IDENTIFICATION OF KNOWLEDGE GAPS FOR REGIONAL AQUIFERS OVERLYING THE BEETALOO SUB-BASIN

SREBA Water Quality and Quantity studies (Project 1)
Water Resources Division Report Number 18/2021

hydraulicfracturing.nt.gov.au

NORTHERN TERRITORY GOVERNMENT

Water Resources Division
Department of Environment Parks and Water Security
PO Box 496
PALMERSTON NT 0831

ISBN
To cite this report:
DEPWS (2021). Identification of knowledge gaps for regional aquifers overlying the Beetaloo Sub-basin: SREBA Water Studies Project 1. WRD Report Number 18/2021. Northern Territory Department of Environment, Parks and Water Security, Northern Territory Government. Palmerston, Northern Territory.

Cover image: Roper River at its confluence with the Elsey Creek, R. Metcalf 23/10/2013

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INTRODUCTION

In April 2018, the Northern Territory Government accepted all 135 recommendations of the Final Report by the "Scientific Inquiry into Hydraulic Fracturing in the Northern Territory", and committed to their implementation. Thirty five (35) of the above-mentioned recommendations are associated with the Strategic Regional Environmental and Baseline Assessment (SREBA).

The report and associated details are available at:
frackinginquiry.nt.gov.au/inquiry-reports/final-report

A SREBA consists of baseline studies across six domains:

1. Water quality and water quantity studies
2. Aquatic ecosystems studies
3. Terrestrial ecosystems studies
4. Greenhouse gas studies
5. Environmental health studies
6. Social, cultural and economic studies

As part of the SREBA, the Department of Environment, Parks and Water Security (DEPWS) requires studies on water quality and water quantity within the Beetaloo Sub-basin areas as outlined in the Water Quality and Quantity Studies guidance note in the Strategic Regional Environmental and Baseline Assessment (SREBA) Framework (DEPWS, 2020). The SREBA Framework outlines the critical data gathering and knowledge improvements required to adequately complete a SREBA. These studies are required to provide a baseline across the region; to identify aspects that may be sensitive to development and to consider the potential cumulative impacts of multiple projects.

During 2019 and 2020, the Water Resources Division appointed an independent expert panel (IEP) to provide direction on the groundwater projects required to deliver on the SREBA objectives. The IEP's final report has since been incorporated into the SREBA Water Studies Scope of Work (DEPWS, 2021), which comprises of eight sub-projects:

1. Identification of knowledge gaps in the conceptual model of the regional surface water and groundwater systems overlying the Beetaloo Sub-basin.
2. Establishment of baseline of groundwater chemistry and groundwater levels.
3. Characterisation of inter- and intra-aquifer connectivity and aquifer parameters.
4. Characterisation of groundwater and surface water interactions, recharge and discharge processes for regional aquifers overlying the Beetaloo Sub-basin.
5. Update and re-calibrate the groundwater surface water model.
6. Hydrological assessments and mapping for catchments overlying the Beetaloo Sub-basin.
7. Definition and assessment of cultural water values.
8. SREBA Water Baseline Report for groundwater flow, water quality and quantity.

This report will fulfil the requirements of Project 1: the identifications of knowledge gaps for regional aquifers overlying the Beetaloo Sub-basin.

Report purpose

The purpose of this report is to collate and review the existing knowledge and data on the Beetaloo Sub-basin in relation to the groundwater resources overlying the Beetaloo Sub-basin. Due to the nature of water occurrence in the Beetaloo Sub-basin area, a focus has been given to the hydrogeological conceptual understanding, interaction between groundwater and surface water systems (rivers, springs, wetlands) and groundwater quality. The aquifers considered include the Cambrian Limestone Aquifers (CLA), and the underlying basalt and Neoproterozoic sandstones. It also aims to identify information gaps, to recommended and prioritise further work to address the identified knowledge gaps.

LITERATURE REVIEW

The earliest regional descriptions of the hydrogeology of the CLA and basalt were Randal (1967) and Randal (1973). The latter study covered most of the present study area. Much of the basic knowledge accepted today was first identified in these studies. Some of the main findings were:

- The regional groundwater flow is generally northwards.
- Groundwater flows across the geological basin boundaries.
- There is a groundwater divide in the south eastern Barkly Tablelands between northwest flow that ultimately reaches the Roper River and eastward flow into Queensland.
- Local water levels suggest that individual aquifers within the two main formations (Anthony Lagoon Formation and Gum Ridge Formation and equivalents) are interconnected despite local barriers. Similarly the two formations can be regarded as regionally connected.
- Recharge was considered to mainly occur through areas of outcrop and lateritised outcrop on the basin margins and also within the basins. Open sinkholes were also recognised as likely avenues for recharge. Water could also percolate through the basal Cretaceous sands into the CLA.

A campaign of hydrogeological mapping was carried out in the Barkly area (Rooke, 1997a & b; Matthews and Rooke, 1997; Rooke and Tickell, 2003; Tickell, 2003), the Sturt Plateau (Yin Foo and Matthews, 2000 & 2001; Knapton, 2000) and the northern Barkly (Zaar, 2009; Fulton and Zaar, 2009). These maps delineate aquifers and show aquifer yields, water quality and water development options.

An integrated surface water and groundwater model was developed by Knapton (2006 & 2009) to assist with management of water resources in the parts of the Daly and Roper catchments that are covered by the CLA. The model has recently been updated (Knapton, 2020) and peer-reviewed (Middlemis, 2020), and extended southwards in order to include the aquifers overlying the Beetaloo Sub-basin. Knapton (2020) identified four likely mechanisms of recharge for areas of near-surface karst:

- Direct recharge when surface water exceeds soil moisture deficits and evapotranspiration, occurring by vertical percolation through the unsaturated zone.
- Macropores – channelled precipitation through root casts and regolith solution tubes, with the rapidly infiltrated water having limited interaction with sediment and rocks in the unsaturated zone.
- Local indirect recharge where surface water is channelled into karstic features such as dolines (sinkholes) in areas where the Mesozoic cover is relatively thin. Tickell (2005), Knapton (2006) and Fulton and Knapton (2015b) consider this to be a poorly understood component of recharge.
- Localised indirect recharge occurs along ephemeral drainage lines such as Dry River and the tributaries that feed Elsey Creek.

In a study of the Oolloo Dolostone, a karstic aquifer in the Daly Basin, Wilson et al. (2006) compared chloride concentrations and stable isotopes (deuterium and oxygen-18) signatures in the unsaturated zone with those in the groundwater and concluded that recharge is dominated by bypass flow and not by slow movement through soil horizons. The most likely mechanism was considered to be via sinkholes and or macropores.

Surface and groundwater assessments of the Roper and Daly catchments were done as part of the Northern Australia Sustainable Yields Project (CSIRO, 2009a and 2009b). These studies described groundwater conceptual models, conducted catchment wide water balances, modelled groundwater and identified knowledge gaps. Amongst several knowledge gaps identified, two are particularly relevant to the current work. The first was that "more work is required to evaluate recharge processes especially in relation to Cretaceous cover over the Tindall Limestone and the role of macropores and sinkholes". The other key recommendation was that quantitative relationships between flow and specific ecological entities (for example, macrophyte populations, fish passage, faunal and floral habitats, etc.) need to be developed for the Roper River.

Local and regional groundwater assessments aimed at quantifying the groundwater resources and improving hydrogeological knowledge were done by Jolly et al. (2004), covering the south eastern Daly Basin and northern Georgina Basin extending from Mataranka south to Dunmarra, Bruwer and Tickell (2015) covering south eastern Daly Basin from Mataranka to Daly Waters, and Tickell and Bruwer (2020), covering the Georgina Basin from Daly Waters to 100 km south of the Barkly Highway. These included water balance studies, recharge estimates, identification of recharge areas, through flow calculations and drilling. Sinkholes (dolines) in the Wiso and southwestern Daly basins were investigated by Morris and Simons (1985) and Alkamade (1991) in order to identify hazards that could affect the future Alice Springs to Darwin railway line. This work gave some insight into sinkhole distribution and mode of formation, potentially important information in relation to groundwater recharge.

