The Cambrian Limestone Aquifer, Northern Territory: Review of the Hydrogeology and Management Rules to Ensure Protection of Groundwater Dependent Values

Prof. Matthew Currell[1,2], Dr Christopher Ndehedehe[2]

Environment Centre NT

[1]School of Engineering, RMIT University
[2]Australian Rivers Institute, Griffith University

Executive Summary

This report presents a concise review of the hydrogeology of the Cambrian Limestone Aquifer (CLA) in the Northern Territory (NT), and the ecological and cultural values sustained by its groundwater. It examines risks to these values associated with different approaches to the assessment of groundwater license applications in the CLA, including using the Top End and Arid Zone contingent rules, which apply in areas without a Water Allocation Plan (WAP), and other approaches proposed in draft WAPs (e.g., Georgina-Wiso). The report concludes with recommendations about appropriate methods and safeguards to protect the CLA's groundwater and the values it sustains, in line with recommendations of the Pepper Inquiry. The major focus is the areas of the CLA where WAPs are in progress – Flora Tindall, Mataranka and Georgina Wiso.

The Cambrian Limestone Aquifer (CLA) ranges from <50 m to over 400 m thick, covering much of the NT. The aquifer comprises inter-layered limestone and mudstone. Groundwater occurs largely within secondary porosity (fractures and karst features). The CLA is overlain by younger Cretaceous rocks; where these are absent, recharge to the aquifer and/or discharge to surface water occur. Below the CLA sits the Beetaloo sub-basin, a sequence of Proterozoic sedimentary rocks that host saline groundwater, oil and gas. The CLA occurs in three basins - Daly, Wiso, and Georgina. There is cross-basin connectivity between the equivalent limestone units within these.

Local recharge within each CLA basin appears to exceed rates of throughflow between adjacent basins, based on environmental tracer data and modelling. Throughflow remains poorly quantified but appears nonetheless to be a significant part of the water balance. There are also indications of vertical inter-aquifer connectivity - e.g., deep groundwater below the CLA contributing to spring flows at Mataranka Thermal Pools (in addition to CLA groundwater). Recharge to the CLA occurs by diffuse percolation of rainfall in areas where Cretaceous cover is thin or absent, at rates generally between <1 and 30 mm/yr, increasing from south to north. There is also evidence of recharge at higher rates (>100 mm/yr), associated with karst features (e.g., sinkholes). Discharge of groundwater to the surface appears to be limited to small but environmentally and culturally significant areas, where it sustains vitally important groundwater dependent ecosystems (GDEs).

Groundwater from the Tindall Limestone flows to the surface via springs, wetlands, and the channels of the Roper and Flora rivers and associated tributaries. These groundwater flows support significant vegetation communities and aquatic ecosystems within spring pools, groundwater-dependent sections of streams, and downstream waterbodies. Fauna drink from groundwater-fed pools and terrestrial vegetation utilises groundwater where the CLA water table is shallow. GDEs are also found within the aquifer matrix, i.e., stygofauna, including crustaceans, within caves and cavities in the rock. These groundwater dependent sites, waters, fauna, and vegetation and are of great cultural significance to Aboriginal peoples of the region. Aboriginal peoples' oral accounts highlight the interconnectedness of the region's groundwater, surface water and landscape, and both human and non-human living communities, as well as ancestral beings.

WAPs are not currently in place for the region encompassing the CLA and Beetaloo sub-basin, but are expected to be finalized in 2022-23, in accordance with recommendations from the Pepper Inquiry. A draft WAP for the Georgina-Wiso region is currently open for public review. Current rules for groundwater licensing where WAPs are not finalized use the Top End and Arid Zone contingent rules, to set caps on groundwater extraction rates for consumptive use in a given area. The Top End rules allow for allocation of groundwater licenses up to a fraction (20%) of estimated recharge. This approach is broadly in line with other groundwater management jurisdictions in Australia and worldwide, which calculate a Sustainable Yield as a fraction of recharge and/or discharge with the intention of balancing extraction with a need to maintain long-term groundwater access and limit impacts on GDEs. It should be noted however, that this method and/or the value of 20% may not always achieve these aims, due to complicated re-distribution of water balances in response to groundwater extraction. It remains unclear whether extracting 20% of recharge in aquifers currently classified as Top End (such as the Tindall Limestone) would have unacceptable consequences for GDEs. Preliminary analysis indicates significantly reduced flows to the Roper River could result, which would be particularly noticeable during dry periods.

The Arid Zone rules, which apply to the south of a line delineating northward and southward flowing surface water catchments of the NT, contain two clauses relevant to groundwater. The first states that licensed extractions should have no detrimental impacts on GDEs; the second allows for depletion of 80% of total pre-development groundwater storage, over a 100-year timeframe. These two aspects of the rules are contradictory. It is not possible for the first aim to be achieved if the second part is permitted. In accordance with the conclusions of the Pepper Inquiry, using storage volumes to calculate sustainable yields is not in line with ecologically sustainable development and risks harm to groundwater dependent values. Aquifers should not be described in terms of total storage when considering sustainable yields or 'safe' extraction rates. It is the water flows to and from the aquifer sustaining other aspects of the water cycle and dependent values (e.g., flows to springs, rivers and vegetation) that are most important in assessing sustainable yield. These flows are normally very small in comparison to the total water in an aquifer's storage; hence, extracting even small proportions of overall storage can have significant water cycle consequences (e.g., reduced baseflows and/or loss of groundwater dependent ecosystems).

The Arid Zone contingent allocation rules appear to be one of the only cases in Australia where a storage-based approach is applied to the determination of a 'sustainable' yield. If this approach were to be adopted in WAPs covering the CLA and Beetaloo sub-basin and/or remains in use more generally, it would allow for unsustainable development of groundwater, with serious potential consequences for groundwater dependent ecosystems, cultural values and water users. In the Daly Basin/Tindall Limestone section of the CLA, where the Mataranka springs and Roper River occur, extraction at rates that cause long-term storage depletion would endanger these and other important GDEs, by reducing spring discharge, river baseflow and water table levels.

The current draft WAP for the Georgina Wiso region proposes an estimated sustainable yield (yearly extraction cap) of 262.6 GL/year, estimated to be 40% of long-term averaged recharge. It is unclear how or why the value of 40% of recharge was determined to represent a sustainable level of extraction. In the Georgina and Wiso Basins, knowledge of the water balance, hydrogeology and groundwater dependent ecosystems are currently not sufficient to fully understand the effects of such extraction. The recharge estimate used to derive the ESY is model-derived and has considerable uncertainty. It is nearly double the value derived from earlier runs of the same model, and higher than some field-based estimates, meaning the ESY may constitute a larger fraction of recharge than assumed. The current data also indicate that recharge is considerably lower than the long-term average in most years (and may be negligible under the typical climate), except for rare events where rainfall (and recharge) far exceeds the rolling long-term average. Such periods have likely occurred only three or four times over the past century. The vast majority of estimated recharge to the Georgina and Wiso basins is associated with a single event in 1974. The recurrence interval for such recharge events, and details of their mechanism remain unknown. Therefore, under the proposed ESY, in most years, significant aquifer overdraft (extraction far exceeding recharge) would be permitted. Such overdraft may occur for many consecutive years (or decades), before the next episodic recharge event occurs.

Drawdown associated with consecutive years (or decades) of aquifer overdraft in the Georgina and Wiso basins would endanger stygofauna communities and reduce cross-basin discharge fluxes within the CLA, e.g., to the Tindall Limestone aquifer (upon which key GDEs noted above depend). Currently, groundwater discharge mechanism(s) from these two basins is poorly understood. There may be additional groundwater dependent ecosystems within or close to the edge of the plan area sustained by CLA groundwater (such as springs in the western Wiso Basin, or un-mapped deep-rooted vegetation communities). These GDEs may suffer reduced access to groundwater for extended periods between recharge events due to extraction at the proposed ESY, threatening their survival. Water quality risks, such as migration of saline water into fresher parts of the aquifer, and potential aquifer integrity issues associated with concentrated extraction in particular regions have also received limited or no attention in the draft WAP. Better characterization of GDEs, recharge and discharge mechanisms and rates, and more comprehensive assessment of these risks are urgently required before appropriate management rules can be adopted to ensure the Georgina-Wiso WAP does not lock in negative impacts on environmental and cultural values.

Sustainable management of groundwater extraction throughout the CLA should adopt a management approach in line with contemporary best practice, that sets:

1) **Volumetric extraction rate limits** which in the long-term ensure:
   A) groundwater flows and levels do not decline in such a way as to compromise the health of the groundwater dependent ecosystems, water quality and aquifer integrity. This requires careful analysis of recharge and discharge flux rates, environmental dependencies on these flows, and the extent of 'capture' and drawdown caused by pumping at different rates.
   B) the renewability of groundwater resources, ensuring prevention of long-term storage depletion and/or detrimental capture of surface flows - recognising the value of the Roper River, Mataranka springs and other GDEs supported by the CLA.

2) **Clearly defined and well monitored groundwater level thresholds**, determined to be the elevations required to sustain environmental and cultural values of groundwater dependent sites and ecosystems – including through the maintenance of throughflows between the CLA basins. When these levels are approached or crossed, reductions in groundwater pumping should be triggered, in line with level-based management approaches adopted in other parts of Australia and internationally. Trigger levels must be set appropriate distances from environmental assets seeking to be protected to account for time-lags.

Setting both a cap on total extractions in declared management zones, along with a series of water level thresholds and buffer zones to protect GDEs, would be in line with international best practices, if implemented alongside a robust monitoring program. Further, any rules developed to allow trading of groundwater should restrict the trade of extraction permits into areas close to high value GDEs. Together, these measures would ensure protection of key values supported by the CLA's groundwater. This management approach should be informed by a continuing program of inter-disciplinary science and community consultation, focusing on groundwater requirements of GDEs, and modelling to determine relationships between flows to these, extraction volumes, gradients, and time.

Knowledge gaps which should be addressed urgently include better qualitative and quantitative information on inter-basin and inter-aquifer flows (topics currently being investigated), better quantification of flows from the CLA and other aquifers to springs and streams (including those that have been less studied than Mataranka Thermal Pools and the Roper River), and eco-hydrological studies (including more extensive stygofauna surveys). These studies should determine the groundwater levels, flow rates and quality required to sustain key environmental and cultural values, as well as possible downstream consequences of reduced spring flows, river baseflows and groundwater throughflows of various magnitudes. Understanding what community stakeholders consider to be acceptable risks and impacts, and making public all relevant supporting scientific data and analysis informing WAP rules, should form part of the process of determining extraction rate caps and triggers. There is also a need to consider climate change and variability, with mechanisms to account for this built into long-term integrated water resources management.

Keywords: Groundwater sustainability, Cambrian Limestone Aquifer, Groundwater Recharge, Sustainable Yield, Groundwater Dependent Ecosystems, Cultural Value of Water, Northern Territory.

Cover Image: Pandanus species at Bitter Springs, Elsey National Park, Northern Territory, Australia. Source: Wikimedia Commons.

Suggested Report citation: Currell, M.J., Ndehedehe, C., 2022. The Cambrian Limestone Aquifer, Northern Territory: Review of the Hydrogeology and Management Rules to Ensure Protection of Groundwater Dependent Values. Report prepared for Environment Centre NT.

Introduction

This report, prepared at the request of Environment Centre NT, is designed to provide a concise, up-to-date review of literature and technical information about the Cambrian Limestone Aquifer (CLA), and current groundwater policies in the Northern Territory, in order to:

a) Consider the adequacy of current groundwater licensing arrangements under the *Water Act* – with a specific focus on the use of the Top End and Arid Zone contingent rules in water planning, and other proposed management rules in draft Water Allocation Plans

b) Make recommendations regarding the determination of sustainable yields and other management rules for Water Allocation Plans, and other relevant policies governing groundwater licensing within the CLA and Beetaloo sub-basin.

Recent groundwater licensing decisions and challenges to these[1] highlight that there is ongoing debate regarding the above issues, and a need for clear, scientifically informed analysis of the most appropriate mechanism(s) to ensure protection of groundwater dependent environmental, cultural, and economic values. The Pepper inquiry into Hydraulic Fracturing in the NT highlighted significant risks associated with the groundwater licensing arrangements in place at the time of the inquiry; these arrangements have remained largely un-changed since then. Recent licensing decisions signal an intent to apply the Arid Zone contingent rules (or similar management approach) over a larger geographic extent than has previously occurred, warranting thorough review of the potential risks and implications of this. Draft water allocation plans also include other methods to determine estimated sustainable yields within plan areas, based on recharge rates (which may or may not be protective of groundwater-supported values). This report delves into these issues and other knowledge gaps highlighted in the Pepper Inquiry and makes recommendations attempting to address these.

Appendix A lists the four main tasks/questions ECNT requested be addressed in this report. The subsequent structure of the report (in four sections) corresponds with these four topics. Subsequent to the commissioning of the report, ECNT also requested that the proposed groundwater management rules put forward in the draft Georgina Wiso WAP – released to the public in November, 2022 (Northern Territory Government, 2022a), be analysed and discussed (and this is done throughout the report).

The report draws upon literature that includes both technical work commissioned by or conducted within Northern Territory government agencies, as well as peer-reviewed scientific literature, including reports by national science agencies (e.g. CSIRO and Geoscience Australia) and academic institutions (e.g., relevant peer-reviewed journal papers).

[1] E.g., NT Land Corporation, application KG08988; Fortune, groundwater extraction licence WDPCC10000

1. Hydrogeology of the Cambrian Limestone Aquifer

a) Thickness, structure and properties

The Cambrian Limestone Aquifer (CLA) is an extensive carbonate aquifer underlying much of the Northern Territory to the north of Alice Springs and south of Katherine, encompassing most of the Barkly Tableland and Sturt Plateau. The aquifer system occurs within three major sedimentary basins; Daly, Georgina and Wiso (Fig. 1). The division between these three basins hosting the CLA corresponds with the presence of basement highs in the underlying rocks (at the basins' edges), above which the CLA aquifers thin and occur relatively close to the surface (e.g., Fig. 2). These basement highs are not complete hydrogeological or hydraulic boundaries; as such, there is some connectivity between the basins, with groundwater flowing from the southern two (Georgina and Wiso) providing inflows to the northern basin (Daly), in accordance with regional groundwater flow gradients (Tickell and Bruwer, 2017; Evans et al., 2020; Oberprieler et al., 2021). The primary limestone aquifer units of the CLA have different names within the three basins (Table 1):

Table 1: Major Cambrian Limestone Aquifer (CLA) units across the three major sedimentary basins (after Tickell and Bruwer, 2017; Bruwer and Tickell, 2015 and Evans et al., 2020).

