fracking inquiry

From: Geoff Hokin [redacted]
Sent: Friday, 16 February 2018 8:11 AM
To: fracking inquiry
Subject: Imperial presentation 5th Feb 2018
Attachments: IOG letter to NT Fracking Task Force 15_02_2018.pdf; A Summary Review of the Hydrology of the McArthur Basin Central Trough.pdf

The Hon. Justice Pepper
Chair
Scientific Inquiry into hydraulic Fracturing in the Northern Territory

Dear Justice Pepper,

Please find attached to this email a letter from our company executive chairman and an addendum presentation to that made by him to the panel on the 5th of February in Darwin.
The purpose of the letter and attached report is to provide further information to address questions raised by some members of the panel during that presentation.

Regards,

Geoff Hokin
Principal Advisor Exploration & Operations

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IMPERIAL
OIL & GAS

The Hon. Justice Rachel Pepper
Hydraulic Fracturing Taskforce
GPO Box 4396
Darwin, NT 0801, Australia

Via Email: fracking.inquiry@nt.gov.au

16th February 2018

RE: Presentation to the Panel for the Scientific Inquiry into Hydraulic fracturing in the Northern Territory Monday 5th February 2018.

Dear Justice Pepper,

We thank you for the recent opportunity afforded to our company on Monday 5th February to make a further presentation to the panel in relation to the unique nature of the McArthur Basin Central Trough region of the Northern Territory. Through the course of that presentation the panel members asked several questions regarding the hydrology of the region.

In addition to the information given on the day we are pleased to provide, In order to address a number of those questions raised, a supplementary report of information on the known hydrology of the region. The attached report is a summary literature review of available public domain data from the various Departments within the NT Government and other sources. This includes some information from a review of relevant water bores within the region.

Included within this report are references to water quality baseline studies undertaken by independent environmental consultants identifying the current known state of the health of the water within the region. The outcomes of these reports have previously been provided to the NT Department of Primary Industry and Resources Energy Division. These studies form the base for Imperial's ongoing environmental research across the region.

We will be pleased if the panel would accept this information as a supplementary submission to that recently made.

Yours faithfully,

Bruce Mcleod
Executive Chairman & CEO
Empire Energy Group
Level 7, 151 Macquarie St. Sydney NSW 2001

A Summary Review of the Hydrology of the McArthur Basin Central Trough

Feb 2018

A Summary Review of the Hydrology of the McArthur Basin Central Trough

Prepared for

Imperial Oil & Gas Pty ltd
Level 7, 151 Macquarie Street,
Sydney NSW 2001

Internal Company Report
February 2018

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Introduction:

This report has been developed to provide a summary of the available data in relation to aquifers that are known to, or may, be present within the Central Trough of the McArthur Basin. This area includes the regions known as the Walker Trough in East Arnhem Land (previously known as the Northern Batten Trough) and the Batten Trough (previously known as the Batten Fault zone) (figure 1). Principle rivers that impact the East Arnhem Region of the Central trough of the McArthur Basin are the Koolatong River, Walker River and the Roper River. South of the Roper River the Central trough of the McArthur Basin contains the Towns River and Little Towns River, the Limmen Bight River, Rosie Creek and the McArthur River.

This report is based on an extensive literature review and summarises the available information to facilitate an understanding of the regional hydrology.

The Arafura Swamp and bioregion is not included in the area of study for the purpose of this report as it is situated outside the central trough zone.

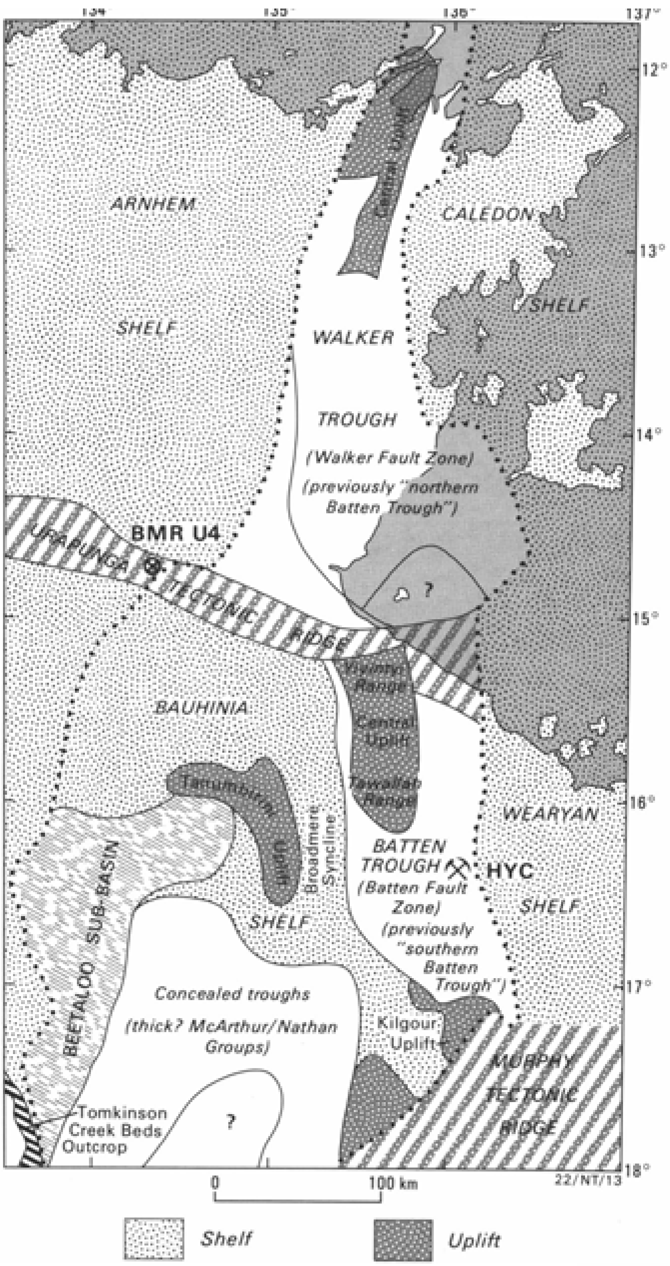

Figure 1: Principal tectonic elements of the McArthur Basin central trough. Image from Plumb & Wellman 1987.

LANDFORMS AND HYDROLOGY OF THE EAST ARNHEM REGION

East Arnhem land generally lies within the McArthur Basin, which consists of quartz sandstone, conglomerate, siltstones, limestone and volcanic rocks of the Mid - Late Proterozoic (600 - 1,600 million years ago). The northern edge of the bioregion includes part of the Arafura Basin, which consists of Late Palaeozoic (250 million years ago) quartz sandstones, shales and cherts. Further deposition of sediments occurred during the Tertiary and Quaternary (65 million years ago) periods, covering many of the low-lying areas of the region with sand and some clays and silts (Kerle, 1996).

The eastern part of Arnhem Land is predominantly gently sloping terrain with scattered low hills and breakaways. Within the bioregion, rivers run towards the north (e.g. Goyder River), east towards the Gulf of Carpentaria coast (e.g. Walker Rivers) and south east, flowing out of the bioregion into the Roper River (e.g. Phelp, Wilton and Mainoru Rivers). Principle Rivers that impact the East Arnhem Region of the Central trough of the McArthur Basin are the Koolatong River, Walker River and the Roper River. South of the Roper River the Central trough of the McArthur Basin contains the Towns River and Little Towns River, the Limmen Bight River, Rosie Creek and the McArthur River.

The Arnhem Inlier forms basement to sedimentary and minor volcanic rocks of the McArthur Basin in north-eastern Arnhem Land. It comprises granites, migmatite and metasedimentary rocks. The Pine Creek Orogen underlies the west of the region. It consists of multiple sequences of deformed and metamorphosed Palaeo-proterozoic successions, which are unconformably overlain by the Palaeo- to Mesoproterozoic McArthur Basin in the east. Archaean granite-gneiss, granite and minor metasedimentary rocks are exposed as small inliers and form the basement to Palaeo-proterozoic strata. The McArthur Basin underlies the centre and east of the region. The McArthur Basin succession comprises sandstone, shale, carbonate, and interbedded volcanic and intrusive igneous rocks.

The Arafura Basin underlies the central northern part of the region. It consists of Neoproterozoic sediments. Onshore Arafura Basin sediments unconformably overlie Proterozoic strata of the McArthur Basin and Pine Creek Orogen. Neoproterozoic sedimentary strata of the Arafura Basin consist of shallow marine sandstone, mudstone, and minor carbonates, which were deposited on a stable platform. The on-shore Money Shoal Basin is relatively undeformed and is composed primarily of Cretaceous aged sediments. The basin contains mildly deformed, largely flat-lying sediments; these consist of Cretaceous successions of marine and continental clastics, predominantly sandstones with minor coals, shales, claystone's and marls. Money Shoal Basin strata overlie Proterozoic strata of the Pine Creek Orogen.

The current drainage system probably came into existence in the Cretaceous when uplift in the north of the Northern Territory resulted in a drainage divide between inland draining streams to the south and streams draining to the sea in the north. The alluvial plains that cover an extensive area along the coastal northern edge of the region are underlain by primarily marine sediments that have been deposited in the last 10,000 years since the end of the ice age. Table 1 provides a summary of the drainage basins within the McArthur Basin and figure 2 illustrates their regional location.

Table 1: A summary of the drainage basins of the East Arnhem area. A regional location is provided in figure 2.

Location		Drainage area Km^2	Drainage region catchment
1	NE Arnhem	14,950	Timor Sea/Gulf of Carpentaria, Blyth River, Goyder River, Buckingham River and Noolatong River
1	East Arnhem	14, 460	Timor Sea / Gulf of Carpentaria Blyth River, Goyder River, Noolatong River and Walker River
3	East Central Arnhem	12,550	Gulf of Carpentaria Walker River and Roper River
4	Limmen Sabkha Zone	860	Gulf of Carpentaria Towns River

Climate

The dominating climate characteristics of the area are classified by the Köppen climate classification as a tropical savannah climate (BOM, 2013). Tropical savannah climates have monthly mean temperatures above 18°C in every month of the year and typically a pronounced dry season, with the driest month having precipitation less than 60 mm and also less than 100 mm total precipitation (McKnight, 2000). During the dry season, May to November, nearly every day is warm and sunny and afternoon humidity averages around 30%. There is very little rainfall between May and September.

The wet season is associated with tropical cyclones and monsoon rains. The majority of the rainfall occurs between December and April, when thunderstorms are common and afternoon relative humidity averages over 70% during the wettest months.

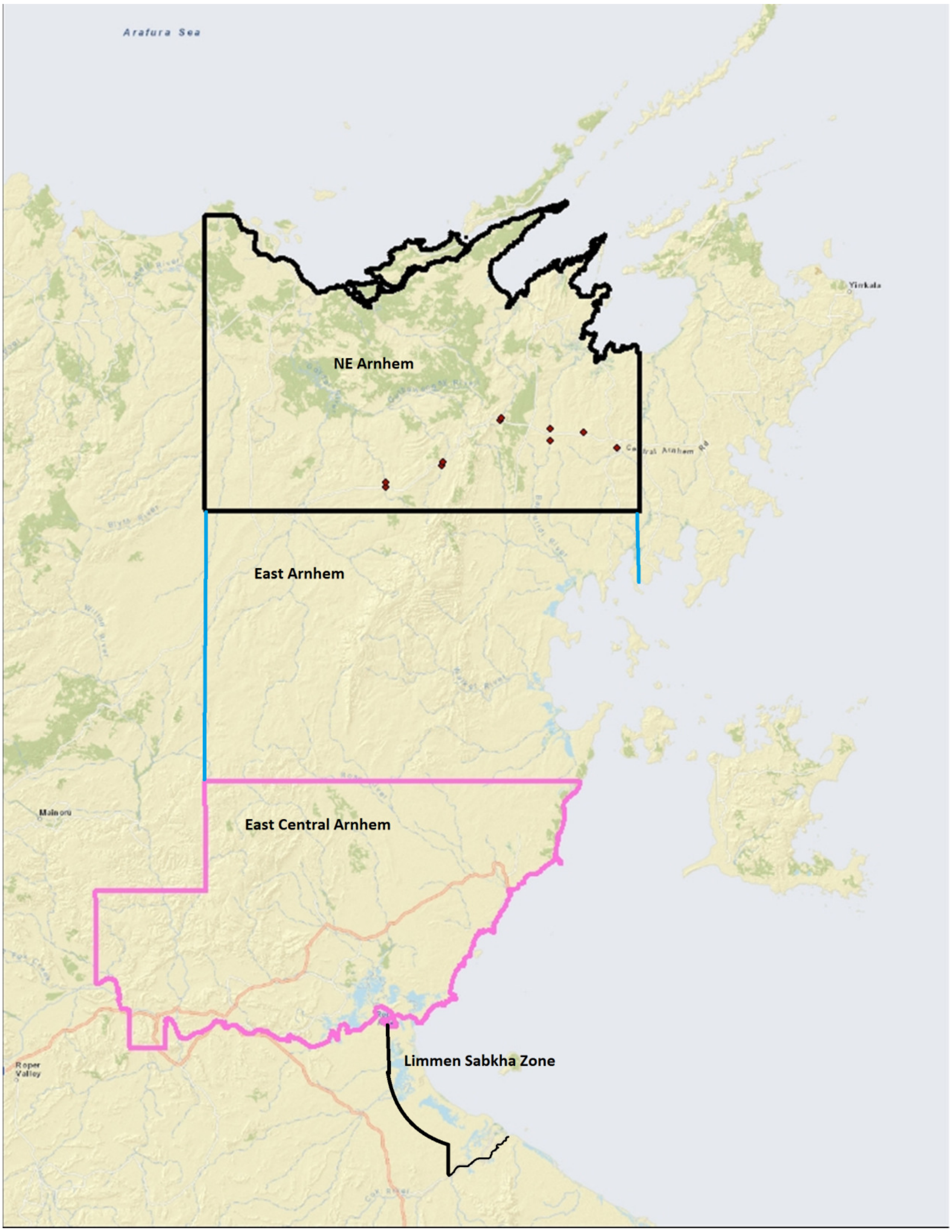

Fig. 2: Regional Location of drainage zones

Wet/dry season - precipitation

Precipitation measurements are available from two BOM weather stations (Table 2). Evaluation of daily precipitation records indicate that the wet season begins approximately mid-December. In the year 2012 when baseline studies were commenced by the company the wet season began on December 17. Until this date there had not been any recorded rainfall in December at the Lake Evella weather station.

Table 2: BOM Weather stations

Station	Number	Latitude	Longitude	Elevation (m)	Data Type	Years
Lake Evella	14515	12°30'5'' S	135°48'0'' E	70	Daily and Monthly Precipitation	1991-2012
Numbulwar	14505	14°16'43'' S	135°44'20'' E	10	Monthly Precipitation	1960-2012

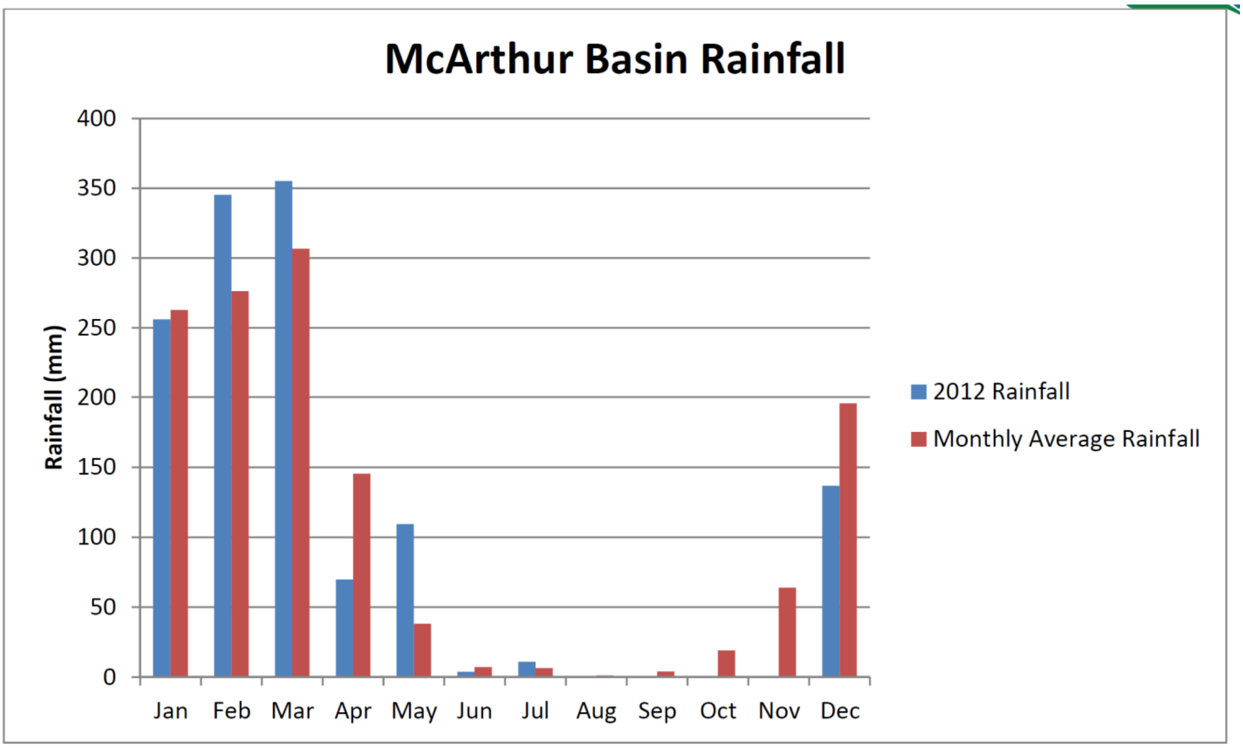

Figure 3: McArthur Region rainfall

Soils

The soils on the rocky outcrops and hills are shallow and stony. The low plateaux and peneplains contain some deep well drained soils. Deeper alluvial soils occur on some of the plains within the region. For more soils information refer to the Digital Atlas of Australian Soils.

Vegetation

Plant surveys in this bioregion have been limited. Connors, *et. al.,* (1996) identifies 852 plant species within the region. These are listed at: www.nt.gov.au/paw/fauna/bau/intro.htm

The majority of this region is covered by open forest and woodland dominated by Darwin Stringybark (*E. tetrodonta*). There are also patches of monsoon forest scattered throughout the woodlands, particularly where there are permanent springs. The woodland communities vary according to topography. The most common community which occurs on the undulating plains is a Darwin Stringybark (*E. tetrodonta*) / Darwin woolly butt (*E. miniata*) open forest with a sparse to open shrub layer and a dense ground layer dominated by sorghum species. On the rugged sandstone plateau and rocky outcrops there is low open woodland of variable-barked bloodwood (*Corymbia dichromophloia*) and Darwin woolly butt, with a variable mid layer and ground layer dominated by curly spinifex (*Plectrachne pungens*). Stringy bark and rusty bloodwood (*Corymbia ferruginea*) may also occur.