Fulton and Knapton (2015) conducted a desktop hydrogeological study of the Beetaloo Basin including the Roper Group, Bukalara Sandstone, Kalkarindji Suite volcanics and the CLA. It included compilation of existing data on Roper Group aquifers derived from porosity/permeability testing of cores and pressure and water quality information from drill stem tests. The most recent and comprehensive assessment of the Beetaloo Sub-basin, overlying aquifers and surface water catchments was carried out as part of the stage 2 of the Geological and Bioregional Assessment Program (GBA) (Huddlestone-Holmes et al., 2020). A key outcome of the study is a hydrogeological conceptual model describing aquifers, aquitards, regional flow patterns and groundwater chemistry. The report contains several technical appendices including hydrogeology (Evans et al., 2020), geology (Orr et al., 2020), protected matters (Pavey et al., 2020), hydraulic fracturing (Kear and Kasperczyk, 2020), petroleum prospectivity (Hall et al., 2020) and chemical screening (Kirby et al., 2020). Information related to the hydrogeological conceptual model is contained in the hydrogeology appendix but the geology and protective matters appendices are also relevant to the topic.

Hydrogeological conceptual model

Evans et al. (2020) brought together some of the key hydrogeological studies done in the study area, ranging from Randal (1973) through to Tickell and Bruwer (2019). The following description of the conceptual model is largely taken directly from the work of Evans et al. (2020). It includes aquifer type, distribution, recharge/discharge mechanism and location, flow direction and interconnection with other aquifers. The reader is referred to the original report for more detail.

The geology of the study area consists of a series of stacked sedimentary basins ranging in age from Mesoproterozoic to Cretaceous. The strata are dominantly flat lying and only locally faulted. Most faults mapped by seismic surveys do not appear to penetrate formations above the Roper Group. In general all formations are considerably deeper in the eastern Beetaloo Sub-basin compared to in the western section. The only significant fault known to cut the CLA is the Birdum Fault (Yin Foo and Matthews, 2000). It is a northward extension of an uplifted zone known as the Daly Waters High (Orr et al. 2020).

A recent paper in the Australian Petroleum Production and Exploration Association (APPEA) journal (The APPEA Journal) provided a summary of the current understanding of the stratigraphic sequence in Beetaloo Sub-basin region (Figure 1). The main change included in the Altmann et al. (2020) study is to simplify the Kiana Group to contain only the Cox Formation (and Hayfield Sandstone Member) and Bukalara Sandstone. Confusion has previously existed with Cox Formation and Bukalara Sandstone being named Hayfield mudstone and Jamison sandstone, respectively. These formations are equivalent, which has been supported by recent DEPWS bore drilling (Short 2021), and from herein the naming of Kiana Group formations follows the convention presented in Figure 1.

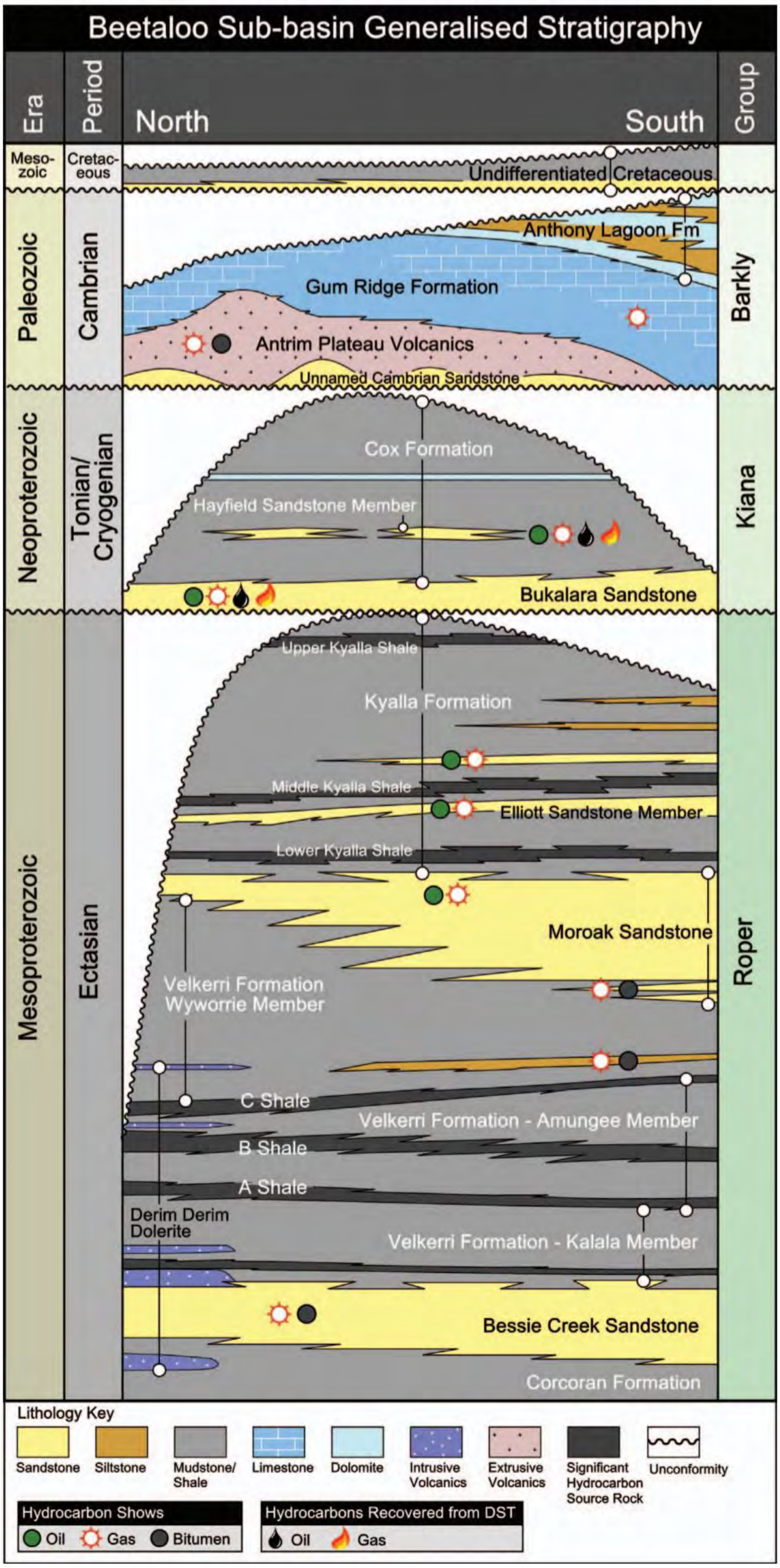

Figure 1: Generalised stratigraphy of the Beetaloo Sub-basin. Reproduced from Altmann et al. (2020).

In the Proterozoic sequence, sandstone formations are the most likely to contain aquifers. Thick intervening mudstone units form as aquitards. The Velkerri and Kyalla formations are two such aquitards and they are the main hydrocarbon plays in the Beetaloo Sub-basin. Direct discharge of groundwater from the Proterozoic aquifers to the surface is only known in areas outside of the limits of the CLA. In some cases such as at the Beauty Spring complex (Zaar, 2009) on Tanumbirini station the spring waters are hot (above 50°C) suggesting that it is fault related. In areas covered by the CLA calculated hydraulic head values indicate the potential for upward leakage to occur from the Roper Group into overlying sequences if connective pathways exist (Evans et al. 2020). In some areas, regional unconformities, uplift on major structures and the local absence of aquitards have brought Mesoproterozoic sandstones into direct contact with shallower aquifers such as the Bukalara Sandstone and the CLA (Fulton and Knapton 2015; Evans et al. 2020). The potential for movement of groundwater between these aquifers is highest in these areas. The presence of radiogenic helium in CLA groundwaters (Deslandes et al. 2019) indicates a contribution of deep groundwater but this has not been quantified due to a lack of data on helium concentrations in the deep source groundwater.

Sandstones such as the Moroak and Bessie Creek sandstones are classed by Evans et al. (2020) as partial aquifers, meaning that for the most part they act as aquitards but are thought to locally form fractured rock aquifers, especially in the vicinity of regional structures. Primary porosity has also been locally preserved around major structures. No bores have directly tested the presence of groundwater in these formations. Cores, drill stem tests and well logs from petroleum wells are the main source of information from which aquifer and groundwater properties have been inferred.

Neoproterozoic units of the Kiana Group unconformably overlying the Roper Group and comprise of the Bukalara Sandstone and Cox Formation. The Bukalara Sandstone is known from water bore records from the Nutwood Downs station and from parts of the Sturt Plateau west of the Stuart Highway, where it occurs at depths of less than 150 m. It is a fractured and weathered rock aquifer with visible primary porosity. Airlift yields generally range up to 5 L/s. Strong water inflows (up to 25 L/s) from the Bukalara Sandstone were reported in four petroleum exploration wells at depths of up to 400 m (Fulton and Knapton, 2015).