Basin	Name of main CLA aquifer units (Upper & Lower)	Comment on usage/aquifer potential
Daly	Jinduckin Formation/Oolloo Dolostone (upper)	A minor aquifer that is thin or absent in much of the basin
	Tindall Limestone (lower)	Major CLA aquifer in the Daly Basin. Equivalent to Gum Ridge Formation (Georgina) and Montejinni Limestone (Wiso)
Georgina	Anthony Lagoon Formation (upper)	Locally high-yielding aquifer, utilized for stock watering
	Gum Ridge Formation (lower)	Thick, extensive and locally high-yielding limestone aquifer, less utilized than Anthony Lagoon Formation due to depth, but considered prospective as a water source
Wiso	Hooker Creek Formation (upper)	Local confining layer and/or aquifer depending on lithology.
	Montejinni Limestone (lower)	Major CLA aquifer in the Wiso Basin. Equivalent to Tindall & Gum Ridge Formations

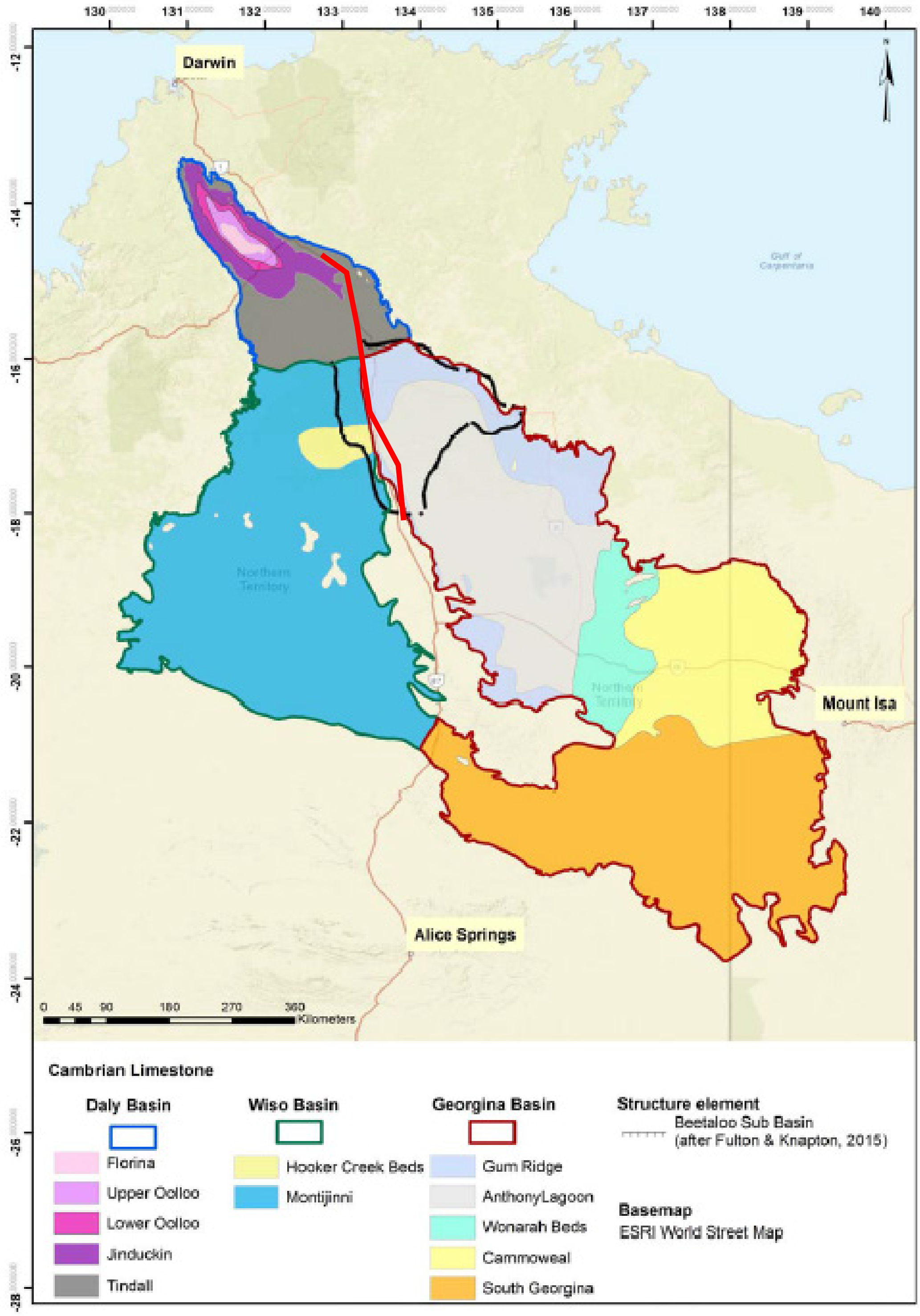


Figure 1: Map showing the three sedimentary basins hosting the Cambrian Limestone Aquifer (CLA) along with the outcrop geology. Modified from Deslandes et al., 2019. Red line shows approximate cross section location for Figure 2 (from Bruwer and Tickell, 2015).

The CLA has outcrops or sub-crops near the surface over significant areas in all three basins (notably at Mataranka, and the southern Wiso and Georgina Basins) but it is generally buried beneath younger sedimentary rocks from the Cretaceous period (Knapton, 2020). There is a time gap of approximately 400 million years between the Cambrian and Cretaceous rocks, and the boundary between the CLA and Cretaceous comprises a weathered erosional surface developed during this time. Significant karst features (sinkholes, caves and other secondary porosity) also developed in the limestone. The boundary permits diffuse leakage of rainfall recharge to the CLA, where the Cretaceous cover is thin (Bruwer and Tickell, 2015).

The CLA is underlain by older Cambrian volcanic rocks (e.g., the Antrim Plateau basalts), and below this, Proterozoic sedimentary rocks, including those of the Beetaloo Sub-basin (e.g., the Roper Group) which host extensive oil and gas deposits (Evans et al., 2020). Together, the Cretaceous, Cambrian, and Proterozoic geological units form a thick sequence (up to 5 km) of stacked sedimentary rocks, including multiple aquifer and aquitard units. The extent of vertical connectivity between the CLA and underlying rocks is a focus of recent and current research programs, as recommended by the Pepper Scientific Inquiry - e.g., through the Strategic Regional Environmental Baseline Assessment (SREBA) program. The most recent reports from these programs note that inter-basin and inter-aquifer connectivity occur, but are generally still not well characterized (Lamontagne et al., 2021; Frery et al., 2022). These studies have found evidence from environmental tracers and geophysics of deep groundwater flow reaching shallow aquifers and/or the surface, e.g., at Mataranka springs (Lamontagne et al., 2021).

Aquifer thickness and structure

The CLA ranges in thickness from approximately 20 to 80 m above basement highs where it outcrops or sub-crops near the surface (including near the Roper River and Mataranka springs), to over 400 m at its thickest extent within the Georgina Basin, comprising the Anthony Lagoon and Gum Ridge formations (Tickell and Bruwer, 2017). Throughout most of the Daly, Georgina and Wiso basins, the CLA ranges between approximately 100 to 300 m thick and can be described as a semi-confined to unconfined aquifer. An example cross-section showing the Tindall Limestone and Gum Ridge Formations (lower CLA units in the Daly and Georgina basins, respectively), overlying and underlying geological units across the Daly/Georgina boundary, is shown below:

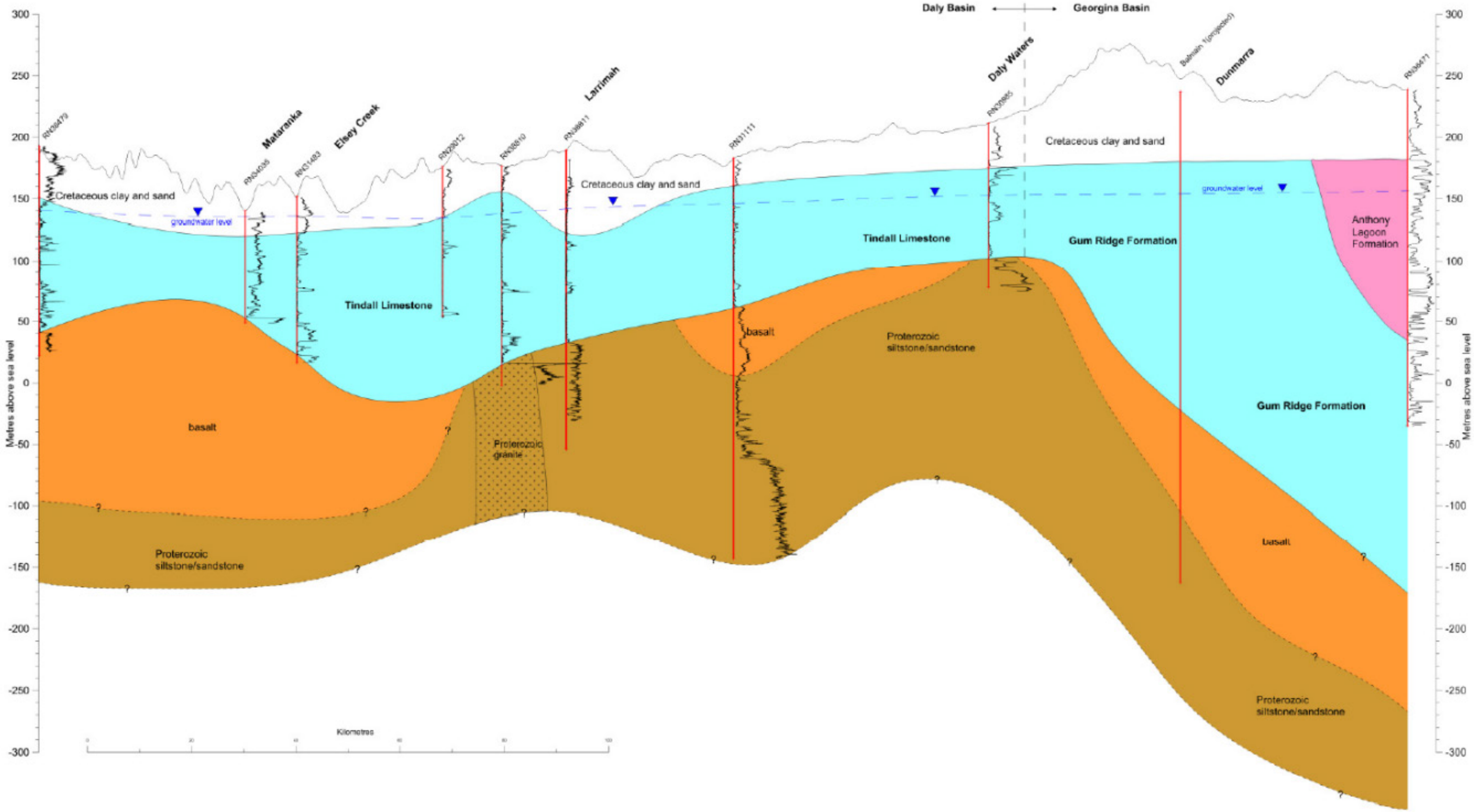


Figure 2: Cross section of the southern Daly and northern Georgina Basin, showing estimated thickness of the CLA, Cretaceous cover, and underlying Cambrian and upper Proterozoic rocks (From Bruwer and Tickell, 2015). Approximate cross section location indicated on Fig. 1.

Aquifer properties

A program of pumping tests has been carried out to assess the CLA's potential bore yields and hydraulic properties in the Daly and Georgina basins. This has determined that aquifer transmissivity values – which determine how much groundwater can be readily extracted and the extent of drawdown in response to pumping - range between relatively low values (~5 m^2/day) up to very high values (over 45,000 m^2/day). These data are summarized in Table 2:

Basin	Unit	Range of transmissivity values (m^2/day)	Estimated groundwater storage capacity (GL)
Daly	Tindall Limestone (lower)	100 to 47,400	28,200 to 56,400
Georgina	Anthony Lagoon Formation (upper)	13 to 8200	1,766,000 to 3,532,000 GL
	Gum Ridge Formation (lower)	5 to 3100	52,500 to 157,500 GL
Wiso	Hooker Creek Formation (upper)		
	Montejinni Limestone (lower)	3 to 9480	

Table 2: Summary of estimated aquifer transmissivity values for main CLA units (after Bruwer and Tickell, 2015; Tickell and Bruwer, 2017; Knapton, 2020).

Transmissivity values of above ~500 m^2/day are generally considered permeable and prospective for development of an aquifer as a water resource[2]. As such, significant portions of the CLA would be considered high-yielding. However, transmissivity values are highly variable throughout the region, e.g., in areas of the Georgina Basin where the Anthony Lagoon Formation comprises low-permeability siltstone (between limestone layers) bores are low-yielding with T values < 50 m^2/day. Knowledge of aquifer hydraulic parameters within the Wiso Basin (e.g., Montejinni Limestone) is relatively limited (see Table 2), as a significant program of pumping tests and related studies has not (to our knowledge) been reported.

Storage capacity

Various estimates of the total amount of groundwater in storage within the CLA have been given, as noted in Table 2. These estimates should be interpreted with caution for two reasons:

1. The CLA is not a 'standard' porous medium (with uniform distribution of void space in which groundwater can be stored). Instead, much of the porosity is secondary, relating to karstic features (sinkholes, dolines) and fracturing. How much water in storage is available for extraction is unlikely to be well described by these bulk estimates. For example, effective porosity values of up to 40% (cited in Tickell and Bruwer, 2017) for the Gum Ridge Formation may over-estimate the availability of water that can be readily extracted.

[2] For example, see Science Direct topic entry under Transmissivity: https://www.sciencedirect.com/topics/earth-and-planetary-sciences/transmissivity

2. Aquifers should not be described in terms of their total storage when considering sustainable yields or 'safe' extraction rates (this topic is covered in detail in Sections 2 and 3 of this report). It is the water flows to and from an aquifer sustaining other aspects of the water cycle and dependent values (e.g., groundwater flows to streams, springs and other aquifers), that is the most important factor in assessing the sustainable yield from an aquifer (not storage volume) (Theis, 1940; Alley et al., 1999; Ponce, 2007). These flows are normally very small in comparison to the total water in an aquifer's storage; extracting even small proportions of overall storage can have significant water cycle consequences (e.g., reduced baseflows and/or loss of groundwater dependent ecosystems). Viewing the aquifer as a single connected 'bucket' of stored water that can be extracted without impacting the broader water-cycle, risks serious harm to water users and the environment (Alley et al., 2002; Bierkens and Wada, 2019).

b) The water balance of the CLA and connections to the broader water cycle

Groundwater Recharge

Groundwater recharge - defined as water that crosses the water table, adding to groundwater stored in an aquifer (Healy, 2010) may take place through a range of mechanisms, e.g., diffuse rainfall infiltration across a wide area vs. focused recharge below specific landscape features; continuous recharge vs. episodic 'event-based' recharge. Direct recharge – i.e., rainfall percolation below the soil zone to the water table, to the CLA is thought to be restricted to areas where the Cretaceous rocks covering the aquifer are thin or absent (Fig. 3). Other recharge mechanisms that have been identified include macropore flow (through large surface cracks) stream and lake water leakage, including surface water losses to karstic features (e.g., sinkholes and dolines) (Bruwer and Tickell, 2015; Tickell and Bruwer, 2017; de Caritat et al., 2019; Deslandes et al., 2019). The latter mechanisms are not well quantified throughout the CLA, though recent environmental tracer sampling by Deslandes et al (2019) allowed for approximate quantification of diffuse (rainfall seepage) and preferential (sinkhole) recharge in certain areas (see Table 3). Based on tritium data, point-based diffuse recharge rates were estimated to be between ~1mm/yr and 30 mm/year, generally increasing from south to north, in accordance with increasing rainfall and decreasing ET rates, while preferential recharge through sinkholes was estimated to occur at significantly higher rates (>100 mm/year) in local areas. Crosbie and Racchakonda (2021) derived similar overall recharge estimates based primarily on chloride data, while De Caritat et al (2019) also identified areas of the Wiso Basin where leakage from surface water bodies (Lake Woods and Newcastle Waters Creek) is the predominant recharge source. They noted Tarrabool Lakes to be a significant recharge feature to the Georgina Basin.

Bruwer and Tickell 2015 estimated recharge to the Daly Basin CLA (Tindall Limestone) to be approximately 330 GL/yr, based on water table fluctuations, Chloride mass balance, and numerical modelling. All these methods are acknowledged to have issues/uncertainties, but the use of multiple lines of evidence provides some level of confidence in the magnitude of the estimates. Tickell and Bruwer, 2017 used chloride data from precipitation and groundwater to estimate recharge to the two major CLA units in the Georgina Basin (Gum Ridge and Anthony Lagoon Formations). These were estimated to be approximately 1 to 10 mm/year on a point basis, which is approximately 0.2 to 3% of yearly rainfall. Quantifying these estimated rates across the extent of the basin's major recharge areas (see Fig. 3

below), results in overall recharge estimates of approximately 20 to 180 GL/year for the Gum Ridge Formation, and 50 GL/year for Anthony Lagoon Formation (Table 4).

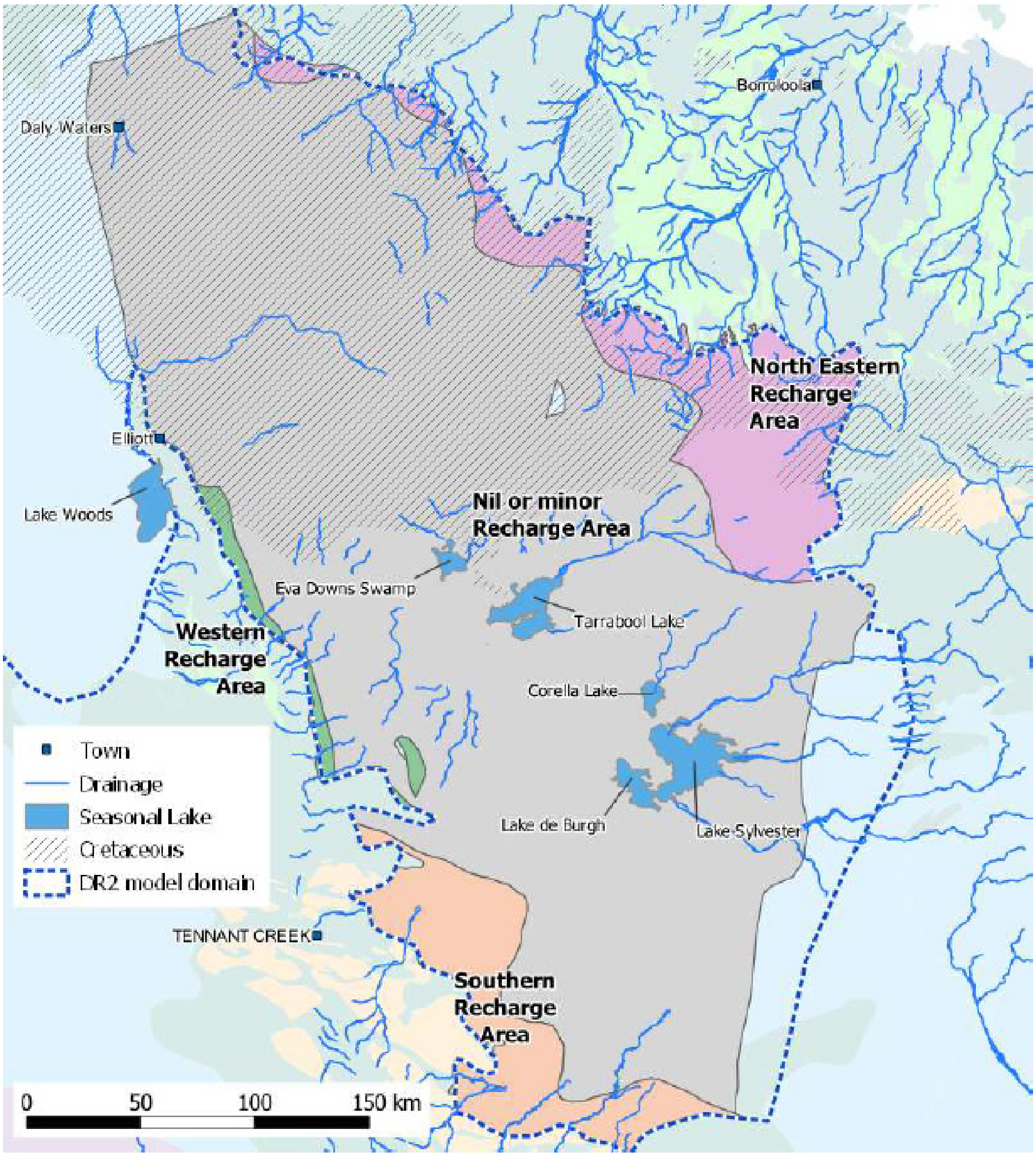


Figure 3 – Mapped or inferred groundwater recharge areas for the Georgina Basin (From Knapton et al., 2020, after Tickell and Bruwer, 2017).

