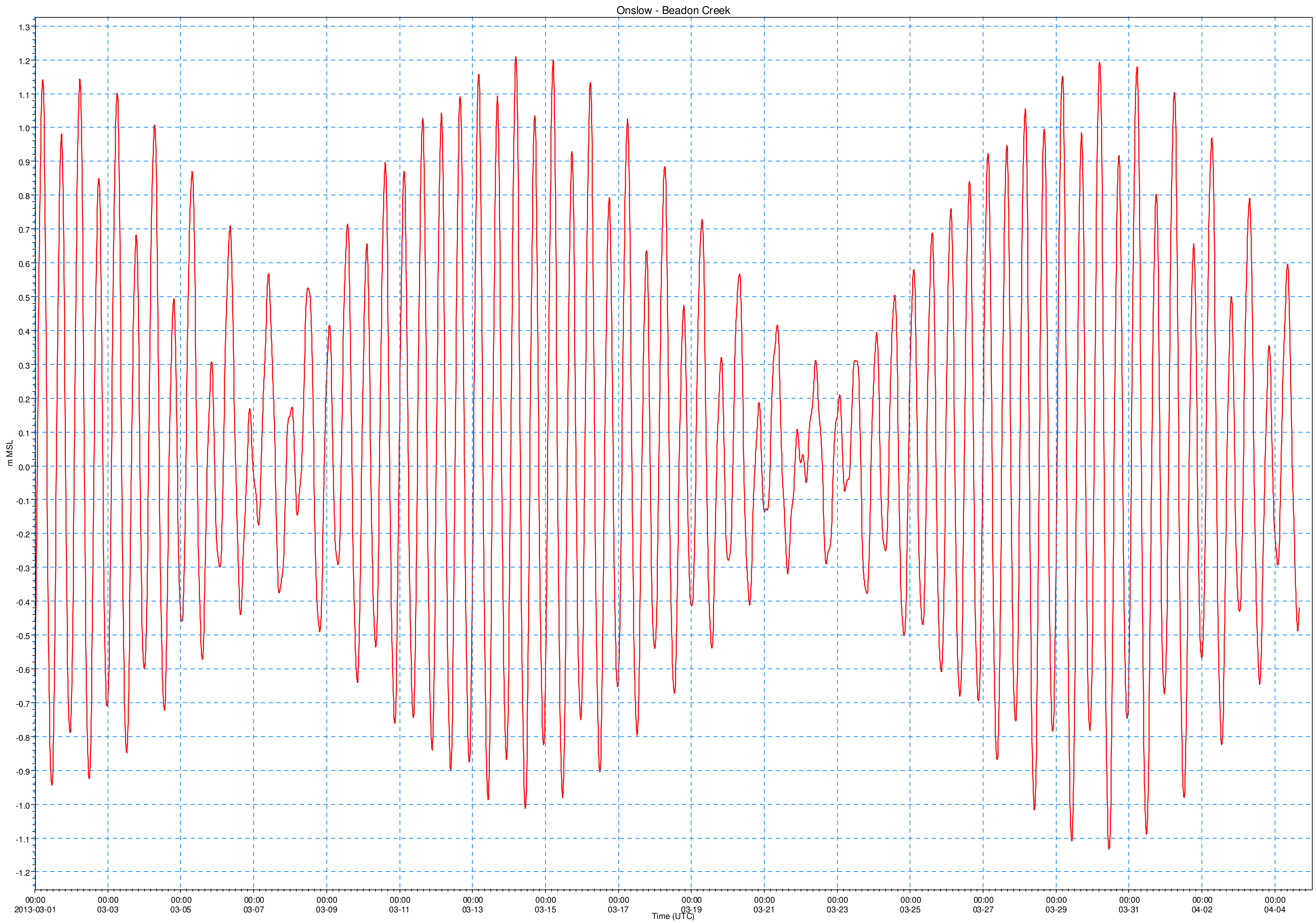
URS

STREAM FLOW CHARACTERISTICS

File No: 42908178-AV-013.mxd Drawn: AV Approved: IB Date: 9/12/2013

Figure: 5-8

Rev. A A3



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ONSLOW WATER INFRASTRUCTURE UPGRADE PROJECT
NORM RISK ASSESSMENT AT QUICK MUD CREEK

TIDAL CURVE AT ONSLOW

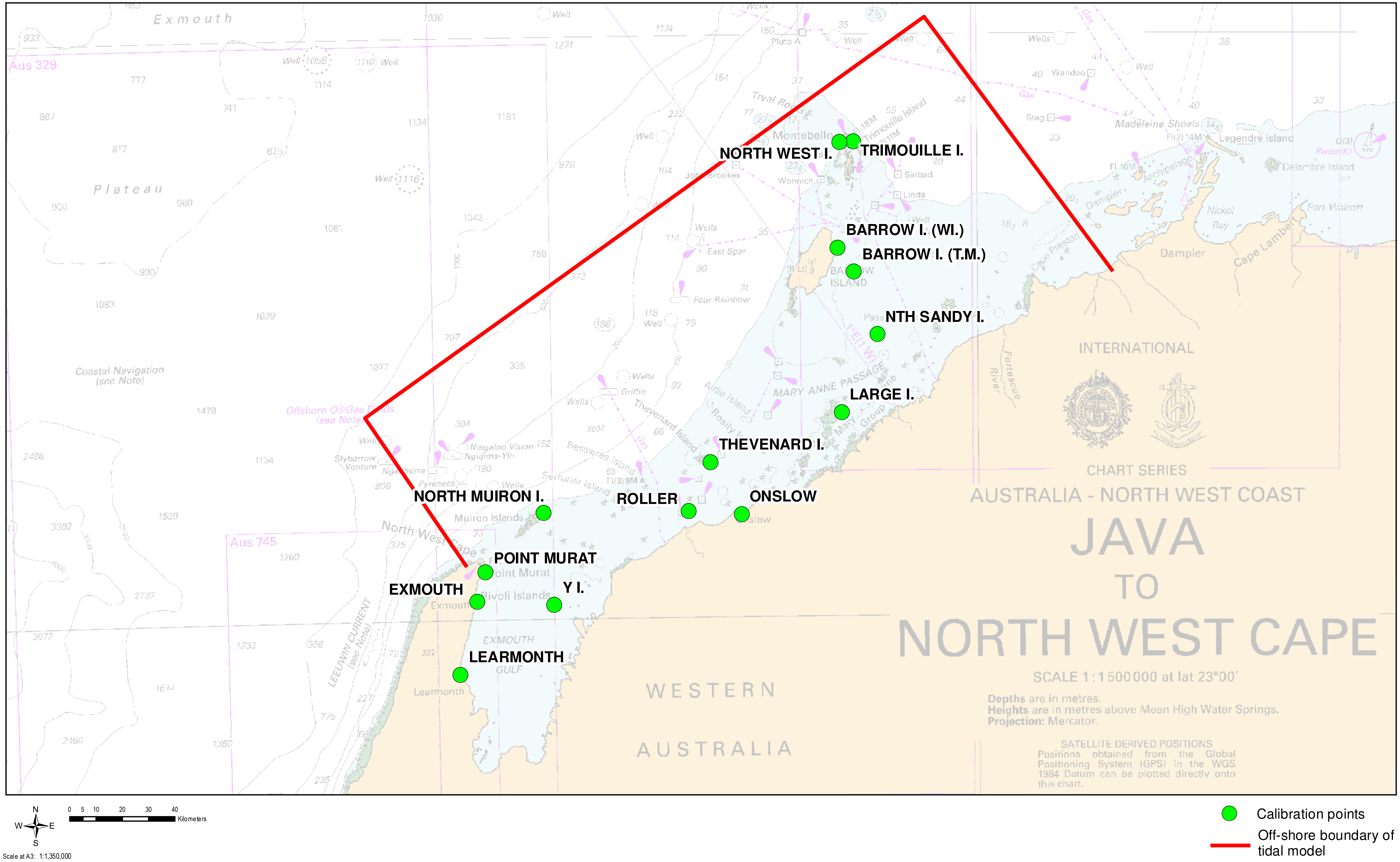
URS

DYNAMICS OF THE TIDAL ESTUARY

File No: 42908178_AV_003.mxd Drawn: AV Approved: IB Date: 28/11/2013

Figure: 6-1

Rev. A A3



Scale at A3: 1:1,350,000

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
NORM RISK ASSESSMENT AT QUICK MUD CREEK

TIDAL MODEL CALIBRATION POINTS

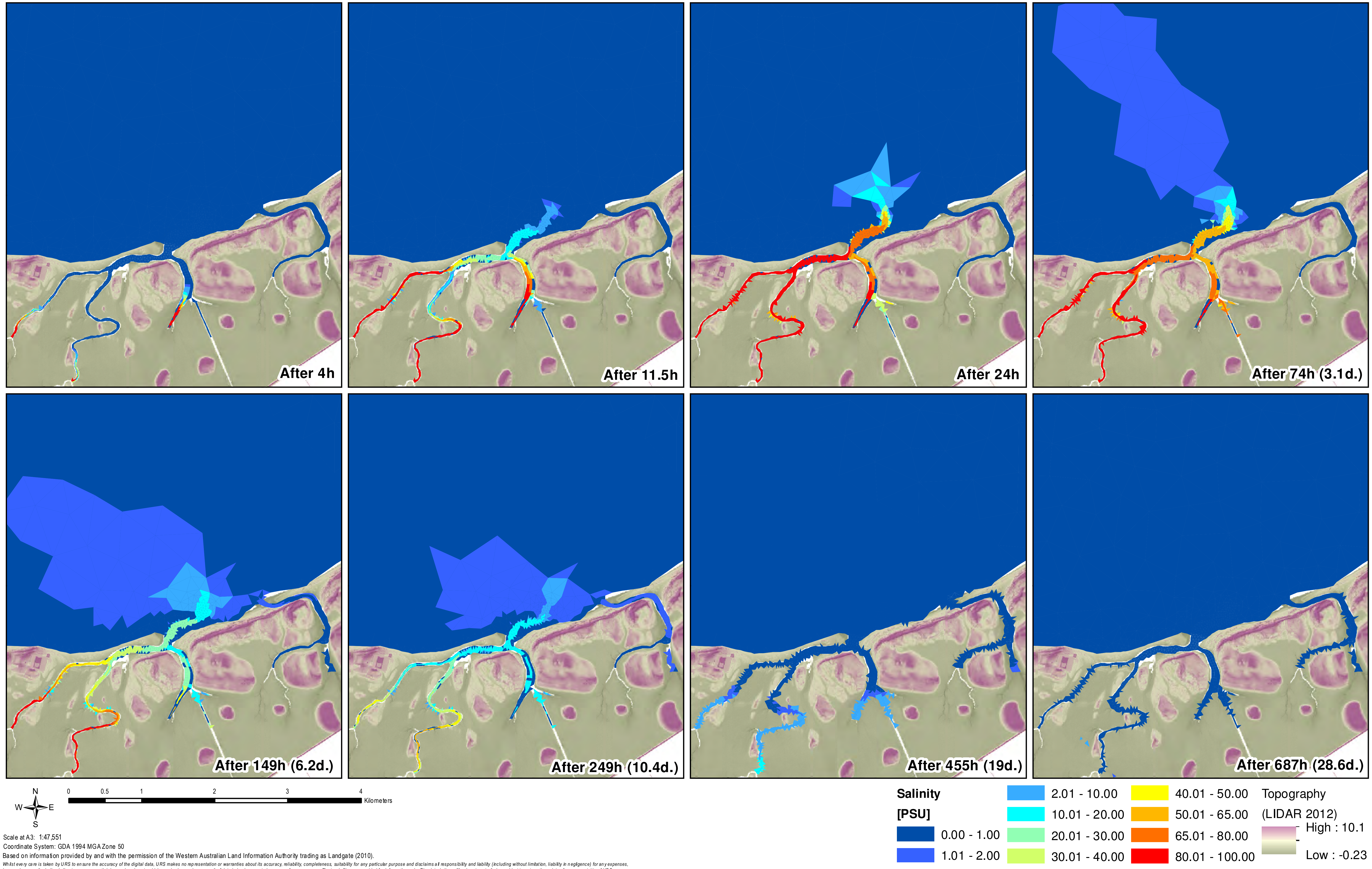
URS

DYNAMICS OF THE TIDAL ESTUARY

File No: 42908178-AV-005.mxd Drawn: AV Approved: IB Date: 28/11/2013

Figure: 6-2

Rev. A A3



Scale at A3: 1:47,551

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
NORM RISK ASSESSMENT AT QUICK MUD CREEK

SALINITY PLUME DISPERSION (SCENARIO AR01)

URS

DYNAMICS OF THE TIDAL ESTUARY

Figure: 6-3

File No: 42908178-AV-016.mxd | Drawn: AV | Approved: IB | Date: 28/11/2013 | Rev. A | A3

A

Appendix A Rainfall Analysis

Climate

Local Weather Stations

There are several Bureau of Meteorology (BoM) weather and rainfall stations in the vicinity of the Project area. These stations inform the local climate and are summarised in Table A-1.

Table A-1 Rainfall Stations in the Vicinity of the Project Area

Station Name	BoM Station	MGA 50 Co-ordinate System	
		Easting	Northing
Onslow Airport	005017	304,438	7,602,507
Onslow Township	005016	304,506	7,606,231
Minderoo	005013	297,658	7,565,976
Urala	005078	274,577	7,591,039
Ashburton North Weather Station	Chevron Property	292,997	7,598,823

A review of the rainfall record for the four rainfall stations in the area (Table A-1) has been undertaken. Plate A-1 shows the data availability for each of the BoM four stations. The data from Ashburton North has not been used because of its short period of record from 2010 to 2013.