The Bukalara Sandstone is confined or semi-confined by the Cox Formation (where present) or the Kalkarindji Suite volcanics but in situations where the volcanics are absent it is in direct hydraulic connection to the CLA. This occurs at the Carpentaria 1 well site, where tested groundwater from the sandstone is fresh to slightly brackish suggesting the possibility of active recharge. The Nutwood Downs area is the only place where direct recharge could occur. Elsewhere any recharge can only take place through the overlying CLA and volcanics. No surface discharge sites related to this aquifer are known.

The Kalkarindji Suite volcanics are widespread particularly in the north of the study area. They are absent in the east and south. In outcrop areas in the Victoria River District west of the study area and on the Sturt Plateau where it is relatively shallow beneath the CLA it contains localised fractured and weathered rock aquifers. It is tapped by many stock bores in these areas. Yields are generally low and "dud" bores are common. Aquifers are associated with open fractures in the weathered zone, local faults, brecciated and vesicular rock at the top of basalt flows and with minor sandstone, chert and limestone interbeds (Randal, 1973). Small springs and seeps emanating from this aquifer are known from the Victoria River District but none have been recognised in the study area. The formation likely has some degree of localised hydraulic connection with the underlying Bukalara Sandstone and the overlying CLA. On a regional scale, however, it acts as an aquitard or a leaky aquitard.

The CLA contains the widespread fractured and karstic aquifers that are utilised for stock and domestic purposes across the study area. It includes two geological formations, a lower limestone dominated unit and an upper siltstone dominated unit. In each of the three Cambrian geological basins, Daly, Georgina and Wiso these units have been given different formation names but they are essentially identical lithologies with similar aquifer characteristics. The lower unit is the major aquifer and is known as the Tindall Limestone, Gum Ridge Formation and Montejinni Limestone in the respective basins. The upper unit also hosts major aquifers but less so than the lower unit. It is termed the Jinduckin Formation, Anthony Lagoon Formation and Hooker Creek in the respective basins.

The Gum Ridge Formation and equivalents consists predominantly of thick limestone packages separated by several thin but laterally extensive siltstone beds. In the case of the Anthony Lagoon Formation and equivalents, siltstone is dominant with numerous thinner limestone and sandstone beds. The main aquifer development is associated with the limestone beds, forming regional to intermediate scale fractured and karstic aquifers.

The Gum Ridge Formation and equivalents host the highest yielding aquifers with bore yields up to 60 L/s encountered. The formation extends for hundreds of kilometres across the three Cambrian basins, forming a continuous aquifer. Water intersections can occur at any level within the formation but cannot normally be correlated between bores. The aquifer is likely formed from a near random network of fractures and karstic channels that are interconnected sufficiently to form a single aquifer. The degree to which the siltstone beds form regional confining layers is unknown.

The Anthony Lagoon Formation and equivalents are best developed in the Georgina and Daly Basins. The Hooker Creek Formation may not present in the study area. The main aquifer development is also associated with the limestone and calcareous sandstone beds, forming intermediate scale fractured and karstic aquifers.

Bore yields are consequently lower, typically less than 5 L/s but reaching 30 L/s. Siltstone is the dominant lithology and extensive units up to 30 m thick often separate the limestone aquifers.

Recharge to the CLA is governed by climate and local geology. At the northern limit of the study area, near Mataranka, annual rainfall averages about 800 mm and has moderately low variability from year to year. In the south, near Tennant Creek, it averages only 400 mm and has high variability. This results in areas north of Daly Waters receiving relatively regular recharge each wet season. To the south, recharge only occurs episodically at times of abnormally high rainfall. Such events can be years to decades apart. Groundwater level records for the southern CLA are few and relatively short.

Local geology also affects recharge including factors such as the thickness and lithology of Cretaceous cover and the amount of pseudo-karstic sinkhole development (see Nelson and Haigh, 1985; McFarlane and Twidale, 1987; Twidale, 1987; Alkemade, 1991; Grimes and Spate 2008). Assessments of these factors have been considered in soon-to-be-released factsheets produced as part of Stage 3 of the GBA program.

The Gum Ridge Formation and equivalents are thought to be recharged in areas where the formation outcrops or has only a thin Cretaceous cover and where sinkholes are abundant. Large areas are likely to receive little or no recharge due to the presence of confining beds such as the Anthony Lagoon Formation and thick clayey sections of Cretaceous strata.

DEPWS has recently required that any new water bore be gamma logged if it is within the area likely to be underlain by the Anthony Lagoon Formation. The purpose of gamma logging is to identify the Anthony Lagoon Formation/Gum Ridge Formation contact and to enable the upper aquifer to be sealed off from the lower if it is present.

The Anthony Lagoon Formation and equivalents are likely recharged in areas where limestones and sandstones outcrop or are near surface. Those conditions occur on the Barkly Tablelands where Cretaceous strata are thin or absent.

Regional groundwater flow in the CLA is to the north and northwest. There are two discrete flow systems separated by the Daly Waters High. On the western side (i.e., the Wiso-Daly-Flora system), water flows northwards in the vicinity of the Buchannan Highway and then through a narrower section of aquifer on the Sturt Plateau where it turns to the northwest and eventually discharges at springs along the Flora River. Recent research undertaken as part of the GBA program has hypothesised that the amount of flow from the springs along the Flora River is not enough to account for the potential recharge over the assumed recharge area (i.e., potentially the whole area overlying the flow system from the northern Tanami region to the Flora River) as determined by chloride mass balance methods (Crosbie and Rachakonda, 2021). The authors infer that this is due to either (or a combination of) groundwater flow bypassing the Flora River, an overestimate of the assumed recharge area, or that there is another flow system that is directed westward from the SW Sturt Plateau, discharging to the headwaters of the Victoria River sub-catchments.

On the eastern side (i.e. the Georgina-Daly-Roper system), the flow system starts at a groundwater divide near Alexandria station and flows northwest under a very low hydraulic gradient, eventually discharging to springs along the Roper River. The contribution from Georgina Basin groundwater to the baseflow in the Roper was assessed to be of the order of 6% of the total baseflow. The bulk of the water therefore originates from the Daly Basin, north of Daly Waters (Tickell and Bruwer, 2017). Outflow of groundwater originating at the head of the flow path, hundreds of kilometres to the southeast, is minor in volume due the very low recharge rates and the travel time to the Roper River is likely of the order of hundreds or thousands of years due to the low hydraulic gradient that drives it.

The east and west flow systems are separated by physical barriers in several places. For example south of Newcastle Creek a ridge of Proterozoic rocks lies between the Wiso and Georgina basins. Immediately west of Larrimah, the CLA has been elevated above the watertable along the western side of the Birdum Creek fault. Further north of there, the Tindall Limestone has been displaced by the same fault forming a barrier to groundwater flow because the limestone on the up-thrown side abuts against Jinduckin Formation and on the downthrown side it abuts against basalt. In areas between these physical barriers along the Daly Waters High there is apparently little flow between the two systems, primarily because the regional flow is parallel to the boundary.

Since the publication of the GBA work (Evans et al. 2020) new groundwater related information has been gathered from several sources including: gas companies installing monitoring bores as required by DEPWS, regional drilling investigations by DEPWS, and CSIRO has released a report on environmental tracers in the Beetaloo basin (Deslander et al, 2019).

Dolomitic rocks were encountered in water bores drilled by Santos at the Inacumba well site and surrounding areas. They lie beneath the Gum Ridge Formation and were initially attributed to the Bukalara Sandstone. It became apparent that it contained only minor quartz sandstone and was dominantly dolostone and siltstone. A named aquifer is required to issue a groundwater extraction license, so DEPWS requested Santos do further investigations using gamma log correlations, more detailed description of the drill cuttings as well as geochemistry on the cuttings. They concluded that the unit is overlain by the Gum Ridge Formation and two sub-units can be recognised; an upper siltstone with minor dolostone and a lower dolostone with minor siltstone. This information is unpublished but is summarised in Tickell (2020). The new unit was informally named the 'Inacumba' aquifer.

It is currently thought that the sequence is actually the Anthony Lagoon Formation and the Gum Ridge Formation. But if this is the case, the unexpectedly thick sequence encountered near the edge of the basin must be the result of localised down faulting perhaps associated with the Mallapunya Fault.