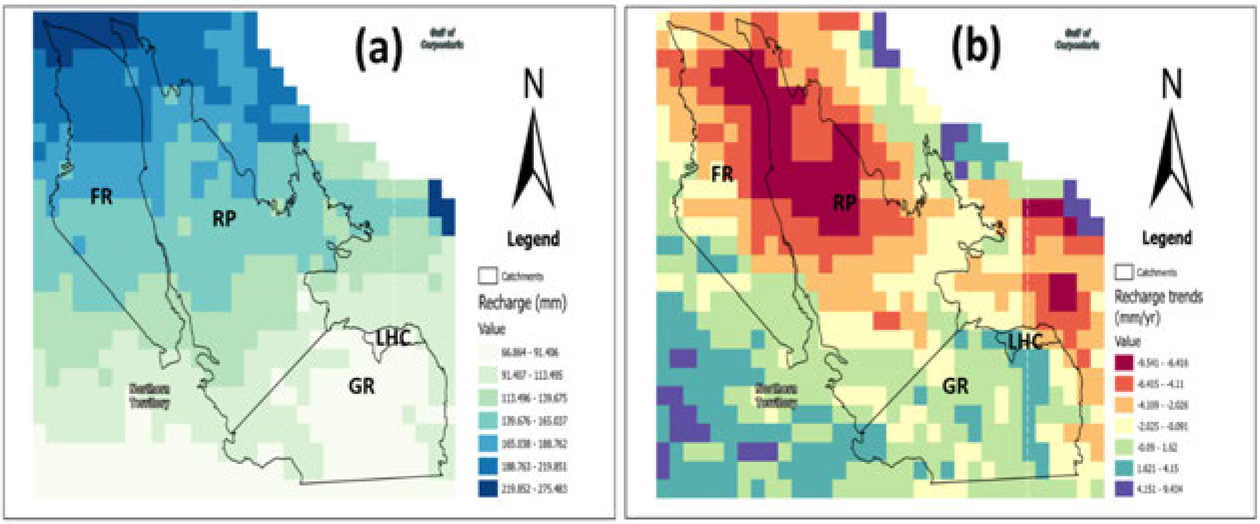
Knapton et al., (2020) reviewed earlier estimates of recharge in the CLA to inform coupled surface-groundwater modelling using MIKE-SHE and FEFLOW. MIKE-SHE estimates recharge based on rainfall, evapotranspiration, vegetation and soil properties (allowing incorporation of preferential flow through macropores). Based on this approach, Knapton et al (2020) estimated recharge to the Georgina basin to be ~315 GL/yr, considerably higher than field-based estimates of Tickell and Bruwer (2017). Sanford (2002), Scanlon et al. (2002) and others have noted that caution is required when using numerical models and/or water balance estimates (with recharge calculated as the residual of other water balance terms) to estimate groundwater recharge. As a generally small part of the water budget, there are significant uncertainties with such estimates, and ground-truthing with field data is essential. Recharge in the Mataranka zone of the Daly Basin was estimated by Knapton (2020) at ~177 GL/year, in line with earlier estimates by Bruwer and Tickell (2015).

Hydrograph analysis in the Georgina Basin (Tickell and Bruwer, 2017) shows that recharge to the southern CLA aquifers (Georgina and Wiso basins) is mostly associated with rare, intensive wet periods, when 5-year moving average rainfall exceeds the long-term average. Major water table rises, indicating significant recharge, have been recorded only twice since monitoring began; in the mid-1970s and early 2000s. Recharge is likely to be well below the long-term average in most years, but substantially above long-term averages only during such rare wet events.

The recently released draft Georgina Wiso WAP estimates recharge rates to the Georgina and Wiso Basins to be approximately 660 GL/year; i.e., significantly higher than the previous model-based estimates outlined in Table 3. The 660 GL/year value is based on updated coupled surface water-groundwater modelling - the same model reported in Knapton, (2020). The estimate is however nearly double the recharge reported for the Georgina Basin in the previously documented modelling. This is likely due to the use of the most recent 50 year-period of data (1970 to 2020, a relatively wet period), as opposed to the full length of available climate records – Knapton, (2020) used the longer period of 1900 to 2019 climate data. Notably, the majority (two thirds) of the recharge contributing to the overall total over the revised modelled conducted for the draft WAP occurred during 1974, an extremely wet year which saw an estimated 21,280 GL of recharge. There is very little data to indicate the mechanism or geographic extent of this large, episodic recharge event, nor any indication as to how frequently such events may recur. As such, the estimation of average recharge in the draft WAP, is very heavily dependent on a single recharge event nearly fifty years ago, for which data are mostly lacking. This is critically important when assessing whether extracting a fraction of the averaged recharge rate derived using the model – e.g., 40%, as proposed in the plan – can be considered appropriate as a sustainable yield (see further discussion in section 2 and 3 below).

In recent years, estimation of groundwater recharge has also been attempted using satellite remote sensing methods, in particular the Gravity Recovery and Climate Experiment (GRACE), launched by NASA in 2002. The use of these data is still generally considered to require careful ground-truthing, as there are multiple sources of uncertainty and potential error (e.g., Chen et al., 2016). In the Murray Darling basin and elsewhere, the agreement between satellite and in-situ data from monitoring bores suggests GRACE data can track groundwater dynamics (e.g., Rateb et al., 2020; Chen et al., 2016) with limited uncertainties compared to outputs from models and other sources (see Scanlon et al., 2002). Estimation of recharge and/or groundwater storage changes with GRACE is only feasible over large geographical areas, as the satellite data have limited local-scale resolution.

Preliminary analysis in this report shows that the large scale of the CLA allows for meaningful use of GRACE to examine recharge rates and water balance trends (Figure 4 and Table 3). Annual recharge in the Daly Basin was estimated from GRACE data for 2003-2016 based on the difference between maximum groundwater depth observation in a particular year and the shallowest observation in the following year. Soil moisture, derived from the Global Land Data Assimilation System model (GLDAS-Noah), was subtracted from the overall GRACE signal for terrestrial water storage change. Preliminary recharge estimates using this method resulted in high rates (> 200 mm/yr) in the northern Flora River catchment, reducing gradually towards the south, and slightly reducing over time (Fig. 4b). Recharge in the Gregory River catchment ranged from 66-90 mm/yr and appeared to be slightly increasing with time. The recharge estimates broadly align with those proposed by Deslandes et al., (2019) and chloride mass balance data by Crosbie and Rachakonda (2021), though they are higher than previous estimates.



FR-Flora River; **RP**-Roper River; **GR**-Gregory River; **LHC**-Lawn Hill Creek

Figure 4 – Spatial patterns of annual groundwater recharge in four catchments of the Cambrian Limestone Aquifer estimated from the Gravity Recovery and Climate Experiment satellite (2003-2016). (a) Shows the average annual recharge and (b) the trends in annual recharge during the period. Data sourced and processed by C. Ndehedehe

This preliminary analysis indicates that, notwithstanding uncertainties relating to estimates of soil moisture, GRACE can be used as an independent line of evidence for recharge to the CLA, and to examine its responses to climate variability and water extraction. In the CLA, recharge is primarily being driven by annual rainfall and possibly also the strongly annual temporal patterns of surface water extent (de Caritat et al., 2019).

Table 3: Summary of recharge estimates for the CLA

Study	Basin/Unit(s)	Point-based recharge rate estimates (mm/year)	Volumetric recharge rate (CLA)	Method(s) used
Deslandes et al., 2019	Southern Daly (Tindall), Northern Georgina (Anthony Lagoon & Gum Ridge Fm),	1 to 25 mm/yr (diffuse, increase south to north); 140 to 190 mm/yr (preferential	Not quantified	Tritium, Chloride mass balance (recharge rate); CFCs, SF6 and noble gases

	Northern Wiso (Montejinni Lstone)	recharge through sinkholes)		(qualitative insights)
Bruwer and Tickell, 2015	Daly Basin / Tindall Limestone	8.7 to 28.5 mm/yr (in areas of shallow/exposed CLA)	Approx. 330 GL/yr (possible range from 286 to 722 GL/yr).	Water table fluctuations, Chloride mass balance, water balance, model
Tickell and Bruwer, 2017	Georgina Basin / Anthony Lagoon Formation	0.9 to 12.2 mm/yr (areas of shallow/ exposed CLA)	20 to 179 GL/yr (Gum Ridge Fm) 51 GL/yr (Anthony Lagoon Fm)	Chloride mass balance
Crosbie and Rachakonda, 2021	Entire CLA	5 to 156 mm/yr including: 5 to 18 mm/yr (Georgina); 9 to 31 (Wiso); 49 to 156 (Daly) (5th to 95th percentiles)		Chloride mass balance, constrained using baseflow separation and remote sensing data
Knapton et al., 2020	Georgina Basin & Daly Basin		315 GL/yr (Georgina); 177 (Daly)	Coupled ground-surface water modelling
Northern Territory Government, 2022a	Georgina & Wiso Basins		608.4 GL/yr (Georgina); 48 GL/yr (Wiso) (Additional estimates compiled in background report – NTG, 2022b)	Coupled ground-surface water modelling
This study (preliminary estimates only)	Daly Basin (Flora, Roper, Gregory River catchments)	174 mm, 87 mm, 84, and 144 mm for the Flora River, Gregory River, Lawn Hill Creek and Roper River catchments.	Not quantified	GRACE satellite data

Groundwater flow patterns

Regionally, groundwater flows from the southern parts of the Barkly Tableland, Sturt Plateau and Wiso Tableland (within the Georgina and Wiso basins) to the north, following the gentle decline in topography (Fig. 4). Flow patterns within the Daly Basin continue this northerly-directed flow-path within the Tindall Limestone, towards the Roper River and Mataranka Springs on the east of the basin, and towards the Flora River and associated springs on the western side of the basin (e.g., Top Springs). In the Daly Basin, there is also flow from the northern margins (near Katherine) towards the south, with groundwater flows again converging upon and discharging to the Mataranka Springs and Roper River (Fig. 4). At the northern extent of the Daly Basin, there is further northward-directed groundwater flow in the Tindall Limestone, which discharges into the Daly River through many springs (Fig. 4).

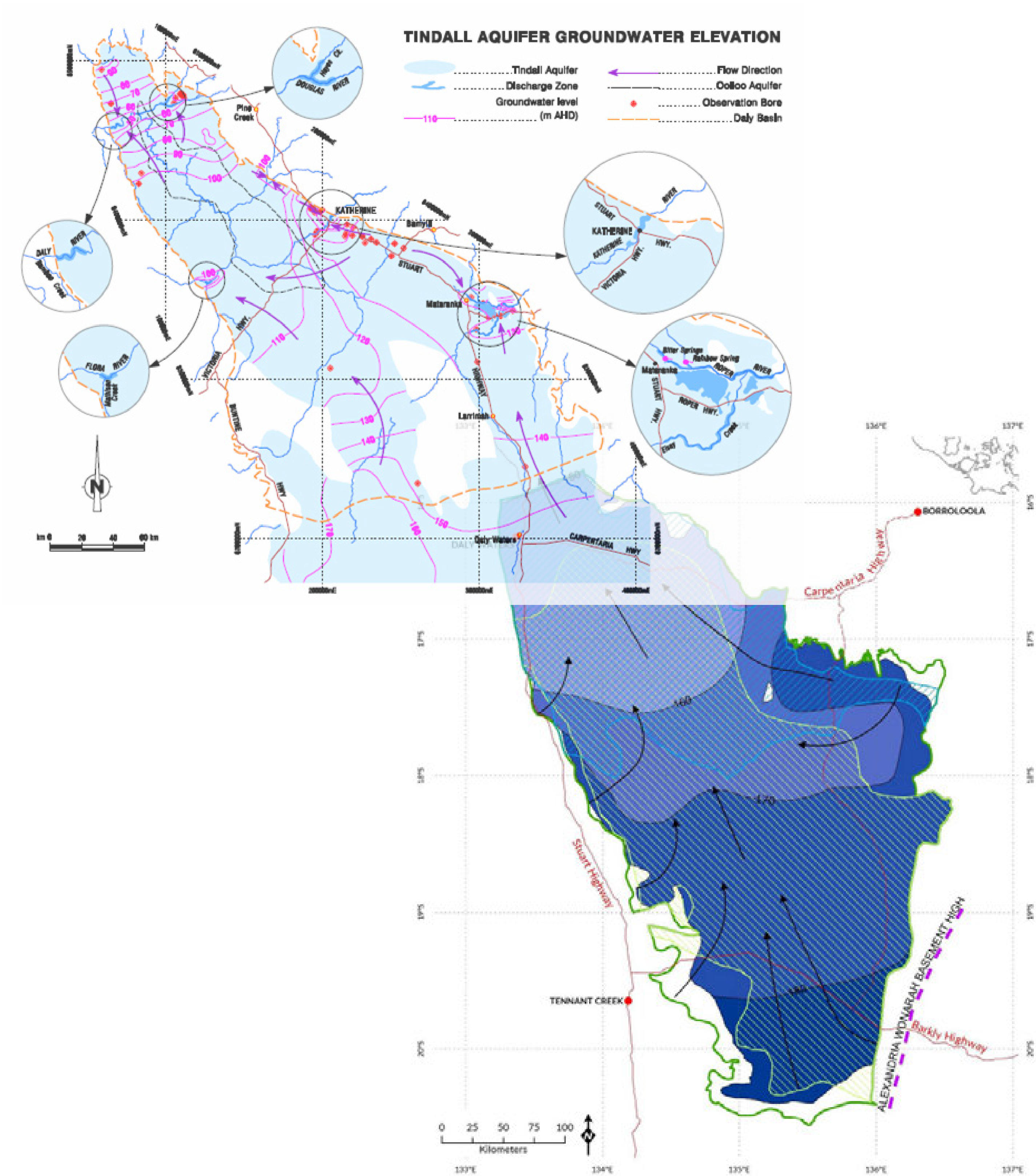


Figure 4 – Composite map of approximate groundwater level contours in equivalent Cambrian limestone aquifer units across the Georgina Basin (bottom image) and Daly Basin (top image). Maps from Tickell (2007) and Bruwer and Tickell (2015).