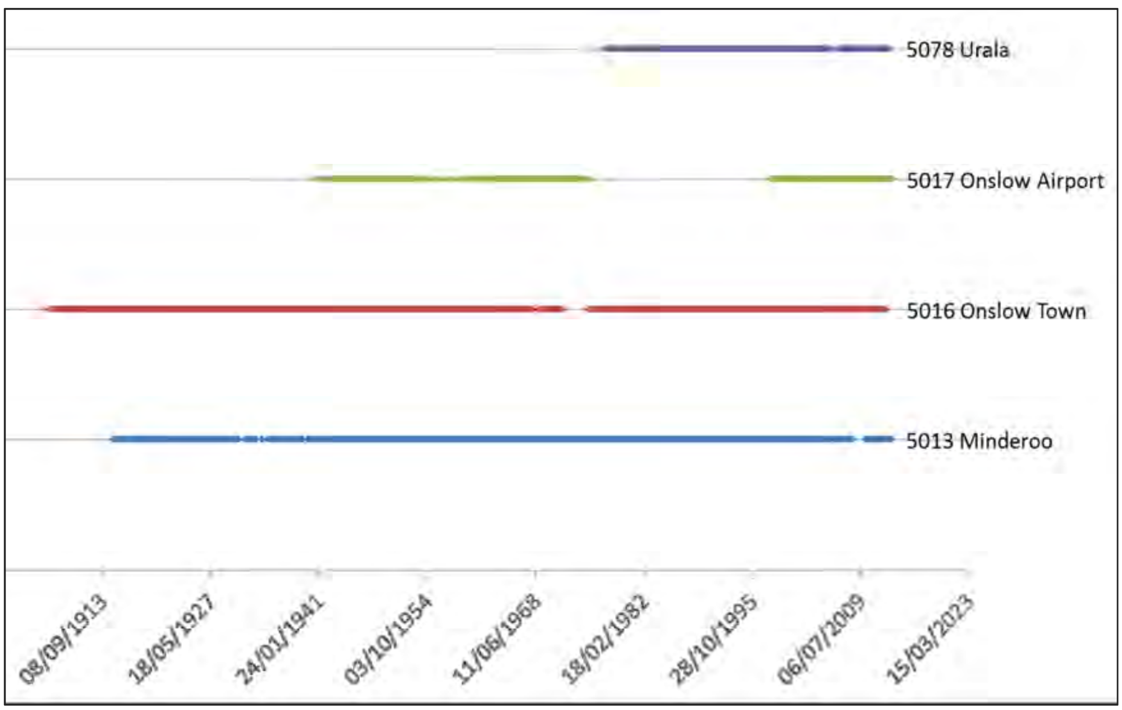


Plate A-1 Rainfall Data for Four BoM Stations in the Project Area Vicinity

A comparison of the daily rainfall data for Onslow Airport and Onslow Town (Plate A-2) shows that there is a reasonable correlation.

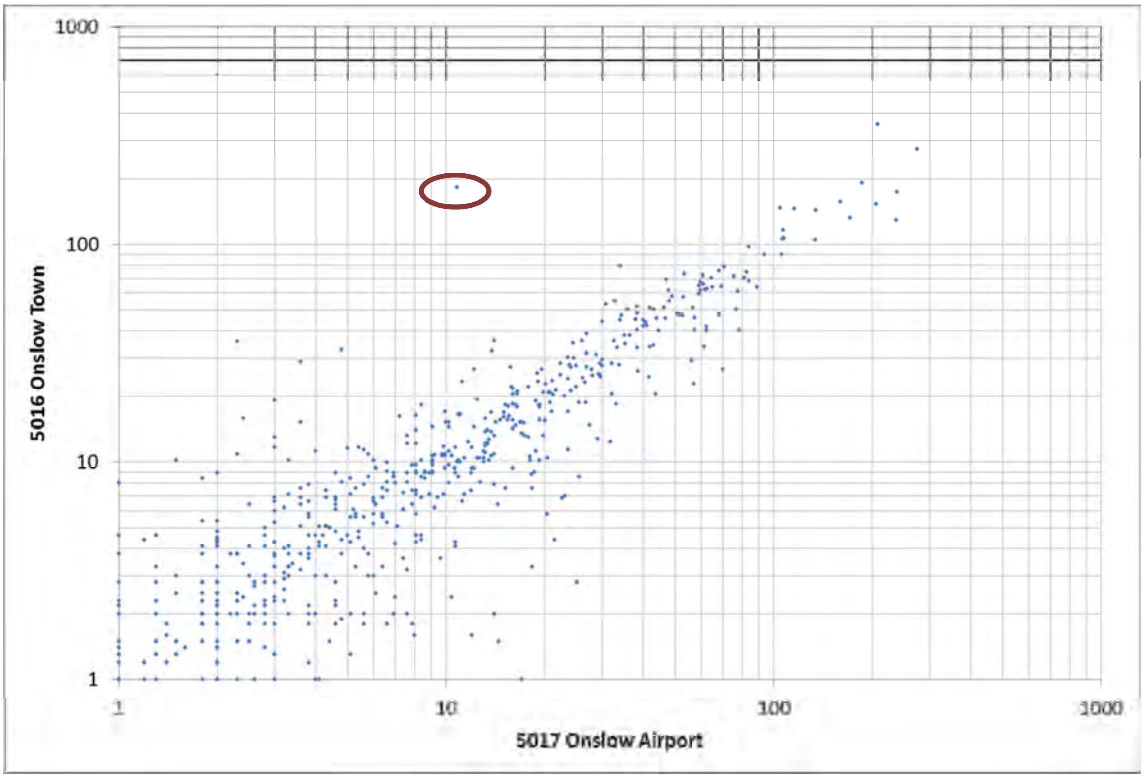


Plate A-2 Comparison of Onslow Town and Airport Daily Rainfall Data

A number the rainfall event depths of significant difference are evident and these have been examined. For example, events in February 1961 and another in March 2008 (circled in Plate A-2) have been and with tabulated as shown in Table A-2.

Table A-2 Daily Rainfall for Onslow Town and Airport for Two Different Rainfall Events

Rainfall Event 1			Rainfall Event 2		
Date	**Town**[1]	**Airport**[2]	**Date**	**Town**[1]	**Airport**[2]
09/02/1961	0.0	0.0	26/03/2008	0.0	73.4
10/02/1961	43.7	40.6	27/03/2008	0.0	95.4
11/02/1961	44.2	30.0	28/03/2008	182.7	10.8
12/02/1961	274.1	274.1	29/03/2008	22.0	15.8
13/02/1961	15.2	10.2	30/03/2008	3.0	2.8
14/02/1961	2.8	2.8	31/03/2008	1.9	0.6
15/02/1961	0.0	0.0	01/04/2008	9.0	18.6

Notes:
[1] Values are in mm from BoM station 005016.
[2] Values are in mm from BoM station 005017.

The March 2008 event provides contrast compared to the February 1961; the earlier event shows very similar daily rainfall data at both stations and the March 2008 event does not.

From the tabulated data it is apparent that a rainfall event may extend over several days. During 28th March 2008, the peak rainfall of 182.7 mm/day at the Town site occurs with no rain on the previous two days (BoM 005016). Conversely, the Airport Station (BoM 005017) had only 10.8 mm of rain on this day, but recorded 73.4 and 95.4 mm/day during the previous two days. This difference in the 24-hour rainfall depth over a relatively small area perhaps highlights variations in the frequency of recording of daily rainfall and that there may be significant spatial variations in rainfall depth within a single small catchment. These data do, however, provide a basis for understanding the rainfall within the Project area.

The data from both the Onslow Town Station and the Onslow Airport have been collated and assimilated to create a single database termed Onslow Station.

Drought in the Wider Catchment

The wider catchment is characterised by the rainfall records for Minderoo and Onslow. The analysis for Onslow was repeated with the revised condition of the critical rainfall occurring at both Minderoo and the combined Onslow Stations. This does mean that if the rainfall at one station is just under the threshold whilst the other station is over the threshold the event will not be considered to break the drought. This more stringent criteria is considered to be conservative and likely to result in more lengthy periods of drought. Additionally there are a few data gaps in the Minderoo data set that cannot be filled with other data, these are treated as zero rainfall and may artificially skew the data to longer periods of drought.

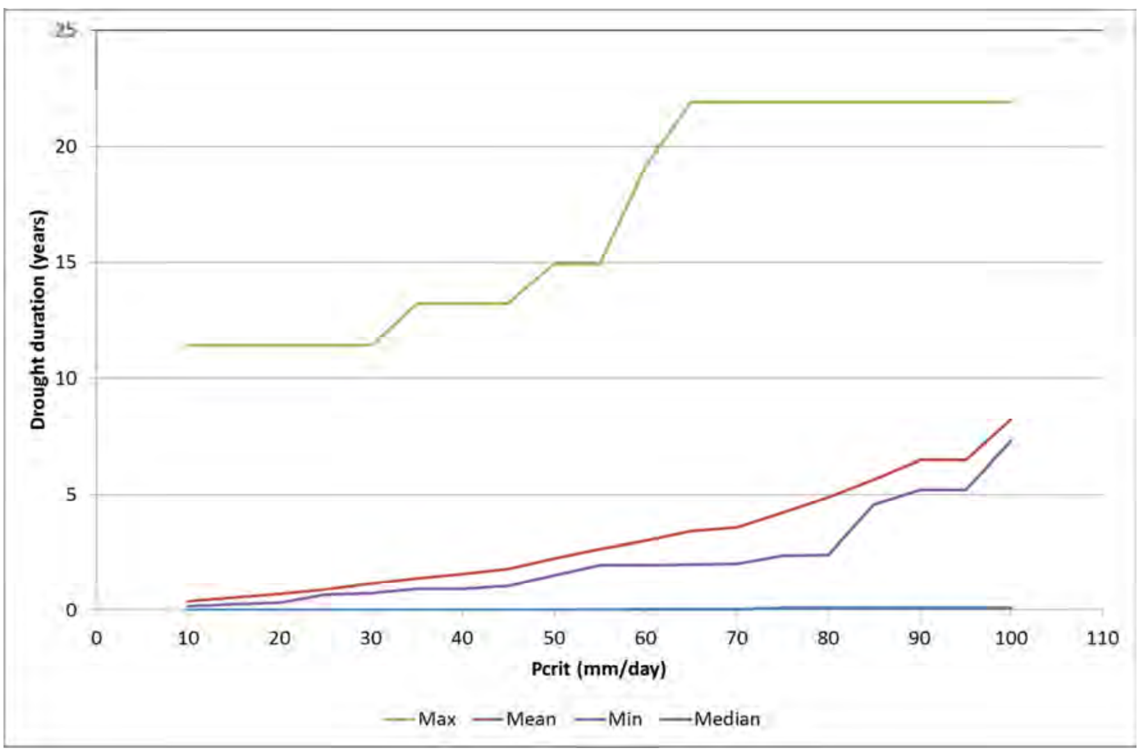


Chart A-1 Drought Duration (years) for Different Critical Rainfall Depths (mm/day) where a Drought is Broken if Rainfall at all Four Stations is Higher than the Critical Value

Wind Patterns

Onslow Town Wind Records

The Onslow Town station recorded wind in the period from January 1957 to July; there is a gap in the data record of approximately four years between October 1971 and March 1975. This effectively divides the data set in two periods shown in Table A-3.

Table A-3 Onslow Wind Data Record Periods

Period	P1	P2
Start Date	01/01/1957 09:00	01/03/1975 09:00
End Date	08/10/1971 09:00	19/07/2012 09:00

Throughout the dataset there are records at a nominal 3 hour interval from 09:00 to 21:00; however the consistency of the time of day that values are recorded is very poor. Additionally there appears to be a seasonal variation in the first and last readings of the day, possibly to tie in with daylight saving time or the working day. This is further complicated by the use of both local and 'standard time' to record the data. During daylight saving periods a mixture of local and standard time has been used.

Nonetheless a summary of the number of records by hour has been compiled from the data and is shown in Table A-4. This shows that for Period 1 there is a significant record for the times of 09:00 and 15:00; however for Period 2 all times apart from 21:00 have a significant record with 06:00, 09:00 and 15:00 having the highest returns.

Table A-4 Number of Wind Records by Hour for BoM Station 005016

Hour	00:00	03:00	06:00	09:00	12:00	15:00	18:00	21:00
Period 1	38%	33%	0%	100%	0%	100%	2%	0%
Period 2	72%	72%	93%	99%	75%	98%	76%	0%

To take these issues into account the data has been analysed as two separate periods and also for only the 09:00 and 15:00 data as two separate datasets. The resulting wind roses for the four data sets are shown below in Plate A-3. The wind rose for Period 1 09:00 shows clearly that the sector size of 22.5 degrees is possibly not appropriate. The data was reviewed and it was identified that the directions were generally recorded in 22.5 degree directions, corresponding to the 16 compass directions N, NNE, NE, ENE, E…NNW. However it appears that the eight directions of N, NE, E, SE…NW have also been used more often. This is most likely due to the manual recording of direction and the observers finding it easier to work to eight rather than 16 directions.

Wind speeds are rarely above 50 km/h and the average wind speed at 09:00 for Period 2 is 13.6 km/h and at 15:00 for Period 2 is 17.7 km/h.

The average wind speed by hour is presented in Chart A-2 and the average wind speed for all records is 19.5 km/h.