A number of groundwater monitoring bores have been drilled at gas exploration well sites east of the Stuart Highway. Where both Anthony Lagoon Formation and Gum Ridge Formation are present, separate monitoring bores have been installed in each aquifer. At Origin Energy's Velkerrie and Kyalla sites, the Anthony Lagoon Formation and Gum Ridge Formation are monitored. At Santos Tanumbirini and Inacumba sites, both the Gum Ridge Formation and the 'Inacumba' aquifer are monitored, while at Imperial Oil and Gas's Carpentaria 1 site, only the Gum Ridge Formation is monitored.

DEPWS has drilled new monitoring bores west of the Stuart Highway (Short, 2021). Most are screened in the Montejinni Limestone but at one site the Montejinni Limestone, basalt and Bukalara Sandstone are each screened in separate bores. A pumping test was carried out on the Bukalara Sandstone bore with no response in the overlying CLA monitoring bore after four days of pumping, indicating that the basalt layer in this area acts as an effective seal between the CLA and deeper Neoproterozoic aquifer.

The second GISERA report on environmental tracers (Deslandes et al. 2019) has recently been released by CSIRO. A wide range of environmental tracers were used to study recharge in the CLA, including both recharge rates and mechanisms. Some of the key findings are that recharge occurs along the flow path so that nearly all the bores sampled are mixtures of older and younger waters. In some cases the older water originates from distant upstream recharge areas while in other cases it may be sourced from deeper aquifers. Sinkholes are identified as important pathways for recharge.

STUDY AREA

The study area defined here encompasses the majority of the groundwater catchment of the Cambrian Limestone Aquifers (Figure 2).There are two north flowing catchments; the Georgina Basin-southeastern Daly Basin and the Wiso Basin-southwestern Daly Basin. The eastern and western boundaries of the study area follow a 10 km buffer drawn outside of the margins of the Georgina-Daly and Wiso-Daly Basins, respectively. The southern and south western boundary on the Georgina Basin side also follows the same buffer.

The northern boundary was drawn to include the two main discharge features, springs along the Roper and Flora rivers and it follows the groundwater divide between flows to the Flora-Roper and Daly-Katherine Rivers. The southern boundary on the Wiso Basin side follows the limit of the area of pastoral land. Any groundwater flow from south of that boundary is considered negligible due to the areas arid climate. There is also very limited access and very sparse existing groundwater data in that area. The southeastern boundary on the Georgina Basin side is a groundwater divide between north flows to the Roper River and east flows to the Gregory River in Queensland.

The whole of the Beetaloo Sub-basin (see "Concealed Geological Boundaries" on the NTG's Strike website) is included in the study area. It also includes a shallower extension of the sub-basin, located south of the Carpentaria Highway, and immediately east of the main body of the sub-basin.

The hydrogeological study done as part of the GBA program (Evans et al., 2020) was done over a smaller area than the current study area. The main difference between the two areas is that the current one extends further south in order to encompass the whole groundwater flow system particularly in the Georgina Basin.

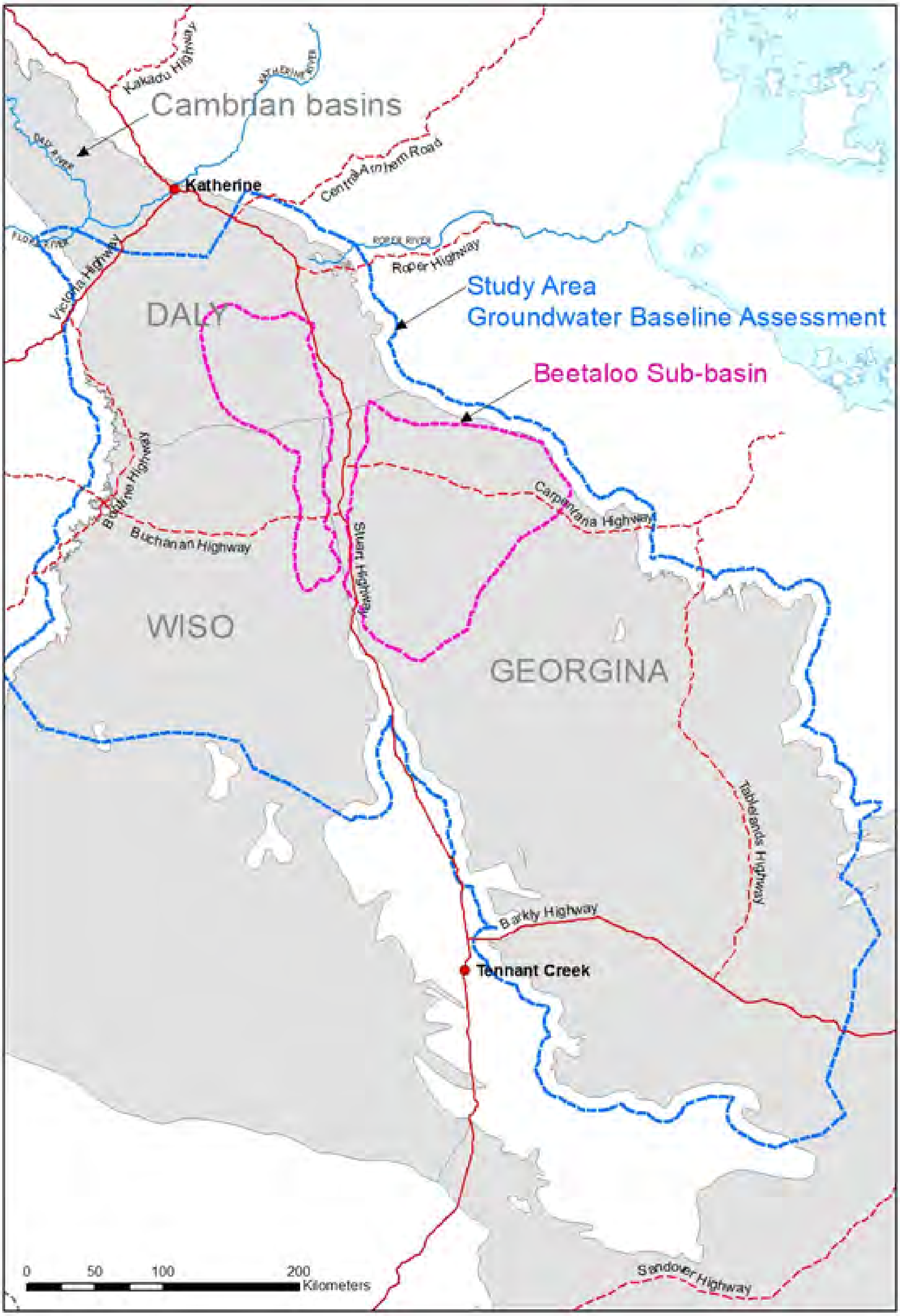

Figure 2: Locality map.

CLA connectivity, current evidence

Critically evaluate the current evidence to understand if major aquifers (i.e. Anthony Lagoon and Gum Ridge aquifers) behave as a single aquifer or if there are several isolated aquifers within these regional formations.

— Anthony Lagoon and Gum Ridge

In order to understand how the CLA functions it is necessary to determine if major aquifers (i.e. Anthony Lagoon and Gum Ridge aquifers) behave as a single aquifer or if there are several isolated aquifers within these regional formations. Gum Ridge Formation and Anthony Lagoon Formation (and equivalents) are sub-horizontal carbonate dominated formations. The Anthony Lagoon Formation consists dominantly of siltstone (individual beds up to 30 m thick) with thinner layers of dolostone/limestone and dolomitic sandstone interbedded. The underlying Gum Ridge Formation is dominantly dolostone with several thin but extensive shale/siltstone interbeds.

Chapman (2019) correlated borehole gamma logs in the CLA where it overlies the Beetaloo Sub-basin and found that in the Anthony Lagoon Formation many individual limestone and shale layers were continuous on a regional scale. Similarly she found that the minor shale horizons in the Gum Ridge Formation are also regionally extensive. This suggests that the shale/siltstone layers should act as barriers to vertical groundwater movement.

The evidence to date on the degree of connectivity between the two aquifers is inconclusive. There are three monitoring sites in the study area that each has two bores; a shallower one slotted in the Anthony Lagoon Formation and a deeper one slotted in the Gum Ridge Formation. In all three sites, the Gum Ridge Formation water levels are slightly higher than those in the Anthony Lagoon Formation, varying from 1.0 to 0.02 m higher. This could either indicate the aquifers are not connected or that there is some degree of connection with an upward hydraulic gradient. On the other hand the major ion chemistry appears to be similar in both aquifers at each site suggesting good hydraulic connection.