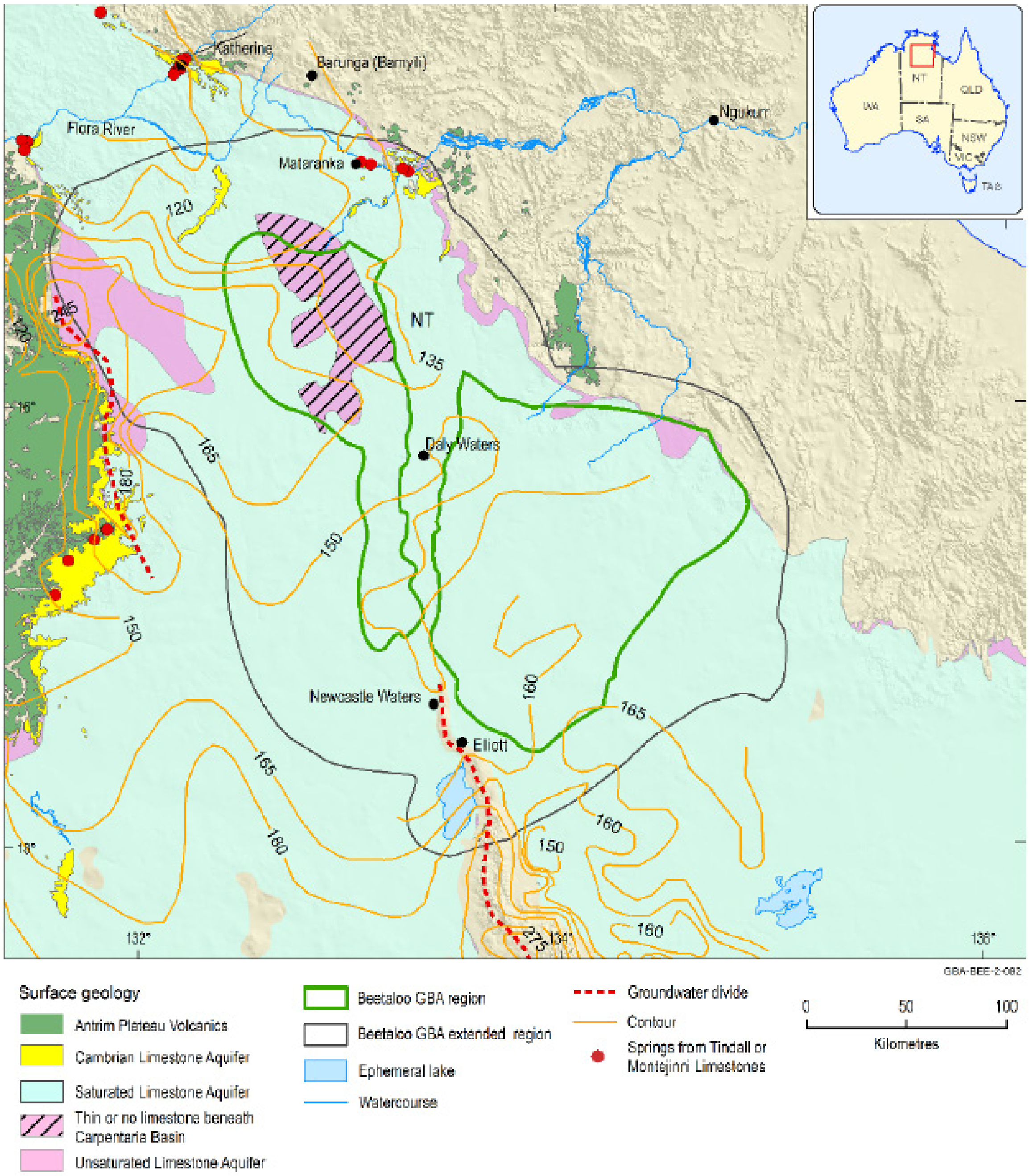


Figure 5: Approximate water level contours: Montejinni Limestone, Wiso Basin and Tindall Limestone, southern Daly Basin, with Beetaloo sub-basin indicated. From: Evans et al., (2020).

Throughflow between different CLA units in the three basins

The extent of connectivity along regional groundwater flowpaths, i.e., the amount of throughflow from the Georgina and Wiso basins into the Daly Basin along its southern boundary, and the importance of such throughflow (as opposed to more localized recharge), in sustaining fluxes and levels in the Tindall Limestone, remains a major knowledge gap (Evans et al., 2020). This has significant implications for how the CLA is likely to respond to groundwater extraction in different regions - i.e., the extent of localized vs. regional impacts. The groundwater contour patterns mapped and shown in Fig. 4 and Fig. 5 indicate that groundwater flow in the main CLA units continues from the northern extents of the Georgina and Wiso Basins into the Daly Basin, i.e., throughflow from the southern basins into the Daly. The mapping of stygofauna assemblages recently by Rees et al (2020) and Oberprieler (2021) indicated that there is a high degree of connectivity within the CLA across the three basins - if this was not so, more localized endemic stygofauna communities would be expected. This is further supported by similarities in the hydrochemistry of groundwater along flow paths that cross the basin boundaries (Evans et al., 2020).

Tickell and Bruwer (2017) note that despite the equivalence between the Tindall Limestone and Gum Ridge Formation across the Daly/Georgina basin boundary and regional flow directions, recharge and flow patterns are somewhat different in the two basins, and localised recharge and flow within each basin are also important:

> "There is a notable difference in the flow pattern in the Gum Ridge Formation compared to that in the Tindall Limestone, its equivalent in the Daly Basin. In the latter case, where the Formation outcrops along the basin margin, flow is parallel to the margin and groundwater discharges to streams which are generally perpendicular to the margin. In the Georgina Basin, groundwater levels are too deep to discharge to streams, so the flow pattern is basin-wards from the margins and then to the north-west." (Tickell and Bruwer, 2017)

On the basis of pumping test data, hydraulic gradients and aquifer geometry, Tickell and Bruwer (2017) estimated throughflow from the Georgina Basin (Gum Ridge Formation) to the Daly Basin (Tindall Limestone) to be approximately 2 GL/year. Knapton (2020) proposed somewhat larger estimates of groundwater throughflow from the Georgina to Daly basin, with 1.6 to 16 GL/yr transferring as throughflow (Figure 6). This is still a relatively small contribution to the Tindall Limestone's water balance in comparison to rainfall recharge within the basin itself (Table 4), however it may be important for sustaining water levels and flows through the Daly Basin. Carbon isotope dating also points to somewhat complicated relationship between groundwater flow patterns, recharge, and inter-basin connectivity:

> "From carbon isotopes, Suckow et al. (2018) noted that apparent groundwater ages became younger northward along an inferred regional flow path trend, from the Georgina Basin to Daly Basin. This is the opposite of what is usually expected, which is that groundwater becomes older along a confined flow path. One explanation for the apparent carbon age trend is that recent recharge is occurring in the northern part of the trend, with older groundwater at the southern end of the flow path in the Georgina Basin. Other interpretations and complicating factors, put forward by Suckow et al. (2018) are: there is not a continuous regional flow path (flow paths are more localised), unknown processes are influencing the carbon isotope results, or that flow velocity is high enough along the flow path that not enough time is available for significant radioactive decay to occur in carbon isotopic system." (Evans et al., 2020).

Knapton (2020) summarised a basic water balance for the Georgina & Daly basins, encompassing throughflow and estimates of groundwater discharge to the Roper River and Mataranka Springs, as outlined in Figure 6. Groundwater contour mapping shows that groundwater flow divides between and within the three basins are important controls on flow patterns and inter-basin connectivity, and that these are controlled by topography and geological structure (e.g., faulting); particularly in the Wiso Basin, where flow towards Top Springs on the western basin margin is important in addition to the northward directed flows into the Daly Basin towards the Flora River (Fig. 5).

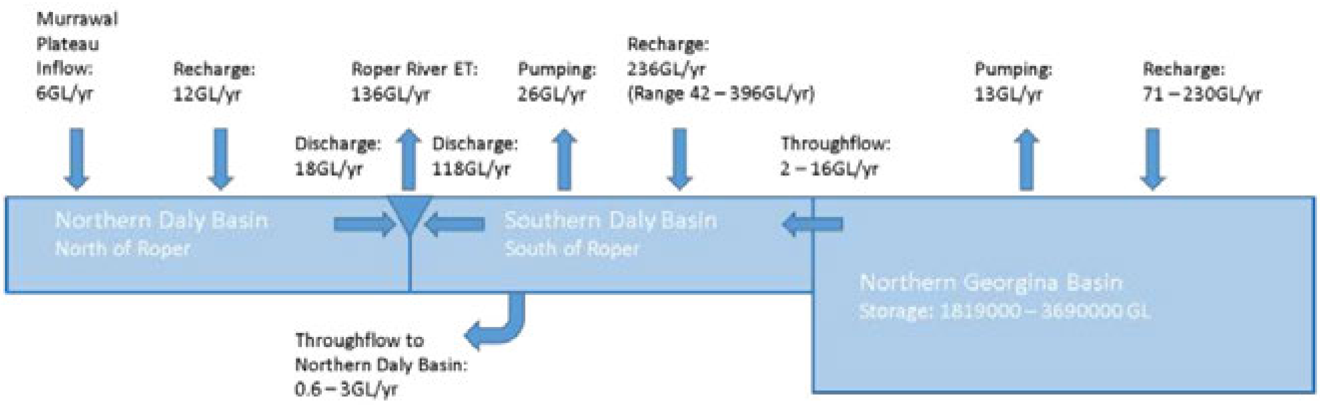


Figure 6: Indicative water balance for the Roper River basins encompassing estimated recharge, discharge and throughflow rates. From Knapton, (2020).

Groundwater discharge

Discharge of groundwater from the Tindall Limestone within the Daly Basin occurs to the Roper River and its southern tributaries – e.g., Elsey Creek, via springs (including Mataranka Thermal Pools) and diffuse discharge to the river channel along a significant length within the upper catchment (Figure 7). These flows make up a very significant proportion of the Roper and its tributaries' flow in the upstream section of the catchment, and support important Groundwater Dependent Ecosystems and cultural values (Jolly et al., 2004; Karp, 2008; Barber and Jackson, 2011; Bruwer and Tickell, 2015; Lamontagne et al 2021). CLA groundwater discharge to the surface has been estimated to be approximately 3 to 4 m^3/second downstream of the Mataranka springs (Knapton 2006; Fulton and Knapton, 2015), equating to approximately 260 to 345 ML/day, encompassing flow from both north and south (Evans et al., 2020). Springs along the Flora River on the western side of the Daly Basin receive approximately 2.3 m^3/second of discharge at the end of the dry season and the river is estimated to gain approximately 2 to 5 m^3/second of flow from the Tindall Limestone (see Evans et al., 2020, citing Knapton, 2006). Further information about the flows from the CLA to the surface and the values they sustain are discussed in further detail in section 1c, below.

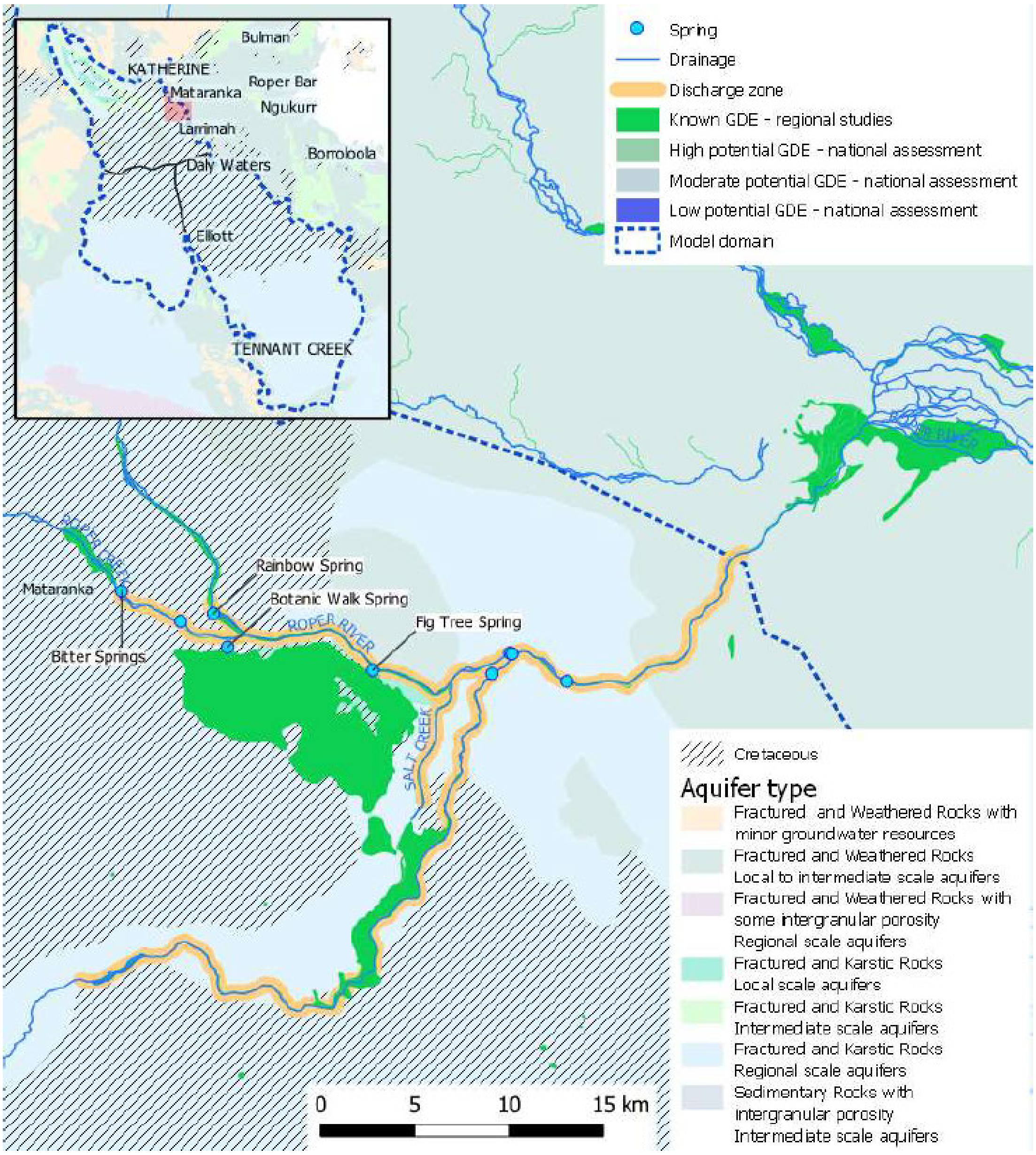


Figure 7 – Mapped locations of groundwater dependent ecosystems receiving discharge from the CLA in Mataranka region (From: Knapton, 2020). The major tributary to the south is Elsey Creek.

Additional groundwater discharge from the CLA is associated with evapotranspiration by groundwater dependent vegetation, in areas of shallow water table (Knapton, 2020).

In the Georgina Wiso basin, there is very limited understanding of groundwater discharge mechanisms. The draft Georgina Wiso basin WAP hypothesises that groundwater outflow from the CLA in these two basins only takes place through (relatively small volumes) of groundwater throughflow to the Daly Basin to the north, with no additional groundwater discharge through ET or groundwater flows to springs and other surface features. This is premised on the assumption that CLA groundwater levels are uniformly deep below ground level (difficult to assess currently, due to a lack of comprehensive monitoring bore coverage), and that vegetation communities are not able to access groundwater from deep water tables. This matter requires further careful analysis. The idea that recharge to the aquifer is not balanced by comparable amounts of groundwater discharge would be unusual for a large, relatively un-developed aquifer system. Typically, aquifers that have limited groundwater extraction are thought to come to a long-term equilibrium where recharge + inflow is approximately balanced by discharge + outflow (Theis, 1940; Alley et al., 1999).

Evans et al., (2020) note that CLA groundwater may provide flows that sustain Top Springs on the western side of the Wiso basin; however, field studies are lacking to verify this or determine the rate(s) of discharge. The water level mapping presented by Evans et al., (2020) and other Bioregional Assessment reports also indicates that there are areas where CLA groundwater levels are likely to be within 20 m of the surface. Whether there are deep-rooted vegetation communities that are adapted to utilise such groundwater (e.g., *Acacia* species able to grow deep tap-roots, Lamoureux et al., 2016) is not known. Further field evidence is clearly needed to resolve the above issues and determine where and how much groundwater discharge occurs from the Georgina and Wiso basins, and what values are sustained by these flows.

Timescales of flow and aquifer response times

The timescales of groundwater flow between recharge and discharge areas within the CLA are not well known, nor is it well understood how long the system may take to reach a new equilibrium in response to significant disturbance, such as a major and rapid increase in groundwater extraction rates, or a step-change in the regional climate conditions. Analysis of basin time-constant (τ) as per equation 1 below, is one way to approach this question (Schwartz et al., 2010; Currell et al., 2016). Numerical modelling can also estimate these time-dependent responses and lags.

$$\tau = \frac{L^2 S_S}{K}$$

$$\tau_{step} = \frac{L^2}{D_h}$$

Where L = length of the flow system, K = hydraulic conductivity [L/T], Ss = Specific Storage (dimensionless), Dh = Hydraulic diffusivity (transmissivity/storativity) [L^2/T]. Value of τ (in units of time) represent approximate period required for a groundwater flow system to re-equilibrate following a major hydrological change/disturbance. After Currell et al., 2016.