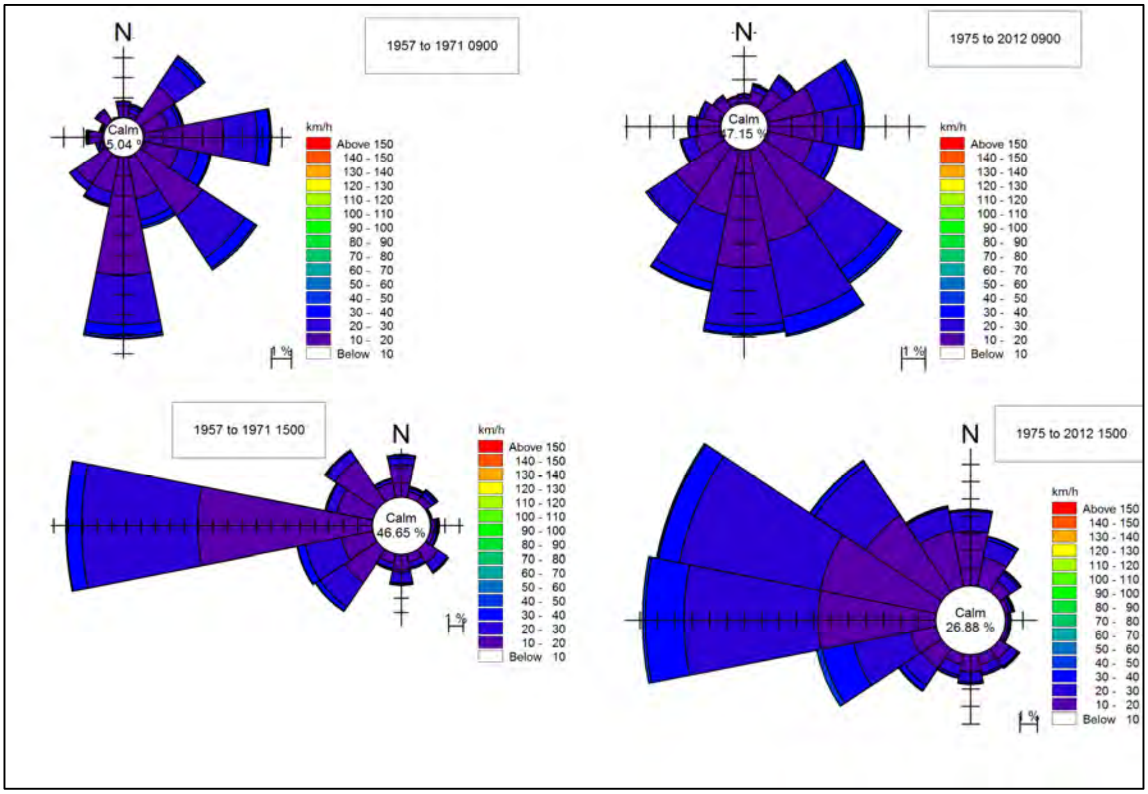


Plate A-3 Wind Roses for Onslow Town Weather Station (BoM 005016)

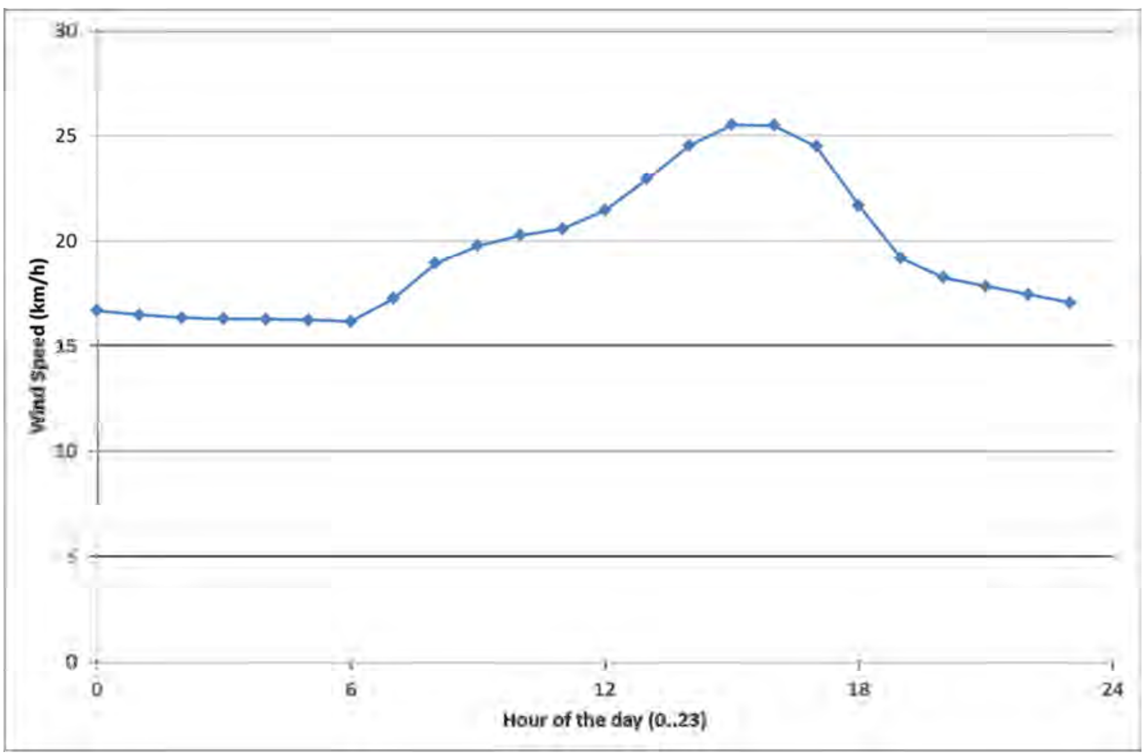


Chart A-2 Average Speed Wind at the Onslow Airport

Appendix B E052FG-S Geological Log

BORE COMPLETION REPORT

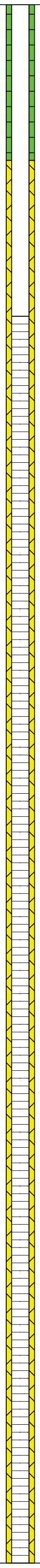
URS Australia Pty Ltd
Level 3, 20 Terrace Rd, East Perth WA, 6004
Phone: (08) 9326 0100
Fax: (08) 9326 0296

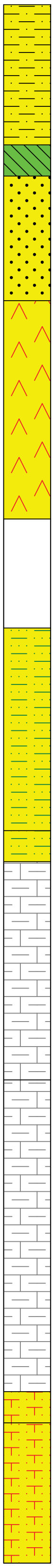
BOREHOLE **E052FG-S**

DESCRIPTION **Shallow Groundwater Monitoring Bore**

DRILLING COMPANY	**Hagstrom Drilling**
DRILLING METHOD	**Mud Rotary**
TOTAL DRILLED DEPTH	**5 m**
HOLE DIAMETER	**122 mm**
TOTAL CASED DEPTH	**5 m**
CASING DIAMETER	**65 mm ID**

PROJECT NAME	**Wheatstone Environmental Monitoring Bores**		
PROJECT NUMBER	**42907100**		
CLIENT	**Chevron Australia Pty Ltd**		
LOCATION	**E052**	EASTING	**300274 mE**
START DATE	**27/10/09**	NORTHING	**7590245 mN**
COMPLETION DATE	**27/10/09**	R.L. OF COLLAR	**3.840 m AHD**
LOGGED BY	**BS**		
SWL	**1.22 m bgl**		





BORE CONSTRUCTION	DEPTH (m)	DESCRIPTION	FIELD EC	AIRLIFT YIELD
Bentonite Seal (0 - 0.5 m)	0	SILTY SANDY CLAY: Low plasticity, red - brown.		
		CLAY: High plasticity, light grey, plant roots.		
75 mm OD, 65 mm ID Blank PN18 PVC casing (+0.21 - 1 m)		SAND: Silty clay. Compacted, red brown.		
	1	CLAYEY SILTY SAND: Fine, red - brown, more compacted and higher clay content, between 1.1 - 1.55. 1.55 - 1.65 is less compacted.		
		SAMPLE LOSS		
9.5 - 13.0 mm Graded Gravel Pack (0.5 - 5 m)	2	CLAYEY SAND: Fine, very soft, red - brown.	92.8 mS/cm	0.25 L/sec
		CLAYEY SAND: Fine, red - brown with gravel of sandstone (calcareous), subangular, poorly sorted, red - grey.		
	3	SILTY CLAYEY SAND: Red - brown with gravel of calcrete, sub- angular, poorly sorted, compacted.		
75 mm OD, 65 mm ID Slotted PN18 PVC casing (1 - 5.00 m)	4	SILTY CLAYEY SAND: Fine, compacted, red- brown.		
		SANDY SILTY CLAY: Fine, red - brown.		
EOH (5 m)	5	SANDY SILTY CLAY: Moderately plastic, red-brown.		

DRAWN BY **CE** DATE **6/11/09** CHECKED BY **DL** APPENDIX

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

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Western Australia 6109

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Quantitative X-Ray Diffraction Analysis

Report Prepared for:	Ludovic Sprauer Catherine Cockurn URS Australia ludovic.sprauer@urs.com catherine.cockburn@urs.com
Samples Received: Samples Analysed:	27-Mar-2013 08-Apr-2013
Written by: Date:	Dr Sharon Ness 09-Apr-2013
Intertek Genalysis Job No:	6.3/1304345

Intertek trading as Genalysis Laboratory Services Pty Ltd.
15 Davison Street Maddington WA 6109
ABN: 32 008 787 237

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www.intertek.com

Introduction

Four (4) samples were submitted for quantitative X-ray diffraction (XRD) phase analysis

Sampling and Preparation

The samples were received as wet powders. They were dried at 60^{o}C for approximately 12 hours.

The dried samples were each coned and quartered down to approximately 20 grams. A grab sample of this aliquot was then taken and micronised.

The micronised samples were then each prepared as an un-oriented powder mounts of the total sample.

A repeat grab was taken from the sample OSW5_Soil for a duplicate analysis

Instrumentation

The XRD patterns were produced on a PANalytical Cubix^{3} XRD fitted with Copper radiation (operating at 45 kV and 40 mA), scanning a range of 1.3^{o} to 65^{o}2θ. A graphite monochromator was used in the diffracted beam.

Qualitative analysis was performed with Bruker Diffrac.EVA 2.1 Search/Match software with the ICDD PDF-2 (2011) database.

Quantitative phase analysis was performed using SIROQUANT^{TM} Version 3 software.

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Results

The quantitative analysis of the crystalline phases of each sample is given in the following tables.

Sample ID **OSW5_Soil**

Phase	Formula	original wt%	duplicate wt%
Amphibole	e.g.(Na,Ca)2(Fe,Mg,Al)5(Si,Al)8O22(OH)2		<1
Bassanite	CaSO4.0.5H2O	11	11
Chlorite	(Fe,Al,Mg)6(Si,Al)4O10(OH)8	1	<1
Expanding clay		<1	<1
Goethite	FeO(OH)	2	1
Gypsum	CaSO4.2H2O	13	15
Hematite	Fe2O3	1	1
Illite/Muscovite	(K,Ca,Na)(Al,Mg,Fe)2(Si,Al)4O10(OH)2	19	16
Kaolin	Al2Si2O5(OH)4	5	5
Quartz	SiO2	14	14
Sodium Chloride	NaCl	34	37

Sample ID **OSW7_Soil**

Phase	Formula	wt%
Amphibole	e.g.(Na,Ca)2(Fe,Mg,Al)5(Si,Al)8O22(OH)2	3
Chlorite	(Fe,Al,Mg)6(Si,Al)4O10(OH)8	6
Goethite	FeO(OH)	2
Gypsum	CaSO4.2H2O	4
Hematite	Fe2O3	1
Illite/Muscovite	(K,Ca,Na)(Al,Mg,Fe)2(Si,Al)4O10(OH)2	24
Kaolin	Al2Si2O5(OH)4	9
Quartz	SiO2	32
Sodium Chloride	NaCl	20

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Sample ID **OSW8_Soil**

Phase	Formula	wt%
Amphibole	e.g.(Na,Ca)2(Fe,Mg,Al)5(Si,Al)8O22(OH)2	1
Bassanite	CaSO4.0.5H2O	2
Chlorite	(Fe,Al,Mg)6(Si,Al)4O10(OH)8	2
Goethite	FeO(OH)	1
Gypsum	CaSO4.2H2O	8
Hematite	Fe2O3	2
Illite/Muscovite	(K,Ca,Na)(Al,Mg,Fe)2(Si,Al)4O10(OH)2	33
Kaolin	Al2Si2O5(OH)4	11
Palygorskite	Mg5(Si4O10)2(OH)2(H2O)8	1
Quartz	SiO2	18
Sodium Chloride	NaCl	20

Sample ID **OSWS_Salt Crust**

Phase	Formula	wt%
Amphibole	e.g.(Na,Ca)2(Fe,Mg,Al)5(Si,Al)8O22(OH)2	1
Cristobalite (poorly crystalline)	SiO2	2
Gypsum	CaSO4.2H2O	1
Quartz	SiO2	1
Sodium Chloride	NaCl	96

Calculation of the phase abundances have been based on the Brindley contrast corrections using a particle diameter of 4 μm.

Uncertainty in the SIROQUANT™ analyses should reflect errors (absolute) of no greater than: +/- 10% for phases 50-95%, +/- 5% for phases 10-50% and +/- 2% for phases 3-10%. Phases of < 3% are approaching detection limit and normally no refinements are made on these.

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Quality Control

NIST Standard Reference Material 656

The standard reference material is a powder which consists of sub-micrometer, equi-axial, non-aggregated grains that do not display the effects of absorption contrast, extinction or preferred orientation.

An aliquot of this was prepared as un-oriented powder mount of the total sample and analysed with SIROQUANT™. The results are as follows:

Sample ID **β 656 (High β Phase Powder)**

		result	std dev	SRM certified	SRM uncert
Phase	**Formula**	**wt%**	**wt%**	**wt%**	**wt%**
Amorphous content		8.8	0.1	8.6	0.81
Si3N4, alpha	SiN4	16.3	0.6	16.3	2.54
Si3N4, beta	SiN4	74.9	0.4	75.1	0.60

Each interval defined by the certified value and its uncertainty is a 95% confidence interval for the true value of the mean in the absence of systematic error.