In the poorly drained soils and riverine areas communities of paperbark (*Melaleuca viridiflora*), screw palm (*Pandanus spirilis*) and river pandanus (*Pandanus aquaticus*) occur. On the saline tidal flats along the coast chenopod shrub lands (samphire) exist.

Fauna

There have been no comprehensive fauna surveys conducted in the region. Connors, *et. al.,* (1996) identifies 231 vertebrate species, including 7 that are rare and threatened. These include the ghost bat (*Macroderma gigas*), chestnut-backed button-quail (*Turnix castanota*), red goshawk (*Erythrotriorchis radiatus*), crested shrike-tit (*Falcunculus frontatus*), lesser wart-nosed horseshoe bat (*Hipposideros stenotis*). The saltwater crocodile (*Crocodylus porosus*) exists in estuaries and major rivers within the bioregion.

Land Tenure & Use

The bioregion is almost entirely (99.1%) Aboriginal Freehold, vested in the Arnhem Land Aboriginal Land Trust. A part of one pastoral leasehold (Mainora) extends across the southern boundary of the bioregion, comprising 0.9% of the total area. There are no formal conservation reserves or indigenous protected areas in the bioregion.

Land use

There are no major industries within the bioregion in the area of study. Extensive cattle grazing occurs on the identified pastoral lease, which extends into the south of the bioregion. Some cattle grazing also occur in some parts of the Arnhem Land. There is some limited tourism.

Condition Of the Landscape

Land degradation

Due to the low population and low level of economic activity, threatening processes are limited, although there are localized impacts of mining on Groote Eylandt and at the bauxite mine on the Gove Peninsula. Other important impacts are feral animals such as buffalo and pigs, weeds such as mimosa (*Mimosa pigra*) and changed fire regimes. Fire regimes have changed from traditional Aboriginal practices of localised frequent cool burns to more extensive and hotter late dry season fires. The combination of these impacts is degrading a high proportion of the monsoon rainforest patches, and also the condition of wetlands within the bioregion (Woinarski, *et. al.,* in prep.).

Pest species

Cane toads are a relatively new arrival to Arnhem Land, and are expected to have a devastating effect on the ecological balance of the region. Pigs, water buffalo and cats are also present in the bioregion and have significant impact on the natural environment. Pigs and buffalo may however be considered a resource by local Aboriginal people. For more details on pests see the Tropical Savanna website site: www.savanna.ntu.edu.au/information/savannaexplorer.html

Weeds are one of the major threatening processes in the region notably mimosa (*Mimosa pigra*) (Woinarski, *et. al.,* in prep.). Connors, *et. al.,* (1996) identify 15 weed species in the bioregion, which are listed on the web page: www.nt.gov.au/paw/fauna/bau/intro.htm . These include bellyache bush (*Jatropha gossypifolia*), spinyhead sida (*Sida acuta*), devil's claw (*Martynia annua*), grader grass (*Themeda quadrivalvis*), hyptis (*Hyptis suaveolens*), and coffee senna (*Senna occidentalis*)

Social & Economic Aspects

The bioregion is almost entirely Aboriginal land, with a low population and limited access. The main centres of population and economic activity are on Groote Eylandt, where there is mining for manganese and the settlements of Alyangula (population 1,231) and Anguruga (717).

Based on the 2012 ABS census statistics the only significant mainland population centres within the region are the Aboriginal settlement of Numbulwar (population 619) at the mouth of the Roper River on the Gulf of Carpentaria, and Ngukurr (973) approximately 160km upstream on the Roper River. Bulman(291) to the west outside the area of study is located on the Arnhem Highway. This highway links the Gove Peninsular to the Stuart Highway to the south east of Katherine, providing dry season access to the community of Gapuwiyak (668) and a number of outstations. The townships of Walker River and Gan Gan scattered through the region along with other smaller communities generally have less than 200 people each. A number of indigenous outstations also exist across the region. However, these outstations are usually occupied by small family groups only and often seasonally. Current accurate population numbers for this region are difficult to obtain. For more information on the Aboriginal people of this region refer to Horton, (1994) and the relevant websites in the reference list.

Surface water and groundwater hydrology

Existing environment

Figure 4 provides a location of the major river basins and the major permanent rivers of the region which are the Roper River Basin – Wilton River, Waterhouse River; the Goyder River

Basin – Goyder River; and the Buckingham River Basin – Buckingham River, Cato River, Giddy River and Latram River. There also are a number of other creeks and streams as well as numerous lesser drainage features. Many wetlands occur within the region including the internationally significant Arafura Swamp in the western portion of North East Arnhem Land, seasonally inundated floodplains, permanent and semi-permanent freshwater lake systems and ephemeral saline lakes.

Relatively minor groundwater extraction occurs in the Roper, Goyder and Buckingham river basins for small community supplies. Dominant water use is principally associated with limited agriculture and residential development. There is relatively minor groundwater extraction in the other drainage basins for small community supplies.

Within the McArthur Basin Central Trough (MBCT) region, in most cases, the creeks dry up each year and do not flow again until the next wet season. The wet season begins approximately one month earlier in the west than in the east of the survey area. Consequently, the flow period in the western section is between November and April/May and in the eastern section between December and June. Baseline water quality is typical of that in relatively undisturbed environments in northern Australia. Surface water quality has been assessed by independent ecological studies conducted by O2 Environmental with a copy of the relevant reports provided to the NT DPIR.

In the Daly, Roper, Goyder and Buckingham basins the trans territory pipeline (TTP) project proposed by Rio Tinto to run from south of Katherine to Nhulunbuy traverses shallow, high-yielding aquifers that have high resource value and environmental beneficial uses that would be sensitive to development impacts. Along this route water bores with measured yields greater than 1 L/s were assessed as having potential as water supplies which pipeline construction, operation and decommissioning activities could impact upon. In the Daly Basin 4 bores were identified. In the Goyder River Basin 3 water bores were identified. In the Buckingham Basin (overlying the Arafura region of Arnhem Land) 31 water bores were identified. These groundwater resources were considered to require a high level of protection.

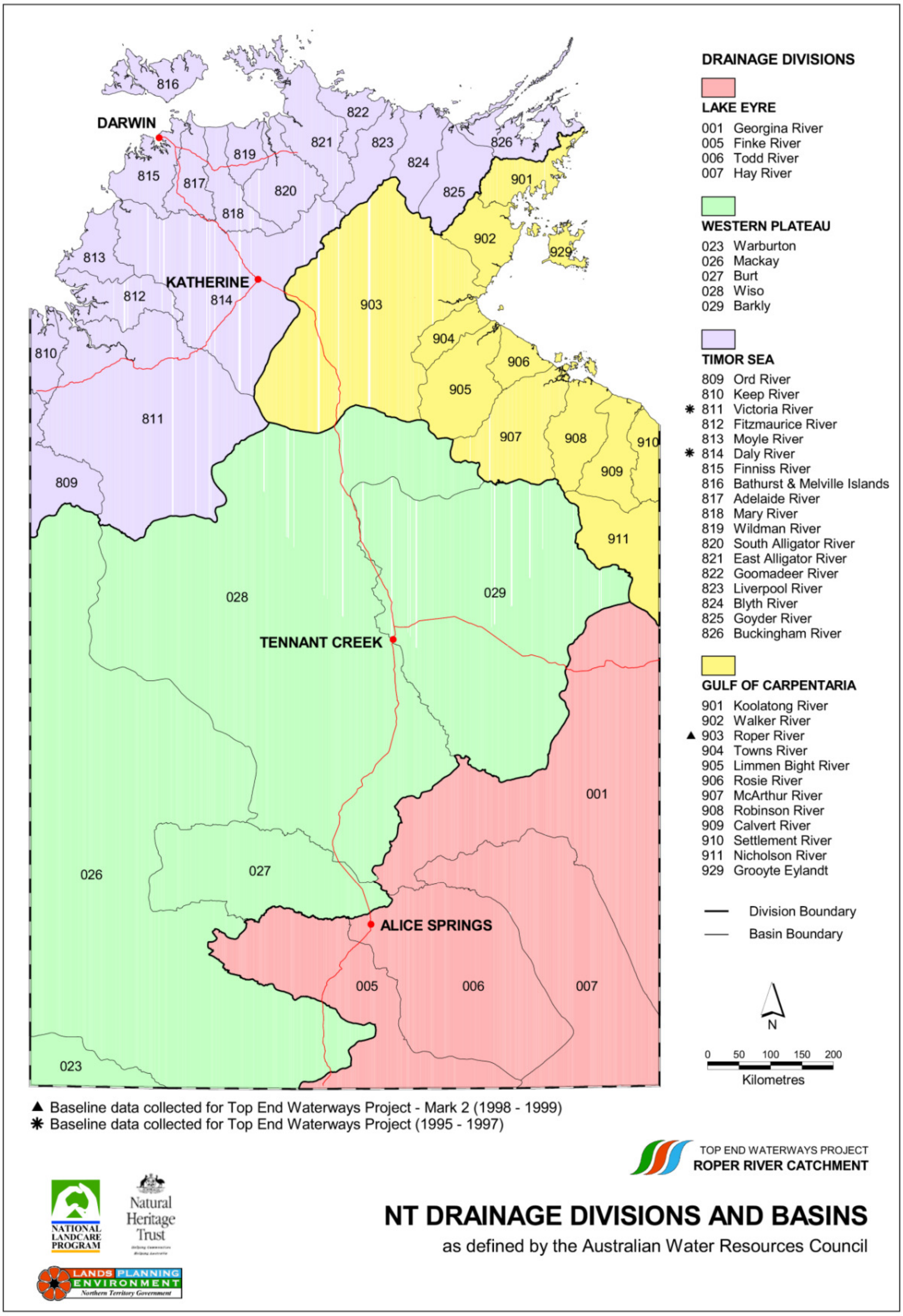

Fig 4. Location of principle rivers within the Central trough of the McArthur Basin.
Image from https://denr.nt.gov.au/__data/assets/pdf_file/0004/254128/ntdrainage.pdf

Waterway Descriptions

The proposed area of activity within the central trough of the McArthur Basin will traverse extensive areas of five major river basins. The Koolatong, Walker, Roper, Towns and Limmen Bight Rivers. Catchment statistics shown in Table 3 identify the size of the surface water resource and perceived development pressure for the major basins within the broader area of the Northern part of the Territory. The largest surface water resource is in the Daly River basin. This basin lies well to the west of the MBCT. The next largest is in the Roper River basin. Resource use (measured by diversions) and development pressure (measured by estimated future use) identify these two catchments as recognised, economic water resources. The surface water resources in other catchments along the right of way are undeveloped and do not currently have recognised development potential. However, the discovery of hydrocarbons (oil & gas) and the construction of the proposed TTP gas pipeline Katherine to Gove may provide development opportunities that will change the perception of low development potential.

Table 3: Catchment statistics

Parameter	Units	Daly	Roper	Goyder	Buckingham
Area	*Km^2*	52,940	79,130	10,360	8,330
Runoff	*ML/yr*	6,740,000	540,000	1,685,000	2800,000
Diversions	*Ml/yr*	7,465	526	0	0
Sustainable yield	*ML/yr*	1,110,000	950,000	302,800	440,000
Estimated use in 2020	*ML/yr*	102,770	620	Nil	Nil
Estimated use in 2050	*Ml/yr*	104,530	720	Nil	Nil
Disturbance		<30%	<30%	<30%	<30%

(Data NT DENRM- water resources)

The surface hydrology of the five major drainage basins that the right of way traverses is described in the following sections.

Daly River Basin

The Daly River is the major river and Katherine River is one of the major tributaries. This basin lies outside the MBCT but is of significance to the Territory and contains the major aquifers that impact large areas of the Northern Territory. The catchment covers 52,940 km^2. The mean annual runoff is 67,400,000 ML/yr. The upper part of the catchment is moderate escarpment country and the lower part around the coastal areas is flat. There is only one major diversion, the Donkey Camp Weir on Katherine River.

Pastoral Leases cover 50%, Aboriginal land covers 20%, National Park covers 9%, and the rest of the catchment is used for horticulture, agriculture and mining. The surface water usage is for urban water supply and irrigation, stock watering, mining, rural water supply and aquaculture. The mean annual rainfall varies from 700 mm in the south to 1500 mm in the north near the coast.

There is a large base flow component to the Daly River system. The basin is largely unmodified. Total diversions have increased from 3,730 ML/yr in 1983/84 to 7,465 ML/yr in 1996/97. The majority of this increase was attributed to urban supply. However 53% of the diversions are for irrigation while 40% are for urban/industrial uses. Agricultural development has put pressure on water quality and has stimulated research into the environmental flow regimes needed to maintain groundwater dependant ecosystems (Erskine *et al.* 2003).

Graphs of mean monthly discharge records for the Daly River, the Katherine River and Bradshaw Creek indicate that ephemeral stream flow ceases slightly later than areas further west, with the flow free period extending between May and November. No field survey information is available for drainage system crossings in the Daly River Basin.

The Daly basin lies on a bed of Cambrian limestone and sandstone formations, but the surface formations are mostly of Cretaceous origin (Jolly 1984; Jolly *et al.* 2000). The area is characterised by three types of fractured, karstic rocks known as Tindal limestone (limestone and siltstone), Oolloo limestone (dolomitic sandy limestone) and the Jinduckin Formation (a mixture of limestone, siltstone and shale). All three rock types contain extensive unconfined aquifers that serve as the primary groundwater resources in the area and, as a result, provide the base flow of the majority of the rivers and creeks in the Daly Basin. it is known that the depth to the water table within this basin varies from one year to another in response to rainfall amount. At sites underlain by Tindal limestone the water table can vary during the course of a year from 3-25 m. The hydrogeological mapping do not identify the area as having groundwater resources available for agricultural development. None of these aquifers occur within the MBCT region either north or south of the Roper River.

There are only limited data available for groundwater levels in the Proterozoic carbonates within the Daly Basin. The data for bore RN021689 located in an outlier of the Dook Creek Formation near Beswick in Arnhem Land indicates that significant recharge occurred in 75 percent of wet seasons during the 20-year period when water levels were measured. In the remaining 25 percent of wet seasons minimal recharge appears to have occurred.

Groundwater discharge from the Dook Creek Formation provides the dry season flow for the Mainoru and Wilton Rivers and Flying Fox Creek within the upper Roper River catchment. The Dook Creek Formation is also the source of dry season flow in the Goyder River within East Arnhem which flows into the Arafura Swamp. Williams et al., (2003) estimated a mean annual recharge rate of 90 mm/year (1884 to 1999) for the area of the Dook Creek Formation that provides the source of dry season flows in the Goyder River.

Goyder River Basin

There are no infrastructure or diversions within this river basin. This basin is within Aboriginal land. About 4.5% of the land area has soils with few limitations to agriculture. Goyder is the major river, and Gulbuwangay River is the major tributary. Both these rivers join in the lower part of the basin and discharge into the Arafura Sea. Both these rivers originate from the escarpment country and flow through the low valleys into low mildly sloping country. The mean annual rainfall varies from 900 mm in the south to 1100 mm in the north. There is no surface water licensing, and surface water usage is zero. No potential development issues have been identified for this catchment.

The aquifer type consists of poorly consolidated sandstone or limestone and has high porosity and permeability. The aquifer has a narrow intersection with the headwaters of the Goyder River.

Buckingham River Basin

There are no major infrastructure or diversions for surface water extraction within this basin. This basin is within Aboriginal land. The potential for agricultural development is considered to be low. There are few rivers that flow from the escarpment country in the west and low hill country in the east to the sea. The lower part of the basin is mildly sloping to flat country. The main rivers are Woolen, Buckingham, Habgood, Cato, Peter John and Giddy. The mean annual rainfall varies from 1300 mm in the south to 1400 mm in the north. No surface water licenses have been issued, and no surface water usage has been recorded. Graphs of mean monthly discharge records for Durabudboi River and Yirrkala Creek indicate that flow ceases between June and December.

Roper River Basin

There are no major infrastructure or diversions for surface water extraction within this river basin. However there is "run of river" extraction for public water supply for two communities, and irrigation. About 60% of the area is pastoral leasehold with the majority con fined to the upper reaches of the river basin and 35% is Aboriginal land. There are twenty five pastoral leases within the SWMA and another nine partly so. The MBCT is downstream from these areas. Soils with few limitations for agriculture cover about 38% of the area. The Roper is the main river that drains the whole area into the Gulf of Carpentaria. The Phelp, Wilton, Waterhouse and Hodgson rivers are the main tributaries of Roper River. They flow from the escarpment country through well-defined valleys and finally flow into Gulf of Carpentaria through mildly sloping low valleys. The mean annual rainfall varies from 600 mm in the south to 900 mm in the north. A surface water license has been issued for a community water supply, and three licenses for irrigation. Surface water is also used for stock watering.

Tourism, Irrigated Agriculture, Marine and Riparian uses are the likely potential developments. Forecast usage of surface water is mainly for public water supply, irrigation and stock watering. The forecast use is based on the assumption that cattle numbers in the leasehold would be 85% of its carrying capacity in 2020, and 100% in 2050. This increase in the cattle numbers represents the growth rate noted in the NT Overview Report. Cattle consumption is assumed as 50 litres per day per head. It is also assumed that 10% of the stock water consumption is from surface water. Population growth in the rural area is based on the growth rate noted in NT Overview Report. Irrigation forecast is assumed as 150% of the present usage in 2020, and 200% in 2050. The forecast use figures are only rough estimates.

Groundwater Resources

Recharge processes in the northern areas are considered to be distributed rather than localised in particular parts of the landscape (Chin *et al.* 2000). Licensing for groundwater extraction is organised around eight Groundwater Management Units (GMUs). These represent selected major aquifer systems within gazetted "Water Control Districts" across the Northern Territory and Unincorporated Areas (UAs). Both GMUs and UAs are sub-areas of Groundwater Provinces that are the hydrogeological basins within the NT.

Aquifer types

There are three major aquifer types in the Arafura region. These types are fractured rocks, karstic carbonate rocks and Cretaceous sediments, all of which are briefly described below and their areal extent is shown on Figure 5 below.

Fractured rocks

A variety of Precambrian (older than 500 million years) rocks form the bedrock of the area. These are mainly sedimentary but also include granite and volcanic rocks. Sandstone, siltstone and greywacke are the main sedimentary rock types. In some areas they are flat-lying while in other areas they have been folded, faulted and show low grade metamorphism. Water is usually intersected in weathered fractured zones within the fractured rocks. Groundwater yields are controlled by the degree of fracturing of these units and are likely to be greater in areas located along large scale joints and fault zones.