Based on preliminary analysis of aquifer dimensions and hydraulic properties (Table 2), time constants on the order of 500 to 50,000 years would apply to the Georgina and Daly Basin flow systems (assuming a continuous, connected flow path across the length of the basin(s), see Fig. 4). The aquifer system(s) would be expected to take hundreds to tens of thousands of years to reach a new steady-state (where inflows and outflows reach a stable equilibrium) following a major hydrological change. This does not mean that increasing rates of groundwater extraction in the short term would take this length of time to impact on groundwater levels and discharge to the surface - such impacts would begin to manifest immediately close to the points of extraction and spread over time throughout the system as it re-equilibrates. Rather, τ values indicate the timescale required for the full effects of a major hydrological change to manifest. These concepts are discussed further in Section 2. In the numerical model for the Daly basin used by Bruwer and Tickell (2015) to assess potential impacts of increased groundwater extraction on Roper River baseflow, it took approximately 300 years for a new steady state to be reached, following a new wellfield extracting 20% of estimated recharge. Decreases in discharge to the river began to occur rapidly, exceeding 15% within 25 years. This timeline is consistent with earlier modelling by Knapton (2004).

Radiocarbon and other environmental tracer data in Deslandes et al., (2019) also give an indication of timescales of recharge, throughflow and discharge in the CLA (Figure 8); however, caution must be applied in the estimation of 'age' of groundwater, as groundwater isotopic data appear not to follow a clear horizontal and/or vertical flowpath (such as a piston flow or exponential piston flow model, for which calculation of groundwater velocities can be achieved). Most ^{14}C results from groundwater samples in the CLA range from 10 to 100 percent modern carbon (where 100 pmC represents modern/recent recharge), and also contain tritium (albeit at relatively low concentrations) 'excess air' and modern gases such as SF6. The detection of these 'young' groundwater age tracers indicates active recharge throughout much of the region, which possibly overprints groundwater 'ageing' along regional flowpaths (Deslandes et al., 2019).

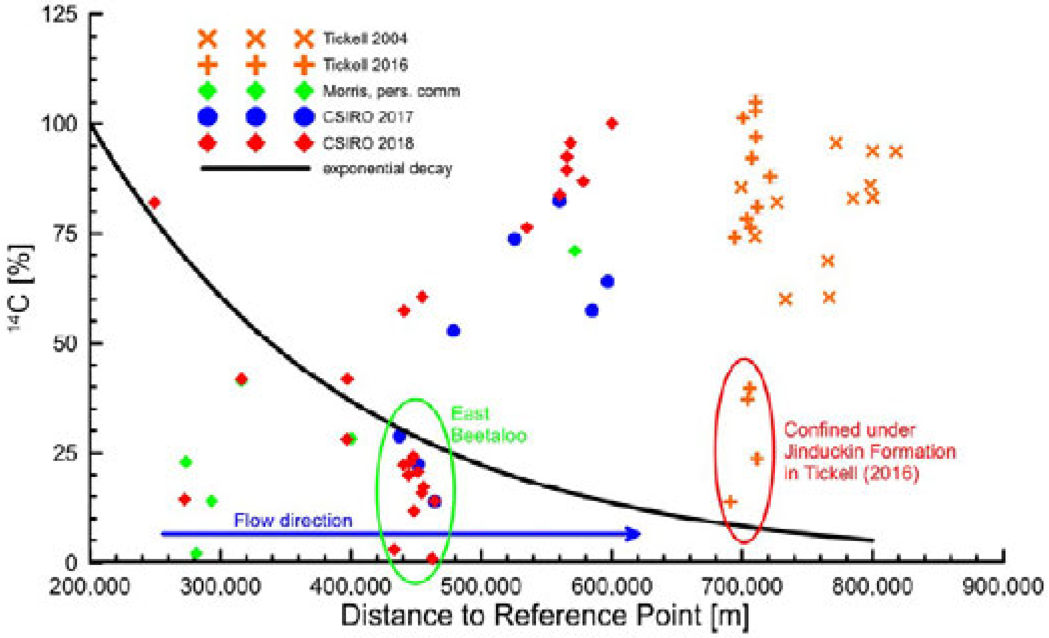


Figure 8: Summary of radiocarbon data from the CLA, from Deslandes et al., (2019).

c) The dependencies on the key groundwater systems from hydrological, environmental and cultural perspectives.

In the Daly Basin, discharge of water from the Tindall Limestone to the Roper River is a significant proportion of the river's flow in the upper catchment, and supports important Groundwater Dependent Ecosystems (Karp, 2008; Bruwer and Tickell, 2015; Evans et al., 2020; Lamontagne et al 2021). These groundwater flows sustain the river and its tributaries through dry periods – i.e., the river is fully dependent on groundwater following periods of low rainfall. Discharge from the CLA is also the predominant source of water sustaining the Mataranka Springs, which flow to the Roper River in its headwaters. Karp, (2008) explained:

> "The springs in the Roper start from the upstream junction of the Waterhouse River and Roper Creek (which join to become the Roper River) and extend east to the edge of the limestone basin. This region is the most significant in terms of groundwater and surface water interactions with the Mataranka Basin providing much of the base-flow in the Roper River."

Locations of the Waterhouse River, Roper Creek and downstream section of the Roper River are shown in Figure 9; essentially this region is the beginning of the Roper River catchment, and thus discharge from the Tindall Limestone provides permanent flows at the source of the river, which sustain all downstream sections. Figure 7 also shows mapped areas of groundwater discharge in this area.

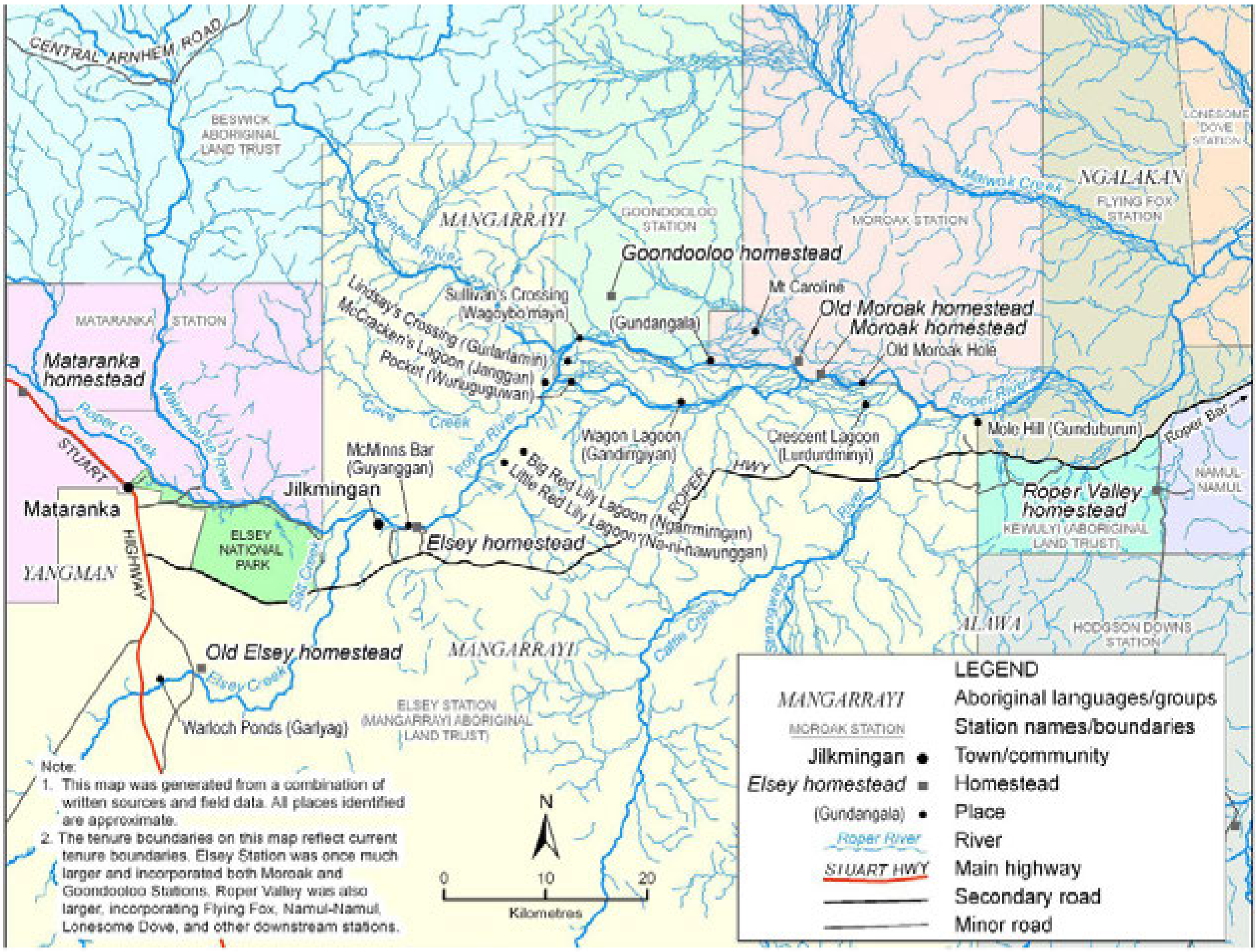


Figure 9: Detailed map of sites in the upper Roper River catchment (from Barber and Jackson, 2012).

Karp (2008) showed that the zone where the Roper River crosses the Tindall Limestone and receives discharge from the aquifer is associated with a sharp increase in river flows, which then decline gradually moving downstream, implying limited additional baseflow inputs to the river:

> "Clearly the karstic springs in the Tindall aquifer provide significant flow to the river in the Mataranka Basin with the rate of increased flow being high in this region. Similarly, immediately downstream of the Basin, the subsequent decrease in flow is significant and is associated with losses to swamps and wetlands such as Red Lily Lagoon and 57 mile Waterhole"

Karp (2008) further stressed the dependence of the river (including downstream sections) on Tindall Limestone groundwater discharge and management implications of this dependence:

> "Analyses of data collected during a comprehensive survey in October 1980 show only small changes in water quality in the non-tidal sections of the Roper River extending some 200 kilometres from the junction of Roper Creek and Waterhouse River to Roper Bar (Figure 4.13). **This suggests that during the dry season, the limestone aquifers in the Mataranka basin provide the main supply of water flow in the Roper River. Thus, the management of the groundwater resources in the Mataranka Basin is crucial to the viability of the downstream reaches of the Roper River.**"

Source(s) of groundwater discharge to springs
Recent research by Lamontagne et al (2021) used environmental tracers to better define the sources of groundwater discharge for individual springs within the Mataranka Thermal Pools (springs) complex. This research identified that there is flow from the CLA both from northern and southern flow systems within the Tindall Limestone aquifer (see Fig. 4) and a component of deeper flow (probably from the Antrim Plateau Volcanics) and shallow, recent recharge, in different springs (see locations in Fig. 10):

> "Major ions, Sr, $^{87}Sr/^{86}Sr$, $\delta^{18}O\text{-}H^2O$, $\delta^2H\text{-}H_2O$, ^3H, ^{14}C-DIC were consistent with regional groundwater from the Daly and Georgina basins of the CLA as the sources of water sustaining the major springs (Rainbow and Bitter) and one of the minor springs (Warloch Pond). However, 3H = 0.34 TU in another minor spring (Fig Tree) indicated an additional contribution from a young (probably local) source. High concentrations of radiogenic 4He (> 10–7 cm3 STP g–1) at Rainbow Spring, Bitter Spring and in nearby groundwater also indicated an input of deeper, older groundwater. The presence of older groundwater within the CLA demonstrates the need for an appropriate baseline characterisation of the vertical exchange of groundwater in Beetaloo Sub-basin ahead of unconventional gas resource development."

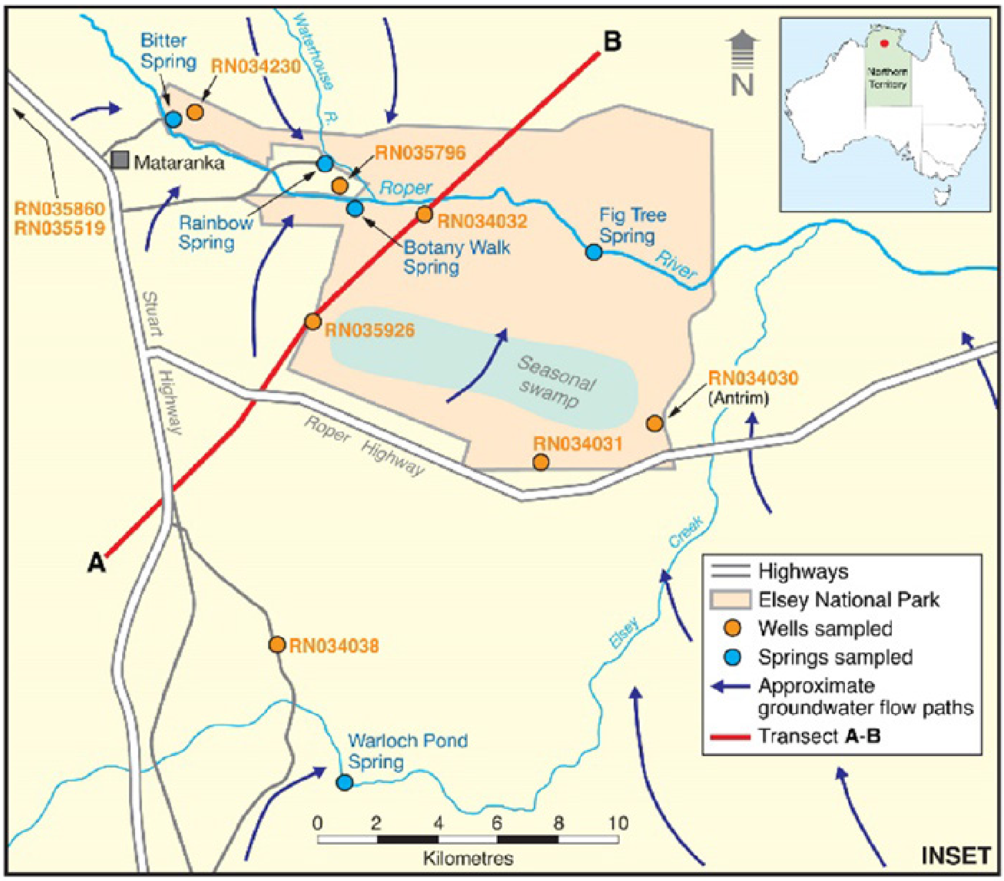
This indicates some level of inter-aquifer connectivity between the CLA and underlying units, either locally (i.e., just at the Mataranka Springs due to local structural geology) and/or regionally. This topic remains a knowledge gap and current research is examining the extent of inter-aquifer connectivity more extensively (Evans et al., 2020).

Locations of groundwater discharge
Most visible groundwater discharge to the Roper River from the CLA occurs into wetlands and spring pools located within Elsey National Park (Fig. 7; Fig. 9), which then flow to the Roper River. Discharge via the main river channel itself also occurs (Karp, 2008); evidence of this includes tufa (calcium carbonate deposits from discharging karst groundwater) along the riverbanks, and major ion chemistry in the springs and river which match CLA groundwater (Karp, 2008). Elsey Creek, which flows into the Roper River from the south, is also sustained by CLA discharge, including from Warloch Pond Spring (Lamontagne et al., 2021). Venting of groundwater discharge to permanent waterholes (e.g. Longreach waterhole) along Elsey Creek has also been identified. Additional tributaries of the upper Roper from the south are also likely sustained by Tindall Limestone groundwater (Fig. 7; Short, 2020).

Springs also provide flow to the Flora River on the western side of the Daly Basin – this is the regional groundwater discharge zone for the CLA northwards out of the Wiso Basin (Fig. 4). Top Springs on the western side of the Wiso basin (See Fig. 5) are also thought to be sustained by discharge from the CLA (Evans et al., 2020). There appear to be less data and less extensive investigation of mechanism of discharge, rates of flow, environmental and cultural values, and vulnerability of these springs, in comparison to Mataranka Springs – a major knowledge gap which should be addressed for the determination of management rules in the Georgina-Wiso WAP.

Groundwater salinity
Water quality in the CLA is variable, with salinities ranging from below 500 mg/L to over 10,000 mg/L. Groundwater is generally considerably fresher in the northern (higher recharge) regions of the CLA and tends to be more saline in the south. Tickell and Bruwer (2017) mapped groundwater salinities for the Georgina Basin and found little correlation with bore/aquifer depth. This indicates that zones of saline water may inter-mingle with or occur close to fresher groundwater, with associated implications for water quality (e.g., creating a risk of salinization if extraction rates in high quality groundwater bores occur close to saline groundwater zones).

Figure 10: Location of Mataranka Thermal Pools within Elsey National Park (Lamontagne et al., 2021).



Ecological and cultural significance of the Roper River, Mataranka Springs & GDEs

The Roper River and Mataranka springs are of high cultural significance for Aboriginal peoples of the region, as documented by Barber and Jackson (2011), Barber and Jackson (2012) and others (e.g., Merlan, 1982). The region is also associated with significant ecological values (Faulks, 2001; Duong and Stokeld, 2021), which are part of the cultural landscape managed under customary law by Traditional Owners:

> "From an Indigenous perspective, the country and the places it contains are active participants in the life of human beings, responding to events and actions in the world, particularly the actions of those people with whom it is strongly connected ancestrally. Therefore an important first step in the proper management of both land and water is appropriate conduct by human beings." (Barber and Jackson 2011).