A common way to determine connectivity is to pump one aquifer and monitor for a drawdown in the other. A pumping test has been conducted south of Dunmarra in which the Gum Ridge was pumped while water levels in the Anthony Lagoon Formation were monitored (Tickell and Bruwer, 2017). No response was detected. A problem with this test was that the pumping rate was relatively low at 12 L/s and the duration of the tests was only 24 hours. Given the high transmissivity of the Gum Ridge Formation and its great extent, both the pumping rate and test time would need to be much greater to elicit a measurable drawdown in the Anthony Lagoon Formation if the aquifers are connected.

In the Daly Basin, near Katherine, the equivalent aquifers, the Tindall and Jinduckin, are known to have significantly different water quality and water levels (Tickell 2018) indicating that they are not hydraulically connected to each other.

The Anthony Lagoon Formation is preserved in the centre of a broad basin structure. It is underlain and is surrounded by Gum Ridge Formation and has no known surface discharge features associated with it. Its groundwater must therefore discharge into the Gum Ridge Formation on its down gradient (north) side. This must indicate that the two aquifers are hydraulically connected. The degree and mechanism of this connection is currently not understood.

Another unknown is the degree to which the siltstone beds in the Gum Ridge Formation form barriers to vertical groundwater flow. The only work done to investigate this is a study of the Tindall Limestone at Katherine (Tickell 2012) in which monitoring bores were installed both above and below prominent shale layer. Water levels were 0.16m higher in the shallower aquifer and it was concluded that the shale formed a barrier to vertical groundwater movement at that site.

AQUIFERS BENEATH THE CLA

This section deals with aquifers that lie beneath the CLA and above the Roper Group. These include Kalkarindji Suite volcanics and Bukalara Sandstone.

The CLA directly overlies basalt of the Kalkarindji Suite volcanics in much of in the northern part of the study area, in particular including most of the extent of the Beetaloo Sub-basin. The volcanics are notably absent in isolated patches above the Daly Waters High (Orr et al. 2020), a prominent up-lifted structure which follows the Stuart Highway. They are also absent over the eastern most side of the Beetaloo Sub-basin on Tanumbirini Station. There does not appear to be a prominent zone of weathered zone at the top of the formation which might otherwise have formed an aquitard between the basalt aquifer and the overlying CLA. In the study area the volcanics attain a maximum recorded thickness of 440 m in Chanin 1.

Tested yields of generally less than 1 L/s but up to 5 L/s are associated with sparse open fractures, local faults, brecciated and vesicular rock at the top of basalt flows and with minor fractured sandstone, chert and limestone interbeds (Randal, 1973). Higher air lift yields have been rarely encountered. For example, in Server 1, 33.5 L/s was found in a 1.5 m cavity of unknown origin at the base of the basalt. Water was struck in basalt in 133 bores and the majority of these are located west of the Stuart Highway. Forty percent have airlift yields <0.5 L/s and 50% were 0.5 to 5 L/s.

The groundwater quality in the volcanics is fresh and shows a general Ca-Na cationic and HCO3 anionic-dominated signature (Evans et al. 2020). Bores sampled are dominantly located north of the Buchanan Highway and west of the Stuart Highway where the volcanics are relatively shallow. No aquifers in the volcanics east of the Stuart Highway have been sampled because they lie at depths beyond the reach of normal water bores.

Basalt forms localised and generally low yielding fractured rock aquifers. Some aquifers in the upper section of the formation are possibly hydraulically connected to the overlying CLA but deeper ones are much less likely to be. In holes that penetrate thick sections of basalt, water intersections are sparsely distributed. On a regional scale the volcanics act as an aquitard or a leaky aquitard. A recent pump test conducted by this Department found no water level response in the CLA after four days of pumping the sandstone aquifer beneath the volcanics at 16 L/s (Short, 2021).

Numerous petroleum exploration wells and other bores have encountered sandstone between the Kalkarindji Suite volcanics and the Roper Group. In many cases the sandstones lying directly beneath the volcanics have been attributed to the Bukalara Sandstone. Despite the presentation of a simplified stratigraphic summary of the Beetaloo Sub-basin in Altmann et al. (2020), a preliminary study by the NTGS (Munson, 2020) suggests that more work is required to clarify the stratigraphic nomenclature of the Neoproterozoic sequence.

Most of the sandstones consist of fine to medium grained quartz and sandstone. Information on groundwater occurrence in these rocks is mainly limited to a few deeper water bores west of the Stuart Highway. A recently drilled DEPWS investigation bore, RN041145, in that area encountered sandstone beneath the volcanics. It appears to have a weathered horizon at the top of the core and has visible porosity as well as open fractures. The sandstone was pump tested at 16 L/s and had a TDS of approx. 2000 mg/L. It is likely that the sandstone is Bukalara Sandstone (Short, 2021; T. Munson pers.comm. Dec 2020). At this site, the groundwater level in the sandstone aquifer is approx. 6 m higher than the levels of the CLA at the same location.

The main source of hydrogeological information about the Bukalara Sandstone in deeper parts of the sub-basin (east) is from cores and drill stem tests. The rock is a fine to very coarse grained sandstone that is mostly confined between the Kyalla Formation beneath and the Cox Formation above.

Fulton and Knapton, (2015) used bottom hole pressure readings from drill stem tests in petroleum wells to make a general assessment of the vertical pressure gradients between the CLA and older formations including the Bukalara Sandstone (identified as Jamison sandstone). In Balmain 1 and Jamison 1 pressures were 115 and 135m higher in the Bukalara Sandstone than in the CLA, indicating that the potential for upwards groundwater flow between the two aquifers exists.

Amungee NW1 encountered an airlift yield of 40 L/s in the Bukalara Sandstone at a depth of 309 m. No water quality measurements were noted. The sandstone found beneath the Gum Ridge Formation in RN041679 at the Carpentaria 1 drill site is a fine sandstone with good primary porosity. Overall the sandstone aquifers have not been adequately tested.

A pumping test conducted on RN041242 in the 'Inacumba' aquifer found suggestions of connection to the overlying Gum Ridge Formation. A monitoring bore in the latter aquifer showed minor drawdown during the test but it was too small to distinguish the cause from other effects such as barometric pressure changes. Water quality in the two aquifers were near identical (Santos, 2020). In the case of the Carpentaria 1 site, Gum Ridge Formation directly overlies the Bukalara Sandstone and the two aquifers are likely to be hydraulically connected.

KNOWLEDGE GAPS

Table 1 summarises the current state of knowledge about information considered essential to establish a pre-development baseline assessment for each of the main Cambrian and Neoproterozoic aquifers. Each item has been given a relative ranking – Poor, Moderate or Good – reflecting how much is known about the particular process or in the case of monitoring networks, how adequate it currently is. Knowledge gaps are now discussed under each of the six key topics listed in Table 1.

Topic	Anthony Lagoon Formation	Gum Ridge Formation	Basalt	Neoproterozoic sandstones
Water level network	MODERATE	GOOD	POOR	POOR
Water quality network	MODERATE	GOOD	POOR	POOR
Aquifer connectivity	POOR	POOR	POOR	POOR
Aquifer extent and thickness	MODERATE	GOOD	MODERATE	POOR
Aquifer parameters	MODERATE	MODERATE	MODERATE	POOR
Recharge and discharge processes	POOR	GOOD	POOR	POOR

Table 1: Current state of knowledge.

Water level network

The main aim of a baseline water level monitoring network is to define the “pre-gas development” regional flow pattern in the main aquifers. It will also establish the ranges of any changes in water levels such as seasonal or longer term fluctuations. The information obtained will contribute to the understanding of the degree of connectivity between aquifers and recharge processes such as amounts, frequency, locations and mechanisms.

Water levels are currently only measured in sparsely distributed sites by DEPWS, Power Water Corporation and gas companies (Figure 2). The DEPWS sites are mainly concentrated in the Mataranka area and are visited twice a year, at the end of the wet season and at the end of the dry season. Many of the bores are equipped with water level loggers. The earliest monitoring by DEPWS began in the early 1990s.

Power Water Corporation measures groundwater levels at Elliott near their town production bores. The levels are measured twice yearly. Gas companies have been installing monitoring bores at exploration well sites. In areas where both Anthony Lagoon Formation and Gum Ridge Formation contain aquifers, separate monitoring bores have been installed in each. Manual measurements are made quarterly and most bores are equipped with water level loggers and the data is submitted to DEPWS on a regular basis. The earliest monitoring began in 2018.