Karstic carbonate rock – Proterozoic carbonates (includes the Dook Creek Formation)

The major karstic aquifer in the region occurs within the Proterozoic carbonate rocks of the Dook Creek Formation. The Dook Creek Formation contributes very significant dry season flow to the Goyder and Blyth rivers. The Goyder River is the main source of water during the dry season for the Arafura Swamp. The detailed hydrogeology of the Proterozoic carbonates is not known as little investigation work has been undertaken.

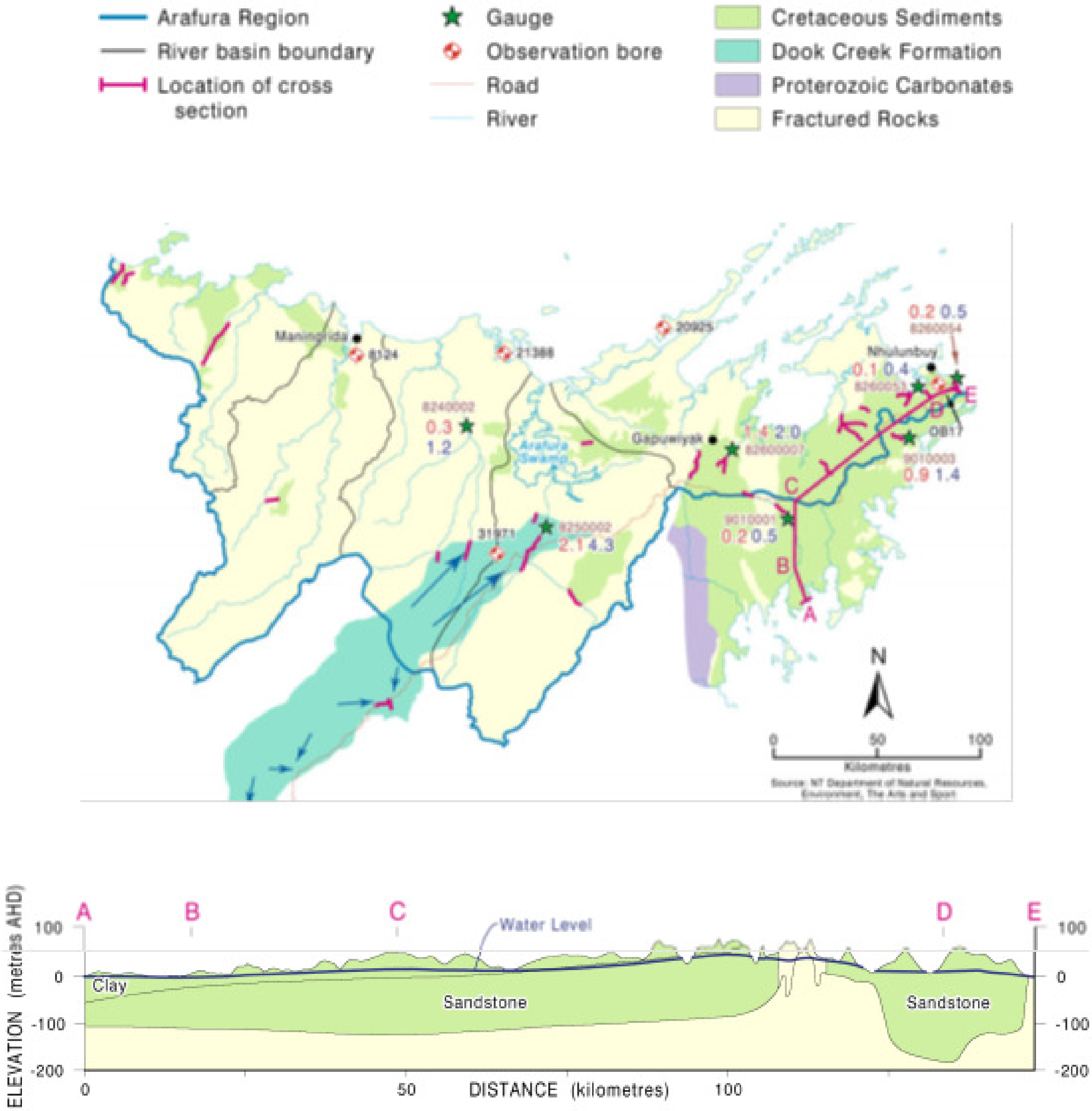

Figure 5. Hydrogeology of the Arafura region with dry season gauged flows (map provided by NRETAS, 2009)

Cretaceous sediments

The Cretaceous sediments form a mantle of lateritised claystone and sandstone covering much of the area. On Figure 5 sediments have only been mapped where it is expected that they form the major aquifer at that locality. However they overlie the karstic rock aquifers over much of the region. The beds are sub-horizontal and may be divided into an upper claystone and siltstone unit and a basal sandstone unit. Outcrop is generally sparse due to the soft nature of the rock but in places silicification has altered them to porcellanite and quartzite.

In the north east the formation may be over 100 m thick with most of that thickness being permeable sandstone (cross section in Figure 5). The Cretaceous sandstone aquifer contributes significant dry season flows to many rivers across the region, particularly in the north east. The sandstone provides the source of water for most communities in north east Arnhem Land and for the bauxite mine near Nhulunbuy.

In the Northern East Arnhem Land area regional groundwater discharge from the Cretaceous sediments provides the dry season flow for Wonga Creek and the Durabudboi, Angurugu, Emerald and Amagula rivers. Changes in dry season stream flow rates occur in response to changes in the amount of rainfall that recharges the aquifer during the preceding wet season.

The changing recharge rate is reflected in the variation in water level measured in monitoring bores intersecting the aquifer. The data indicates that in this region annual groundwater rises due to recharge during the wet season vary from minimal during the 1989/90 wet season to 4.5 m in 1993/94 and 1998/99. Prowse et al. (1999) demonstrated that periods of relatively low groundwater levels correspond to periods when stream flows are relatively lower in the perennial rivers of Groote Eylandt; likewise higher groundwater levels correspond with higher flows.

Inter-aquifer connection and leakage

In the region there is likely to be some degree of connection between the fractured rock aquifers, karstic carbonate aquifers and the basal sandstone of the Cretaceous sediments. However, there is no data to demonstrate or quantify these processes. Each of these aquifers are relatively shallow in nature due to the overall stratigraphy of the area.

Recharge, discharge and groundwater storage

Recharge occurs only in the wet season when rainfall intensity and duration is sufficient, and leads to a rise in groundwater levels. In the dry season the levels naturally fall as groundwater is either transpired or discharged to wetlands and rivers, where it evaporates or is discharged to the sea. The amount and rate at which the groundwater levels rise and fall depend on the type, size and other physical properties of the aquifer as well as the amount of recharge.

Recharge beneath native vegetation is dominated by bypass flow and not diffuse movement through soil horizons. The most likely mechanism for this is via macro-pores such as cracks and root holes in the soil. Sinkholes and stream sinks have been located over the Proterozoic carbonates.

Groundwater discharge occurs across the region mostly as evaporation and transpiration (ET). Groundwater discharge is also important for maintaining perennial reaches of many rivers within the region. The most visible of these discharges take the form of springs on or adjacent to the banks of rivers such as the Blyth, Goyder, Habgood, Cato and Latram, as well as Yirrkala and Jungle Creeks. However the majority of discharge occurs as diffuse discharge through the beds of rivers. The Northern Territory Government currently maintains one river gauging station for all of the above perennial rivers in Arnhem Land.

A number of the towns in the region obtain their water supply from aquifers developed in sandstone of Proterozoic age. The sandstone has been fractured and extensively weathered to depths of up to 100 metres. The variability of recharge rate to the fractured rock aquifers is reflected in the variability in water levels measured in monitoring bores intersecting the aquifer. The variation in water level in bore RN008124 over the 15-year period for which records exist ranged from a low of 1 m in 1989/90 to a high of 9 m in 1994/95; the mean annual variation was approximately 4 m.

Water Quality

Background water quality information of the region has been established in a 2012 independent study undertaken by O2 Environmental Pty Ltd. Typical water quality settings for northern Australia based on the Australian Water Quality Guidelines (ANZECC and ARMCANZ 2000) have been reproduced in Tables 4, 5, 6 & 7. These values have been determined from regional data and are inherently conservative. The background ranges established by the O2 study were within the guideline values. The analysis demonstrates that background water quality is typical of relatively undisturbed ecosystems. Turbidity in NT rivers is generally low for base flow conditions while turbidity in wetlands will vary greatly, depending on general condition of catchment or river draining into the wetland, recent flow events & water levels.

Extreme water quality results can occur naturally that are well outside the standard ranges presented in the ANZECC guidelines as a consequence of seasonal influence.

In-situ Water Quality

The dry season measurements presented provide an indication of the typical water quality which is uninfluenced by resource extraction operations. The following section summarise the measured water quality within each region. it is important to note that the values presented in the following tables are of an undisturbed ecosystem as no mining has been conducted in this region. More recently though a number of mining companies, including BHP and Rio Tinto, have applied for the grant of exploration mineral mining tenements across these areas. These mineral tenements overlap the petroleum exploration tenements currently under application and negotiation by Imperial Oil and Gas Pty ltd. The location of these can be seen on the Strike® http://strike.nt.gov.au/wss.html;jsessionid=vl61odcarf9d22helvauyuqk website managed by the NT Dep't Primary Industries and Resources.

Table 4: NE Arnhem Land in situ dry season water quality summary.
(table from Dry Season Water quality report – O2 Environmental, 2012)

	Parameter	LOR	Units	Sites and Sample Number						
				180-1-1 Dec-12	180-2-1 Dec-12	180-3-1 Dec-12	180-4-1 Dec-12	180-5-1 Dec-12	QA1 (180-3-1) Dec-12	QA2 (180-4-1) Dec-12
Physio-Chemical Stressors	Temperature	-	°C	32.6	31.6	32.7	30.6	32.7	32.7	30.6
	Electrical Conductivity	-	µS/cm	44	206	69.3	50	563	69.3	50
	Turbidity	-	NTU	1	0	2.9	0	2.9	2.9	0
	pH	-	-	7.24	7.5	6.73	6.47	7.94	6.73	6.47
	Total Dissolved Solids	-	mg/L	29	109	33.7	23.8	189	33.7	23.8
	Dissolved Oxygen	-	mg/L	2.17	4.92	2.95	5.13	5.55	2.95	5.13
	Total Hardness as $CaCO_3$	1	mg/L	6270	58	8	13	222	8	-
	Suspended Solids	5	mg/L	71	<5	<5	<5	<5	<5	-

Electrical conductivity (EC) was the only elevated water quality parameter, location 180-5-1, when compared to the adopted trigger values. The remainder of the sample locations for the NE Arnhem region were within the suitable range for EC.

Table 5: East Arnhem in situ dry season water quality summary.
(Table from O2 environmental 2012)

	Parameter	LOR	Units	Sites and Sample Number						
				181-1-1 Dec-12	181-2-1 Dec-12	181-3-1 Dec-12	181-4-1 Dec-12	181-5-1 Dec-12	181-6-1 Dec-12	181-7-1 Dec-12
Physio-Chemical Stressors	Temperature	-	°C	32.3	-	35.4	32.7	33.5	-	-
	Electrical Conductivity	-	µS/cm	306	360	96.4	774	258	-	-
	Turbidity	-	NTU	0	0	8.7	0	0	-	-
	pH	-	-	7.78	7.68	6.76	7.34	7.6	-	-
	Total Dissolved Solids	-	mg/L	155	187	47.3	415	131	-	-
	Dissolved Oxygen	-	mg/L	3.89	3.81	3.4	3.12	3.68	-	-
	Total Hardness as $CaCO_3$	1	mg/L	155	195	26	208	116	-	-
	Suspended Solids	5	mg/L	<5	<5	8	<5	<5	-	-

Within the east Arnhem area four of the five samples expressed elevated EC levels. The remainder of the water quality samples were within adopted trigger limits.

Table 6: East Central Arnhem in situ dry season water quality summary

	Parameter	LOR	Units	Sites and Sample Number				
				182-1-1 Dec-12	182-2-1 Dec-12	182-3-1 Dec-12	182-4-1 Dec-12	182-5-1 Dec-12
Physio-Chemical Stressors	Temperature	-	°C	31.8	30.7	34.3	32.8	33.4
	Electrical Conductivity	-	µS/cm	736	539	109.2	380	1329
	Turbidity	-	NTU	0	0	124.6	6	0
	pH	-	-	7.48	8.16	8.48	8.19	8.27
	Total Dissolved Solids	-	mg/L	310	285	-	-	-
	Dissolved Oxygen	-	mg/L	3.55	4.24	4.61	2.78	3.78
	Total Hardness as $CaCO_3$	1	mg/L	274	297	33	212	390
	Suspended Solids	5	mg/L	<5	<5	20	6	<5

Within east central Arnhem area four of the five samples expressed elevated EC and pH levels, while one location expresses elevated turbidity. The remainder of the water quality samples were within adopted trigger limits.

Table 7: Limmen Sabkha zone in situ dry season water quality summary

	Parameter	LOR	Units	Sites and Sample Number 183-1-1 Dec-12
Physio-Chemical Stressors	Temperature	-	°C	30.7
	Electrical Conductivity	-	µS/cm	908
	Turbidity	-	NTU	0
	pH	-	-	7.93
	Total Dissolved Solids	-	mg/L	495
	Dissolved Oxygen	-	mg/L	3.24
	Total Hardness as $CaCO_3$	1	mg/L	314
	Suspended Solids	5	mg/L	<5

Within the Limmen zone electrical conductivity (EC) was the only elevated water quality parameter when compared to the adopted trigger values. The remainder of the water quality samples were within adopted trigger limits.

Groundwater Depth

Shallow groundwater depth is associated with wetlands, floodplains and drainage lines. Logged information on bores within the TTP pipeline corridor was used to estimate the standing water level during the dry season. Wet season groundwater levels are likely to rise closer to the surface.

Groundwater variation reported in the Daly Basin (Erskine *et al.* 2003) indicates variation between 2 and 62 m during the course of the year. No bore log information or standing water level data were available for the Roper River Basin. However, groundwater studies describe seasonal variation in the shallow aquifer and indicate dry season standing groundwater levels below 2 m (Zaar 2003). Bore logs in the Buckingham River Basin near Gove indicate standing water levels between 0.2 and 35.6 m in shallow, unconfined aquifers. Shallow groundwater levels are closely linked to annual rainfall and stream flow. The shallow groundwater level rises rapidly during the wet season in response to rainfall and provides stream base flow into the dry season, with groundwater levels falling rapidly in the subsequent dry season.

Surface–groundwater interaction

Rivers with perennial reaches, where dry season flow is sourced from karstic rocks, include the Goyder, Blyth and Habgood. Perennial rivers where dry season flow is sourced from Cretaceous sediments include the Cato and Latram, as well as Yirrkala and Jungle creeks. The Goyder River is entirely fed by groundwater during the dry season and accordingly provides the major water source for the Arafura Swamp at this time (Williams et al. 2003). Evapotranspiration requirements for the swamp were determined by Williams et al. (2003) to be approximately 5 mm/day.

LANDFORMS AND HYDROLOGY OF THE ROPER RIVER REGION AND SOUTHERN MCARTHUR BASIN CENTRAL TROUGH

The study area is part of the Gulf Fall and Uplands region and includes the catchment of the Roper River and its tributaries. The Roper River is a large, perennial flowing river located in the wet / dry tropics of the Northern Territory of Australia. The study area includes the catchment of the Roper River and its tributaries (refer figures 4 and figure 6).

The catchment forms part of the drainage system known as the Gulf Fall and has an area of 82 000 km^2. The study area is drained by ten rivers and three major creeks, some of which are also perennial. These are: the Roper, Phelp, Hodgson, Arnold, Wilton, Mainoru, Jalboi, Strangways, Chambers and Waterhouse Rivers, and Maiwok, Flying Fox and Elsey Creeks. The Roper River starts as Roper Creek (also called Little Roper River) and becomes the Roper River downstream of the Waterhouse River junction near Mataranka. The Elsey Creek system drains the large Sturt Plateau region, which is located in the south-western section of the catchment. The Arnhem Land Plateau, rising up to 440m, and the Wilton River Plateau are located in the northern section of the catchment, and consist predominantly of Kombolgie siliceous sandstone.

The Roper River flows generally in an easterly direction, although the geology of the catchment influences the direction of the drainage systems. This middle section of Roper River is also very braided and flow is often in multiple channels. The normal tidal limit of the Roper River is at Roper Bar Crossing approximately 145km by river inland from the river mouth. The Roper River traverses the alluvial coastal plain eastward for this 145 km before entering the Gulf of Carpentaria. There are currently no large surface water storages on the Roper River or its tributaries.

There are two important wetlands identified within the Roper River Catchment (Environment Australia, 2001). They are:

(i) the Limmen Bight (Port Roper) Tidal Wetlands System (situated in the Limmen Sabkha zone identified in figure 2), which is the second-largest area of saline coastal flats in the Northern Territory and is a good example of a system of tidal wetlands (intertidal mud flats, saline coastal flats and estuaries), with a high volume of freshwater inflow, typical of the Gulf of Carpentaria coast; and,

(ii) the Mataranka Thermal Pools which is a good example of tropical springs and associated permanent pools (one of the best known in the Northern Territory). The Mataranka Pools are situated well upstream and outside the MBCT region.

Natural Environment

The bioregion falls within the monsoonal northern Australia, although there is a wide range of conditions within this region. Rainfall decreases from about 1,000 mm in the north to 400mm in the southeast. Although summer rainfall is dominant throughout the region, rainfall in the northwest is more strongly concentrated in the January — March period than in the southeast.

The study area is located within the monsoonal tropics. The dominant feature of the north-west monsoon is the occurrence of two distinct seasons, an almost rainless dry season from May to September, and a wet season from November to March. April and October are transitional months. (Woodroffe *et al.*, 1986).

Vegetation

Within the Roper river catchment area from Mataranka to the Gulf 1,342 species have been identified in the bioregion, including 46 that are rare and threatened (Connors *et. al.,* 1996). For a complete list of rare and threatened species refer to: www.nt.gov.au/paw/fauna/bau/intro.htm

Within the MBCT region of the Roper River catchment The area is sparsely populated except for the Aboriginal communities located at Numbulwar to the north of the EP, Ngukurr, Urapunga, Hodgson Downs and Djilkminggan. To the east of the NBCT is the township of Borroloola. All locations are outside the boundary of the MBCT. However within the region lies the mothballed Western desert Iron Ore mine and to the west of the MBCT is the defunct Sherwin Iron Ore mine.