Barber and Jackson interviewed Aboriginal peoples of the Roper region, and their views help to give a sense of the central and fundamental importance of water in their lives and culture:

> "Water is life, gives life to the land. It feeds the environment, keeps country cool and healthy. We don't like to damage country. Its good for fishing, swimming, camping. We use it for teaching too- cultural stories, bedtime stories, camping beside the river. Its our heritage. We need it to visit, enjoy life. M.H.
>
> If there was no water, all the life would be dead. The animals would be gone if the river dried out. R.S.
>
> Water is needed for the animals and the sacred areas. Water for the country and the people. D.D.
>
> We are dependent on that river. J.R.

Water is for healing. The water runs out at the crossing. When we get sick, we go and drink the water. M.R

There is a spring close to Beswick community. That water never dies, it will always be there. It gives us water to drink, and for the animals too. J.M."

In the context of early steps in the water planning process, Barber and Jackson (2011) further documented how the Indigenous peoples of the area understand the connectivity between groundwater and surface water, and the importance of upstream flows of these waters for everyone downstream:

> "We are upstream, we are the point of origin. We are guardians for the downstream people and they are the guardians for us. The Elsey mob are getting us involved because we are upstream. They've got the surface water for us, and we've got the underground water for them. The ownership of the two goes hand in hand." A.M.

In line with other accounts of the integral role played by water within living cultural landscapes that connect Aboriginal peoples with their ancestors and other living entities, the cultural significance of water is about more than a collection of 'sacred sites' in a landscape, which may nonetheless play special roles in Indigenous beliefs, ceremonies and Dreaming stories, but cannot describe in full the significance of above and below-ground waters connecting and sustaining the lands collectively termed 'Country' (Ah Chee, 2002; Marshall, 2017; Moggridge, 2020). Nonetheless, the sites discussed below represent important localities featuring in Aboriginal hunting and fishing patterns, stories, songs and ceremonies:

Red Lily Wetlands: Barber and Jackson (2012) document the importance of the Red Lily Lagoons (approximately 20 km downstream of Salt Creek and the eastern extent of Elsey National Park – see Fig. 9), both culturally and economically to the Indigenous peoples of the Roper valley. They documented how the pre-colonial practice of constructing weirs to restrict flows along small tributaries of lagoons was used by Aboriginal people to keep the lagoons filled with water as the dry season progressed, allowing the hunting season to continue for longer and over a more extensive area than could otherwise occur. Eventually this practice was stopped at Red Lilly in the mid-20th Century, as the managers at downstream Roper Station successfully argued in court that it damaged their livelihood by restricting downstream river flows (Barber and Jackson, 2012). Traditional owners continued the practice in other nearby areas (see Barber and Jackson, 2012).

Barlyurra: "Barlyurra is a site complex rather than a specific site. It straddles the Roper River in the vicinity of Red Lily lagoon and upstream. It includes the sites Warrwarrag, Garawi Yirrij, Wa-gardjag, Ngalarrg, Na-Yumbunggan, and Lunjan. The members of the Barlyurra group are affiliated with these sites through the Wijwij, or possum, dreaming. Amy Dirngayg told a story of the possum making a hair belt. There is also a snake dreaming, the detail of which is secret to men and therefore the subject of restricted evidence. Na-Yumbunggan is a ceremony ground for men's ceremony, although Jessie Roberts said that the presence of tourists using the river has caused the cessation of ceremonies on that site. The area is Bangariyn-Ngarrijbalan country, which meets with Gamarra-Burrala country somewhere to the west of Guwarlmbarlg." (Commonwealth of Australia 1990: 107, cited in Barber and Jackson, 2011).

Waterholes & permanent springs: As documented by McGrath (cited in Barber and Jackson 2011), waterholes were a critical part of the Aboriginal economy and a setting for major ceremonies. They were sites of intense conflict during colonization of the northern frontier.

> 'There is a heavy concentration of sites along the Roper River, where permanent water is available. Other sites tend to be associated with permanent waterholes in the

ephemeral waterways. There is no neat pattern of Dreaming tracks associated with sites. Rather, Dreaming tracks intertwine. (Commonwealth of Australia 1997:113)"

"Much of this country is well watered and well provided with trees. The Mangarrayi pride themselves on their association with the riverine country along the Roper and other bodies of water within their country. (Merlan 1982:146)"

An example of the significance of one such site was documented in Barber and Jackson, 2011:

"The first site visited by the Dreaming on the claim area is Gorowan, on Salt Creek. The Dreaming then visited Na-Burl (Elsey Falls), Murrwale and Barlmarrag, all on the Roper River. Between Murrwale and Barlmarrag is a waterhole, into which the Garawi jumped and in which it submerged. It travelled underground to the north and re-emerged at Nganawirdbird. This is a place of great significance. It consists of a large sinkhole and limestone cave at the top of a hill. Inside, various limestone features have been painted; they represent the internal organs of the plains kangaroo. The site is on the register of the national estate, pursuant to the Australian Heritage Commission Act 1975. p108."

Barber and Jackson (2011) also document how the ancestral being, known as the Rainbow Serpent, is understood by Aboriginal peoples to populate the Dreaming landscapes of the Roper region - as in many other Indigenous peoples' Dreaming stories Australia wide. The serpent is associated with the underground water flows that connect different parts of the country and keep certain places supplied with permanent water, as told by Bill Harney, Wardaman elder:

"The spring him fill up with water from the ground, so now him dry [dry season]… that river still runnin' from that spring. Him bin that spring all the time. Important because that Rainbow Serpent they sit down there longa spring every time … When him dry you know that the spring gotta have him water because that Rainbol [regional Aboriginal Kriol term for Rainbow Serpents] there." Cooper and Jackson 2008:27.

The serpent connects the peoples and waters of landscapes that are very distant from the Katherine/Mataranka area, as far as Borroloola on the Gulf of Carpentaria:

"The story of the Walalu, Stranger Rainbow Serpent is very important and very sacred…The Walalu is sometimes called Yankarra, which is Yanyuwa [language] for "the Stranger", he is called this because he came from such a long way away and, once he moves through Garrwa and Yanyuwa country he keeps moving all the way into Marra country, he moves through Alawa and Mangarrayi country, and finishes his journey at the Mataranka hot springs which is far to the west." (Yanyuwa families et al. 2003).

Water and its aquatic species figure prominently in Indigenous peoples' beliefs and stories (e.g. conception stories) regarding birth, death and connection between ancestral spirits/beings and living people, animals and plants:

"Birth is important too. The couple bear a child and that child comes out from the spring. The kids come from the water. It's the same story, even when we die. The water is a way that adopted kids come into that country. They get born into there, and they are automatically part of that country. The spirits greet us." M.R and M.H. cited in Barber and Jackson (2011) p19.

"The returning wanggij in some cases is described as incorporeal, but sometimes it may come in the form of an aquatic species, like a fish, since the Mangarrayi believe that children emerge from water. Although the wanggij is said to look for its father, it may first be recognized by someone else. (In the instances I was told of, this was always by a close patrilineal relative; one woman caught her brother's child as a barramundi, as is now evidenced by the fact that the hook, which tore its mouth, left a scar that the child bears".

Large (particularly riparian) trees: As outlined in Jackson and Barber (2013), Merlan (1982) recorded how Indigenous peoples of the upper Roper believe that large trees – often located near important water sites – embody individuals from current or recently deceased generations:

> "Trees do have the name. Name of that person. The ones which grow in special places. When we see the Dreaming tree, we know not to touch that. Don't put a fence line through there, put it around it." (R.R.)

This links living Aboriginal people to 'both the lines of descent and to the totemic creatures who created the land' (Jackson and Barber, 2013, p.11).

Ecological values and conservation management

Faulks (2001) conducted an ecological assessment of the Roper River and sub-catchments, and found generally stable riverbeds, limited disturbance of river corridors, creeks, rivers channel, and bank habitats in very good or condition, despite widespread evidence of some disturbance by exotic animals. Exotic vegetation was also found to be widespread. Vegetation found to be dependent on the groundwater flows to the Roper River, its tributaries, and springs (Mataranka Thermal Pools) include communities of *Livistona rigida* (palms) which has restricted distribution in the Top End region and thus considered to be of high ecological significance (Faulks, 2001). These palms require shallow, steady water tables (i.e., < 2 m below surface) before they become stressed and vulnerable to fire. Faulks summarized the findings of earlier surveys of the vegetation of Elsey National Park by Lucas and Manning (1989):

> "The riparian vegetation adjacent to the Roper River within Elsey National Park was described as being diverse, both floristically and structurally. *Pandanus aquaticus*, *Terminalia erythrocarpa*, *Melaleuca* spp., *Eucalyptus camaldulensis* and *Livistona rigida* form dense stands along the river banks. Lush communities of *Livistona rigida* as well as *Ficus platypoda* were associated with springs." (Faulks, 2001).

Knapton (2009) summarised GDEs of the Roper River region, noting the importance of groundwater in sustaining Mataranka Thermal Pools, Red Lily Lagoon, Flying Fox Creek, Mainoru River and Wilton River. In addition to the *Livistona* palm communities, riverbank vegetation, including *Melaleuca argentea* and *Barringtonia acutangular* are thought to almost exclusively utilize groundwater (i.e., they are obligate GDEs). Large *Livistonia* palm and melaleuca communities occur along Elsey Creek and in the vicinity of springs in Elsey National Park and other sections of the Roper River channel. Riparian vegetation communities associated with the permanent water provided by CLA discharge are relatively small in terms of land area, but serve as critically important habitat for animal species – both local and migratory (Woinarski et al., 2000).

Remote-sensing based mapping by Short (2020) further identified distinct regions of groundwater-dependent terrestrial vegetation in Mataranka, using normalized difference moisture and vegetation indices (NDVI/NDMI). Vegetation that persists during dry periods, due to perennial access to groundwater, was identified at permanent water bodies and in areas away from river corridors, which correlated with zones of high (shallow) water tables (Fig. 7).

Stygofauna communities - fauna which live within aquifers, are another type of GDE that widely occur and for which knowledge and data are gradually growing worldwide. A stygofauna survey was conducted in the CLA within the region encompassing the Beetaloo sub-basin and Roper River system, in response to this being identified as a key knowledge gap in the Pepper inquiry. The results are reported by Rees et al., (2020) and Oberprier et al (2021). The surveys identified a diverse range of stygofauna species occurring in the CLA dominated by crustaceans, including the blind shrimp *Parisia unguis*. The widespread occurrence of specific stygofauna across great distances in the CLA is consistent with a high level of connectivity throughout the aquifer system (as opposed to stygofauna which exhibit a greater level of short-range endemism, which indicate localized evolution and habitat conditions). Identified species showed relatively little correspondence with stygofauna communities documented in other regions such as Western Australia, where stygofauna surveys have covered a larger and relatively diverse range of settings (Rees et al., 2020).

2. Risks to groundwater dependent ecosystems and associated values from current allocation rules (storage-based estimates of sustainable yield)

The predominant risks associated with an increase in groundwater extraction rates from the CLA are:

i. Reduced flows of groundwater to the Roper River, Mataranka Thermal Pools and other streams, springs and wetlands of the region. If these groundwater discharge flows and/or CLA groundwater levels were to decline below key thresholds, complete loss of springs and baseflow to rivers may occur. This would lead to the loss of vegetation communities and animal habitat, and incalculable loss and damage to the cultural values associated with both specific sites (e.g., springs, waterholes, and wetlands) and the health of 'country' and Aboriginal culture from a holistic point of view (see section 1c). Stygofauna may also lose their habitat if extensive drawdown occurs in regions of the aquifer they inhabit.

ii. Interference to existing water users and water supplies in the region. For example, a significant drop in groundwater elevations in the CLA may lead existing extraction bores used for stock/pastoral water supply to lose pressure or (in extreme cases) run dry. This is particularly significant in the Daly Basin, where there are already quite a number of pastoral bores utilising CLA groundwater. Significant loss of dry season river flows in the upper Roper River would lead to a reduction in downstream river flows, affecting downstream surface water users. In dry periods, this could (for example) result in saltwater ingress affecting the Ngukurr Aboriginal Community (Jolly et al., 2004; Zaar, 2009). Non-consumptive uses of water (e.g. tourism, fishing and hunting) may also be impacted, with flow-on economic effects and impacts on Indigenous customary uses.

Depletion of significant volumes of storage within an aquifer are also associated with other irreversible negative consequences such as:

- land subsidence and compaction of the aquifer matrix: In limestone terrains this can lead to collapse structures (e.g. sinkholes) at the surface. Aquifer compaction can also impact on aquifer properties, e.g., reducing transmissivity and future groundwater storage capacity (Ojha et al., 2018). This typically affects unconsolidated sediments but has also been documented to impact carbonate aquifers of similar type to the CLA (Laroque et al., 1998).

- Degradation of water quality, through drawing in poorer quality water from layers adjacent, above or below the CLA. It is known that the salinity of groundwater can be variable in different parts of the CLA – for example with TDS concentrations exceeding 10,000 mg/L in parts of the Georgina Basin (Tickell and Bruwer, 2017), but there is currently limited assessment of risks of migration of saline water bodies into fresher parts of the aquifer system under the influence of groundwater extraction.

The rest of this section reviews current water policies in the Northern Territory and assesses the extent to which the above consequences are likely to occur under these policy settings if there is a significant increase in demand for groundwater from industries such as irrigated agriculture and shale gas. Section 3 outlines management approaches that can ensure protection of the groundwater dependent values and avoid these negative consequences.

The Northern Territory Water Allocation Planning Framework

Under the Northern Territory Water Act, water licensing is conducted based on rules set out in Water Allocation Plans for each region. However, large areas of the NT, including the area encompassing most of the CLA and Beetaloo Sub-basin, do not yet have declared water allocation plans. Only 28% of licenses in the NT occur within areas with a declared WAP (O'Donnell et al., 2022). In accordance with recommendation 7.7 of the Pepper Inquiry, it is understood that the NT Government is currently working on Water Allocation Plans that will encompass the CLA's major sub-zones (Mataranka, Flora Tindall, Georgina Wiso), with the goal of releasing these in 2022-23. Currently, the only publicly available WAP draft is the Georgina-Wiso plan (Northern Territory Government, 2022a).

In the absence of a water allocation plan, the current policy governing groundwater licensing is the Northern Territory Water Allocation Planning Framework, which defines two separate zones of the Territory - Top End and Arid Zone. Within these two zones, different rules apply governing the amount of groundwater that can be extracted from a given aquifer.

In the Top End Zone:

> At least 80 per cent of annual recharge is allocated as water for environmental and other public benefit water provision, and extraction for consumptive uses will not exceed the threshold level equivalent to 20 per cent of annual recharge.

In The Arid Zone:

> There will be no deleterious change in groundwater discharges to dependent ecosystems, and total extraction over a period of at least 100 years will not exceed 80 per cent of the total aquifer storage at start of extraction.

These rules are the basis for calculating an "estimated sustainable yield" (ESY) in a given region. Surface water extractions are also subject to different rules within the two zones.

It is unclear what rules will be adopted in the different water allocation plans currently in development. For example, it is unclear how an ESY (overall cap on licensed extractions for a given region) will be determined, and what additional groundwater management rules (e.g., mechanisms such as trigger levels to protect groundwater dependent ecosystems) will apply within the water allocation plan areas. From available minutes on the public record, and statements by the NT government, it appears that the Top End, Arid Zone or other rules that calculate ESYs based on a percentage of aquifer storage, may be used as a basis for developing the plans. For example, minutes of the Mataranka Tindall Water Advisory Committee[3] indicate that it has been proposed that the Arid Zone rules be applied to the Tindall Limestone near Larrimah, despite this region being north of the Top End/Arid Zone boundary (i.e., within the Top End zone).

The draft Georgina-Wiso WAP appears to have adopted an approach that bases the ESY on a fraction of the average groundwater recharge (similar to the Top End rule), however the fraction of recharge is substantially higher than for the Top End rule, and there are considerable issues which call the methodology used to develop the proposed ESY into question (see the section on Recharge above, and further discussion below in section 3).