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Discussion

General

Quantification of the crystalline mineral phases was performed with the SIROQUANT™ software package. This software uses the full-profile Rietveld method of refining the profile of the calculated XRD pattern against the profile of the measured XRD pattern. The total calculated pattern is the sum of the calculated patterns of the individual phases.

Results are given as weight % of the total crystalline phases. **No determination for amorphous content was undertaken**.

Corrections are incorporated the process that allows for a more accurate description of the mineral's contribution to the measured pattern and to allow for variation due to atomic substitution, layer disordering, preferred orientation, and other factors that affect the acquisition of the XRD scan.

The limitations of qualitative XRD analysis are as follows:

1. There is a limit of detection of 1-2% on most crystalline phases.
2. The detection of a phase may be dependent on its crystallinity..
3. Where there exist multiple phases, overlap of diffracted reflections can occur, thus rendering some ambiguity into the interpretation.
4. Some phases cannot be unambiguously identified as they are present in minor or trace amounts.

The limitations of quantitative XRD analysis by a full-profile Rietveld method are as follows:

1. The limitations for qualitative XRD analysis apply
2. The method as described is standardless: it relies solely on the published crystallographic data available for each phase. Some data may not exactly describe the phases present.
3. Particle size is important with respect to the absorption of the X-rays by the sample. Hand grinding will usually produce a particle size of ≤10 µm which is, in most cases, sufficient to minimize absorption contrast effects. However, this particle size may not be sufficient to minimize the absorption contrast effect if the samples contain a significant amount of iron-bearing phases. This is because the absorption contrast between them and other lower absorber phases is the most severe when analysed with Copper radiation. Micronising reduces the particle size to that more suitable for analysis with this radiation.

The accuracy of the analysis is dependent on sampling and sample preparation in addition to the calculated profiles being exactly representative of the chemistry of the component phases and their crystallinity. Some preferred orientation effects and reflection overlaps may occur which cannot be adequately resolved.

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Western Radiation Services
analytical laboratory & consulting
ABN 64 135 436 092

1 March 2013

Ludovic Sprauer
URS
Level 4, 226 Adelaide Terrace
PERTH WA 6000

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REVISED QUOTATION

We are pleased to provide the following revisesd quotation, based on your telephone/email enquiry of 1 March 2013 for the analysis of five water and five solid samples.

Western Radiation Services will conduct radiometric analysis of samples, as presented to us, using NATA accredited procedures. In some instances, work will be sub-contracted out to approved laboratories.

Description of analysis (liquids)	**Rate/sample**
Gross Alpha Beta by Liquid Scintillation Counting	$130.00
Potassium Correction - outsourced	$ 35.00
Radium-226 & Radium-228 by Gamma Spectrometry	$320.00
Thorium-228 & Lead-210 by Gamma Spectrometry	$150.00
Uranium-234, Uranium-238 & Thorium-232 by ICPMS	$100.00
Total Uranium & Total Thorium by Calculation	$ 70.00
One litre preserved bottles	$ 7.00ea
One litre non preserved bottles	$ 6.00
Sample Disposal (per sample)	$ 1.00

Please note all prices are GST and freight excluded.

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MDL: (liquids)

Gross Alpha – LSC	0.060 Bq/l	Gross Beta - LSC	0.135 Bq/l
Radium-226	0.100 Bq/l	Radium-228	0.100 Bq/l
Thorium-228	0.100 Bq/l	Lead-210	0.100 Bq/l
Uranium-234	1 ug/l	Uranium-238	1 ug/l
Thorium-232	1 ug/l		

Method: (liquids)

LTP No. 16	Liquid Scintillation Counting
LTP No. 4(a)	Gamma Spectrometry Analysis
ICPMS	Inductively Coupled Plasma Mass Spectrometry

Turnaround time for analysis:

The estimated turnaround time for Gross Alpha Beta (both methods) is one to two weeks, TAT for Gamma Spectrometry, on liquid samples, is four weeks from receipt of samples.

Requirements:

Two litres of sample is required for the above analysis. One litre should be contained in a preserved bottle, the other in a non preserved bottle. A purchase order is required prior to commencement of analysis.

Description of analysis (solids)	**Rate/sample**
Radium-226 & Radium-228 by Gamma Spectrometry	$320.00
Thorium-228 & Lead-210 by Gamma Spectrometry	$150.00
Lead-212 & Lead-214 by Gamma Spectrometry	$150.00
Bismuth-212 & Bismuth-214 by Gamma Spectromety	$150.00
Thallium-208 & Americium-241 by Gamma Spectrometry	$150.00
Potassium-40 by Gamma Spectrometry	$150.00
Uranium-234, Uranium-238 & Thorium-232 by ICPMS including digest	$100.00
Total Uranium & Total Thorium calculations	$ 70.00
Plastic sample containers	$ 6.00ea
Sample Preparation	$ 55.00
Sample Disposal (per sample)	$ 1.00

MDL: (solids)

Radium -226	0.03 Bq/g	Radium-228	0.03 Bq/g
Thorium-228	0.03 Bq/g	Lead-210	0.03 Bq/g
Lead-212	0.03 Bq/g	Lead-214	0.03 Bq/g
Bismuth-212	0.03 Bq/g	Bismuth-214	0.03 Bq/g
Thallium-208	0.03 Bq/g	Americium-241	0.03 Bq/g
Potassium-40	0.03 Bq/g	Uranium-234	1 ug/l
Uranium-238	1 ug/l	Thorium-232	1 ug/l

U-234, U-238 & Th-232 by ICPMS will be acid digested to perform this analysis.

Method: (solids)

LTP No. 4(a)	Gamma Spectrometry Analysis
ICPMS	Inductively Coupled Plasma Mass Spectrometry

Turnaround Time for analysis

Turnaround time for solid samples is two weeks from receipt of sample.

Requirements

The amount required for the above above analysis is 100gms of dried and pulverised sample, if not in this form the quoted sample prep charges applies.

If you have any questions or require further clarification, please contact us by e-mail at admin@westernradiation.com.au or by telephone (08) 9470 3000.

Kindest Regards,

TeresaMesch

Teresa Mesch
Sales Consultant

Western Radiation Services
analytical laboratory & consulting
ABN 64 135 436 092

Accredited Laboratory
No: 14174

30 August 2013

Ref: 7561
Order No: 42908272

URS Australia (Perth Office)
Level 4, 226 Adelaide Terrace
PERTH WA 6000

Attention: Ludovic Sprauer

ANALYTICAL REPORT

The results (to 95%, 2σ confidence level) for Radium-226 and Radium-228 analyses of one (1) liquid sample, as received at our laboratory on 5 August 2013, are detailed below.

WRS No	Client Sample ID	Ra-226 (Bq/l)	Ra-228 (Bq/l)
7561-1	OSW5	<MDL	<MDL

MDL: Radium-226 0.100 Bq/l Radium-228 0.100 Bq/l

Method: LTP No. 4(a) Gamma Spectrometry Analysis

The reported expanded uncertainty of measurement is stated as the standard uncertainty of the measurement ± 5.6 %, multiplied by the coverage factor k=2, which corresponds to a coverage probability of approximately 95%.

Madassar A. Qureshi
Authorised Signatory

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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

						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)	SO_4^-	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

Western Radiation Services
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ABN 64 135 436 092

NATA
Accredited Laboratory
No: 14174

9 July 2013

URS Australia (Perth Office)
Level 4, 226 Adelaide Terrace
PERTH WA 6000

Attn: Ludovic Sprauer

ANALYTICAL REPORT

The results (to 95%, 2σ confidence level) for Gross Alpha/Beta, Radium 226 and 228, Thorium-228, Lead-210, Uranium 235 & 238, Thorium 232, total calculation of Uranium and Thorium analyses of two (2) liquid samples, three (3) solid samples and one (1) salt crust sample, as received at our laboratory on 25 March 2013, are detailed on page two to four of this report.

Liquid Samples MDL:

Radium-226	100 mBq/l	Radium-228	100 mBq/l
Thorium-228	100 mBq/l	Lead-210	100 mBq/l
Alpha	60 mBq/l	Beta	135 mBq/l
Uranium-238	0.1 µg/l	Uranium-235	0.1 µg/l
Thorium- 232	0.1 µg/l		

Solid Samples MDL:

Radium-226	30 mBq/g	Radium-228	30 mBq/g
Thorium-228	30 mBq/g	Thalium-208	30 mBq/g
Bismuth-212	30 mBq/g	Bismuth-214	30 mBq/g
Lead-210	30 mBq/g	Lead-212	30 mBq/g
Lead-214	30 mBq/g	Potassium-40	30 mBq/g
Alpha	60 mBq/g	Beta	135 mBq/g
Uranium-238	0.1 µg/g	Uranium-235	0.1 µg/g
Thorium-232	0.1 µg/g		

Method: LTP No. 4(a) Gamma Spectrometry Analysis
LTP No. 16 Liquid Scintillation Counting

Madassar A. Qureshi
Authorised Signatory

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Liquid Samples

Gamma Spectrometry

WRS No.	Sample Client ID	Ra-226 (mBq/L)	Ra-228 (mBq/L)	Th-228 (mBq/L)	Pb-210 (mBq/L)
7347-1	EO52FG-S 18/3/13 11:20-LIQUID	<MDL	<MDL	<MDL	<MDL
7347-2	OSW5-S 18/3/13 14:00-LIQUID	<MDL	<MDL	<MDL	<MDL

The reported expanded uncertainty of measurement is stated as the standard uncertainty of the measurement ± 5.6 %, multiplied by the coverage factor k=2, which corresponds to a coverage probability of approximately 95%.

Liquid Scintillation Counting

WRS No.	Client Sample ID	Alpha (mBq/l)	Beta (mBq/l)	K (mg/l)
7347-1	EO52FG-S 18/3/13 11:20-LIQUID	<MDL	<MDL	6500
7347-2	OSW5-S 18/3/13 14:00-LIQUID	<MDL	<MDL	550

The reported expanded uncertainty of measurement is stated as the standard uncertainty of the measurement ± 7.5 %, multiplied by the coverage factor k=2, which corresponds to a coverage probability of approximately 95%.

Uranium and Thorium by Calculations from ICPMS Data

WRS No.	Client Sample ID	Total Uranium (mBq/l)	Total Thorium (mBq/l)
7347-1	EO52FG-S 18/3/13 11:20-LIQUID	<MDL	<MDL
7347-2	OSW5-S 18/3/13 14:00-LIQUID	<MDL	<MDL

Solid Samples

Gamma Spectrometry

WRS No.	Sample Client ID	Ra-226 (mBq/g)	Ra-228 (mBq/g)	Th-228 (mBq/g)
7347-3	OSW5 18/3/13 14:00-SOLID	<MDL	<MDL	<MDL
7347-4	OSW5 18/3/13 14:00-SALT CRUST	<MDL	<MDL	<MDL
7347-5	OSW7 18/3/13 15:20-SOLID	<MDL	31.6 ± 4.5	35.4 ± 4.2
7347-6	OSW8 18/3/13 15:40-SOLID	<MDL	45.2 ± 5.7	40.0 ± 4.5

WRS No.	Sample Client ID	Bi-212 (mBq/g)	Bi-214 (mBq/g)	Tl-208 (mBq/g)
7347-3	OSW5 18/3/13 14:00-SOLID	<MDL	<MDL	<MDL
7347-4	OSW5 18/3/13 14:00-SALT CRUST	<MDL	<MDL	<MDL
7347-5	OSW7 18/3/13 15:20-SOLID	39.2 ± 19.8	<MDL	35.4 ± 4.2
7347-6	OSW8 18/3/13 15:40-SOLID	<MDL	<MDL	40.0 ± 4.5

WRS No.	Sample Client ID	K-40 (mBq/g)	Pb-210 (mBq/g)
7347-3	OSW5 18/3/13 14:00-SOLID	273 ± 25	<MDL
7347-4	OSW5 18/3/13 14:00-SALT CRUST	34.4 ± 5.2	<MDL
7347-5	OSW7 18/3/13 15:20-SOLID	430 ± 36	<MDL
7347-6	OSW8 18/3/13 15:40-SOLID	495 ± 41	<MDL

WRS No.	Sample Client ID	Pb-212 (mBq/g)	Pb-214 (mBq/g)
7347-3	OSW5 18/3/13 14:00-SOLID	<MDL	<MDL
7347-4	OSW5 18/3/13 14:00-SALT CRUST	<MDL	<MDL
7347-5	OSW7 18/3/13 15:20-SOLID	32.8 ± 2.7	<MDL
7347-6	OSW8 18/3/13 15:40-SOLID	40.3 ± 3.2	32.3 ± 3.9

The reported expanded uncertainty of measurement is stated as the standard uncertainty of the measurement ± 5.6 %, multiplied by the coverage factor k=2, which corresponds to a coverage probability of approximately 95%.