The Chapter 1 Introduction to Western Desert Resources Limited Roper Bar Iron Ore Project (2012) EIS states that "Without denigrating the value of the proposed Limmen National Park, it has been assigned potential National Park status due to the fact that it has not been able to support pastoral or other potential economic activities to date. This is not uncommon, especially in the Northern Territory where many conservation estates and Indigenous Lands have gained their current status due to them not being wanted by pastoralists or other

potential land users." The report further states that "The declaration of the National Park may attract more visitors to the region and offer some economic development activities and jobs, but such outcomes are expected to be minor and comparisons to other high profile, including joint managed and traditionally owned,
National Parks in the NT can be used to validate this statement."
The land mainly supports Indigenous use and conservation, but other uses include mining as described having been undertaken by Western Desert Resources to the south, recreation and tourism.
The southern half of the MBCT region south of the Coxs River supports cattle grazing on pastoral lease land, which extends into the south of the bioregion. There is some limited tourism. The Limmen National Park overlies portions of the MBCT.
The Limmen National Park has been subject to very little biological research, leaving an uncertain picture of the biological richness of the Southern Gulf of Carpentaria (Griffiths *et al*., 1997).

The dominant vegetation communities are eucalypt woodlands with hummock grass or tussock grass understorey (Connors *et. al.,* 1996). However, the varied topography, particularly in the northwest is reflected in the diversity of plant communities. The most widespread communities In the southeast are a low open woodland of snappy gum (*Eucalyptus leucophloia*) with bloodwood (*Corymbia terminalis*), ironwood (*Erythrophleum chlorostachys*) over curly spinifex (*Plectachne pungens*) hummock grassland. Other associations include northern box (*E. tectifica*) with white grass (*Sehima nervosum*) and golden beard grass (*Chrysopogon fallax*).

Variable barked bloodwood (*Corymbia dichromophloia*) and Stringybark (*E. tetrodonta*) also form low open woodland with Darwin woolly butt (*E. miniata*). In some areas woodlands include rusty bloodwood (*Corymbia ferruginea*), lancewood (*Acacia shirleyi*). Coolabah (*E. microtheca*) occurs along some creeks and there are extensive paperbark swamps (*Melaleuca citrolens*) (Kerle, 1996).

In the north west of the region woodland communities include stringy bark, cypress pine (*Callitris intratropica*) and silver box (*E. pruinosa*) (Connors *et. al.,* 1996). Northern cypress-pine has suffered where traditional Aboriginal fire regimes have been changed (Woinarski, *et. al.,* in prep.). Vine thickets are scattered along the rivers through the sandstone country and contain relict species including, rushes and reeds and the fern *(Lygodium microphyllum*) as well as undescribed species of ferns (Morton *et. al.,* 1995).

The mangrove plant communities along Roper River (except the Limmen Bight River) show the lowest level of floristic diversity (i.e. 4-14 species) of all tidal waterways surveyed across the Northern Territory and Kimberley region of Western Australia (Wells, 1985). It is considered by Wells (1985) that the mangrove plant communities are greatly influenced by climatic variations and that there is a gradual decline in mangrove species richness southwards on both the east and west coasts of Australia. Messel *et al*. (1980) noted that mangrove associations form the fringing riverside vegetation up to 100km along Roper River from the mouth.

Freshwater plant species begin to appear amongst riverside vegetation 67km from the Roper River mouth. Weed species (in particular Parkinsonia, Hyptis and Grader Grass) were perceived to be causing localised problems throughout the catchment, particularly in disturbed areas, intensive use areas and along watercourses (Kerin, 1993). A number of weed species have invaded sections of Elsey National Park (CCNT, 1994a). There were 17 introduced plant species listed for the Park including *Parthenium hysterophorus*, Devil's Claw (*Martynia annua*), Parkinsonia (*Parkinsonia aculeata*) and Rubber Bush (*Calotropis procera*) (Griffiths, 1997).

Fauna

The *Limmen Bight (Port Roper) Tidal Wetlands System* is a major migration stop-over area for shorebirds (especially godwits and knots), and one of the most important coastal sites in the Northern Territory in terms of shorebird numbers, especially the Port Roper mudflats. The seagrass beds are a major breeding area for prawns and an important feeding area for Dugong and the Green Turtle (Poiner *et al*., 1987; ANCA, 1993). Medium densities of the Saltwater Crocodile (*Crocodylus porosus*) occur in the Roper River estuary (ANCA, 1993) and, overall, the area of suitable nesting habitat for *C. porosus* is extensive on the Roper

Land Tenure & Use

Most of this bioregion is pastoral leasehold land. There are also extensive areas of Aboriginal freehold land. 66.3% of the NT portion of the bioregion (or 69,530 sq. km) is pastoral leasehold, 26% (27,302 sq. km) is Aboriginal freehold, and 6.7% is reserved area (7,067 sq. km). A large National Park has been established at Limmen Gate in the Northern Territory (Woinarski, *et. al.,* in prep.) from a relinquished pastoral station.

Cattle grazing is the dominant use within the region. This is characterized in the region by a low input of labour and capital and few fences. The industry is generally of marginal profitability or non-viable in the region.

On Aboriginal land in the Northern Territory some traditional mosaic burning regimes are being maintained (Tropical savanna site fire). There is one large lead and zinc mining enterprise at McArthur River, and there are several smaller operations in the broader bioregion including the mothballed Western Desert mine on the Towns River.

Land degradation

Degradation of some areas by overstocking of cattle has been documented (Woinarski, *et. al.,*). Morton, *et. al.,* (1995) also notes that the rocky ranges of this bioregion are a significant biological refuge but these require better cattle management, as well as improved fire management. Monsoon rainforests in the region are being degraded by inappropriate fire regimes, weeds and feral animals. Inappropriate fire regimes are also now reducing the floristic diversity of heath land vegetation in sandstone plateau and escarpment areas. This is impacting on the abundance and distribution of fauna associated with these areas, including the carpentarian grass-wren (*Amytornis dorotheae*) (Woinarski, *et. al.*). There are localised impacts of tourism on some sites (Connors *et. al.,* 1996).

Pest species

Pest animals include cane toads, horses, pigs and cats. (For more details refer to Connors *et. al.,* 1996, www.savanna.ntu.edu.au/information/savannaexplorer.html) . Connors *et. al.,* 1996 identify 25 weed species in the bioregion, these include bellyache bush (*Jatropha gossypifolia*), spinyhead sida (*Sida acuta*), Noogoora burr (*Xanthium pungens*), Parkinsonia (*Parkinsonia aculeata*), mesquite (*Prosopis spp.*), khaki weed (*Alternanthera pungens*) and hyptis (*Hyptis suaveolens*). Mexican poppy (*Argemore ochroleuca*) occurs in some catchments including the McArthur River. Rubber vine (*Cryptostega grandiflora*) is a potential threat to this bioregion, it is already a major problem on the Queensland side of the border.

Social & Economic Aspects

The pastoral industry in this region is very extensive, and supports a sparse population. There is a significant Aboriginal population in the region. Aboriginal lands include Wannyi / Garawa on the Northern Territory side of the Queensland border, Alawa, Hodgson Downs, Yutpundji Djindiwirritj, and parts of Garawa, Narwinbi, Beswick, Mara at Borroloola and Hodgson Downs, Ngukurr and Numbulwar and Arnhem Land. The bioregion is within the Katherine ATSIC region. For more information on the Aboriginal people of this region refer to Horton, (1994) and the relevant websites in the reference list.

The upper reaches of the Towns River meander through the mining area of the failed Western Desert iron ore mine south of the Roper River. The head of the catchment has an elevation of approximately 30.5 m (AMSL) and flows into the Gulf. The Towns River is approximately 84 km long (Bonzle Digital Atlas of Australia, 2011).

The Towns River lies south of the Roper River and north of the Limmen Bright River and McArthur River. Yumanji Creek (Little Towns River) and Magaranyi River both flow into the Towns River. The Towns River has similar characteristics to the larger Roper and McArthur rivers. The highest flows occur during the wet season, predominantly due to cyclones and monsoonal rainfall. However, in contrast to the larger rivers, the Towns River is ephemeral and usually runs dry during the dry season.

Roper River System

Messel et. al. (1980) identify the perennial nature of the spring-fed Roper River; the floristic diversity and restricted range of the riparian vegetation; and the representation of “tufa” formations have been identified as important natural resources within Elsey National Park (CCNT, 1994a) to the west of the MBCT area. The Park is considered to have moderate conservation values in a regional context and contains a number of flora and fauna species of conservation significance (Griffiths, 1997).

The damage caused by feral animals includes: overgrazing; trampling and foraging causing soil disturbance, accelerated erosion, invasion and spread of weed species; destruction of habitats by rooting, burrowing and wallowing, reducing the aesthetic and productive value of land and reducing the lands ability to resist erosion (CCNT, 1994a; Telfer, 1998). The feeding behaviour of these introduced animals has the potential to modify the natural floristic composition of certain areas and/or result in competition for food with native herbivores (CCNT, 1994a).

The mean annual rainfall recorded for Mataranka Homestead Resort, Nutwood Downs, Mainoru and Maranboy is 792.6 mm, 694.2 mm, 747.3 mm and 823.3 mm respectively (NT Bureau of Meteorology, 2000). Over 90% of the mean annual rainfall throughout the Roper River catchment falls during the wet season (November to March). The mean monthly rainfall varies from 0 mm during the dry season to 216.2 mm during the wetter months. Table 8 shows the mean monthly rainfall recorded for various locations within the region.

Table 8. Summary of Climate Data for Locations within the Roper River Catchment

Location	Daly Waters (1873 - present)	Larrimah (1952 - present)	Ngukurr (1910 - present)	Flying Fox Stn (1996 - present)
Mean daily Min-Max Temp Range (^{0}C)	19.1 - 34.2	19.8 - 34.0	20.8 - 34.2	20.3 - 34.9
Mean 9am relative Humidity (%)	54.4	62.0	65.8	64.1
Mean 3pm Relative humidity (%)	30.6	35.4	35.3	39.5
Mean Annual Rainfall (mm) [no. years]	669.2 [101]	805.3 [45]	752.4 [55]	992.7 [3]
Mean Monthly rainfall Range (mm)	1.6 – 163 (July - Feb)	0.3 - 198.8 (Aug - Jan)	0.4 - 172.5 (Aug - Jan)	0 - 216.2 (Aug - Feb)
Highest Recorded Daily Rain (mm)	180.1 (Nov 1896)	408.6 (Jan 1987)	271.5 (Jan 1976)	117.1 (Feb 2001)
Mean Number of Rain Days per Year	56.4	66.7	51.4	74.8
Mean Total Annual Evaporation (mm)	2,405.5	-	2,219.2	1,523.3

Source: Climate and Consultancy Section, NT Bureau of Meteorology (2000-2001)

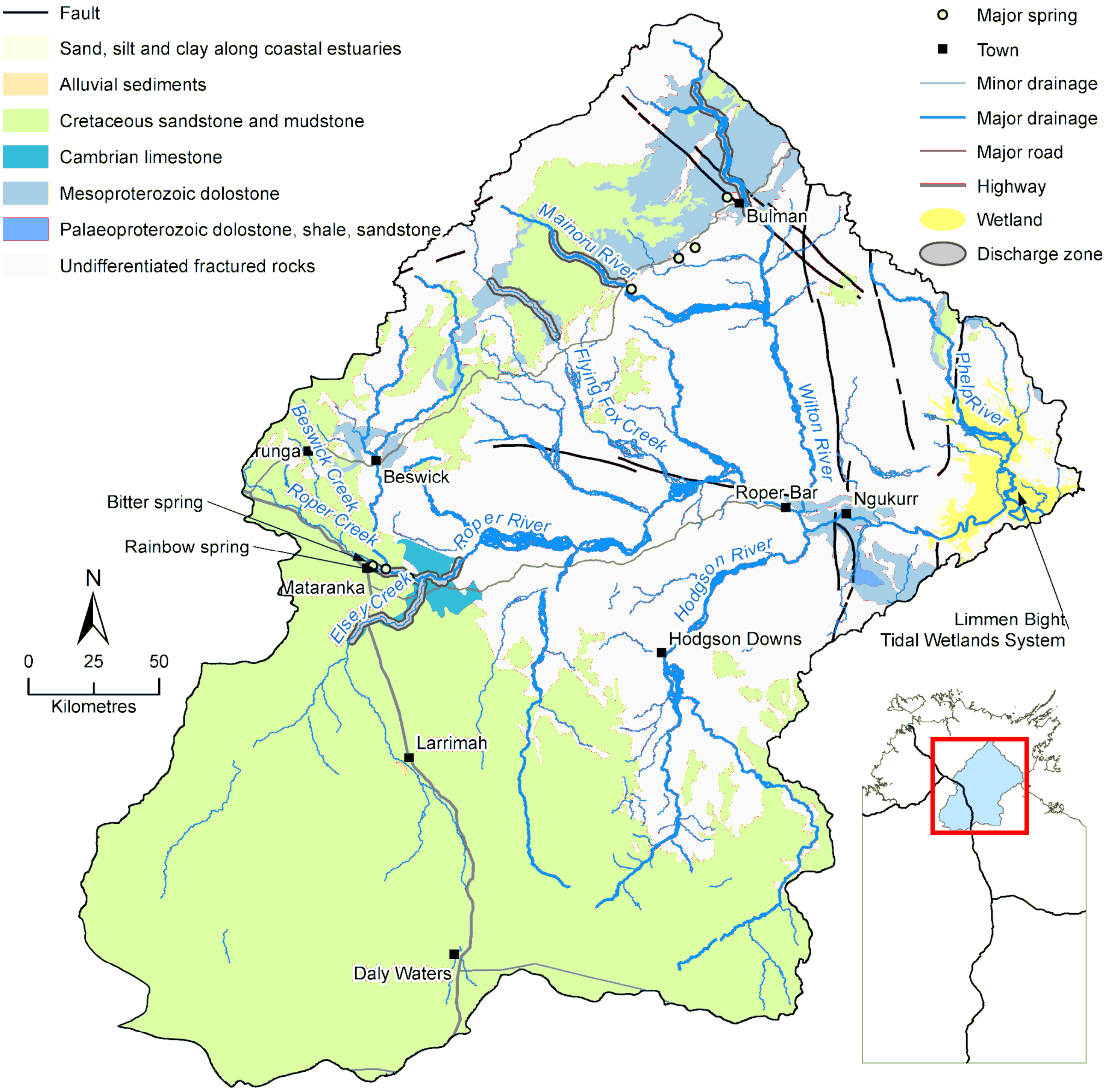

Figure 6: Groundwater Model of the Roper River Catchment
from Gulf Water Study Integrated Surface - Part B: MIKE11 Surface Water Model

The average yearly evaporation greatly exceeds the average rainfall, which is typical for the northern Australian climate (Sivertsen and Day, 1985). Lucas and Manning (1989) reported that evaporation exceeds rainfall for nine months of the year at Mataranka and peaks at the start of the build-up season (October and November). Rain is usually high-intensity falls. Most of the region’s rain comes as hard, intermittent, tropical showers, often associated with thunder and lightning (Bauer, 1964) or as monsoon troughs and tropical lows, which are often the remains of cyclonic depressions.

Landforms

There are two major underlying geological units in the bioregion. Towards the coast is the McArthur Basin consisting of Proterozoic (545-2500 million years ago) marine and continental sediments and volcanics (1,000 — 2,500 million years old). Further inland is the Georgina Basin consisting of Devonian to Late Proterozoic (350 — 1,000 million years ago) marine sediments and volcanics.

Surveys providing detailed land systems, land unit or soils mapping have been carried out for areas throughout the Roper River catchment conducted by the Northern Territory Soil Survey. Within the Roper River catchment there were six major landforms identified ranging from plateau surfaces; plateau escarpments; gorges and ridges associated with the dissected plateau and hills; plains; drainage lines, associated floodplains and billabongs; salt pans and tidal flats.

The Arnhem Land Plateau, dominated by Kombolgie sandstone, rises up to 440m above sea level. Other plateaus include Wilton River Plateau and the Sturt Plateau. A total of 62 land systems were mapped and described as part of the 'Land Systems of the Roper River Catchment, Northern Territory' survey (Aldrick and Wilson, 1992). These land systems have been grouped into six "geomorphic provinces". These geomorphic provinces provide a basis for predicting the susceptibility of land to degradation (Aldrick and Wilson, 1992).

The Sturt Plateau, covering the south-western section of Roper River catchment, has been described as an old uplifted erosion surface of some 250m elevation. It is a flat to gently undulating plain that is deeply weathered, covered by thick laterite and associated soils and supports predominantly savannah vegetation (Day *et al.*, 1985). A total of 19 land systems were mapped and described as part of the 'Land Resources of the Sturt Plateau' survey (Day *et al.*,1985); eight of these land systems comprise gently sloping to almost level plains and four comprise alluvial plains on the Sturt Plateau.

Geologically the Roper River catchment is complex (Aldrick and Wilson, 1992). The geology of the Roper River catchment has been mapped and described at a scale of 1:250,000 by the Northern Territory Geological Survey and Australian Geological Survey Organisation (formerly Bureau of Mineral Resources). A geological map of the Northern Territory, at a scale of 1:2,500,000, has been compiled using the 1:250,000 geological map series (Ahmad, 2000) and is available from the Northern Territory Geological Service in Darwin. It is significant to note that as displayed in figure 6 only a very limited area of the Roper River catchment actually overlies the MBCT region.

Stream Flow and Groundwater

Stream flow gauging commenced in the Northern Territory in 1952 and the first flow gauge station was set up in the Roper River catchment in 1953 at Elsey Homestead (Dep't of Transport and Works, 1980). Table 9 shows the location of the flow gauge stations within the

Roper River catchment. Rainfall data for the region are supplemented by information from pluviometer (automatic rainfall recorders) stations. In addition to daily rainfall recordings carried out by the Bureau of Meteorology there are nine pluviographs operating in the Roper River catchment for flood hydrology work. These are located at Beswick; on Chambers and Daly Waters Creeks; and Roper River downstream of Mataranka and at Red Rock. The stream flow contributions to the Roper River from Elsey and Flying Fox Creeks, Hodgson, Waterhouse and Wilton Rivers (on which flow gauge stations exist or have existed) vary considerably. In particular, the flow from the Elsey Creek system has a small contribution despite having the largest catchment area in the Roper River catchment.