The Top End/Arid Zone delineation

Figure 10 shows the current boundary between the Top End and Arid Zones, based on a technical report completed by the NT Water Resources Division in 2020[4]. The line essentially relies upon surface water catchment boundaries – with northward flowing catchments forming the Top End, and inland-flowing catchments forming the Arid Zone. The report reviews additional climate and hydrological datasets (e.g., soil moisture, evapotranspiration,

---

[3] https://depws.nt.gov.au/__data/assets/pdf_file/0008/1049453/mataranka-tindall-wac-meeting-11-minutes-and-appendices.pdf

[4] Classification of the Top End and Arid Zone for Northern Territory water resources. Water Resources Division Technical Report 55/2020.

runoff, deep drainage), which also broadly correspond with a transition in climate and hydrological conditions across the line (e.g., the 600 mm/year mean rainfall contour). However, this average rainfall contour does not align with an accepted definition of arid, which generally defines arid zones as having less than 250 mm rainfall per year (Holzapfel, 2008). This applies only to the south of Tennant Creek in the NT. It is also noted in the report, that the boundary line does not represent a distinct or meaningful boundary with respect to the aquifers and groundwater flow systems of the Northern Territory:

> "It is acknowledged that aquifer boundaries rarely align with surface water catchments. However, it is not practical to determine a boundary based on aquifers when there can be a large degree of uncertainty in where a boundary might be defined. Aquifer boundaries, where they have been mapped, may be subject to change by tens to hundreds of kilometres with improved information. By contrast, surface water catchment boundaries are easily defined and readily derived from high-quality (high spatial resolution) national scale elevation data. Once defined, surface water catchment boundaries are not likely to change in the future and are a much better basis upon which to set a boundary such as the Top End/Arid Zone boundary."

Based on the line delineated in the Technical Report (Fig. 11, Fig. 12), the entire Daly Basin, encompassing the Tindall Limestone, and northern Wiso and Georgina basins are within the Top End zone. Figure 12 shows draft boundaries for different water allocation plan districts. The Flora Tindall, Mataranka and northern Georgina Wiso WAP areas are within the Top End zone, while the southern Georgina Wiso WAP area (encompassing most of this WAP area) sit within the Arid Zone. Noting that (as outlined in section 1b), recharge to the Tindall Limestone within the boundaries of the Daly Basin is substantial and appears to exceed throughflow from the Georgina Basin, it is doubtful that the use of Arid Zone rules anywhere within the Daly Basin accords with the notion that the CLA is a 'low recharge high storage' aquifer (see Table 3 and Fig. 4). Hence, even if the Arid Zone rules were to be considered an appropriate management regime for such aquifers (this topic is addressed further below), their use within the Daly Basin would be questionable.

Basis of the Top End/Arid Zone rules

Limited information was identified to explain the original rationale for dividing the Northern Territory into the two zones for the purposes of water management. However, testimony to the Australian Senate in 2003 by the former NT Water Controller, Mr Ian Smith, gives an indication of the basis:

> "The simplest way to explain the allocation framework [as it applies in the Top End zone] is that we seek to retain at least 80 per cent of river flows and 80 per cent of the ground water resource for environmental use. Thereby, in a planning sense and in our licensing procedures, we are looking to license up no more than 20 per cent of the available river flow anywhere in a catchment and, essentially, no more than 20 per cent of the ground water recharge. In a ground water balance sense and in a regional sense, that means that we are retaining at least 80 per cent of the discharge to the environment from ground water systems."

With respect to the Arid Zone rules Mr Smith commented:

> "The behaviour of our aquifers is different in the south than in the north. Our recharge mechanisms are fundamentally different and are much lower, but we have much larger storage. Our policy for aquifers in the southern two-thirds is to

> permit mining of the resource over at least 100 years, but our mining at this stage is limited to 80 per cent of the aquifer storage at the start of extraction.[5]"

The rationale for allowing up to 80% of storage to be depleted from aquifers in the Arid Zone may derive partly or in whole from an understanding of the water needs of the township of Alice Springs - where groundwater supplies domestic water to one of inland Australia's largest communities. Groundwater recharge to the aquifer supplying Alice Springs is very limited (estimated to be approximately 750 ML/year) and current allocations (approximately 11,000 ML/year) far exceed this recharge, resulting in long-term depletion of storage in the aquifer (DLRM, 2016). The Arid Zone contingent rules allow this over-draft of the aquifer, in the interests of sustaining water for the township's essential needs. The application of the same rules elsewhere in the NT needs to carefully consider this context – i.e., overdraft of groundwater to supply essential water to a major township is different to applications to extract water at unsustainable rates for economic development. The current WAP still limits depletion of storage in the Amadeus Basin to 25% (not 80%) over 100 years (DLRM, 2016).

---

[5] Rural and Regional Affairs and Transport References Committee Senate transcript 18/11/2003: https://parlinfo.aph.gov.au/parlInfo/search/display/display.w3p;query=Id:committees/commsen/7147/0004

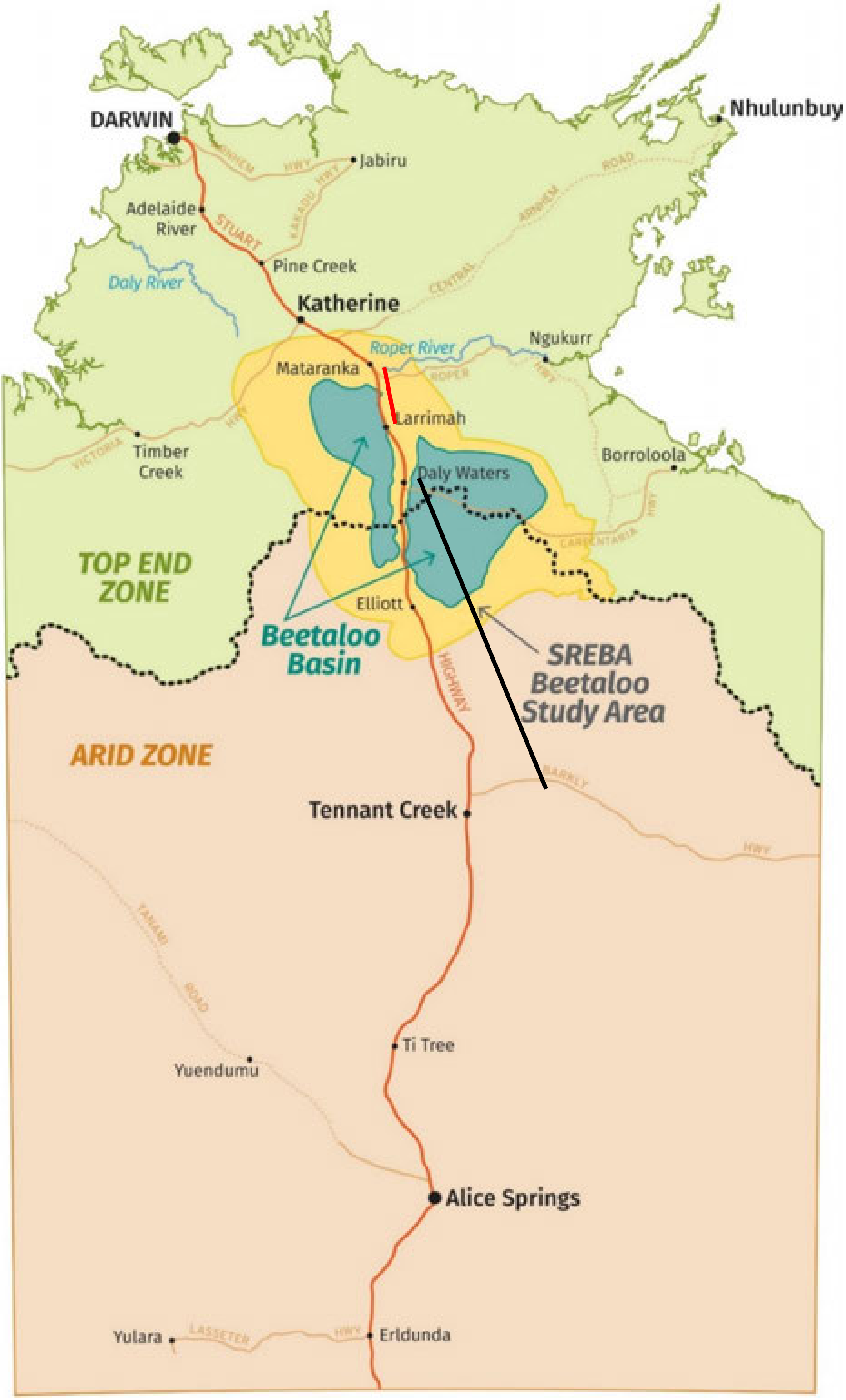


Figure 11: The Top End and Arid Zone boundary, as defined in the Northern Territory Water Allocation Planning Framework, also showing Beetaloo sub-basin and SREBA study area. Red and black lines show approximate locations for Fig. 15. Image credit: First Class Communications.

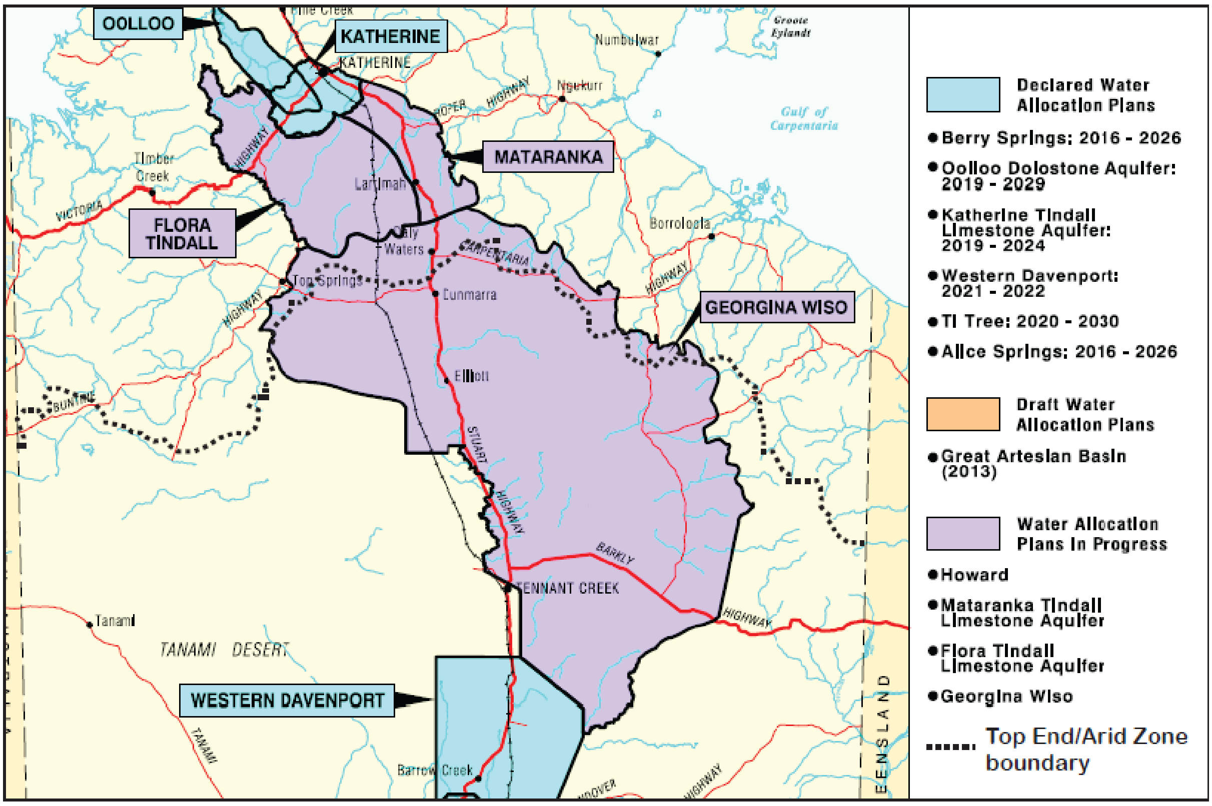


Figure 12: Map of water allocation plan districts where water allocation plans are currently being developed (as of October 2022), with current Arid Zone/Top End boundary marked.

Recent expert opinion on the Top End/Arid Zone rules

The Pepper inquiry reviewed the NT Water Allocation Planning Framework and found that the use of the Arid Zone contingent rules (for onshore gas or any other extractive use) would: '..essentially permit 'mining' of the groundwater resources and would be ecologically unsustainable'. Recommendation 7.7 of the inquiry stated that Water Allocation Plans should be developed for the northern and southern Beetaloo sub-basin with the following principles:

- The new northern Sub-Basin water allocation plan provides for a water allocation rule that restricts the consumptive use to less than that which can be sustainably extracted without having adverse impacts on other users and the environment; and
- The southern Sub-Basin water allocation plan prohibits water extraction for any onshore shale gas production until the nature and extent of the groundwater resource and recharge rates in that area are quantified.

In a recent groundwater licence application near Larrimah that was initially granted to the Northern Territory Land Corporation, but then withdrawn, the Water Resources Review Panel concluded that the use of different allocation rules in the northern and southern parts of the CLA (which, as outlined in Section 1, are to some degree hydraulically connected), is problematic:

> "The application of a significantly different allocation criteria of 20% of storage available for consumptive use (Top End Zone) to 80% of storage available for consumptive use (Arid Zone) to different portions of an aquifer system with high geologic and hydraulic connectivity is not consistent with proper groundwater management. It is not logical to have significantly different allocation criteria in neighbouring management areas for a hydraulically and geologically continuous aquifer, especially if it important to maintain throughflow and natural discharge to the Roper River."

The panel also agreed with the opinion expressed by the Director of Water Planning and Engagement at the time that:

> "Drawing down storage by 80% as proposed by the contingent allocations in the NT WAP Framework will not provide for the environmental and cultural water requirements supported by the aquifer. The lowering of the height of the upper surface of the aquifer after 100 years of extraction has the potential to reverse the hydraulic gradient removing through flow to areas near the southern side of the Roper River and cause water to flow in the opposite direction towards Larrimah.[6]"

These opinions accord with the most up-to-date literature and science on the topics of aquifer responses to groundwater extraction, prevention of aquifer depletion, protection of GDEs, and sustainable groundwater management approaches to achieve these aims (Alley et al., 2002; Ponce, 2007; Gleeson et al., 2012; Doody et al., 2019; Bierkens & Wada, 2019; Walker et al., 2021). These topics are discussed further below.

Problems with the use of a percentage of storage as a basis for sustainable yield

The concept of a Sustainable Yield in the management of groundwater resources has developed over the past hundred or more years. This has occurred in line with evolving views on sustainable water and other resource management, increasing understanding of the interconnections between groundwater and other parts of the water cycle, and awareness of the ecological and cultural values sustained by groundwater flows.

Early concepts regarding the sustainability of groundwater usage began with the 'Safe Yield', which corresponded with the idea that if groundwater extraction did not exceed annual recharge to an aquifer, the aquifer would be protected against long-term storage depletion, thereby allowing ongoing access to the resource into the future (Lee, 1915; Todd, 1959).

It was subsequently shown that this was an overly simplistic way to define 'safe' or 'sustainable' groundwater yield, most importantly because it does not account for the critical role played by groundwater discharge in maintaining surface flows to streams, springs, and connected ecosystems (Theis, 1940, Alley et al., 1999, Seward, 2006), and the ways that these flows, as well as recharge itself, may be changed significantly by groundwater pumping. Groundwater is simply one part of the water cycle, during which it is stored for a period in an aquifer, on its way between infiltrating the land surface (as percolating rainfall) and reaching the oceans or atmosphere via discharge to streams, submarine groundwater or evapotranspiration. As such, extracting the annual recharge flowing into an aquifer deprives the downstream environment (within and/or external to the aquifer), of these flows, which may cause unacceptable environmental, social, cultural and/or economic impacts.

C.V. Theis's seminal work "On the source of water derived from wells" (1940), demonstrated how aquifers and their connected surface waters respond to groundwater extraction in a combination of three ways:

1. The amount of water in storage within the aquifer is reduced (storage depletion)
2. Additional recharge will be drawn into the aquifer from the surface (if it is available in the form of excess or 'rejected recharge')
3. The amount of groundwater discharge to the surface (e.g., baseflow to streams and flow to springs and wetlands) will be reduced

Alley et al (1999) summarised these changes pictorially (reproduced as Fig. 13 below). The second and third changes to the pre-existing water balance are collectively termed 'Capture' by most hydrologists (following Theis). This reflects the fact that this water, which would

[6] Water Resources Review Panel, *Re: Controller's Decision to Grant Groundwater Extraction Licence TLAM10002*, 17 May 2021.

otherwise be available as flows to the surface at some point in time, is re-directed to the pumping wells, meaning the surface is ultimately deprived of it (Theis, 1940).