Origin Energy is also monitoring water levels in unequipped station bores on their lease areas as well as in selected road and DEPWS bores. These have been monitored sporadically with manual measurements but some are also equipped with water level loggers. Two barometric pressure loggers are also installed in their lease areas. Problems with land access have limited the number of these sites that are presently monitored.

The majority of the monitoring bores are slotted against the Gum Ridge Formation, so that the aquifer has a good spatial coverage of water levels in the areas overlying the Beetaloo Sub-basin and north to the discharge zones in the Roper and Flora Rivers.

A notable absence of current monitoring bores occurs in the areas south of the Beetaloo Sub-basin. It would also be useful to target areas along the margins of the Georgina Basin identified in Tickell and Bruwer (2017) as likely recharge areas of that aquifer. Eight sites have been included on Figure 2 as suggested locations to complete the water level monitoring network. Sites 2 and 6 include multiple bores at a site to monitor more than one aquifer. Sites 3 and 5 are located in likely recharge areas. Water levels in the Anthony Lagoon Formation are currently monitored at five sites including three Origin Energy well sites.

The basalt has no water level monitoring bores, while the Neoproterozoic sandstone has only two, one at the Carpentaria 1 well site and one between Larrizona and Gorrie stations. No sites are recommended here for monitoring in the Kalkarindji Suite volcanics as it is considered more likely to act as a series of unconnected localised aquifers rather than as a single aquifer.

In the case of the sandstone aquifers, the area west of the Stuart Highway is the logical place to initially drill monitoring bores as it is relatively shallower there, within the depth range of most water drilling rigs. At least two new sites could be drilled there to establish the regional flow direction and gradient as well as any potential for vertical flow. East of the Stuart Highway the sandstones lie at greater depths so would be more difficult and expensive to drill. At least one hole is recommended, preferably near the site for a gas exploration/production well. The Amungee NW1 well site would be the preferred site as the Bukalara Sandstone is known to be at just over 300 m depth at that location (site 13).

The addition to the network of the seven new sites together with monitoring bores at future gas well sites should give an adequate coverage for a water level baseline in both the Anthony Lagoon and Gum Ridge aquifers.

A water level monitoring network for the CLA should be the first priority as it is the most extensive and widely used aquifer.

Water quality network

Collection of baseline water quality will record the “pre-gas development” concentrations of the major ions and other specified chemicals. The range over which these concentrations naturally change over various time scales will also need to be established. The water quality information will also be useful in establishing the degree of intra- and inter- aquifer connectivity.

Water quality is currently measured by the gas companies in the well site monitoring bores. Water samples are taken monthly and results regularly submitted to DEPWS. At each well site the Gum Ridge Formation is sampled as well as any other major aquifer if present. These include the Anthony Lagoon Formation, ‘Inacumba’ aquifer and Bukalara Sandstone.

A limited number of DEPWS monitoring bores in the Mataranka area have been sampled twice a year for the past 5 years to establish baseline water quality including major ions and pesticides. Power Water Corporation monitors water quality at town production bores including; Elliot, Newcastle Waters, Daly Waters, Larrimah and Mataranka. The waters are tested for major ions and health related parameters at three monthly intervals.

In order to extend the water quality network to the wider study area the simplest method would be to utilise stock bores that are currently operational. There is a widespread network of such bores and in many cases the aquifer that is tapped has been identified. The bores shown on Figure 3 as “previously sampled by CSIRO…..” are ones where one off samples were taken as part of the GISERA (CSIRO), Origin Energy, and GBA (Geoscience Australia) programs as well as various other Geoscience Australia projects. These sites are only a small subset of stock bores that could potentially be used for sampling. There are currently no bores monitoring water quality in the basalt, one in the ‘Inacumba’ aquifer and none in the Bukalara Sandstone. In areas where the Bukalara Sandstone is at depths beyond the reach of most water drilling rigs an alternative method for gathering new information from the sandstone aquifers could be for gas companies to drill those sections with air or to run drill stem tests on potential aquifers when practical. Although this would only be once-off information rather than monitoring, it could result in useful water quality and water level information.

The most important areas to monitor water quality should be within the area covered by the Beetaloo Sub-basin and slightly down gradient. Monitoring upstream or lateral to the sub-basin is unlikely to ever detect any impacts related to gas exploration/production. From a long term point of view, the major springs associated with the Flora and Roper rivers should be monitored. Eight suggested new monitoring sites have been included in Figure 3. Sites 11 and 12 are the Roper and Flora River springs which discharge from the Tindall Limestone. Sites 9 and 7 are just downstream of each lobe of the Beetaloo Sub-basin, while 8 and 10 cover the western lobe (all Tindall Limestone). Sites 13 and 15 sample the Bukalara Sandstone. Where possible existing equipped bores have been selected as sampling sites.

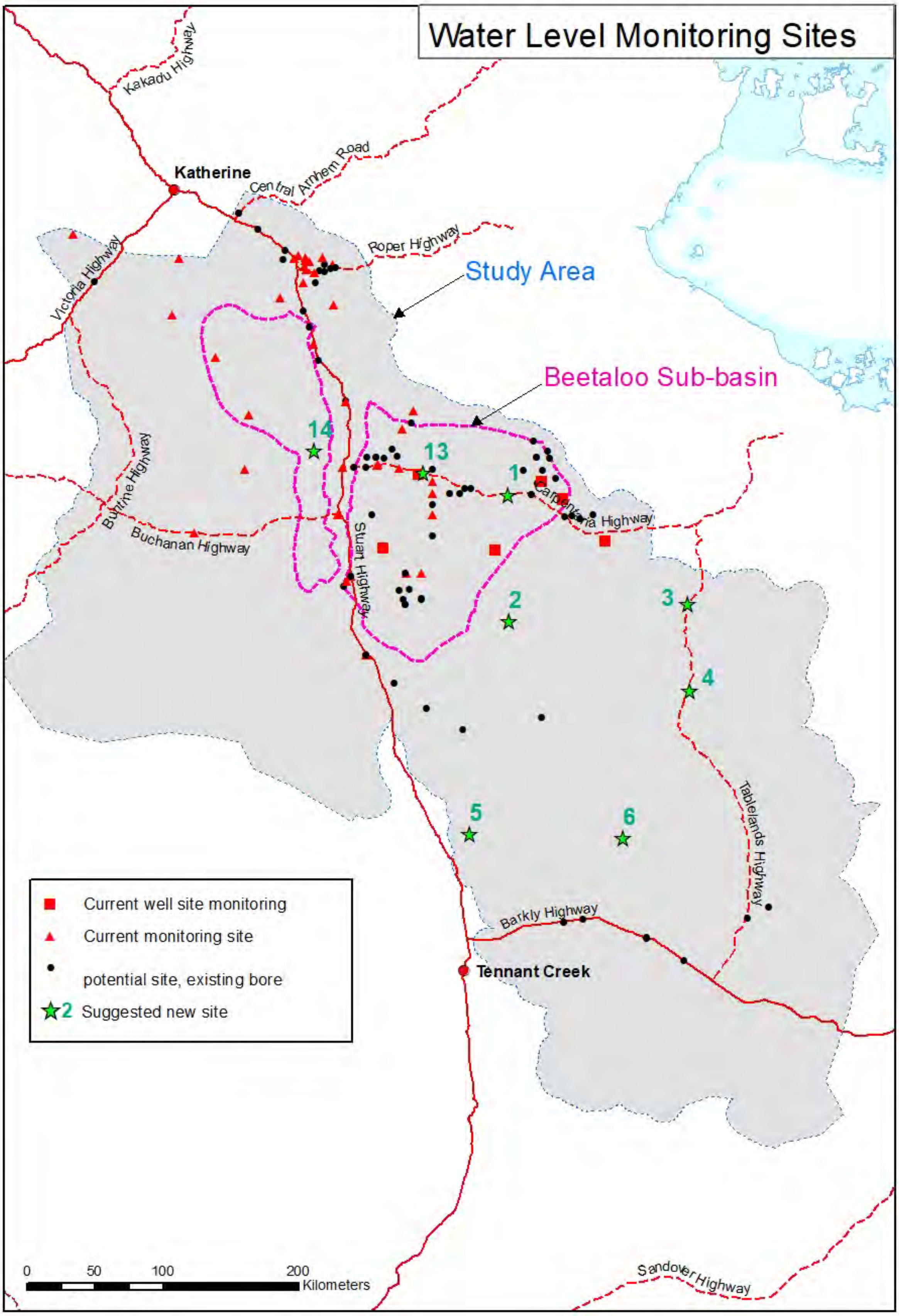

Figure 3: Water level monitoring sites.