Table 9.Summary of Stream Flow Information for the Roper River Catchment

Gauge Station Number	Tributary Catchment Area (km2)	Mean Annual Flow Volume (m3)	Mean Annual Discharge (m3/sec)	Median Annual Discharge (m3/sec)	Mean Monthly Discharge (min-max) (m3/sec)
G9030124 Daly Waters Creek	777	8,691,000	1.0	0.6	1.1 (0-5.1)
G9030001 Elsey Creek	18,785	98,330,000	10.1	4.6	8.3 (0-54.1)
G9030176 Roper River	5,610	500,700,000	20.5	13.6	20.4 (0.7-182.5)
G9030250 Roper River	47,400	2,269,000,000	88.8	66.9	100.9 (0-420.4)
G9030089 Waterhouse River	3,110	184,900,000	9.8	7.6	11.2 (0.3-77.4)
G9030108* Flying Fox Creek	1,350	31,280,000	1.2	0.7	1.5 (0.1-5.3)
G9030102* Hodgson River	14,200	1,044,000,000	83.7	78.7	89.6 (2.4-254.4)
G9030146* Wilton River	12,400	1,565,000,000	65.6	65.9	127.1 (0-282.5)

* Closed Gauge Station

Source: Figures obtained from 'Hydsys'. Stream flow information is based on data from some stations that are no longer in operation or have a limited number of gauging's and, consequently, the ratings that generate the stage-to-discharge relationship cannot be guaranteed.

The concentration of monsoonal rains during the wet season, November to March, is reflected in marked seasonal changes in stream flows. In the wet season, river flows increase due to rainfall runoff. Generally, river discharge tends to increase as the wet season advances even though, in a normal wet season, the rainfall may be more or less uniformly distributed from December through March. Rainfall can be variable and high intensity falls can occur (e.g. highest daily rain recorded at Larrimah was 408.6 mm and occurred in January 1987).

Those gauge stations recording a minimum monthly discharge that is greater than zero throughout the year, are located on Hodgson, Waterhouse, Wilton and Roper Rivers, and Flying Fox Creek. The dry season flows or "base flow" in these river systems is attributed to groundwater discharge from springs or seepage points. The contribution of groundwater becomes increasingly important as the dry season progresses because these river systems would otherwise become isolated pools or dry up completely. The many springs in the Mataranka area and in the reach of the Roper River as far as Elsey Homestead, are due to discharges from the regional limestone aquifer - Tindal Limestone (Yin Foo, 2000b). The springs are natural outflow points for groundwater, occurring where the water table has been incised by the river bed. The result is that the flow in the Roper River is maintained throughout the year.

Groundwater discharge from aquifers in the Dook Creek Formation provides dry season flow in Flying Fox Creek, Mainoru River and some of the Wilton River (George, 2001a). Table 9 shows the mean monthly discharge recorded for two gauge stations located on Roper River as well as gauge stations on Hodgson and Wilton Rivers. These rivers are perennial or permanent flowing rivers recording flows throughout the dry season.

The lowest mean monthly discharge along Roper River occurs in September and October and ranges from 1.5m^3/sec near Mataranka to 1m^3/sec at Red Rock. The highest mean monthly discharge recorded for Wilton and Hodgson Rivers occurs in March and is 557m^3/sec and 377m^3/sec respectively. The lowest mean monthly discharge recorded for these two stations occurs in July and August and is 0.5m^3/sec and 0.2m^3/sec respectively. Each of these locations lie outside the McArthur Basin Central Trough region.

These stations recorded their highest mean monthly discharge in February-March and their lowest discharge in September-October. Mean monthly discharges for Flying Fox Creek and Waterhouse River ranged from 0.4-6m^3/sec and 0.2-34m^3/sec respectively.

Both of these systems recorded flows during the dry season indicating that they are spring-fed (i.e. groundwater discharge is contributing to these flows). Extraction of water from rivers and creeks (i.e. surface waters) occurs for stock and domestic purposes within the Roper River catchment. Where greater volumes of surface waters are needed for irrigation, domestic or mining purposes, 'Water Extraction Licences' are required. These extraction licences are issued and managed by the Department of Lands, Planning and Environment under the *NT Water Act*. There are currently six Water Extraction Licences for the Roper River. Four of these licenses are for community water supply purposes and another two are located at Roper Bar for domestic purposes and maintenance of gardens. The maximum yearly extraction figures set for these six licences totals 403 ML.

Aquifer types

There are three major aquifer types in the Roper region. These types are fractured rocks, karstic carbonate rocks and Cretaceous sediments, all of which are briefly described below.

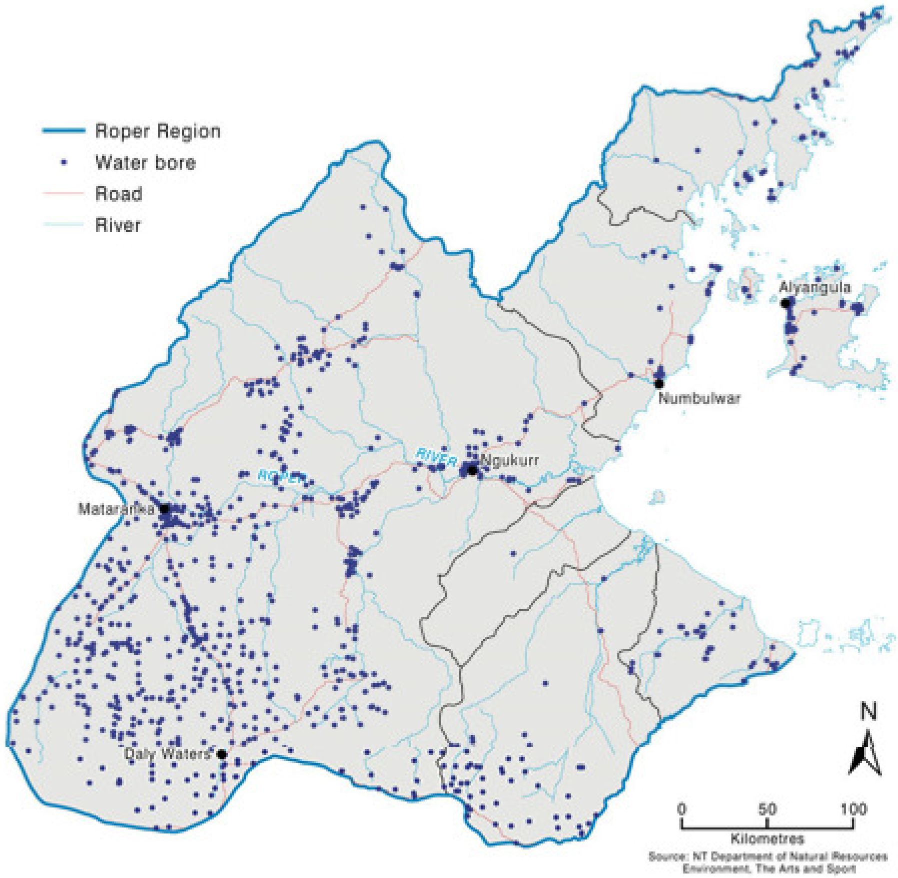

Fig 7: Location of groundwater bores in the Roper region (map provided by the Northern Territory Department of Natural Resources, Environment, The Arts and Sport)

Fractured and weathered rock aquifers

A variety of Precambrian rocks form the bedrock of the area. These are mainly sedimentary but also include granite and volcanic rocks. Sandstone, siltstone and greywacke are the main sedimentary rock types. In some areas they are flat-lying while in other areas they have been folded, faulted and show low grade metamorphism. In the Early Cambrian (500 million years ago) volcanic eruptions produced an extensive sheet of basalt flows, now known as the Antrim Plateau Volcanics. These underlie the Daly, Wiso and Georgina basins.

Water is usually intersected in weathered fractured zones within the fractured rocks. Groundwater yields are controlled by the degree of fracturing of these units and are likely to be greater in areas located along large-scale joints and fault zones. Fractured rock aquifers developed in Proterozoic sandstone have been developed as a water supply source for a number of small communities in the region. Insufficient data on water levels is available to provide comment on annual water level variations.

Carbonate rocks with yields of 0.5 to 5L/s aquifer types are located through the centre of the region associated with the Batten Trough (MBCT). Carbonate rocks occur in most of the major rock formations of the McArthur Group and within the Balbirini Dolomite of the Nathan Group.

The principal potential aquifers identified within the McArthur Group are the Yalco Formation and the Emmerugga Dolostone.

These formations contain dolomitic rocks such as dololutite and dolomitic siltstone and these rocks are largely reliant on fracturing for aquifer development. They are identified as lower yielding and for water flow the faults and fractures should be targeted. The flow system is defined as local and dry holes are not uncommon in this rock type. Supplies from fractured rock aquifers are commonly small (0.5 – 5 L/s), usually sufficient for stock and domestic uses. Occasionally airlift yields of the order of 10L/s can be encountered but may not be sustainable. Where fracturing has occurred throughout the mass of rock and weathering has enhanced these fractures better yields may be sustained.

Over time aquifers in the Bukalara Sandstone (Neoproterozoic - Ordovician) and rock formations of the Roper Group, which primarily consist of sandstone, have become indurated (cemented) so little primary porosity remains. However, the effects of fracturing and weathering have provided permeability to the rocks allowing some aquifer development.

The Moroak, Bessie Creek, Hodgson and Arnold Sandstones of the Roper Group are similar, consisting of quartzarenite and form resistant pseudo-karstically weathered outcrops occurring as low ridges and small scarps. The spectacular joint controlled karst topography often referred to as 'the lost city' occurs in these rocks, particularly in the Hodgson Sandstone. These formations generally exist across the MBCT as either remnant Mesa plateau's and are disconnected from aquifer recharge.

Cretaceous sediments

The Cretaceous sediments form a mantle of lateritised claystone and sandstone covering much of the area. The sediments have only been mapped where it is expected that they form the major aquifer at that locality. However they overlay the karstic rock aquifers over much of the region. The beds are sub-horizontal and may be divided into an upper claystone and siltstone unit and a basal sandstone unit. Outcrop is generally sparse due to the soft nature of the rock but in places silicification has altered them to porcellanite and quartzite.

In the Wiso and Georgina basins the formation may be up to 75 m thick with the clayey upper unit comprising 60 m of its thickness. The thickness of the sandy unit is variable and ranges from less than 5 m to up to 25 m. Where the upper claystone is thin and eroded, the potential recharge to the underlying limestone aquifer is increased. In most places within the basins the sediments lie above the regional water level. In the north-east the formation may be over 100 m thick with most of that thickness being permeable sandstone.

The Cretaceous sandstone aquifer contributes significant dry season flows to many rivers in the north-east of the region. Changes in dry season stream flow rates occur in response to changes in the amount of rainfall that recharges the aquifer during the preceding wet season. The changing recharge rate is reflected in the variation in water level measured in monitoring bores intersecting the aquifer. The data indicates that annual groundwater rises due to recharge during the wet season vary from minimal during the 1989/90 wet season to 4.5 m in 1993/94 and 1998/99. As previously mentioned Prowse et al. (1999) demonstrated that periods of relatively low groundwater levels correspond to periods when stream flows are relatively lower in the perennial rivers of Groote Eylandt; likewise higher groundwater levels correspond with higher flows.

Sedimentary rocks lie along the north coast of the McArthur River map region. The top (shallow) aquifer occurs in sediments consisting of poorly consolidated alluvium, sand, clays and gravels. Mutton (2006) considered the sediments to be of Cretaceous age or younger and belonging to the overlying Carpentaria Basin.

These sediments were intersected in drill holes RN28349, RN28470 (near Wonmurri on Manangoora Station), drill holes RN35922 and RN35923 (on the adjoining Greenbank Station) as well as in drill holes from mining companies that explored on Seven Emus, Greenbank and Manangoora stations in proximity to the NT/Qld border outside the zone of influence of the MBCT area within the Roper River/McArthur River region (See Mutton 2006, Poltock 1993 for mineral exploration bore information). Below the shallow aquifer a Cretaceous grey mudstone was encountered in a number of the bores. The mudstone varied in thickness from about 10 m in the bores near Wonmurri (RN28349, RN28470) to 45 m in RN35922. Below the mudstone a deeper aquifer in soft, possibly Cretaceous, sandstone was intercepted in the Wonmurri bores around 50 m depth and was high yielding (airlifting 10 L/s). This reflects known sequences in the Carpentaria Basin to the south where sandstone was deposited by fluvial deposition in the Jurassic to Early Cretaceous followed by mudstone in a marginal and shallow marine setting in the middle Cretaceous (Mutton 2006). Not all bores drilled into the sediments yielded water. In bore RN28349 a flow of 3L/s was airlifted from this aquifer. The aquifer was generally encountered above 40 m.

Poltock (1993) offers a completely different interpretation to the sedimentary rock discussed and suggests that they are in part weathered Karns Dolomite. He noted difficulty in 'differentiating between unconsolidated cover sediments and weathered Proterozoic lithologies' and interpreted 'clays and interlayered friable sandstones to represent dolomites and dolomitic sandstone' in mineral exploration drill holes on Southern Greenbank Station. No matter what the origin, what is for certain is that these sediments generally provide yields of about 2 L/s with moderate success rate. Again the location of this study is well to the east of the region of the MBCT.

Karstic carbonate rock – Tindall Limestone, Jinduckin Formation and Proterozoic carbonates (includes the Dook Creek Formation)

The major aquifers in the broader region occur within the carbonate rocks of the Daly and Georgina basins and the Dook Creek Formation. These carbonate rocks are part of an extensive area of carbonate rocks that extend across a large part of the Northern Territory and into Queensland. The Tindall Limestone and its equivalents (the Montejinni Limestone in the Wiso Basin and the Gum Ridge Formation in the northern part of the Georgina Basin) host widespread karstic aquifers. These aquifers have very high permeabilities due to an extensive network of interconnected solution cavities. The Jinduckin Formation and its equivalent (the Anthony Lagoon Beds in the northern part of the Georgina Basin) is mainly composed of siltstone. The formation contains thin, local aquifers in isolated limestone beds.

Lauritzen and Karp (1993) concluded that the Tindall Limestone karst aquifer developed before the Cretaceous period. The permeability of the karst aquifer has been further enhanced since then by the movement of acidic groundwater from the aquifer developed in the basal Cretaceous sandstone where it overlies the limestone. It is believed that the karst aquifer in the Oolloo Dolostone developed in a similar way.

The Tindall Limestone karst aquifer is the main contributor to dry season flow in the upper reaches of the Roper River. The Dook Creek Formation contributes significant dry season flow to the upper reaches of the Wilton and Mainoru rivers and Flying Fox Creek, all of which are tributaries of the Roper River. The Tindall Limestone is the aquifer of most interest to irrigators as it occurs beneath land suitable for irrigation and can yield high flow rates (greater than 50 L/second per bore) from relatively shallow depths. The groundwater catchment of the Roper River extends into the Georgina Basin for more than 400 km outside of the surface water catchment of the Roper River (Tickell, 2005).

The aquifer developed in the Tindall Limestone that lies beneath the Wiso Basin in the South west of the Roper River catchment also provides a significant proportion of the flow in the Flora River which is located in the Daly region. In dry periods such as the 1960s and early 1970s discharge from the Tindall Limestone into the Flora River was critical to maintaining the perennial nature of all of the Daly River.

As the Tindall Limestone aquifer underlies such a large area, its recharge rate can vary significantly due both to the areal variability in rainfall and the presence or absence of Cretaceous sediments overlying it. Knapton (2006) modelled the Tindall Limestone aquifer across those parts of the Daly, Wiso and Georgina basins that discharge either to the Daly River or Roper River. The average annual recharge rate to the area within the Roper River catchment providing spring flow to the upper reaches of the Roper River ranged from a low of less than 1 mm in the south to a high of 73 mm in the vicinity of the Roper River. Limited water level monitoring data exists for the Tindall Limestone in the Roper region.

Again it is significant to note that the Tindall limestone and its equivalent formations are not present within the MBCT as they exist at a stratigraphic level well above the modern ground surface level within the Batten and Walker Troughs to comprise the MBCT.

Karstic carbonate rock

Tindall Limestone, Jinduckin Formation and Proterozoic carbonates (including the Dook Creek Formation)

The major karstic aquifers in the greater region occur within the carbonate rocks of the Daly and Georgina Basins and the Dook Creek Formation. These carbonate rocks are part of an extensive area of carbonate rocks that extend across a large part of the Northern Territory and into Queensland. The Tindall Limestone and its equivalents (the Montejinni Limestone in the Wiso Basin and the Gum Ridge Formation in the northern part of the Georgina Basin) host widespread karstic aquifers. These aquifers have very high permeabilities due to an extensive network of interconnected solution cavities. The Jinduckin Formation and its equivalent (the Anthony Lagoon Beds in the northern part of the Georgina Basin) is mainly composed of siltstone. The formation contains thin, local aquifers in isolated limestone beds.

There are two karstic fractured carbonate regional flow aquifers listed for the region. They are situated in the Cambrian aged Anthony Lagoon Beds and Gum Ridge Formation and hence are referred to as the Cambrian limestone aquifers. The aquifers are located in the south west corners of the two water resource maps. These areas only represent a small part of these aquifers.

The Gum Ridge Formation is the more extensive of the two aquifers and covers an area running from Tennant Creek to Mataranka. They have a regional scale flow system with groundwater travelling roughly north towards Mataranka. The aquifer within the Gum Ridge Formation and its lateral equivalent – the Tindall Limestone, is the aquifer which discharges to the upper reaches of the Roper River and has been modelled as part of the Gulf Water Study (See Knapton, 2009).

The Anthony Lagoon Beds consists of calcareous and dolomitic siltstone, fine grained sandstone, limestone and dolomite. It overlies the Gum Ridge Formation which consists of limestone, dolomitic limestone, siltstone and chert. There is insufficient data to differentiate between the two formations on the McArthur River map sheet

These deposits largely consist of siltstone and sandstone. On Tanumbirini Station to the west of Bauhinia Downs station bordering the western edge of the MBCT these overlying deposits range in thickness from less than 25 m in the north to over 100m in the south.

Within the McArthur River Region the fractured and karstic carbonate local flow system aquifer type is located in a small area in the north situated in the Yalco Formation of the McArthur Group. Although this formation is located elsewhere in the region, it is only here that sinkholes have developed indicating a potentially localised karstic aquifer. No bores have been drilled into this aquifer, however researchers believe that yields up to 10 L/s or more are possible.

Within the McArthur River region all Cambrian Formation aquifers appear to exist at measured depths of less than 100m from surface.