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Liquid Scintillation Counting

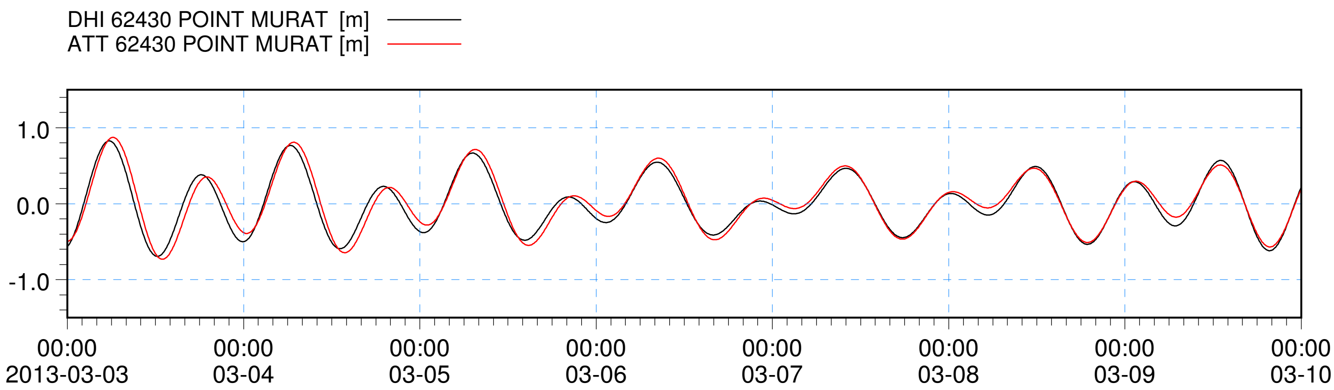
WRS No.	Client Sample ID	Alpha (mBq/g)	Beta (mBq/g)
7347-3	OSW5 18/3/13 14:00-SOLID	<MDL	<MDL
7347-4	OSW5 18/3/13 14:00-SALT CRUST	<MDL	<MDL
7347-5	OSW7 18/3/13 15:20-SOLID	<MDL	<MDL
7347-6	OSW8 18/3/13 15:40-SOLID	<MDL	<MDL

The reported expanded uncertainty of measurement is stated as the standard uncertainty of the measurement ± 7.5 %, multiplied by the coverage factor k=2, which corresponds to a coverage probability of approximately 95%.

Uranium and Thorium by Calculations from ICPMS Data

WRS No.	Client Sample ID	Total Uranium (mBq/g)	Total Thorium (mBq/g)
7347-3	OSW5 18/3/13 14:00-SOLID	39	57
7347-4	OSW5 18/3/13 14:00-SALT CRUST	77	94
7347-5	OSW7 18/3/13 15:20-SOLID	77	103
7347-6	OSW8 18/3/13 15:40-SOLID	13	4