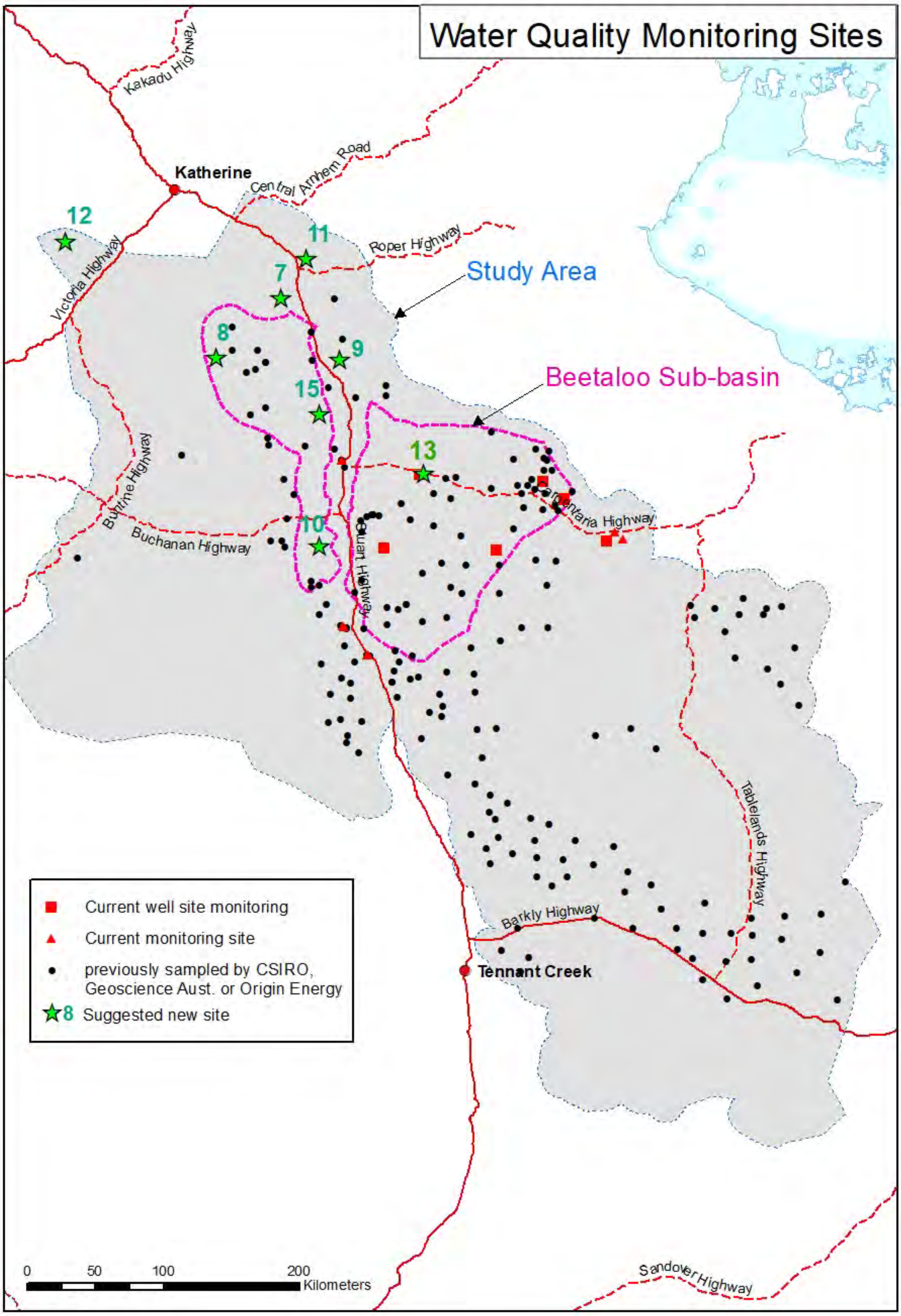

Figure 4: Water quality monitoring sites.

Aquifer connectivity

Aquifer connectivity both between the Anthony Lagoon Formation and Gum Ridge Formation and between individual aquifers within each formation is poorly understood at present. The main ways to determine connectivity are to compare water levels and or water quality from different depths at the same site. This can be achieved by drilling nested bore sites either with multiple piezometers in the one borehole or with several separate bores each monitoring aquifers at different depths. Another method is to conduct a pumping test in one aquifer and to look for a response in another. To date no definite responses of that type have been detected in pumping tests. One problem with that method is that the CLA are highly transmissive and bores would need to be pumped at very high rates for a long period of time to produce any effects in overlying aquifers, if they are connected.

Two Origin Energy well sites have monitoring bores in each aquifer in which water levels and water quality is regularly measured. The DEPWS site RN036471 along the Stuart Highway south of Dunmarra also monitors water levels in each aquifer but water quality is not currently measured there. Details of some of the monitoring results to date are described in Section 4.1 above. The Gum Ridge Formation bores at Origin sites are slotted against the full thickness of the formation and it would be useful to run down-hole flow logs to detect any intra-aquifer movement of groundwater. Several deep road bores on the Barkly stock route have long uncased sections which would also be useful to run flow logs in.

It would be desirable to obtain a more regional perspective on connectivity by establishing a minimum of two additional nested sites to the south of the current sites. One site located at the southernmost part of the Beetaloo Sub-basin and another perhaps along the Barkly Stock Route.

In the case of connectivity between the CLA and deeper aquifers and between Meso-and Neoproterozoic aquifers the locations where those aquifers are in direct contact with each other is known from a few borehole intersections. It would be useful to use existing 3D geological mapping to identify potential areas of connectivity.

Aquifer identification

The identification of aquifers as well as their extent and thickness is basic information needed to make a baseline study meaningful. For example, if a monitoring bore intersects more than one aquifer the water level and water quality data will be ambiguous if the aquifer being monitored in that bore is not known.

On a regional scale, the extent and thickness of both the Anthony Lagoon Formation and the Gum Ridge Formation are relatively well known but less so in the case of the former. In many areas, identifying the geological formations is difficult because bores frequently lose circulation while being drilled, resulting in poor or no return of drill cuttings. Furthermore driller's logs are usually not specific enough to enable identification of the formations. Proper identification is most critical especially near to the limits of the Anthony Lagoon Formation where many water bores could be slotted in either aquifer and still be at similar depths.

A good technique for accurately identifying formations is the down-hole gamma log. The two formations have distinctive gamma log signatures and the boundary between the two can usually be accurately identified. Gamma logs can be run in cased bores so it is recommended here to log selected stock bores where it is feasible to temporarily remove the pump. The aim would be to gamma log a sufficient number of bores and then use the information to assign aquifers to the intervening bores. This has already been done as a first pass with the existing gamma logs but in some key areas the distance between gamma logged bores is too great for accurate assignment of aquifers.

The extent of the basalt is quite well defined because it has a strong magnetic signature and can readily be identified on the airborne aeromagnetic surveys that have been flown over the whole study area. Its thickness is only known from a handful of deep bores that have been drilled through it. Of more interest to this study is the underlying sandstone, commonly but not always, the Bukalara Sandstone. The only information about it also comes from a few sparse bores. Some 34 bores have encountered sandstone directly beneath the basalt or directly beneath the Gum Ridge Formation where the basalt is absent.

As discussed in Section 5 above, there is some uncertainty as to whether or not all these sub-basalt sandstones are a single stratigraphic unit and in fact if they are actually equivalents of the Bukalara Sandstone as described from outcrops to the east of the study area. In some cases the younger "unnamed sandstone" and in other cases the older sandstones such as the Moroak Sandstone, may directly underlie the basalt due to uplift along structures, such as the Daly Waters High (Oor et al, 2020, fig 28). It is important to know whether the sandstone forms a continuous aquifer with relatively uniform properties over its extent or if it is a composite of different sandstones that have contrasting properties. For example older sandstones such as the Moroak Sandstone may be comparatively impermeable and possibly an aquitard while it could be in contact with the Bukalara Sandstone which is a fractured and possibly porous aquifer.