In the Limmen Bight River Region an aquifer of this type is located in the northeast situated in calcrete. Calcrete is a limestone precipitated at, or near the surface by the evaporation of soil moisture. It is formed in the zone where the water table fluctuates. The deposits are often shallow, less than 20m (Tickell, 2008). Drilling investigations by Sandfire Resources within a region in proximity to the Limmen Bight encountered four metres of calcrete above the water table at a site east of the mapped aquifer. Calcrete has been observed in outcrop in the mapped area. When the aquifer area was visited in August 2008 approximately 10 L/s was discharging from the aquifer to a tributary of the Nathan River. The aquifer is the likely source of base flow to the Nathan River. Given that it is shallow and likely to also drain quickly, water supplies from the aquifer may be limited as the Dry season progresses.

Carbonate rocks have been identified separately under the fractured and weathered rocks aquifer category because they impart a very distinct water quality to the rocks. The carbonate is present in the form of dolomite. This aquifer type lies in the Karns Dolomite which is located in the southeast and northeast of the McArthur River Region map. These areas represent the western boundary of the aquifer which is widespread on the adjoining Robinson and Calvert Rivers map. The flow system is local to intermediate.

Carbonate rocks have the potential to be karstic and as identified there is an area of the Karns Dolomite that is karstic, however, generally the Karns Dolomite does not display karstic features. Some dissolution of the rock is likely to have occurred, such as enlarging fractures, but broad scale interconnected cavity development has not taken place.

Bores drilled into the Karns Dolomite have generally yielded water. Yields have varied up to 25 L/s but 3 L/s appears most common. In some of the bores higher yields may have been obtained if drilling had continued. On the McArthur River Region map only one bore has been drilled into the formation (RN035924) air lifting 5 L/s. The standing water level was 9.8 m.

The Karns Dolomite provides the source of base flow to the upper and lower Wearyan River which lies to the west of Borroloola in proximity to the Queensland border. The discharge in the upper Wearyan River is only able to maintain flow for up to a few kilometres down-stream, however spring discharges to the lower Wearyan River can maintain flow for 10 km, to the tidal limit of the river, during wetter periods.

Across the region aquifers have usually been intercepted within the first 60 m of drilling. The deepest bore drilled was RN35920 (163 m), which also had the highest airlift yield at 25 L/s. This bore intersected a variety of strata sequences including dolomitic siltstone, chert, dolomitic sandstone and dolomite reflecting the sedimentary origins of the rock. The yield in the bore increased with increasing depth as aquifers were encountered in fractured and weathered sections.

Inter-aquifer connection and leakage

Within the MBCT the only aquifers in the region that may be in hydraulic connection are the fractured rock aquifers and the basal sandstone of the Cretaceous sediments in some locations. The study area of the Batten Trough (south of the Roper River) is part of the Gulf Fall and Uplands region and part of the catchment of the Roper River and its tributaries.

The area is drained by many rivers and major creeks that include the Roper, Phelp, Hodgson, Arnold, Wilton, Mainoru, Jalboi, Strangways, Chambers and Waterhouse Rivers, and the Maiwok, Flying Fox and Elsey Creeks. Also within the region are the Limmen Bight River and McArthur River and many of their tributaries.

The Roper River starts as Roper Creek (also called Little Roper River) and becomes the Roper River downstream of the Waterhouse River junction near Mataranka. The Roper River flows generally in an easterly direction, although the geology of the catchment influences the direction of the drainage systems. This middle section of Roper River is braided and flow is often within multiple ephemeral channels.

The McArthur River to the south of the region flows generally in a northerly direction from the upland of the Barkly Tableland to the Southern Gulf in the region of the Sir Edward Pellow islands. The McArthur River and its major tributary the Glyde River drain a significant portion of the Barkly tablelands and the low lying country of the Southern McArthur Basin. The geology of this region does influence the drainage system and the extensive cap of the Bukalara Sandstone outcrop in the south of the region provides an extensive network of ephemeral creeks and streams that follow significant faults and joints within the rock formation.

Landforms, Rock Formations and Hydrology of the Roper to the Barkly Region

The MBCT Batten Trough is bounded by the Roper River in the north and the Barkly Tablelands to the south with the Beetaloo Basin forming the western boundary and the Emu fault proximal in the east. This region generally lies within the McArthur Basin, which consists of quartz sandstone, conglomerate, siltstones, limestone and volcanic rocks of the Mid - Late Proterozoic. The northern edge of the bioregion includes part of the Urapunga-Hells Gate Hinge Line, which consists of Neo-Proterozoic age quartz sandstones, shale and chert and exposed volcanic basement rocks. The region comprises predominantly gently sloping terrain with scattered low hills and breakaways.

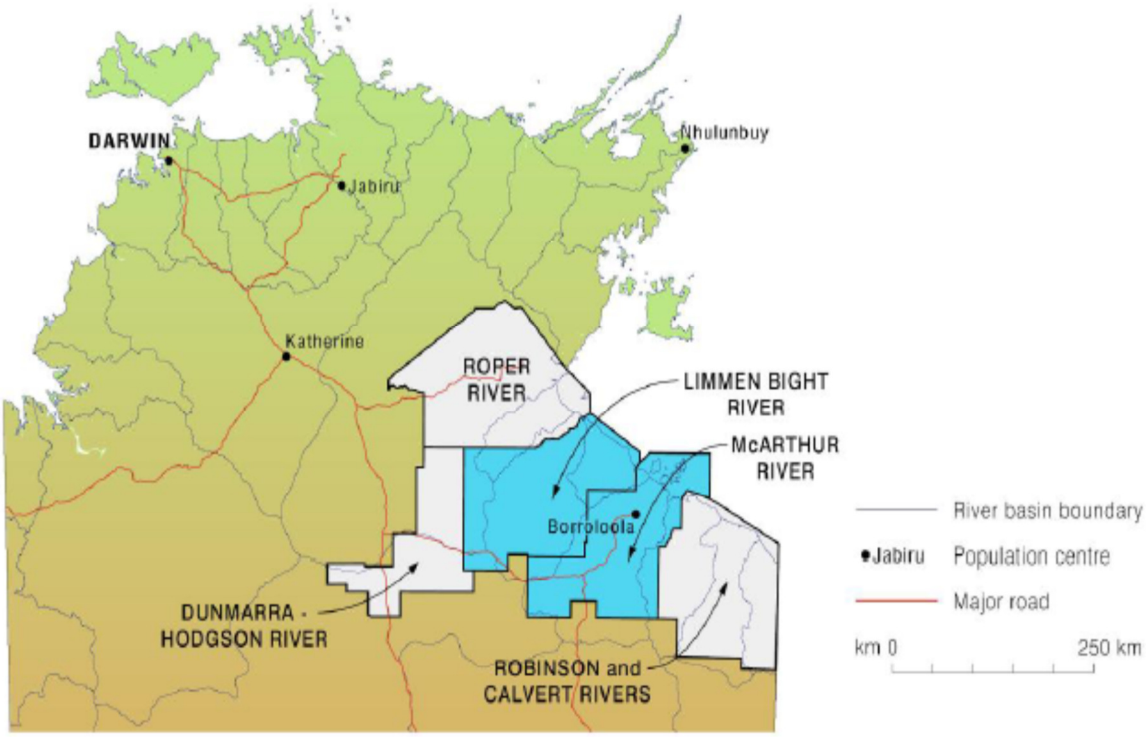

Figure 8: Gulf Region covered by the hydrology study. *The study excludes the area marked as the Robinson and Calvert Rivers. Figure is from Zaar 2009.*

There are two major geological units that underlie the broader region. Towards the coast is the McArthur Basin consisting of Proterozoic marine and continental sediments (545-2500 million years old) and volcanics (1,000 — 2,500 million years old). Further inland is the Georgina Basin consisting of Late Proterozoic to Devonian age marine sediments and volcanics.

The Sturt Plateau, covering the south-western section of the regional river catchment area, has been described as an ancient uplifted erosion surface of some 250m elevation. It is a flat to gently undulating plain that is deeply weathered, covered by thick laterite and associated soils and supports predominantly savannah vegetation (Day *et al.*, 1985). A total of 19 land systems were mapped and described as part of the 'Land Resources of the Sturt Plateau' survey (Day *et al.*,1985); eight of these land systems comprise gently sloping to almost level plains and four comprise alluvial plains on the Sturt Plateau.

Geologically the regional network of river catchments is complex (Aldrick and Wilson, 1992) and the geology of the region has been mapped and described at a scale of 1:250,000 by the Northern Territory Geological Survey and Australian Geological Survey Organisation (formerly Bureau of Mineral Resources). According to Zaar (2009) the greater region of study including the Roper River, Limmen Bight River and the McArthur River regions contain rocks primarily from the McArthur Basin which include the Roper, McArthur and Tawallah Groups. These are old rocks from the Proterozoic eon. The oldest rocks lie at the bottom of the basin and comprise the Tawallah Group.

A Summary Review of the Hydrology of the McArthur Basin Central Trough

The Tawallah and the McArthur Group of rocks are associated with the north trending Batten Trough which runs through the centre of the McArthur River Region map and continues into the eastern sector of the Limmen Bight Region map. The zone is about 50 – 80 km wide. The trough is a sedimentary depression controlled by faults that were active during sediment deposition. There is considerable faulting throughout the Batten Trough (Haines et al., 1993) which is important because faults and fractures can increase the permeability of aquifer rocks and hence bore yield.

The rock formations of the Nathan Group overly the rocks in the McArthur River Group. These include the Karns Dolomite which is located in the eastern part of the McArthur River Region and the Balbirini Dolomite located in the northern area of the Limmen Bight Region. Younger Roper Group Sediments consisting of sandstones, siltstones and mudstones overlie Nathan Group sediments and are situated around and south of Borroloola and in the eastern area of the hydrology study region.

The Bukalara Sandstone, a younger rock from the overlying Georgina Basin, is plateau forming and lies in the centre of the Limmen Bight River map sheet and in the south east of the McArthur River map sheet. The Gum Ridge Formation and Anthony Lagoon Beds are limestone formations younger than the Bukalara Sandstone. They are situated in the southwest of the study region and are overlain by Cretaceous sediments. Cretaceous sediments can also be found in pockets overlying various rock formations throughout the region.

The most recent deposits are from the Cenozoic primarily consisting of sands and clays. They are dominant along the coast and while they may only be several metres thick they mask the underlying rocks.

Topographically the regions lie within the Gulf Fall and the Coastal Plain. The Gulf Fall is defined as the dissected hilly country surrounding the Gulf of Carpentaria. The Coastal Plain is the low lying area between the Gulf Fall and the coast. Drainage is from the higher plateau region towards the coast. The McArthur Basin sedimentary succession comprises sandstone, shale, carbonate, and interbedded volcanic and intrusive igneous rocks.

Within the area regional groundwater studies are limited. As previously mentioned recent studies to the north indicate that major aquifers in the Upper Roper region occur in the Tindall Limestone, Dook Creek Formation and Cretaceous sediments (Tickell, 2009). Each of which lies well outside the MBCT region. These, particularly the Tindall aquifer, recharge in areas where the aquifer intercepts the surface with recharge occurring through karstic conduit systems such as sinkholes and caves resulting from deep weathering (Knapton,2009).

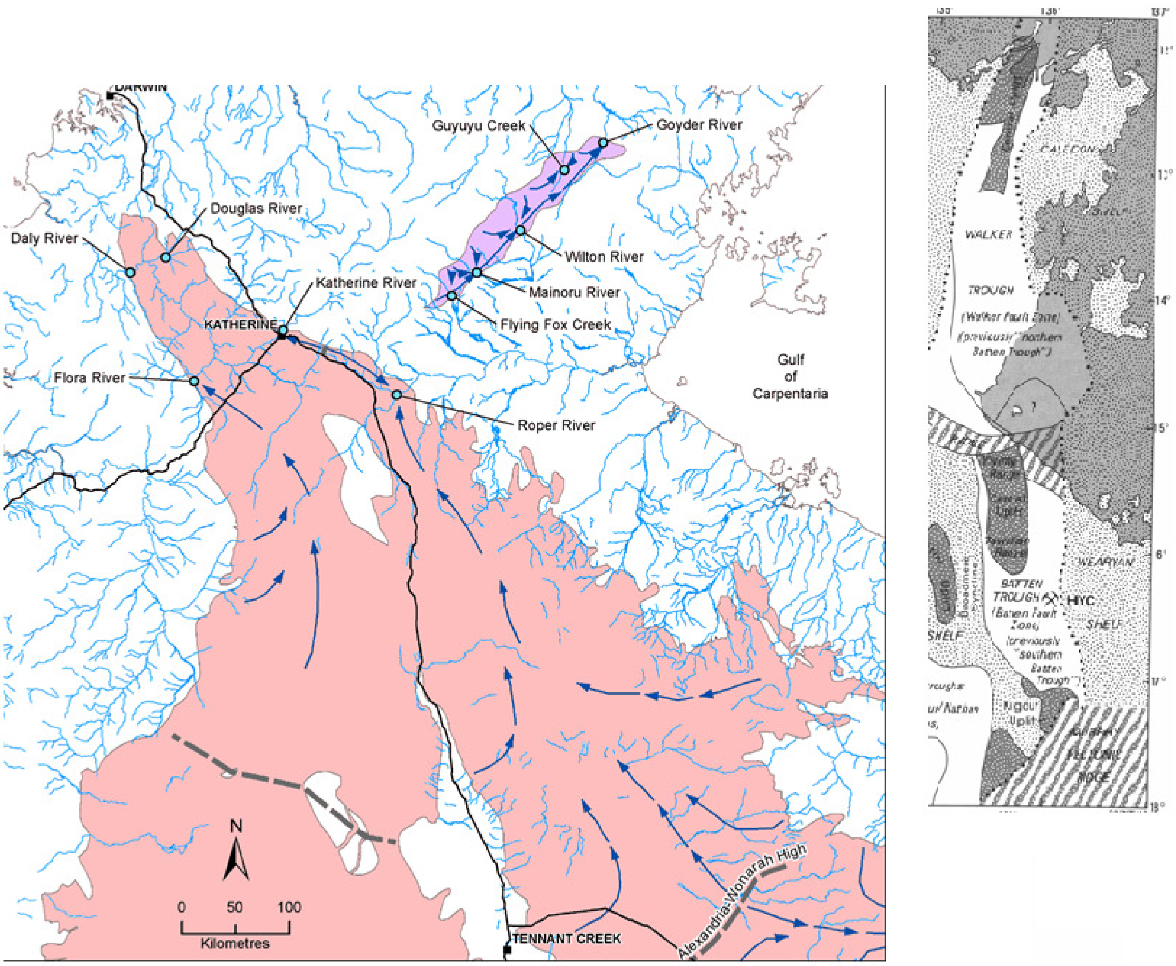

Figure 9: Principle area of the MBCT in relation to the Tindall Limestone.

The figure shown in the hatched box is in relation to regional hydrology. The Blue arrows indicate direction of main aquifer water movement while the pink area is the region of sub crop of the dominant aquifer, the Tindall Limestone. The grey map area identifies the region over which the area of study is concerned [the MBCT]. Groundwater flow within the Cambrian Limestone aquifer system is predominantly from the Alexandria - Wonarah Basement High (Kruse, 2003) in the central Georgina Basin to the major rivers in the Daly Basin to the north. The aquifers do not flow to the NE to the gulf in the McArthur Basin central region.

Identified aquifers of the McArthur Basin :

Gently folded Proterozoic sandstone and shale are the dominant rocks but dolomite, siltstone and greywacke also occur. Aquifers form where these rock types are fractured, mostly in zones shallower than 100 m. Bore yields are mostly less than 2 L/sec but higher yields occur near major fracture zones. Several mines within the region currently use this groundwater for processing and undertake varying levels of dewatering.

Recharge of these aquifers is considered to be of the distributed type (i.e. a recharge that varies spatially and temporally and has different timing and infill points of recharge with the bulk of the input coming through movement of water from outside the area) and a direct local input recharge of probably less than 5 mm/year. Discharge generally occurs via springs and into riverbeds.

Proterozoic dolomite constitute the gently folded Dook Creek Formation. The aquifer associated with this formation is virtually untested but may contain a major groundwater resource. Recharge is of the distributed type, probably within the range 10 to 50 mm/year and most discharge occurs as base flow into riverbeds. This formation occurs to the west north and south of the area of study.

Low-Yielding Proterozoic rocks occur near the town of Bulman on the Central Arnhem Highway to the North east of Katherine in the NT and outside the area of study. This formation comprises various low permeability lithologies in the gently folded Proterozoic McArthur Basin formations. Alternating sequences of shale and siltstone are the dominant rocks but dolerite and granite also occur. Aquifers in these types of rock are either absent or occur in sparsely developed low-yielding fractured rocks. Recharge is likely to be very low.

Cretaceous sedimentary rocks formations comprise poorly consolidated, flat lying Cretaceous sandstones that are virtually untested but may contain a major groundwater resource, similar to that in the Gove Water Control District to the northeast. Recharge within these formations is of the distributed type, probably within the range 10 to 50 mm/year while discharge occurs as base flow into riverbeds. Several of the area's streams maintain dry season flows possibly as a consequence of these aquifers.

Potential aquifers

The Moroak Sandstone

This sandstone is largely located on the Limmen Bight Region map on Broadmere and Bauhinia Downs Stations. No water supply bores have been drilled into the formation but given its similarity to the other Roper Group sandstones, similar yields are anticipated.

The Bessie Creek Sandstone

No supply bores have been drilled into this formation. However drilling investigations undertaken at Minyerri, which is located on the Roper River Region map, established that 'aquifers exist at the contact zone of the Bessie Creek Sandstone with the overlying Velkerri Formation and underlying Corcoran Formation' (Jamieson, 1992). The latter was found to be the more productive of the two aquifers.

Pump tests undertaken have recommended pump rates in these aquifers of below 1L/s. At Minyerri the Bessie Creek Sandstone varied in thickness between 20 – 56 m but on these map regions it is generally much thicker, generally greater than 100 m and up to 300 m thick.