Appendix D MIKE21HD(FM) Calibration Data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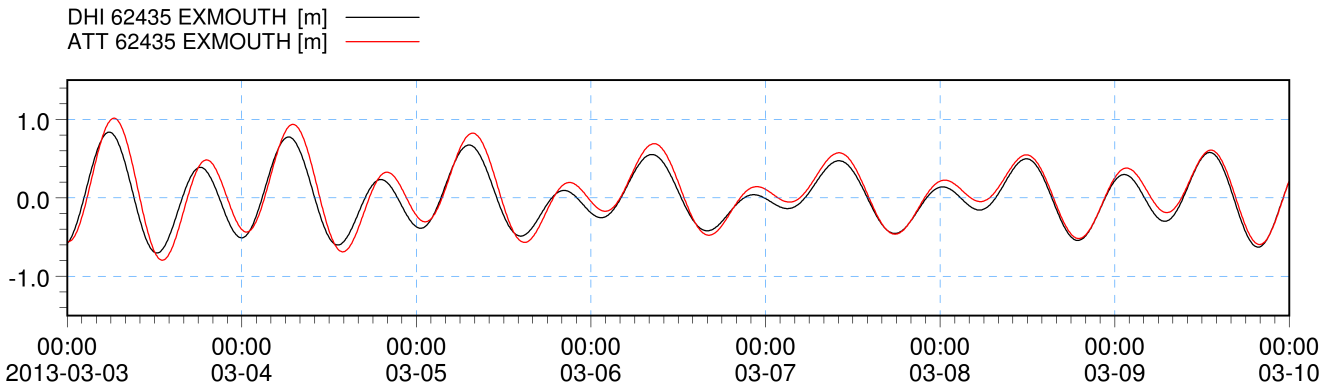
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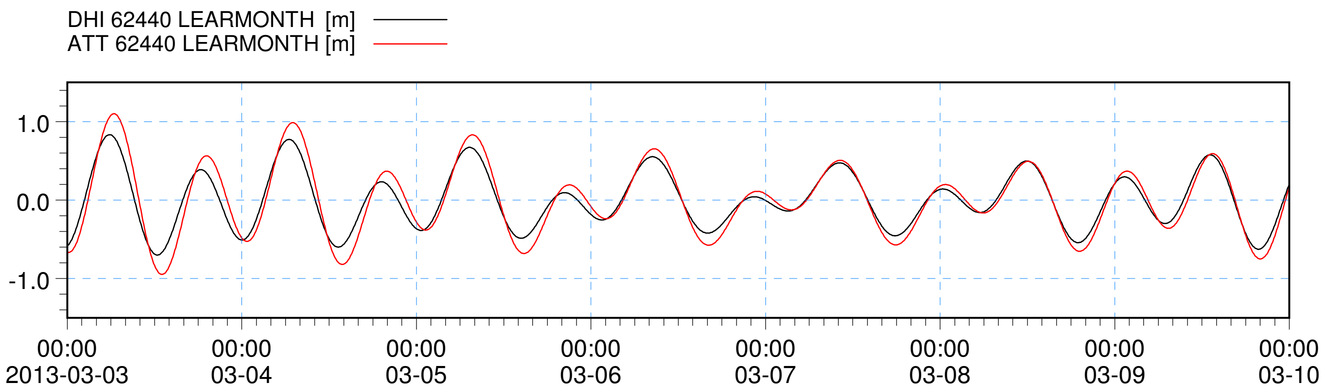
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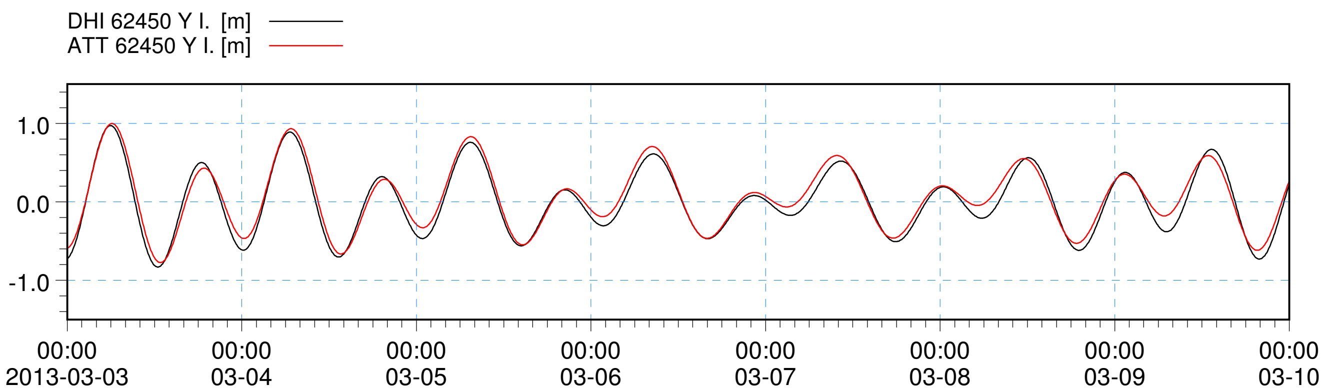
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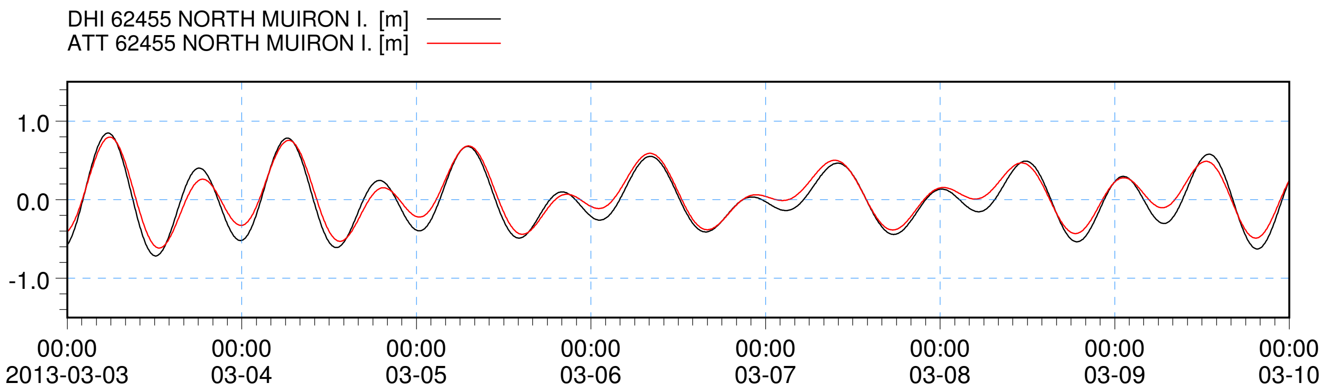
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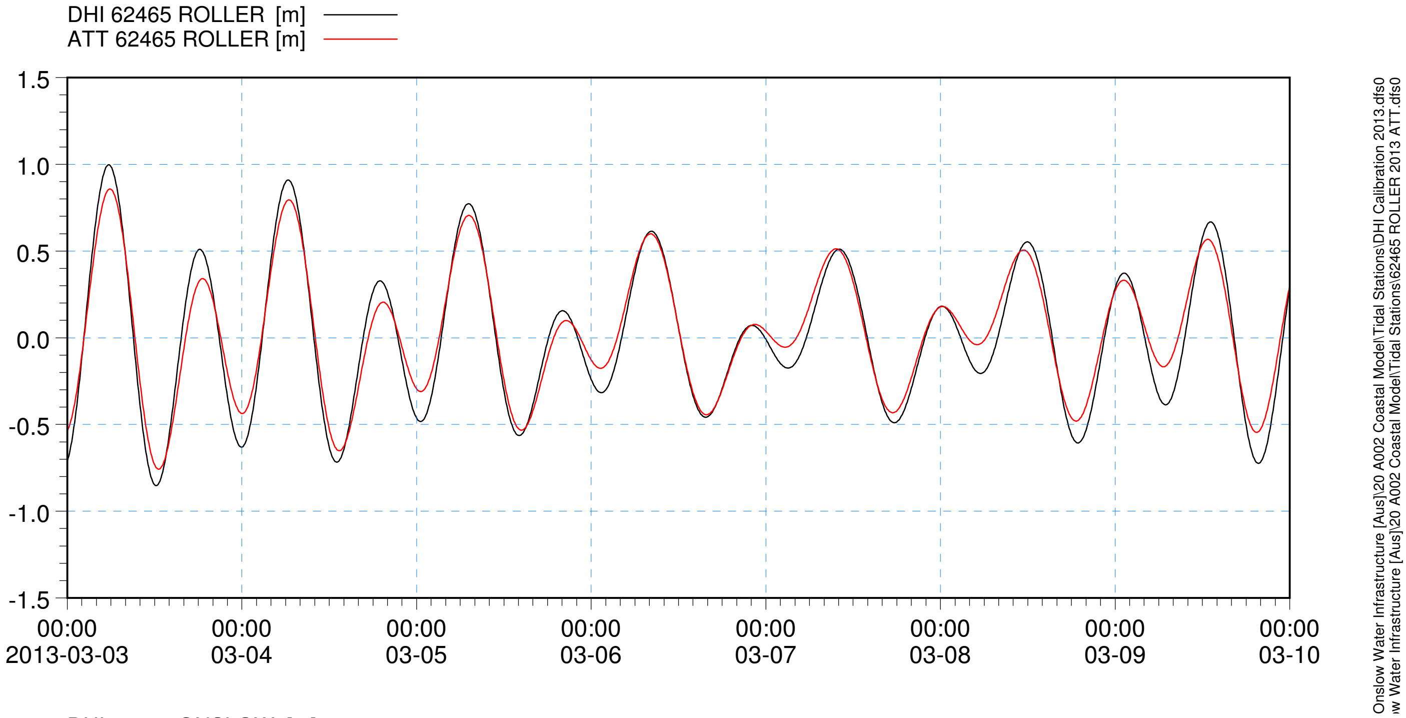
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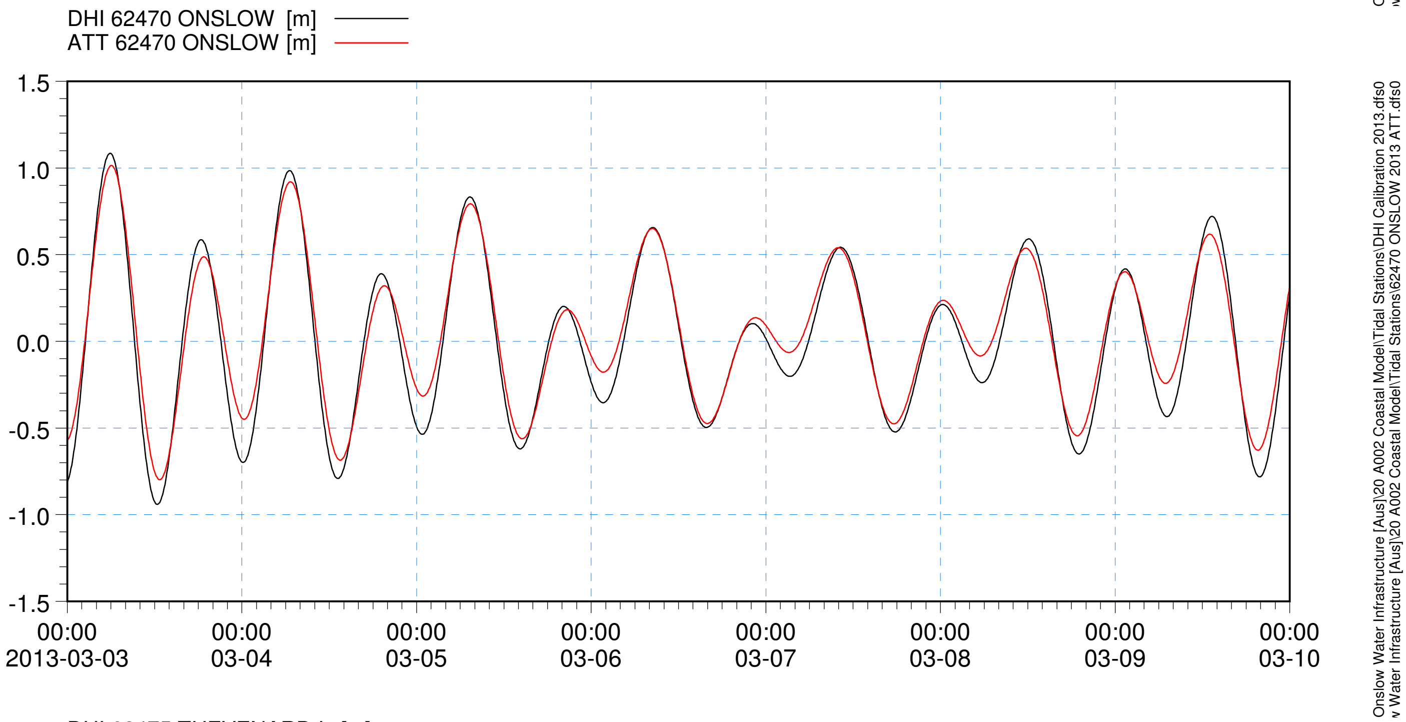
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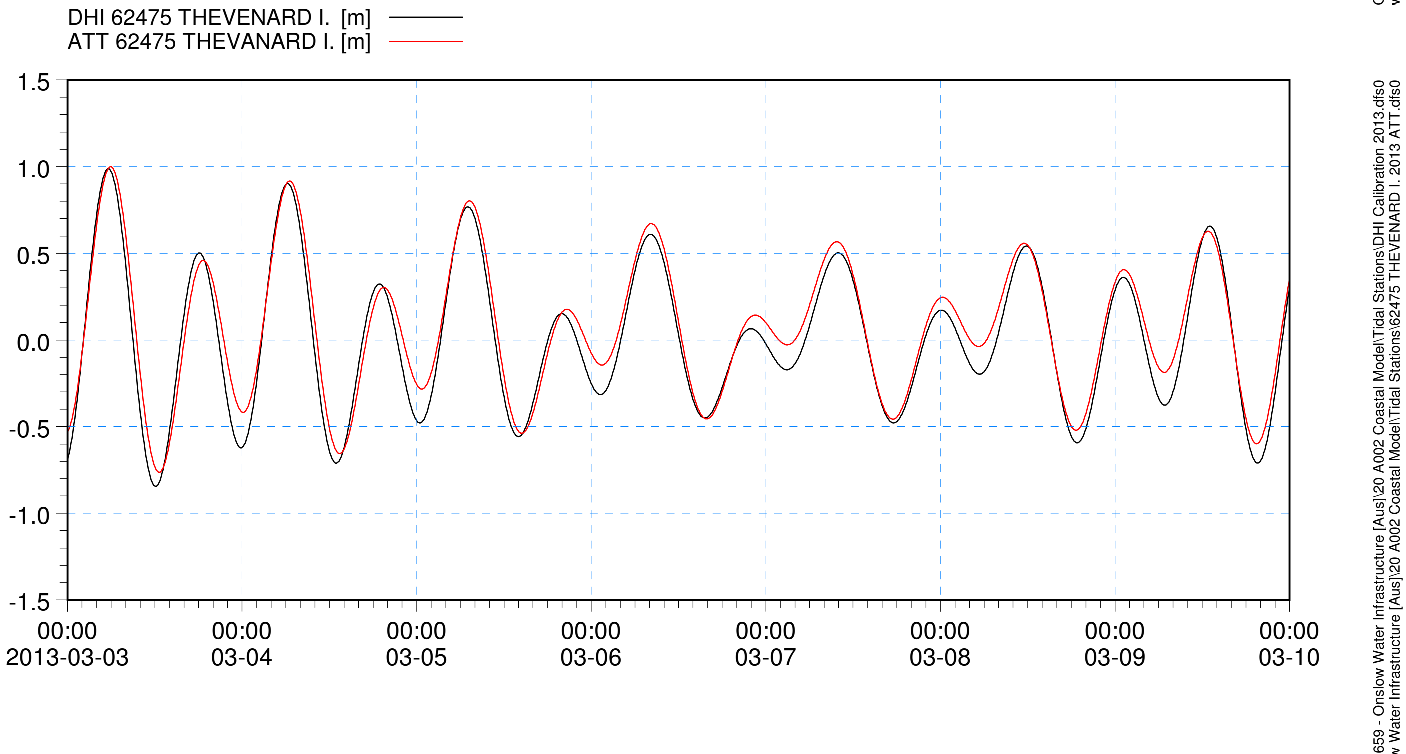
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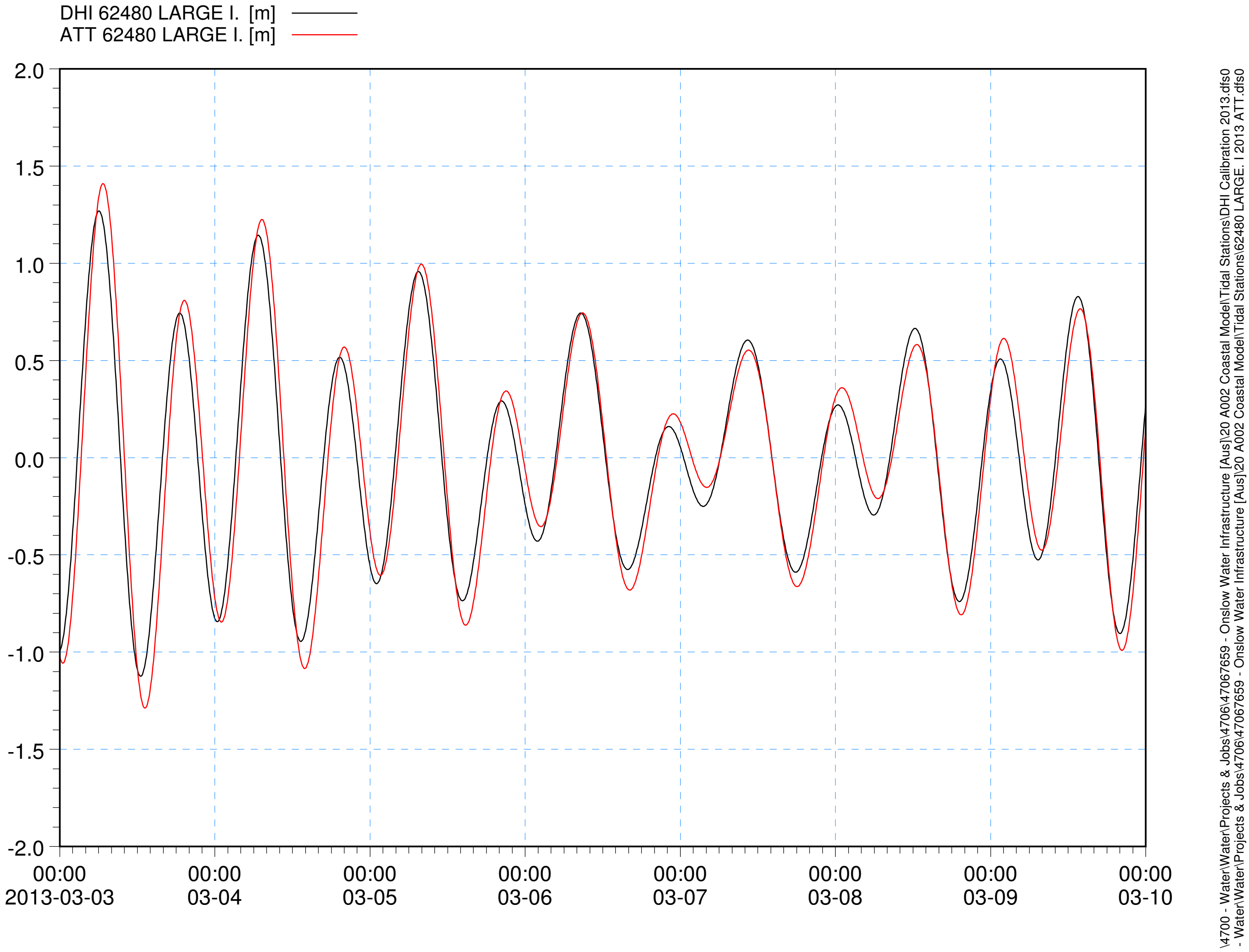
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00:00 03-07
00:00 03-08
00:00 03-09
00:00 03-10
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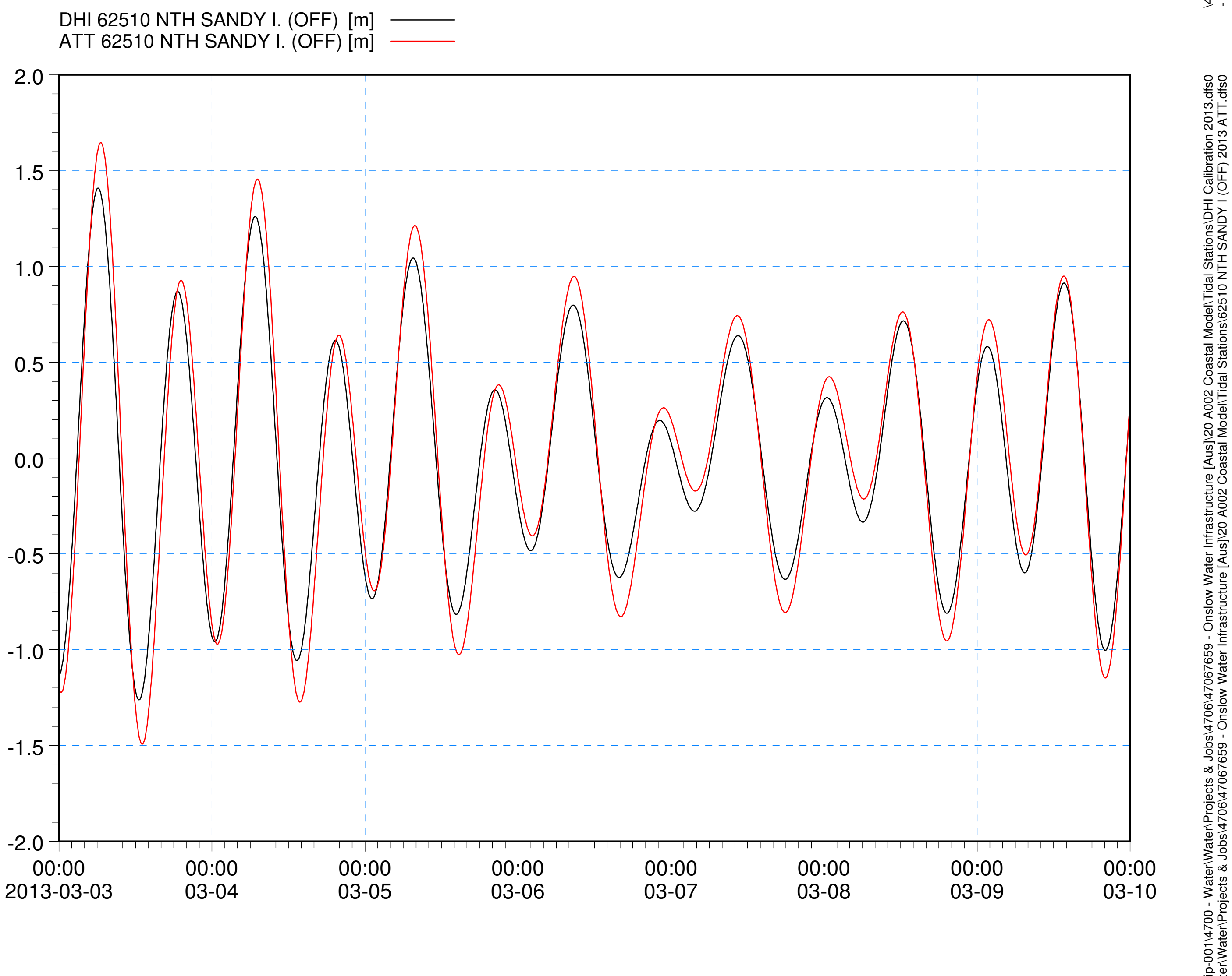
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00:00 03-04
00:00 03-05
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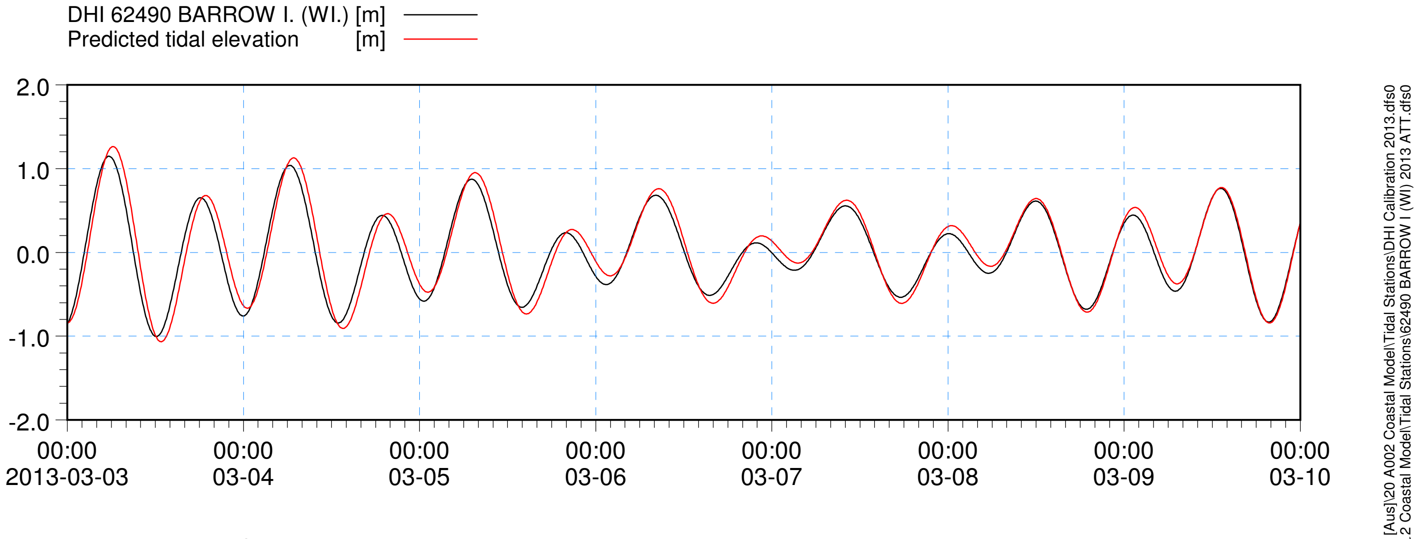