Aquifer parameters

Within the study area 213 bores have been pump tested and of these 41 fall within the limits of the Beetaloo Sub-basin. Sixty percent of tests have been done on bores that are screened/slotted in the Gum Ridge Formation or equivalents, 13% in the Anthony Lagoon Formation or equivalents, 15% in basalt and the remainder either in Proterozoic rocks or in mixed aquifers. The main purpose of most of the tests was to determine optimum pumping rates and pump depth settings. Basic data such as time/drawdown figures and pumping rates are available in most cases but for many bores it is only available as scanned copies of field notebooks. To obtain aquifer parameters (transmissivity and in some cases storage coefficient) the data would need to be digitised and reprocessed. The coverage of data across the study area is reasonably good. A much better understanding of the aquifer properties, particularly transmissivity could be obtained by reprocessing all the pump tests within the study area.

Aquifer parameters can also potentially be derived by using water levels obtained from loggers. If earth tides and barometric pressure changes are present, there are methods that will yield more regional scale values for aquifer parameters. There is currently a limited amount of logger data available but as new bores are added to the water level monitoring network the number should increase significantly.

Recharge and discharge processes for regional aquifers including groundwater surface water interactions

Various studies have made first pass estimates recharge using methods such as chloride mass balance, by difference in water balances and by using the DEPWS FeFlow model (Jolly et al, 2004;, Yin Foo and Matthews, 2006: Knapton, 2006: Tickell and Bruwer, 2019).

The tracer work of Deslandes et al (2019) used state of the art techniques that have added greatly to the knowledge of recharge processes in the CLA. They noted however that several of their results were inconclusive due to lack of information from deeper aquifers. Both the 14C and helium data indicated that all groundwaters sampled are a mixture of older and younger waters. Some of the older waters are coming from deeper aquifers while others are from more distant recharge areas. The source and the proportion of older waters can only be determined by doing tracer measurements of deeper aquifers and aquitards.

The two main flow systems, one west of the Stuart Highway and the other to the east discharge from the Tindall Limestone in springs along the Flora and Roper rivers, respectively. The locations and amounts of discharge is well known following several late dry season stream gauging campaigns mainly since 2000 (e.g. Wagenaar and Tickell, 2013). At Mataranka, discharge also occurs via evapotranspiration in a pandanus/paperbark swamp on the southern side of the river (Karp 2008).

Apart from a few small springs on the western side of the study area no other discharge features are known. Apart from the immediate vicinity of the Flora and Roper rivers, water levels are too deep to allow direct discharge to the surface or for vegetation to tap the watertable.

A GBA project in the Mataranka area is still in progress. It is using environmental tracers to determine sources of water to the Mataranka Springs.

FURTHER STUDIES AND ACTIONS

Several of the recommended studies listed below involve drilling boreholes. Likely numbers of drill sites required for each study are given as a rough estimate. The actual number required will depend on factors such as success in locating existing bores that can be utilised instead of drilling a new bore and whether or not the site can fulfil the aims of more than one of the studies (e.g. water levels, water quality or gamma logging).

Water level network

Expand the existing water level monitoring network in key aquifers (CLA and Neoproterozoic sandstones) with the main aims of achieve an adequate coverage of the whole study area and to characterise the regional flow system in the CLA. A sufficient number of sites should be established in both the Anthony Lagoon Formation and the Gum Ridge Formation (and equivalents). Sites in likely recharge areas should be included and at least two sites should be drilled into the Bukalara Sandstone west of the Stuart Highway and one on the eastern side.

The first step is to search for suitable unused stock or road bores that can potentially be used for water level monitoring. The next step is to drill bores to complete the coverage of the network. The suggested locations of eight new sites to be drilled are shown in Figure 2.

Water quality network

Select up to 50 existing and active production bores suitable to establish a new water quality monitoring network.

Determine which chemical / physical parameters should be routinely analysed.

Sample all bores in the network for a current snapshot of water quality.

Determine the frequency of sampling for ongoing monitoring.

Aquifer connectivity

Drill at least two new nested sites to monitor both the Anthony Lagoon Formation and Gum Ridge Formation. Drill two nested sites to monitor several different aquifers within the one formation. Do this for both of the above formations. At one of these sites conduct two long term (e.g. 7 days or longer) pumping tests, one in the Gum Ridge Formation and one in the Anthony Lagoon Formation. The pumping rates should be the highest practicable. The purpose of the tests is to detect both inter- and intra-aquifer responses and to obtain aquifer parameters.

Run down-hole flow logs in monitoring bores that have long uncased sections or long slotted intervals.

Produce geological map of the base Neoproterozoic and base Gum Ridge Formation using geological surfaces produced by Evans et al. (2020). Use these maps to identify areas where older aquifers are potentially in contact with the Gum Ridge Formation and where Mesoproterozoic aquifers (Moroak and Bessie Creek sandstones) are potentially in contact with Neoproterozoic aquifers (Bukalara Sandstone).

Aquifer identification

Identify suitable stock/road bores to gamma log.

In areas where no suitable bores are present drill a new bore to log.

Analyse gamma logs to determine stratigraphic boundaries and the extent and thickness of aquifers and confining layers.

Apply new stratigraphic/depth information to surrounding bores. Use that information to improve structural and thickness information of CLA formations. Also use it to improve identification of the aquifer(s) tapped in individual surrounding water bores. Water analyses can then be more accurately assigned to a particular aquifer.

Incorporate the updated data to the DEPWS groundwater model.

Aquifer parameters

Examine existing pumping test data for the Gum Ridge Formation, Anthony Lagoon Formation, basalt, 'Inacumba' aquifer and Bukalara Sandstone. Re-interprete the tests if necessary.

Search for water level responses on logger data that is likely caused by earth tides and barometric pressure changes. Analyse this data to determine aquifer parameters and the degree of confinement of the aquifer.

Obtain the range and average values for transmissivity and storage coefficient.

Plot the spatial distribution of aquifer parameters.

Apply this data to the DEPWS model, either as a single average value for the whole area or as individual values for different areas if spatial trends are present.

Recharge and discharge processes for regional aquifers including groundwater surface water interactions

Map sinkholes using satellite imagery. Do field examinations of selected sites to find any regional characteristics (e.g. surface openings present or broad clay filled depressions).

Examine drilling records of Cretaceous strata and map thickness, lithology, depth of weathering and basal sand characteristics.

Construct a map of recharge zones using the sinkhole type and distribution, properties of the Cretaceous strata (thickness and lithology), extent of the Anthony Lagoon Formation, aquifer depth, groundwater levels and water quality. Obtain water samples from monitoring bores drilled into aquifers and aquitards below the CLA including the Bukalara Sandstone and basalt. Analyse for helium and 14C so that the contribution of these deeper waters into the CLA can be estimated.

Install a series of three bores at progressively greater distances from a sinkhole to determine the extent to which tritium penetrates the aquifer. This will enable an estimate of total recharge over the CLA to be made.

Conduct a snapshot sampling of all springs that discharge from the CLA and from those that discharge from older formations adjacent to the CLA. In particular the springs in the Flora River were not included in the current GBA study and nor were the hot springs in the Beauty Creek spring complex which are thought to be sourced from Proterozoic aquifers at considerable depths. The aim of the work would be to investigate sources of the water and residence times.

TIMETABLE

Studies to be completed in next 1-2 years

- Drill new water level monitoring bores at Sites 1, 3, 4, 5, 13 and 14 (Figure 3).
- Drill three bores for tritium sampling as part of a sinkhole recharge project. Interpret the results.
- Desktop and field survey to search for existing bores suitable to use in the water level and water quality monitoring networks. Implement the monitoring regimes.
- Run flow meter logs in up to ten monitoring bores. Run caliper logs in open sections.
- Lift pumps, run gamma and induction logs in up to 10 station bores. Reinstall pumps.
- Interpret results of down-hole logging, reinterpret stratigraphy and aquifer(s) tapped in bores surrounding logged bores. Update bore database and relevant geological surfaces.
- Examine DEPWS pumping test data, reinterpret where necessary. Compile aquifer parameters for each aquifer.
- Analyse logger water level data. Use any barometric or earth tide responses to calculate aquifer parameters and degree of confinement.
- Map recharge zones using information on sinkholes, geology and hydrogeology.
- Snapshot of spring water quality/tracers.

Studies to be completed 2-5 years

- Drilling of water level monitoring bores, Sites 2 and 6 (nested or multiple bores at each site) (Figure 3).
- Conduct and analyse pumping test at one nested site (Site 2).
- Sample the Bukalara sandstone bores for helium and 14C. Estimate the contribution of these deeper waters into the CLA.
- Update DEPWS groundwater model with new geological/hydrogeological data.
- Gas companies to obtain an airlift yield and one off water level and water quality measurements from the Bukalara Sandstone, if that section of strata is able to be drilled with air. Take sidewall cores and conduct drill stem tests on these or deeper aquifers when possible.

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