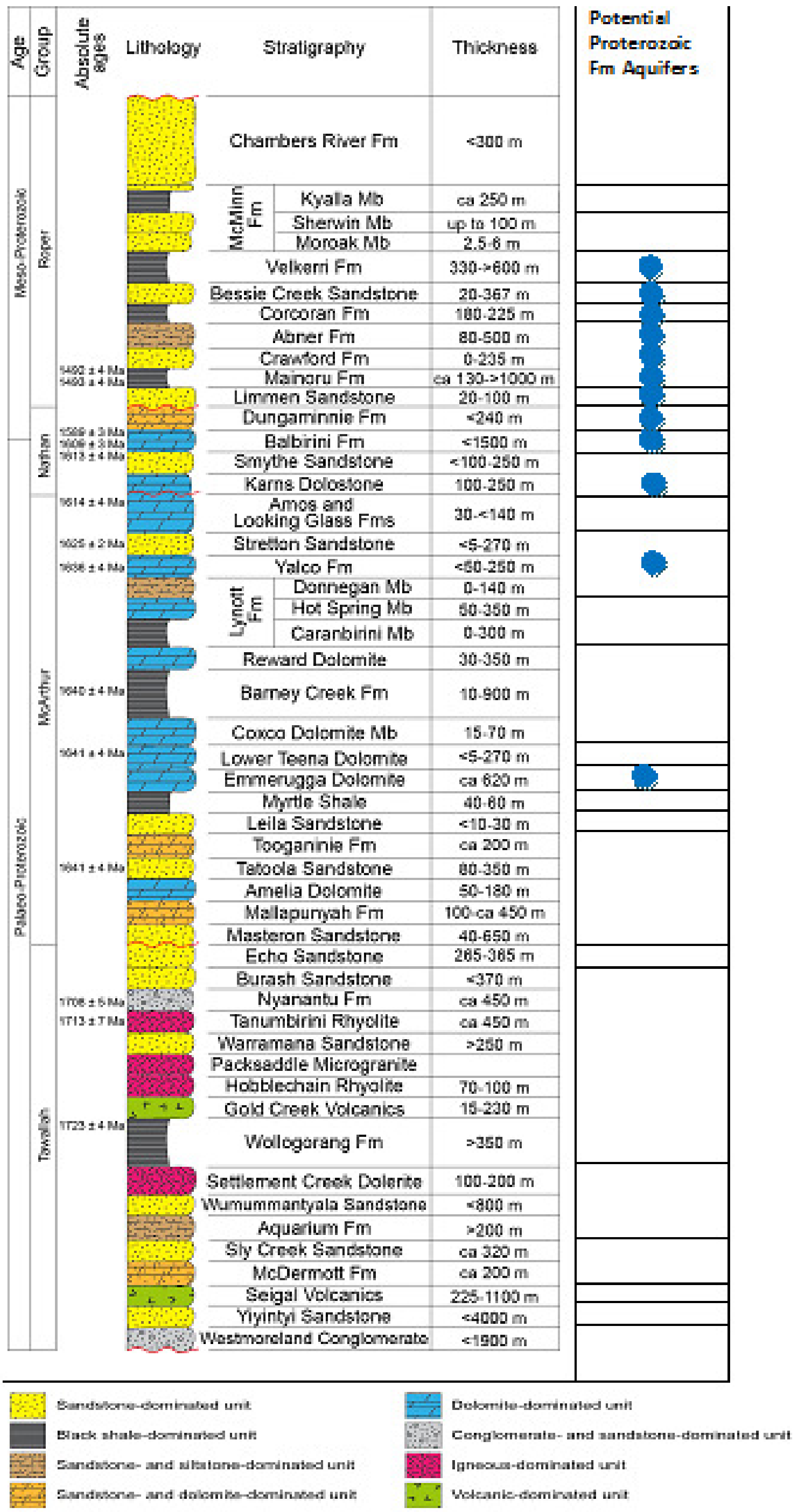

Figure 10: Potential aquifers formations within the McArthur Basin

Abner Sandstone

The Abner Sandstone is composed of three members; the Hodgson Sandstone, the Jalboi Member and the Arnold Sandstone at the base. The Hodgson and Arnold Sandstones are very similar sandstones. The Jalboi Member largely consists of a red mudstone which would act as a semi-confining layer between the sandstones and make a poor aquifer. It belongs to the 'fractured and weathered rocks with minor groundwater resources' category. The sequence occurs on both map regions but the thickness of the members can vary greatly. Above the Hodgson Sandstone lies the Corcoran Formation which is mainly made up of mudstone. Again this is seen as potentially a confining layer with low aquifer potential.

The Abner Sandstone has primarily been drilled at Borroloola to secure a water supply for the town. These drilling investigations reported the thickness of the Abner Sandstone to be no greater than 40 m and hence did not differentiate between the members and simply referred to an aquifer occurring in the Abner Sandstone (Woodford et al. 1995).

Pietsch et al. (1991) also note that the Abner Sandstone 15 km to the southeast of Borroloola is thin compared to the western areas and that the three members of the sandstone cannot be differentiated there. Pietsch et al. have however differentiated the three units around Borroloola on the Bauhinia Downs geology map. The mapping conflicts with results from the water resource investigations, and what Pietsch maps as the Hodgson Sandstone has been interpreted as Bessie Creek Sandstone by Woodford. Although the Abner Sandstone outcrops at Borroloola much of it lies beneath the mudstones of the Corcoran Formation.

Weathering effects such as the dissolution of a carbonate cementing medium in the sandstone is postulated as the probable mechanism for permeability development in the Abner Sandstone (Woodford et al. 1995). Permeability was also noted to be higher in outcropping areas where greatest weathering would have occurred.

The water supply investigations intercepted high airlift yields, greater than 10 L/s, in the bottom 10 m of the Abner Sandstone in a medium grained sandstone. This is likely to be the Arnold Sandstone. It has been identified at Devil Springs 25 km southwest of Borroloola by Pietsch et al (1991) who noted 5 m of white, friable, well sorted medium sandstone lies at the base of the Arnold Sandstone. These strata would provide high yields and is probably what was intercepted at Borroloola.

The high yielding aquifer may be limited to the Abner Sandstone basin in the Borroloola region which stretches as far as the Devil Springs area approximately 30 km to the west. Drilling into the Abner Sandstone outside of the Borroloola area has not replicated these high yields. Pietsch notes that this strata was not intercepted in an investigation bore on the Jandanku Aboriginal Land Trust that penetrated the Abner Sandstone. The strata may be limited to a basin around Borroloola. However there has been no extensive drilling into the lower Abner sandstone outside of Borroloola.

Bukalara Sandstone

The Bukalara Sandstone is generally a fine to coarse grained feldspathic sandstone. It is commonly plateau forming with well-developed jointing. It dominates the southeast of the McArthur River Region map with the Bukalara Range. It also occurs in the centre of the Limmen Bight River Region map in outcrop and under the cover of the Cox Formation which is up to 50 m thick. The Cox Formation consists of very fine sandstone and siltstone.

Jointing (fracturing) within the sandstone is likely to increase the potential yield of the aquifer. Between the two map regions the Bukalara Sandstone has only been drilled in the McArthur River Region where all four bores provided airlift yields up to 7 L/s. On the Dunmarra and Hodgson River Region map the Bukalara Sandstone has been more extensively drilled with yields ranging from 0.3 to 5 L/s.

Minor groundwater resources

In both map regions are areas covered by Proterozoic rock formations consisting of siltstone, mudstone, sandstone and volcanic rocks. Many of these are old rocks that have hardened over millions of years. Fracturing is the most common source of aquifer development in these rocks. Airlift yields can vary considerably dependent on the degree of fracturing. Long term sustainability however is usually limited to small supplies less than 2 L/s. The aquifer flow system is local. The rock formations are generally hard resulting in stable boreholes.

Other groundwater supplies

Alluvial deposits and sand dunes can also provide minor groundwater supplies. These unconsolidated sediments belong to the sedimentary rock aquifer type. They are limited in extent and are not shown on the map. Bores generally yield less than 0.5 L/s. Aquifers can be found in alluvial deposits built up along rivers or on floodplains, particularly where sediments consist of well-rounded gravels and are well sorted (of similar size). Bores drilled in alluvial deposits have a low success rate because of their limited extent, variability in thickness, and gravel, silt and sand content.

Small supplies can be attained from aquifers in sand dunes. Although sand dunes exist within the map sheet they have not been drilled for water supply. The well located on Mooloowa on Vanderlin Island taps groundwater discharging from sand dunes. Interestingly the water quality of the well (G9075065) indicates a carbonate source. The Vanderlin Limestone outcrops on the western side of the island. It is possible that this limestone lies under the sand dunes adjacent to Mooloowa.

Infiltration galleries rather than bores are recommended for extracting water from sand dunes to ensure water quality is maintained. Localised shallow aquifers can also occur in laterite. These are also small in area and are not depicted on the Water Resource maps. They often develop in Cretaceous aged claystone. Through weathering, small cavities (up to centimetre scale) can form in laterite. Root holes and fractures also contribute to the porosity and permeability. Laterite aquifers can provide short term yields of up to 5 L/s but long term yields are usually much lower. This is because the aquifers are shallow, less than 10 m deep, and fill in the Wet season but drain quickly over the Dry season (Tickell, 2008).

Surface water and controls on groundwater hydrology within the southern MBCT region

In most cases, the creeks dry up each year and do not flow again until the next wet season. The wet season begins approximately one month earlier in the west than in the east of the survey area. Consequently, the flow period in the western section is between November and April/May and in the eastern section between December and June. Baseline water quality is typical of that in relatively undisturbed environments in northern Australia.

Water use is principally associated with local pastoral agriculture and relatively minor groundwater extraction for small community supplies. Domestic water supplies are sourced from groundwater, springs, river water and rainwater. Cattle are watered by groundwater, river water, natural waterholes and dams.

In the south of the area the east west trending Favenc Range fringes the Barkly Tableland. This range is composed of Cretaceous sediments and the northern end of the range is a continuous scarp rising to about 30m above the surrounding plain. In the vicinity the McArthur and Roper Group sediments are strongly dissected by a network of creeks.

Most of this region drains to the Limmen Bight, McArthur and Glyde River systems running northwards to the coastal plain with a dendritic drainage of many creeks and small streams. The main tributaries of the Limmen Bight River in the area under study are the Balbirini Creek, Parsons creek, October Creek, Lansen creek, Cat Creek, Crooked Creek, Mantungula Creek, Surprise Creek and the Cox River. To the south east the Glyde River drains into the McArthur River and then into the gulf.

The present drainage system developed post-Mesozoic Era and was largely superimposed upon Proterozoic rocks. Importantly erosion has removed most of the Mesozoic sediments and the drainage structure has been captured by the structural grain of the Proterozoic formations.

Recharge, discharge and regional ground water flow within the southern McArthur Region

Recharge occurs only in the wet season when rainfall intensity and duration is sufficient, and leads to a rise in groundwater levels. In the dry season the levels naturally fall as groundwater is either transpired or discharged to wetlands and rivers, where it evaporates or is discharged to the sea. The amount and rate at which the groundwater levels rise and fall depend on the type, size and other physical properties of the aquifer as well as the amount of recharge.

Recharge beneath native vegetation is dominated by bypass flow and not diffuse movement through soil horizons. The most likely mechanism for this is via macro-pores such as cracks and root holes in the soil. Sinkholes and stream sinks have been located over the Proterozoic carbonates.

Groundwater discharge occurs across the region mostly as evaporation and transpiration (ET). Groundwater discharge is also important for maintaining perennial reaches of many rivers within the greater region. A number of the smaller towns in the greater region obtain their water supply from aquifers developed in sandstone outcrops of Proterozoic age. The sandstone has been fractured and extensively weathered to depths of up to 100 metres. The variability of recharge rate to the fractured rock aquifers is reflected in the variability in water levels measured in monitoring bores intersecting the aquifers.

The only aquifers in the region that may be in hydraulic connection are the fractured rock aquifers and the basal sandstone of the Cretaceous sediments in some locations. According to the literature review there are only two major groundwater systems present in the Roper River catchment.

- The older Meso-proterozoic dolostone unit of the McArthur Basin in the Roper River catchment is called the Dook Creek Formation within the Nathan Group. Overlying the Dook Creek Formation is the Limmen Sandstone at the base of the Roper Group which forms a confining unit. Both these aquifers exist only outside the MBCT.
- Within the Roper River catchment the unit referred to as the Tindall Limestone is a younger Cambrian Limestone member of the Daly Basin, Wiso Basin and Georgina Basin and is not present within the MBCT.

Neither the Dook Creek or Limmen Sandstone formations are found within the area of the Walker or Batten Trough's and reportedly exist only on the east and west Arnhem shelf area.

The stream flow contributions to the Roper River from Elsey and Flying Fox Creeks, Hodgson, Waterhouse and Wilton Rivers (on which flow gauge stations exist or have existed) vary considerably. In particular, the flow from the Elsey Creek system has a small contribution despite having the largest catchment area in the Roper River catchment.

The concentration of monsoonal rains during the wet season, November to March, is reflected in marked seasonal changes in stream flows. In the wet season, river flows increase due to rainfall runoff. Generally, river discharge tends to increase as the wet season advances even though, in a normal wet season, the rainfall may be more or less uniformly distributed from December through March. Rainfall can be variable and high intensity falls can occur (e.g. highest daily rain recorded at Larrimah was 408.6 mm and occurred in January 1987).

Table 10: Major hydro-geological units of the Greater McArthur Basin.

Unit name	Age	Lithology	Hydrologic type	Comment
Dook Creek Formation	Meso proterozoic	Dolostone	Karstic aquifer	Aquifer with major discharge
Limmen Sandstone	Meso proterozoic	Sandstone	Confining aquiclude	Overlies and confines the Dook creek Formation
Antrim Plateau Volcanics	Middle Cambrian	Basalt	Hydrologic basement	Underlies the Tindall Limestone.
Tindall Limestone and equivalents	Middle Cambrian	Limestone	Karstic aquifer	Aquifer with major discharge
Jinduckin Formation and equivalents	Early Ordovician	Shale, sandstone and dolostone	Confining aquitard	Overlies and confines the Tindall Limestone
Mullaman Beds	Early Cretaceous	Claystone and basal sandstone		Overlies large portions of the Tindall and Dook Creek and reduces the amount of recharge

The dry season flows or “base flow” in the Hodgson, Waterhouse, Wilton and Roper Rivers, and Flying Fox Creek river systems is attributed to groundwater discharge from springs or seepage points.

The contribution of groundwater becomes increasingly important as the dry season progresses because these river systems would otherwise become isolated pools or dry up completely. The many springs in the Mataranka area and in the upper reach of the Roper River as far as Elsey Homestead, are due to discharges from the regional limestone aquifer - Tindal Limestone (Yin Foo, 2000b). The springs are natural outflow points for groundwater, occurring where the water table has been incised by the river bed. The result is that the flow in the Roper River is maintained throughout the year.

Both of these systems recorded flows during the dry season indicating that they are spring-fed (i.e. groundwater discharge is contributing to these flows). Extraction of water from rivers and creeks (i.e. surface waters) occurs for stock and domestic purposes within the Roper River catchment.

Recharge

Groundwater recharge rates are variable across the landscape, and depend on soil type, vegetation and topography as well as rainfall amount and other climate variables. The complex interplay between these parameters means there is not a direct relationship between groundwater recharge rates and rainfall amount. There are also complex pathways for water infiltration to water tables. Recharge leads to the rise in groundwater levels and an increase in discharge to the rivers and at the springs. Recharge in the model domain is thought to be via four predominant mechanisms.

- Direct recharge where water is added to the groundwater in excess of soil moisture deficits and evapotranspiration, by direct vertical percolation of precipitation through the unsaturated zone, it is thought that this is the dominant mechanism in areas with Cretaceous cover;
- Macro-pores where precipitation is preferentially 'channelled' through the unsaturated zone and has a limited interaction with the unsaturated zone;
- Localized indirect recharge where surface water can be channelled into karstic features such as dolines (sinkholes), this is a poorly understood component of recharge;
- River recharge when the stage height of the river exceeds the adjacent groundwater level in the aquifer. This is thought to be a minor component of the overall water budget.

Limited study of recharge of regions with outcropping carbonates in the Daly River catchment, an area with similar hydro geological characteristics to the study area, indicate it is dominated by macro-pore and local indirect recharge (Wilson et al., 2006). Water balance and hydrograph analysis have estimated the recharge in outcropping areas of carbonate is approximately 120-140 mm/yr and in areas of Cretaceous cover it is estimated at 40-50 mm/yr (Jolly, 2002). Calibration of the groundwater models concur with these values (Knapton, 2006). Estimates of recharge based on total river discharge indicate a value of between 8 and 32 mm/yr.

The ten year cycle changes in the discharge to the Roper River suggest that the recharge input to the groundwater is relatively close to the discharge area. This is because the discharge from localized systems fluctuate more widely whereas discharge from larger scale systems is much steadier i.e. there is buffering present from the storage in the large groundwater system (Dahl and Nilsson, 2005).

Discharge

During the dry season the groundwater levels decline as groundwater is either transpired or discharged to wetlands or rivers where it evaporates or is discharged to the sea. Natural groundwater discharge is thought to be via three dominant mechanisms. Major discharges occur along the Roper River as it intercepts groundwater flow from the northern Georgina Basin in the upper reaches of the river. The groundwater from the Cambrian Limestone aquifer discharges along the bed of the river (e.g. at Bitter Springs at Mataranka) and via discrete springs (e.g., Rainbow Spring at Mataranka and Fig Tree Spring).

Diffuse discharge occurs in the Elsey National Park near the head waters of the Roper River where the basement approaches the surface forcing groundwater levels above the ground level (Jolly et al., 2004; Tickell, 2005).

Within the Roper River catchment the Dook Creek Formation discharges to the Flying Fox Creek, Mainoru River and the Wilton River where they intersect the dolostone aquifer, several discrete springs have also been mapped (e.g. Weemol Spring). Discrete springs occur where fractures in the Limmen Sandstone allow groundwater to flow to the surface under pressure (e.g. Lindsay Spring, White Rock Spring and Top Spring). Outside of the Roper River catchment the Dook Creek Formation also discharges to Guyuyu Creek in the Blyth River catchment and to the Goyder River in the Northern Arnhem Land region and a number of its tributaries in the Goyder River catchment.

Waterway Descriptions

Within the southern McArthur Basin there are no major infrastructure or diversions for surface water extraction. However there is "run of river" extraction for public water supply for two communities, and irrigation. Additionally the McArthur River Mine has diverted a section of the McArthur River for a distance of approximately six kilometres around the mine.

The Roper and the McArthur Rivers are the main rivers that drain the whole area into the Gulf of Carpentaria. The Phelp, Wilton, Waterhouse and Hodgson rivers are the main tributaries of the Roper River and the Glyde is the main tributary to the McArthur river. They flow from the escarpment country through well-defined valleys and finally flow into Gulf of Carpentaria through mildly sloping low valleys. The mean annual rainfall varies from 600 mm in the south to 900 mm in the north.

In 1971 Kratos Uranium NL undertook an hydrology study on two basins present in the area of interest. The Limmen Bight and Mt Young basins both situated within the MBCT area. According to the Kratos (1971) report cross sections of the Limmen Bight Basin show clearly that this basin must be considered a closed hydrological system except for the possibility of major faults allowing water to penetrate from deeper levels. A study of the widespread occurrence of springs in the basin and the local dips of the stratigraphic units indicate water movement is not due solely to local hydrologic conditions but include artesian influence.