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03-04
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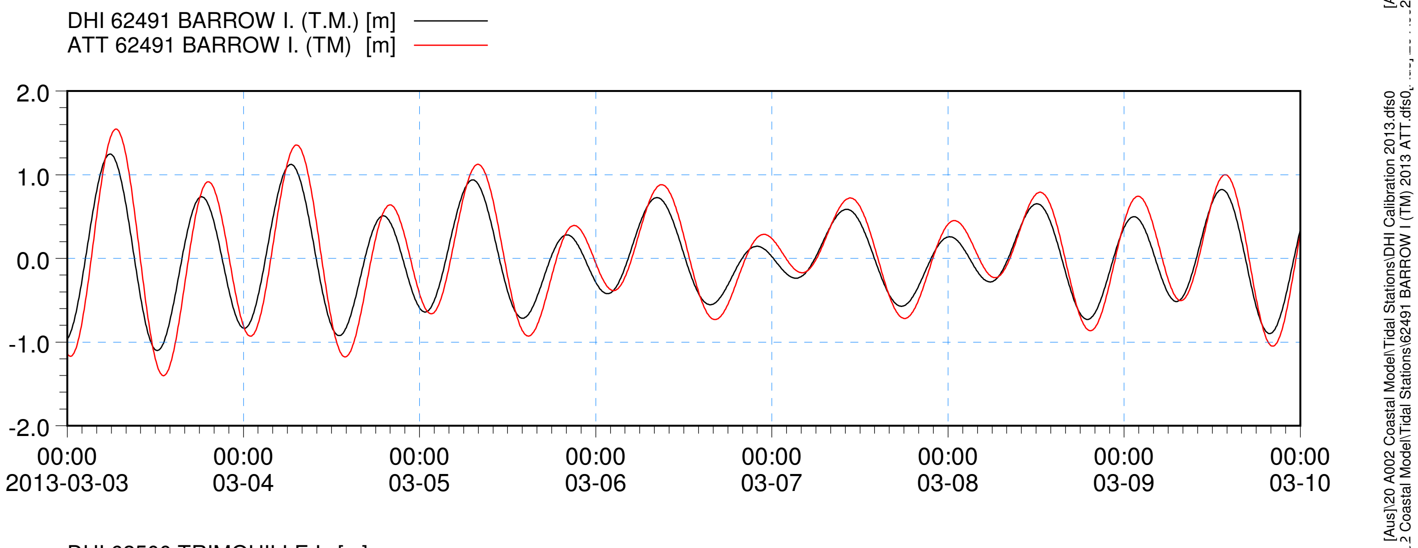
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2013-03-03
00:00
03-04
00:00
03-05
00:00
03-06
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03-07
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03-09
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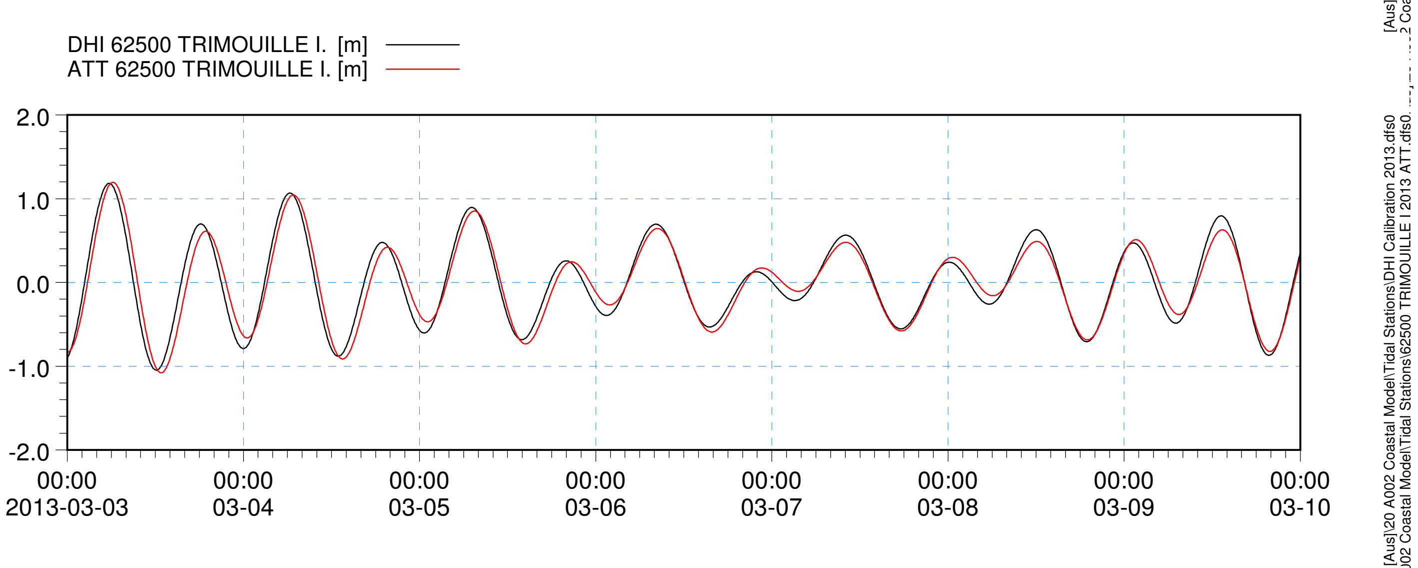
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2013-03-03
00:00
03-04
00:00
03-05
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03-08
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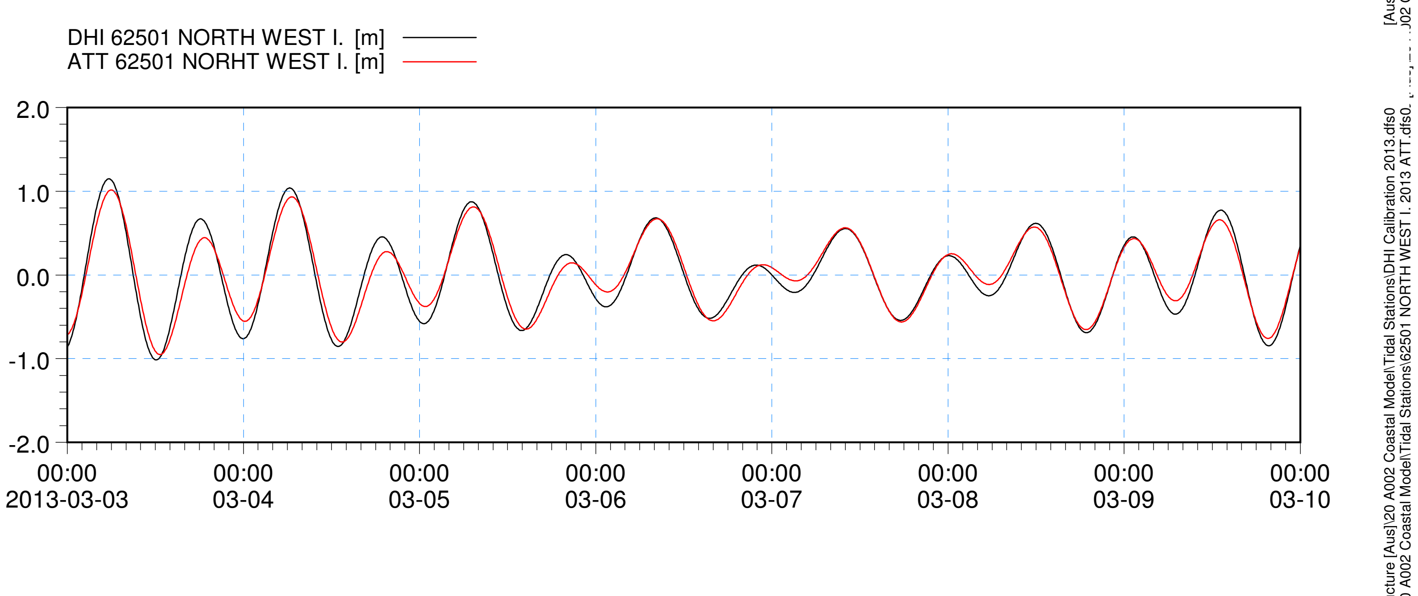
03-10
[Aus]\20 A002 Coastal Model\DHI Calibration 2013.dfs0
02 Coastal Model\Tidal Stations\62500 TRIMOUILLE I 2013 ATT.dfs0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2013-03-03
00:00
03-04
00:00
03-05
00:00
03-06
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03-07
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cture [Aus]\20 A002 Coastal Model\DHI Calibration 2013.dfs0
A002 Coastal Model\Tidal Stations\62501 NORTH WEST I. 2013 ATT.dfs0