It is stated in the report that in both the Limmen Bight and Mt Young basins the probable water recharge beds are at lower elevations than the springs that occur in the basins. Therefore the springs are not due to movement of water under purely artesian conditions due to the non-existence of hydrostatic head.

A Summary Review of the Hydrology of the McArthur Basin Central Trough

As a significant number of springs in the region are at high temperatures the water must come from depths in the order of 1200 to 1800m at least and rise rapidly to the surface to maintain temperatures. To rise this rapidly the water must travel along well defined structural features such as a fault.

Alternately the cold water springs may also have their source at depth. however, in these cases the water moves slower allowing it to cool and may do so through migration through a suitable permeable interface in contact with the structural feature before moving to surface.

A number of formations within the Limmen Bight and Mt Young basins have been identified by the study as being prospective as potential aquifers. These include within the Roper Group formations the Cobanbirini, Laterite sections of the Bessie Creek Sandstone, Corcoran Fm, Abner Sandstone including the Munyi, Hodgson, Jalboi and Arnold Members, Crawford Fm, Mainoru, Limmen SS, and the Bellingarrah Fm.

Porosity studies undertaken by Kratos Uranium suggest that the Hodgson Member and other units of the Abner Sandstone below it are impermeable, whereas the upper units especially the Corcoran Fm are permeable. The research conducted by Kratos suggests that all the water in these areas comes from depth and enters the Corcoran at the boundary with the Abner Sandstone until it eventually emerges at the surface.

A number of studies by the company also identified evidence of palaeo springs suggestive of water at the contact of the Crawford and Mainoru Formations. In addition a significant number of anomalies were identified in proximity to the Mallapunyah Fault where water was identified in the Golliger beds (Tertiary limestone) with further water flows in the Arnold Sandstone Member in the Bauhinia Downs region. Evidence from the Kratos Uranium exploration through the basins suggests that a water source in both the Limmen Bight and Mt Young Basins exists as deep as 4600m.

It has also been identified that a number of potential aquifers exist outside the exploration area and stratigraphically above the formations present within the area of study. These aquifers include the Upper Tertiary Middle Miocene Golliger Beds found on the Barkly Tablelands area to the south and the Neoproterozoic - Ordovician Anthony Lagoon beds (Jinduckin formation); Tindal Limestone (Gum Ridge Formation), and the Oollo Dolostone found to the south in the Georgina Basin and in some situations to the west of the region of study in the Katherine/Matakana area.

The Bukalara Sandstone of the Ediacaran period (ca 635-542mya) is also reported in some literature as having potential as an aquifer. However, within the exploration area (Southern and Central McArthur Basin) this formation lies unconformably on the Nathan and McArthur Group in many places as a discontinuous remnant of the earlier wide spread formation. As a discontinuous remnant the formation is not considered to be a viable aquifer within the region.

Previous Water Resources Studies within the southern McArthur basin

Since its' conception in the 1950's the Water Resources group has been involved with groundwater and surface water assessment and monitoring in the region of study. Knapton *et al*., (2005) present a report on their investigations conducted in 2002 to obtain the bathymetry and water chemistry of the Roper River estuary, downstream of Roper Bar. Coincident with this work, a related study was undertaken and the results were reported in "Inferring Groundwater Inflow to the Roper River (N.T.) from Environmental Tracers" Cook, (2002).

Jolly, *et al.*, (2004) discussed the water resources of the Tindall Limestone aquifer to the south of the Roper River. The report indicates the variation in discharge from the aquifer and likely volumes and location of recharge. It also identifies the losses along the length of the river due to evaporation and transpiration and the need to examine the methodology for determining water allocations within the Roper River catchment.

Faulks, (2001) titled "*An assessment of the Physical and Ecological Condition of the Roper River and its' Major Tributaries*" provides a "snap shot" of the riverine health of the Roper River and provides a comprehensive bibliography of the land and vegetation resources of the catchment. Although this report is not a water resources based study, much of the collected data is relevant to the hydrologic study of low flows in the Roper, especially the comprehensive collection of river channel cross-sections.

Monograph 15 is a compilation of the mapping work undertaken by Messel et al.,(1982) on the tidal waterways in northern Australia. Surveys of the waterways were made using the University of Sydney's research vessel, designed and built for estuarine studies in northern Australia. The Roper River was charted in 1979 and is fully presented in Monograph 15 (Messel et al., 1982). During 1980 and 1986 two major water quality surveys were conducted along the Roper River and its tributaries; the report documenting the results is titled: 'Base flow Water Quality Surveys in Rivers in the Northern Territory, Volume 11 – Roper, Wilton and Hodgson Rivers' (Field, 1988).

Local studies of the groundwater resources within the Roper River catchment focusing on community water supplies have also been completed. In addition regional investigations which included portions of the Roper River catchment have been completed by the Water Resources Division. The regional studies typically produce water resources maps at a scale of 1:250,000 and provides an explanation of the groundwater and surface water resources. The groundwater resources have been classified according to the supply potential and the surface water resources have been classified according to the minimum river flow recorded at the end of the dry season (ranging from rivers that are ephemeral, to rivers with a flow of more than 100L/sec). George, 2001a; George, 2001b; George, 2001c describes the water resources of the Katherine region and south west Arnhem Land 1999-2001.

Zaar, 2003a; Zaar, 2003b; Zaar and Tien, 2003 describes the water resources of western Arnhem Land. The study provides information on the connectivity of surface – groundwater resources in the northern Roper River catchment including the catchments of the Mainoru River and Wilton River.

According to Zaar (2009) in the Limmen Bight Gulf Water Study (Report 17/2009D) **w**ithin the Limmen Bight McArthur River region the aquifers are situated in Cambrian aged limestone formations, namely the Anthony Lagoon Beds and Gum Ridge Formation. The latter is equivalent to the Tindall Limestone. These regional scale aquifers cover the western region over an area from Tennant Creek to Mataranka and provide the key groundwater resource in the western Gulf region. Again it is significant to note that these formations are not represented in the MBCT being at stratigraphic intervals above the modern ground surface level.

Only a single surface water modelling study is known to have been conducted in the Roper River catchment. A flood study of the upper Roper River was conducted in 2001 (Connell Wagner Pty Ltd, 2001). The objectives of the study were to perform a flood risk analysis for the Beswick Community on the Waterhouse River and to establish a model for use in flood warning for the communities of Beswick, Mataranka Resort, Djilkminggan and Elsey Station. These locations are well outside and upstream of the region of potential impact from any field operations to be conducted in the MBCT area.

Puhalovich, (2005) developed a model based on the work by Water Studies. The model was extended to the south east to include the groundwater divide between the Katherine and Roper River and the discharge zones at the upper reaches of the Roper River. It incorporated the contribution to the Tindall aquifer from the inflows from the Cretaceous aquifers in the vicinity of the head waters of the King River using general head boundary conditions.

Knapton (2006) documents the development of a 2D finite element model designed to simulate flows primarily for the Katherine River, however, it encompassed the known extent of the Tindall Limestone and incorporated the discharge from the aquifer to the Daly, Douglas, Flora and Upper Roper Rivers. URS (2008) extended the model to include the upper carbonate sequence (Oolloo dolostone) to model base flow to the Daly River. The groundwater model was coupled to a surface water model of the Daly River developed by DHI (URS, 2008). However, No known modelling has been undertaken for the Dook Creek Formation.

Groundwater Quality

Groundwater quality is affected by evapotranspiration of rainfall and rock type. Rainwater contains salts. As rainwater moves down through the soil to the water table evapotranspiration concentrates the salts. If recharge is low then the salts can become so concentrated that the water becomes unsuitable for human consumption. Low recharge can be due to low rainfall but it is also related to rock type. Fine sandstone for example would have low recharge because the small particle size of the rock allows little water through.

Rock type effects water quality because, as water moves through them, it picks up (dissolves) salts from the surrounding rock. This process is particularly evident in limestone and dolomite because they contain high amounts of calcium or magnesium carbonate which dissolves in acidic conditions and our rainfall is naturally acidic. When these rocks dissolve, calcium, magnesium and bicarbonate ions are released into the water. Hence groundwater rich in these ions is likely to have come from a limestone or dolomite Formation.

An independent preliminary ecological assessment report was undertaken across the region in the dry season 2015 by O2 Environmental Pty Ltd. This study was to follow up on an earlier study across the same region conducted in 2013.

This study reports on the basic ecological status across the Roper River, Towns River, Limmen Bight River, Rosie River and McArthur River catchments. All of these rivers discharge into the Gulf of Carpentaria, and the area consists largely of national park area (Limmen National Park), agriculture (grazing of natural vegetation) and some traditional indigenous lands. The report states that ‘The region is generally in good ecological condition but widespread impacts from weeds, feral animals (especially pigs, buffalo, donkeys and cattle) changed fire regimes and grazing was observed.

Many of the sites had experienced hot fires in the recent past, causing plant death and removal.’ The report also identifies that water quality samples were collected across the region and that most analytes were below detection levels or within guideline values and that turbidity was elevated at the Little Towns River. However these results are expected to vary seasonally and may also be attributed to use of these remnant water holes by pigs, buffalo and cattle. Dissolved oxygen was low at all sites, not uncommon in remnant pools at the end of the dry season.

Naturally occurring elevated heavy metal concentrations above trigger levels were found in water samples of Leila Creek (LC-1) (arsenic) and Towns River (TR-1), Magaranyi River (MR-1) and Little Towns River (LT-1) (copper). These high levels may be a consequence of natural mineralisation, as demonstrated previously in the region in the McArthur River Mine Public Environmental Report of the McArthur River. These elements are known to be a primary target of mineral exploration in the greater area.

Water quality was tested across 12 sites within the primary area for:

Suspended Solids (SS)
Total Hardness as CaCO3
Dissolved Major Cations
Calcium
Magnesium
Sodium
Potassium
Dissolved Metals
Arsenic
Cadmium
Chromium
Copper
Lead
Nickel
Zinc

Dissolved Mercury
Nitrogen
Nitrite + Nitrate as N
Total Kjeldahl Nitrogen as N
Total Nitrogen as N
Total Phosphorus as P
Total Petroleum Hydrocarbons
C6 - C9 Fraction
C10 - C14 Fraction
C15 - C28 Fraction
C29 - C36 Fraction
C10 - C36 Fraction (sum)
Total Recoverable Hydrocarbons
C6 - C10 Fraction
C6 - C10 Fraction minus BTEX (F1)
>C10 - C16 Fraction
>C16 - C34 Fraction
>C34 - C40 Fraction
>C10 - C40 Fraction (sum)
>C10 - C16 Fraction minus Naphthalene (F2)
BTEXN
Benzene
Toluene
Ethylbenzene
meta- & para-Xylene
Ortho-Xylene
Total Xylenes
Sum of BTEX
Naphthalene
TPH(V)/BTEX Surrogates
1.2-Dichloroethane-D4
Toluene-D8
4-Bromofluorobenzene

Results of the sampling and testing program found that most analytes were below detection levels or within adopted guideline values. However, Arsenic was marginally higher than the adopted trigger value at Leila Creek (by 0.001 mg/L) and Copper was marginally higher than the adopted trigger value at Towns River, Magaranyi River and Little Towns River. These high levels may be a consequence of natural mineralisation. Such natural mineralisation has been demonstrated previously in the McArthur River Mine Public Environmental Report of the McArthur River. These elements are known to be a primary target of mineral exploration in the greater area.

Nitrogen and phosphorus were above the adopted trigger levels at most sites and turbidity was above the adopted trigger level at Little Towns River. These results suggest naturally elevated background concentrations of nitrogen, phosphorous and turbidity which will likely vary seasonally. These results are also possibly related to use of these remnant water holes by introduced pigs, buffalo and cattle. Dissolved oxygen was low at all sites, not uncommon in remnant pools at the end of the dry season. Of note were some Total Petroleum Hydrocarbons (TPH) and Total Recoverable Hydrocarbons (TRH) fractions above detection limits at Magaranyi River and Little Towns River.

Regional groundwater flow

Groundwater flow within the Cambrian Limestone aquifer system is predominantly from the Alexandria - Wonarah Basement High (Kruse, 2003) in the central Georgina Basin to the major rivers in the Daly Basin to the north.

Locally flow is directed to the major discharge areas identified above such as the Roper River. Estimates from groundwater levels (Tickell, 2003) indicate low gradients of approximately 0.0001 in the Georgina Basin. However, through flow from the Georgina Basin to the Daly Basin is expected to be of the order of 200-300 L/s based on recharge estimates and Darcian flow estimates using transmissivity and groundwater gradients.

Table 11: Water quality assessment of 12 sites across the Southern MBCT

WATER QUALITY RESULTS

		Sample date	16/11/2015	17/11/2015			27/11/2015			28/11/2015			
Analyte grouping **Analyte**	**Units**	**Water Quality Trigger Value Tropical Australia**	**LC-1**	**McR-1**	**PP-1**	**EP-1**	**LBR-1**	**TR-1**	**MR-1**	**LT-1**	**MC-1**	**RR-1**	**HR-1**
EA025: Total Suspended Solids dried at 104 ± 2°C													
Suspended Solids (SS)	mg/L		152	<5	<5	<5	14	<5	<5	2030	<5	<5	<5
EA065: Total Hardness as CaCO3													
Total Hardness as CaCO3	mg/L		448	254	18	12	540	3690	2380	51	522	377	313
ED093F: Dissolved Major Cations													
Calcium	mg/L		82	31	4	3	53	258	163	9	31	47	48
Magnesium	mg/L		59	43	2	1	99	740	478	7	108	63	47
Sodium	mg/L		17	5	3	2	95	5620	1250	32	98	160	101
Potassium	mg/L		4	4	2	1	12	182	12	13	24	21	13
EG020F: Dissolved Metals by ICP-MS													
Arsenic	mg/L	0.013(AsV)/0.024(AsIII)	0.014	<0.001	<0.001	<0.001	0.008	0.001	0.001	0.004	0.002	<0.001	<0.001
Cadmium	mg/L	0.0002	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Chromium	mg/L	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.013	<0.001	<0.001	<0.001
Copper	mg/L	0.0014	0.001	<0.001	<0.001	<0.001	0.001	0.002	0.002	0.029	<0.001	<0.001	0.001
Lead	mg/L	0.0034	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.025	<0.001	<0.001	<0.001
Nickel	mg/L	0.011	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	0.005	<0.001	<0.001	<0.001
Zinc	mg/L	0.008	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	1.14	<0.005	<0.005	<0.005
EG035F: Dissolved Mercury by FIMS													
Mercury	mg/L	0.00006	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
EK059G: Nitrite plus Nitrate as N (NOx) by Discrete Analyser													
Nitrite + Nitrate as N	mg/L	0.005	0.03	0.04	0.05	<0.01	<0.01	<0.01	<0.01	0.03	<0.01	<0.01	<0.01
EK061G: Total Kjeldahl Nitrogen By Discrete Analyser													
Total Kjeldahl Nitrogen as N	mg/L		1.1	0.3	0.4	0.5	1.4	0.2	1.2	17.3	0.6	0.2	0.1
EK062G: Total Nitrogen as N (TKN + NOx) by Discrete Analyser													
Total Nitrogen as N	mg/L	0.2-0.3	1.1	0.3	0.4	0.5	1.4	0.2	1.2	17.3	0.6	0.2	0.1
EK067G: Total Phosphorus as P by Discrete Analyser													
Total Phosphorus as P	mg/L	0.01	0.18	<0.01	0.18	0.08	0.01	0.02	<0.01	2.24	<0.01	<0.01	<0.01
EP080/071: Total Petroleum Hydrocarbons													
C6 - C9 Fraction	µg/L		<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
C10 - C14 Fraction	µg/L		<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50
C15 - C28 Fraction	µg/L		<100	<100	<100	<100	<100	<100	130	760	<100	<100	<100
C29 - C36 Fraction	µg/L		<50	<50	<50	<50	<50	<50	140	310	<50	<50	<50
C10 - C36 Fraction (sum)	µg/L		<50	<50	<50	<50	<50	<50	270	1070	<50	<50	<50
EP080/071: Total Recoverable Hydrocarbons - NEPM 2013 Fractions													
C6 - C10 Fraction	µg/L		<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
C6 - C10 Fraction minus BTEX (F1)	µg/L		<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
>C10 - C16 Fraction	µg/L		<100	<100	<100	<100	<100	<100	<100	130	<100	<100	<100
>C16 - C34 Fraction	µg/L		<100	<100	<100	<100	<100	<100	230	870	<100	<100	<100
>C34 - C40 Fraction	µg/L		<100	<100	<100	<100	<100	<100	110	140	<100	<100	<100
>C10 - C40 Fraction (sum)	µg/L		<100	<100	<100	<100	<100	<100	340	1140	<100	<100	<100

Data from O2 Environmental 2016 report Preliminary Ecological Assessment Report EP184 and EP187 – End of Dry Season 2015'

Locally the groundwater flow in the Dook Creek dolostone is from the topographically high areas towards the discharge areas along the rivers and at discrete springs. The regional scale groundwater flow is from the topographically high areas in the south west to the topographically lower areas to the north east.

Conclusion

A number of aquifers have been identified across the region with the potential to impact on the regional hydrology of the study area. The majority of the research on these aquifers has occurred outside the region of the McArthur Basin Central Trough as little data, other than the Kratos Uranium study, exists. However, it is apparent from the literature review that other potential aquifers not previously identified as of significance may exist within the Nathan and upper McArthur Group formations within the area primary area of the McArthur Basin.

The principle research conducted by Kratos Ltd in the Mt Young and Limmen Bight Basins has provided the clearest indication of the potential of these aquifers and the possible source of the water as including an artesian component. The research has also clearly indicated that the source of this water is below 4600m and well outside the depth of modern hydrocarbon on shore exploration.

The migration paths proposed for the water source is the major tectonic structures of the basin such as major faults within the region. The research further identifies that significant regional water courses also generally follow the path of these significant structures to intersect other regions for drainage to the gulf.

On the basis of the literature review it is considered unlikely that the proposed research program to be undertaken for hydrocarbons within the MBCT region will encounter or significantly impact any of the identified aquifers with the exception of the shallow (above 100m) aquifers within the more recent Cenozoic clays and karstic fractured surface formations. The presence of flowing springs and the existence of thermal pools in a number of locations throughout the Mt Young and Limmen Basins supports this identification.

The contention by the literature that drilling to date within the identified region has usually resulted in a dry hole supports the theory that the majority of the potential aquifers within the McArthur Basin are either discontinuous, local, no longer connected to recharge points or have secondary silicification mineral overgrowth to destroy any previously existing permeability and or porosity.

Good oil field practices utilized in exploration programs will readily isolate these potential aquifers from exposure to risk of contamination and or depletion.

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