Appendix E Supporting Data for Radiological Dose Calculations

External Dose
Federal Guidance Report No. 12 Dose Factors

	Dose Conversion Factors (Sv/s per Bq/m3)					Dose Conversion Fa	Dose Conv	Dose Conv	Dose Conversion Fact	Dose Conv	Dose Conv	Dose Conv	Dose Conversion Factors (Sv/s per Bq/m3)	
	1 cm thk	5 cm thk	15 cm thk	Infinite thk		1 cm thk	1 cm thk	1 cm thk	1 cm thk	1 cm thk	1 cm thk	1 cm thk	1 cm thk	
Ra-226	4.15E-20	1.16E-19	1.65E-19	1.70E-19		4.15E-20	4.15E-20	4.15E-20	4.15E-20	4.15E-20	4.15E-20	4.15E-20	4.15E-20	
Rn-222	2.54E-21	7.33E-21	1.14E-20	1.26E-20		2.54E-21	2.54E-21	2.54E-21	2.54E-21	2.54E-21	2.54E-21	2.54E-21	2.54E-21	
Po-218	5.70E-23	1.65E-22	2.63E-22	3.02E-22		5.7E-23	5.7E-23	5.7E-23	5.7E-23	5.7E-23	5.7E-23	5.7E-23	5.7E-23	
Pb-214	1.57E-18	4.47E-18	6.70E-18	7.18E-18		1.57E-18	1.57E-18	1.57E-18	1.57E-18	1.57E-18	1.57E-18	1.57E-18	1.57E-18	
Bi-214	9.15E-18	2.68E-17	4.36E-17	5.25E-17		9.15E-18	9.15E-18	9.15E-18	9.15E-18	9.15E-18	9.15E-18	9.15E-18	9.15E-18	
Po-214	5.22E-22	1.51E-21	2.40E-21	2.75E-21		5.22E-22	5.22E-22	5.22E-22	5.22E-22	5.22E-22	5.22E-22	5.22E-22	5.22E-22	
Pb-210	8.27E-21	1.29E-20	1.31E-20	1.31E-20		8.27E-21	8.27E-21	8.27E-21	8.27E-21	8.27E-21	8.27E-21	8.27E-21	8.27E-21	
Bi-210	5.54E-21	1.38E-20	1.86E-20	1.93E-20		5.54E-21	5.54E-21	5.54E-21	5.54E-21	5.54E-21	5.54E-21	5.54E-21	5.54E-21	
Po-210	5.32E-23	1.54E-22	2.45E-22	2.80E-22		5.32E-23	5.32E-23	5.32E-23	5.32E-23	5.32E-23	5.32E-23	5.32E-23	5.32E-23	
Total	1.08E-17	3.14E-17	5.05E-17	5.99E-17		1.07785E-17	1.08E-17	1.08E-17	1.08E-17	1.08E-17	1.08E-17	1.08E-17	1.08E-17	
	Dose Conversion Factors (Sv/s per Bq/m3)					Dose Conversion Fa	Dose Conv	Dose Conv	Dose Conversion Fact	Dose Conv	Dose Conv	Dose Conv	Dose Conversion Factors (Sv/s per Bq/m3)	
Ra-228	0	0	0	0		0	0	0	0	0	0	0	0	
Ac-228	5.97E-18	1.73E-17	2.76E-17	3.20E-17		5.97E-18	5.97E-18	5.97E-18	5.97E-18	5.97E-18	5.97E-18	5.97E-18	5.97E-18	
Th-228	1.22E-20	3.14E-20	4.17E-20	4.25E-20		1.22E-20	1.22E-20	1.22E-20	1.22E-20	1.22E-20	1.22E-20	1.22E-20	1.22E-20	
Ra-224	6.22E-20	1.78E-19	2.62E-19	2.74E-19		6.22E-20	6.22E-20	6.22E-20	6.22E-20	6.22E-20	6.22E-20	6.22E-20	6.22E-20	
Rn-220	2.45E-21	7.08E-21	1.10E-20	1.23E-20		2.45E-21	2.45E-21	2.45E-21	2.45E-21	2.45E-21	2.45E-21	2.45E-21	2.45E-21	
Po-216	1.06E-22	3.07E-22	4.87E-22	5.58E-22		1.06E-22	1.06E-22	1.06E-22	1.06E-22	1.06E-22	1.06E-22	1.06E-22	1.06E-22	
Pb-212	9.11E-19	2.53E-18	3.62E-18	3.77E-18		9.11E-19	9.11E-19	9.11E-19	9.11E-19	9.11E-19	9.11E-19	9.11E-19	9.11E-19	
Bi-212	1.15E-18	3.34E-18	5.36E-18	6.27E-18		1.15E-18	1.15E-18	1.15E-18	1.15E-18	1.15E-18	1.15E-18	1.15E-18	1.15E-18	
Po-212 (64%)	0	0	0	0		0	0	0	0	0	0	0	0	
Tl-208 (36%)	1.96E-17	5.79E-17	9.68E-17	1.23E-16		1.96E-17	1.96E-17	1.96E-17	1.96E-17	1.96E-17	1.96E-17	1.96E-17	1.96E-17	
Total	1.52E-17	4.42E-17	7.17E-17	8.66E-17		1.5164E-17	1.52E-17	1.52E-17	1.52E-17	1.52E-17	1.52E-17	1.52E-17	1.52E-17	
	Dose Conversion Factors (Sv/s per Bq/m3)													
Th-228	1.22E-20	3.14E-20	4.17E-20	4.25E-20										
Ra-224	6.22E-20	1.78E-19	2.62E-19	2.74E-19										
Rn-220	2.45E-21	7.08E-21	1.10E-20	1.23E-20										
Po-216	1.06E-22	3.07E-22	4.87E-22	5.58E-22										
Pb-212	9.11E-19	2.53E-18	3.62E-18	3.77E-18										
Bi-212	1.15E-18	3.34E-18	5.36E-18	6.27E-18										
Po-212 (64%)	0	0	0	0										
Tl-208 (36%)	1.96E-17	5.79E-17	9.68E-17	1.23E-16										
Total	9.19E-18	2.69E-17	4.41E-17	5.46E-17										
														29
TDS in salt solution (g/L)	32	32	32	32		32	32	32	32	32	32	32	32	5.1
Salt crust density (g/cm3)	1.15	1.15	1.15	1.15		1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	4.5
														10.3
Ra-226														
salt solution (Bq/L)	9.6	9.6	9.6	9.6		10.35	1.8	1.6	3.7	11.4	22.8	3.5	3.5	
residue conc (Bq/g)	0.30	0.3	0.3	0.3		0.3234	0.0563	0.0500	0.1156	0.35625	0.7125	0.109375	0.109375	
residue conc (Bq/cm3)	0.3450	0.3450	0.3450	0.3450		0.3720	0.0647	0.0575	0.1330	0.409688	0.819375	0.125781	0.125781	
residue conc (Bq/m3)	3.45E+05	3.45E+05	3.45E+05	3.45E+05		371953.125	64687.5	57500	132968.8	409687.5	819375	125781.3	125781.3	
external dose (Sv/s)	3.72E-12	1.08E-11	1.74E-11	2.07E-11		4.00909E-12	6.97E-13	6.2E-13	1.43E-12	4.42E-12	8.83E-12	1.36E-12	1.36E-12	
external dose (mSv/yr)	1.17E-01	3.42E-01	5.50E-01	6.52E-01	external dose (mSv/month)	1.1E-02	1.8E-03	1.6E-03	3.8E-03	0.139363	0.278726	0.042787	0.042787	
Ra-228														
salt solution (Bq/L)	15.9	15.9	15.9	15.9		17.14	3	2.7	6.1	18.6	37.2	5.7	5.7	
residue conc (Bq/g)	0.496875	0.496875	0.496875	0.496875		0.5356	0.0938	0.0844	0.1906	0.58125	1.1625	0.178125	0.178125	
residue conc (Bq/cm3)	0.5714	0.5714	0.5714	0.5714		0.6160	0.1078	0.0970	0.2192	0.668438	1.336875	0.204844	0.204844	
residue conc (Bq/m3)	5.71E+05	5.71E+05	5.71E+05	5.71E+05		615968.75	107812.5	97031.25	219218.8	668437.5	1336875	204843.8	204843.8	
external dose (Sv/s)	8.66E-12	2.53E-11	4.10E-11	4.95E-11		9.34052E-12	1.63E-12	1.47E-12	3.32E-12	1.01E-11	2.03E-11	3.11E-12	3.11E-12	
external dose (mSv/yr)	2.73E-01	7.98E-01	1.29E+00	1.56E+00	external dose (mSv/month)	2.5E-02	4.3E-03	3.9E-03	8.7E-03	0.319897	0.639794	0.098033	0.098033	
Th-228														
salt solution (Bq/L)	1.4	1.4	1.4	1.4		1.51	0.3	0.2	0.5					
residue conc (Bq/g)	0.04375	0.04375	0.04375	0.04375		0.0472	0.0094	0.0063	0.0156					
residue conc (Bq/cm3)	0.0503	0.0503	0.0503	0.0503		0.0543	0.0108	0.0072	0.0180					
residue conc (Bq/m3)	5.03E+04	5.03E+04	5.03E+04	5.03E+04		54265.6	10781.3	7187.5	17968.8					
external dose (Sv/s)	4.63E-13	1.35E-12	2.22E-12	2.75E-12		4.99E-13	9.91E-14	6.61E-14	1.65E-13					
external dose (mSv/yr)	1.46E-02	4.28E-02	7.01E-02	8.68E-02		1.3E-03	2.6E-04	1.7E-04	4.3E-04					
Radium Doses														
24-7 Dose (mSv/yr)	**3.91E-01**	**1.14E+00**	**1.84E+00**	**2.30E+00**		3.6E-02	6.4E-03	5.7E-03	1.3E-02	0.45926	0.91852	0.14082	0.14082	
2,000 hr/yr dose (mSv/yr)	**8.92E-02**	**2.60E-01**	**4.21E-01**	**5.25E-01**		0.008315441	0.00146	0.001295	0.002956	0.104854	0.209708	0.032151	0.032151	
24-7 Dose (mSv/yr)														
Radium and Thorium Doses						1.3E-01	2.2E-02	2.0E-02	4.5E-02	1.4E-01	2.8E-01			
24-7 Dose (mSv/yr)	**4.05E-01**	**1.18E+00**	**1.91E+00**	**2.30E+00**		2.9E-01	5.2E-02	4.6E-02	1.0E-01	3.2E-01	6.4E-01			
2,000 hr/yr dose (mSv/yr)	**9.26E-02**	**2.70E-01**	**4.37E-01**	**5.25E-01**		1.6E-02	3.1E-03	2.1E-03	5.2E-03	4.6E-01	9.2E-01			
24-7 Dose (mSv/yr)						4.4E-01	7.7E-02	6.8E-02	1.6E-01					

Inhalation Dose, Particulates
ICRP 68 Inhalation Dose Factors

		Sv/Bq
Ra-226		1.60E-05
Rn-222		0
Po-218		0
Pb-214		4.80E-09
Bi-214		2.10E-08
Po-214		0
Pb-210		1.10E-06
Bi-210		8.40E-08
Po-210		3.00E-06
	Total	2.02E-05

		Sv/Bq
Ra-228		2.60E-06
Ac-228		2.90E-08
Th-228		3.90E-05
Ra-224		2.90E-06
Rn-220		0
Po-216		0
Pb-212		3.30E-08
Bi-212		3.90E-08
Po-212 (64%)		0
Tl-208 (36%)		0
	Total	4.46E-05

		Sv/Bq
Th-228		3.90E-05
Ra-224		2.90E-06
Rn-220		0
Po-216		0
Pb-212		3.30E-08
Bi-212		3.90E-08
Po-212 (64%)		0
Tl-208 (36%)		0
	Total	4.20E-05

Ra-226 conc (Bq/g)	0.300	in airborne solids
Ra-228 conc (Bq/g)	0.496875	in airborne solids
Th-228 conc (Bq/g)	0.04375	in airborne solids
Dust loading (mg/m3)	0.1	Healy 1979, NBS 464, RESRAD
Dust loading (g/m3)	0.0001	
Inhalation rate (m3/hr)	1.25	US EPA
Exposure time (hr/yr)	2,000	
Conversion factor (mSv/Sv)	1,000	

Ra-226 dose (mSv/yr)	1.52E-03
Ra-228 dose (mSv/yr)	5.54E-03
Th-228 dose (mSv/yr)	4.59E-04
2,000 hr/yr dose (mSv/yr)	**7.52E-03**

Dose = (Soil conc) x (Dust load) x (Inhal. rate) x (Expos time) x (DCF)

References

Healy, J.W. and J.C. Rodgers, "Limits for the Burial of the Department of Energy Transuranic Wastes," LA-UR-79-100, Los Alamos Scientific Laboratory, 1979.

ICRP Publication 68, "Dose Coefficients for Intakes of Radionuclides by Workers," July 1994.

Atmosphere Downwind

Dust source area (m2)	64,000	entire pond area assumed dry
Source width (m)	100	perpendicular to wind direction
Source length (m)	640	parallel to wind direction
Distance to receptor (m)	5,000	Site B to salt crystalliser ponds
Average wind speed (m/s)	5.4	based on 19.5 km/hr
Wind frequency, from South	0.06	estimated from wind rose
Wind transit time (s)	119	time for wind to travel the length of the source
Air volume (m3/s)	5400	Blowing along source, 10-m high
Dust suspension rate (g/s)	0.54	grams per second of contaminated dust suspended by wind
Briggs parameter, a	0.06	Class D stability
Briggs parameter, b	0.0015	Class D stability
Briggs parameter, c	-0.5	Class D stability
Sigma-y (m)	1963.49	
Sigma-z (m)	102.90	

Chi/Q = (wind freq) / [(pi) x (wind speed) x (sigma-y) x (sigma-z)]

Chi/Q (s/m3)	1.7505E-08	
Q, dust source (g/s)	0.54	
Downwind conc. (g/m3)	9.45E-09	
Ratio, downwind/onsite	9.45E-05	(downwind dust concentration) / (onsite worker dust loading)
Dose at salt crystal. ponds	**7.10E-07**	**mSv/yr**

Ingestion of Fish from Estuary

ICRP 68 Ingestion dose conversion factors

		Sv/Bq	
Ra-226		2.80E-07	
Rn-222		0	
Po-218		0	
Pb-214		1.40E-10	
Bi-214		1.10E-10	
Po-214		0	2.80E-07
Pb-210		6.80E-07	
Bi-210		1.30E-09	
Po-210		2.40E-07	
	Total	1.20E-06	

		Sv/Bq	
Ra-228		6.70E-07	
Ac-228		4.30E-10	6.70E-07
Th-228		7.00E-08	7.00E-08
Ra-224		6.50E-08	
Rn-220		0	
Po-216		0	
Pb-212		5.90E-09	
Bi-212		2.60E-10	
Po-212 (64%)		0	
Tl-208 (36%)		0	
	Total	8.12E-07	

Source	Time	Weighted Average	Weighted Worst-case Average Ra-226	Weighted Worst-case Average Ra-228	Weighted Average Ra-226	Weighted Average Ra-228	Weighted Average Th-228
29	12	6.1	0.0	0.0	2.2	3.6	0.3
26	11	5.1	0.0	0.0	1.8	3.0	0.3
12	8	2.0	0.0	0.0	0.7	1.2	0.1
5	6	0.9	0.0	0.0	0.3	0.5	0.0
29	21	10.3	0.0	0.0	3.7	6.1	0.5
26	20	8.8	0.0	0.0	3.2	5.2	0.5
12	19	4.0	0.0	0.0	1.4	2.4	0.2
5	19	1.8	0.0	0.0	0.6	1.0	0.1
29	19	9.4			3.3	5.5	0.5
26	19	8.4			3.0	5.0	0.4
12	17	3.6			1.3	2.1	0.2
5	15	1.5			0.5	0.9	0.1
			0.0	**0.0**	**1.8**	**3.0**	**0.3**
			0.0	0.0	1.6	2.7	0.2

		sum	5.1	4.5	10.3
Ra-226 cor	1	Bq/L	1.8	1.6	3.7
Ra-228 cor	1	Bq/L	3	2.7	6.1
Th-228			0.3	0.2	0.5
Ra-226 cor	50		50		
Ra-228 cor	50		50		
Doses					
Ra-226 (m:	3.50E-02		6.31E-02	5.61E-02	1.30E-01
Ra-228 (m:	8.38E-02		2.51E-01	2.26E-01	5.11E-01
Th-228			2.63E-03	1.75E-03	4.38E-03
Total	1.19E-01		0.317093	0.28407	0.645194

Bio conc factor Ra (L/kg)	50	ANL 2001 (RESRAD Model)
Fish consumed (kg/yr)	2.5	FAO 2006 value divided by 12 months

Ra-226 conc in estuary (Bq/L)	3.7	Bq/L
Ra-228 conc in estuary (Bq/L)	6.1	Bq/L
Th-228 conc in estuary (Bq/L)	0.5	Bq/L
Ra-226 conc fish (Bq/kg)	185	
Ra-228 conc fish (Bq/kg)	305	
Th-228 conc fish (Bq/kg)	25	

Doses

Ra-226 (mSv/yr)	1.30E-01
Ra-228 (mSv/yr)	5.11E-01
Th-228 (mSv/yr)	4.38E-03
Total	6.45E-01

FAO [2006]. State of World Aquaculture 2006. Fisheries Technical Paper, No 500 – refer to Chapter 4, Table 1. Food and Aquaculture Organization of the United Nations.

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