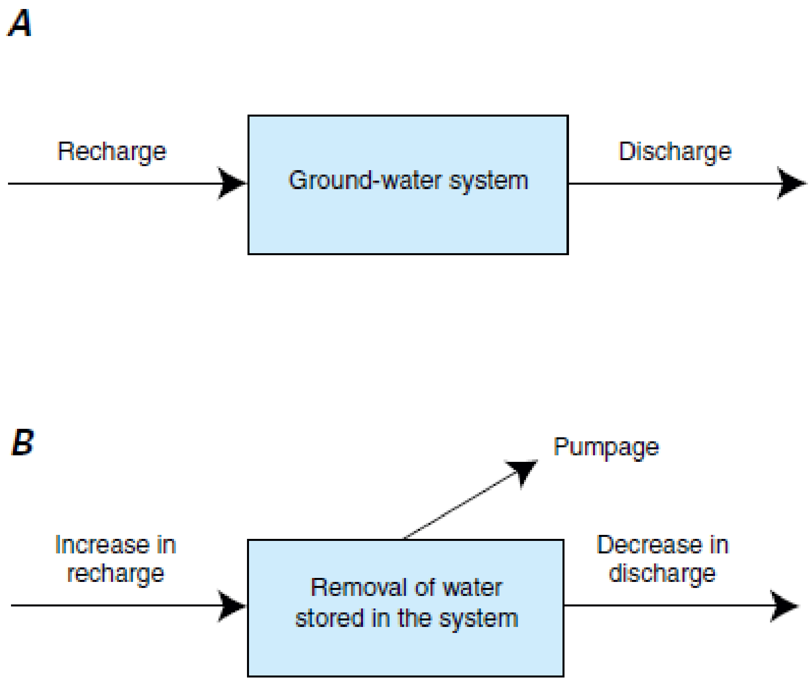


Figure 13: Conceptual diagram representing the three changes which occur (in some combination) when extraction of groundwater disturbs an existing water balance. From Alley et al., (1999).

It has become widely accepted (and demonstrated in modelling studies) that in the long-term, the majority of groundwater extraction is balanced by Capture – i.e., pumping a particular volume over time will result in an equivalent reduction in water discharging from the aquifer. For example, modelling by Konikow and Leake (2014) showed that in the United States, much of the water extracted within major groundwater pumping districts ultimately reduces baseflows to streams. As such, establishing the importance of these baseflows and acceptable levels of impact to these, should be a top priority for sustainable groundwater management.

As pointed out by Theis (1940), depletion of storage is generally an important response of an aquifer to pumping in the early phases of extraction; however, in the long term, Capture will inevitably become the dominant source of water to wells, as the inter-connected groundwater-surface water system approaches a new equilibrium water balance. While in many cases the timescale to reach this point of equilibrium is very long (e.g., Bredehoeft and Durbin, 2009), and in the interim, significant fractions of the pumped water may be derived from storage depletion, the setting of sustainable yield volumes should ultimately focus on determining where the loss(es) of groundwater discharge will occur (and any additional recharge drawn into the aquifer from the surface), and how important these waters are from environmental, economic, and socio-cultural perspectives (Alley et al., 1999, Seward, 2006; Ponce, 2007; Pierce et al., 2013). Direct impacts of storage depletion (e.g., drawdown to the point that GDEs can no longer access groundwater) must also be considered.

The determination of recharge rates is still an important pre-requisite for assessing sustainable groundwater extraction; setting sustainable yields as a fraction of recharge is a way to ensure ongoing access to groundwater into the future, and allows analysis of whether extraction at different rates can be considered ‘renewable’ or ‘non-renewable’ (Bierkens and Wada, 2019). This is in line with current thinking about the sustainable use of natural resources, according to the principle of inter-generational equity (World Commission on

Environment and Development, 1987). Further, recharge is often similar to natural discharge from an aquifer. Thus, setting extraction rates as a fraction of recharge in an aquifer or groundwater 'catchment' will generally limit (but not entirely prevent) reductions in groundwater discharge to springs and streams from that aquifer. However, at least equal or arguably greater focus should be on determining the rates of discharge of groundwater to groundwater dependent streams, springs, wetlands, vegetation and fauna, and the extent to which water sustaining these will be intercepted or reduced by pumping at a given extraction rate. This must be reflected both in the policy rules for setting sustainable yields, and in the focus of scientific work undertaken to define what this should be for a given aquifer/region.

The NT contingent water allocation rules and sustainable yields

The Arid Zone contingent rule (with respect to groundwater) encompass two components:

a) No deleterious effect on GDEs
b) Aquifer storage can be 'depleted' by up to 80% of initial storage volume on a 100-year timeframe

These two parts of the rule may seem to be distinct criteria for assessing the sustainability of groundwater extraction; however, they are strongly inter-dependent and, in systems which receive limited recharge (where the rule is applied), contradictory. In settings where recharge is small relative to storage, extracting 80% of the storage volume will inevitably result in the loss of groundwater flows to connected surface water systems and other GDEs. GDE health depends upon the maintenance of aquifer water levels above thresholds which allow groundwater discharge to springs and baseflow to rivers, ET by vegetation, and to support stygofauna inhabiting the subterranean space of the aquifer. Maintaining GDEs also depends upon the maintenance of flux rates to surface discharge points. This is *related* to maintenance of aquifer water levels, but often in a non-linear way (as illustrated in Fig. 14):

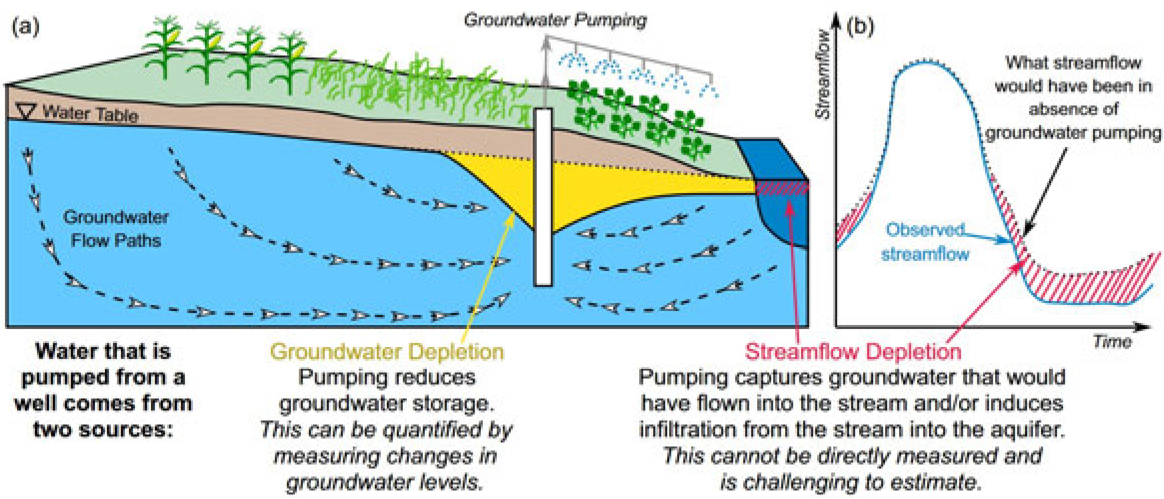


Figure 14 - Example showing how groundwater extraction causes a combination of groundwater storage depletion, and reduction in flows from the aquifer to streams or other surface GDEs, through 'Capture'. From Zipper et al. (2022).

As discussed above, in the long term, most groundwater extraction is balanced by a reduction in the amount of groundwater discharge to the surface or near surface (i.e., GDEs). This may be facilitated by a reduction in throughflow rates between adjacent aquifers (as would apply in the case in the CLA across the Georgina/Daly and Wiso/Daly boundaries) as well as through reduction in flux rates near the GDE(s). If a GDE is fully dependent on groundwater, and there aren't other available sources of 'Capture' to balance extraction, the reduction in flux may result in a 1:1 reduction in water availability to the ecosystem (Hatton and Evans, 1998).

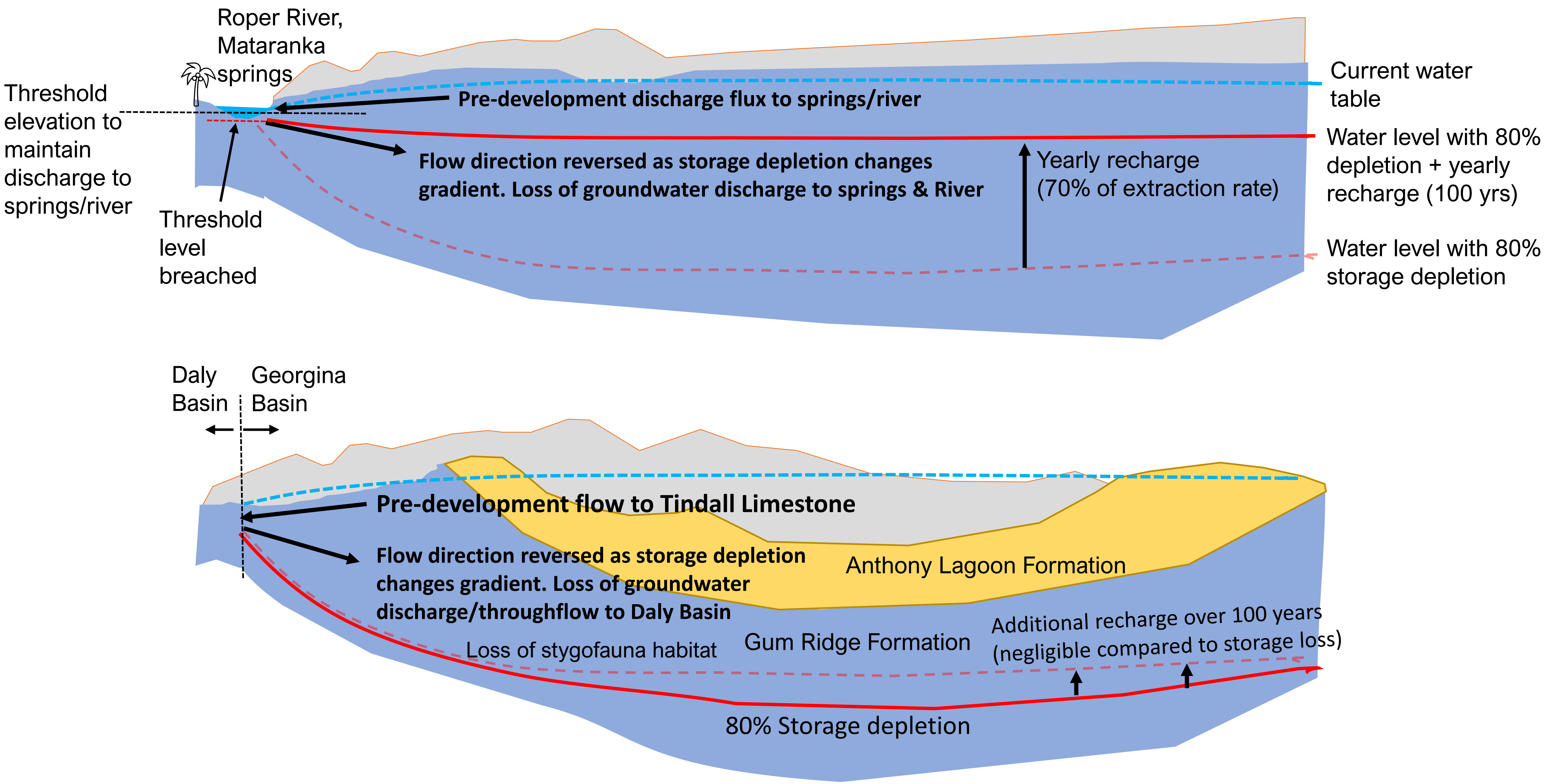
The depletion of water in storage that occurs during the early phases of groundwater extraction - which, in large aquifer systems with long response times, may continue for hundreds or thousands of years, will inevitably cause changes to groundwater levels and flow gradients. |GDEs may be lost entirely as a result of these changes. This can occur by one or both of the following:

a) The groundwater levels at the point of discharge reduce below a threshold elevation (usually the land surface height or root zone depth), which causes groundwater flows to the (near) surface at this point to cease, thereby depriving the GDE of water completely (Figure 15)

b) The groundwater flow gradients change in direction, to the point that groundwater from the aquifer in question no longer flows in the direction of the GDE, and flux from the aquifer to the GDE ceases (again, depriving it of water) – Fig. 14 & 15. This mechanism can cause the loss of springs and baseflow without causing any significant drop in the groundwater *levels* at the point of discharge (e.g., Currell, 2016; Fig. 15). This is why GDE management programs dependent on maintaining water levels only, without also considering effects of pumping on hydraulic gradients and flow rates towards the ecosystem (and setting a cap on rates of extraction accordingly), may be ineffective at protecting GDEs (Noorduijn et al., 2019). Note that throughflow between basins - such as the flows from the Georgina Basin into the Daly Basin, which replenish groundwater along its southern boundary, would be reduced by such changes to groundwater flow gradients (Fig. 15b).

The depletion of even a small amount of the water in storage in an aquifer will change groundwater levels and flow gradients and risk either or both of a) and b). In a case where 80% of the storage volume is depleted, and the recharge rate is small relative to overall storage, it is almost certain that both will occur, as shown conceptually in Figure 15.

Regarding the proposed estimated sustainable yield in the draft Georgina-Wiso WAP (calculated as 40% of recharge, averaged over a 50-year period): As discussed in section 1b, it is likely that in most years this extraction rate would far exceed recharge (as recharge is rare and episodic), and that this situation may persist for many consecutive years or decades. In this scenario, a significant level of storage depletion is likely to occur in between major recharge events. The flow-on effects of such periods of storage depletion – e.g. on throughflows to the Tindall Limestone, groundwater quality, or GDEs (which are to date poorly characterized , remain unknown.



Roper River,
Mataranka
springs
Threshold
elevation to
maintain
discharge to
springs/river
Current water
table
Pre-development discharge flux to springs/river
Water level with 80%
depletion + yearly
recharge (100 yrs)
Flow direction reversed as storage depletion changes
gradient. Loss of groundwater discharge to springs & River
Yearly recharge
(70% of extraction rate)
Threshold
level
breached
Water level with 80%
storage depletion
Daly
Basin
Georgina
Basin
Pre-development flow to Tindall Limestone
Flow direction reversed as storage depletion
changes gradient. Loss of groundwater
discharge/throughflow to Daly Basin
Anthony Lagoon Formation
Additional recharge over 100 years
(negligible compared to storage loss)
Loss of stygofauna habitat
Gum Ridge Formation
80% Storage depletion

c)

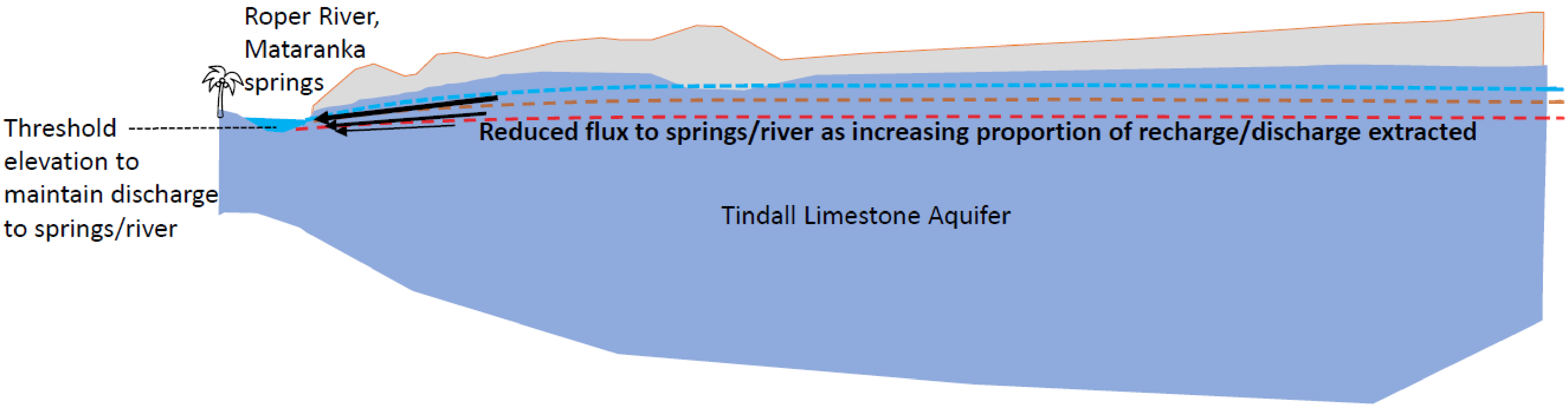


Figure 15: Conceptual diagrams showing how depletion of storage causes consequences for groundwater dependent ecosystems, surface water and inter-aquifer flows. Extraction of any significant proportion of storage will reduce rates of groundwater discharge to the surface and/or adjacent aquifers. Depending on the ratio of recharge to total storage, and extent to which discharge flows are captured by pumping at different locations and rates, these flows may be entirely lost. Example (a) conceptually represents the Tindall Limestone aquifer with 80% of estimated storage (28,200 to 56,400 GL) extracted over 100 years, with recharge of 330 GL/year (after Bruwer and Tickell, 2015). The red line represents the approximate water level, incorporating extraction offset by yearly recharge. Flow to the Roper River and springs is lost, due to change in groundwater flow directions and the capture of discharge. (B) Potential effect of depleting 80% of storage in the Georgina Basin. Due to minimal recharge, storage depletion would reverse hydraulic gradients. Throughflow into the Tindall Limestone (Daly Basin) would become a net loss of water to the Georgina Basin (Gum Ridge Formation), which is likely to reduce flows to GDEs in the Daly basin. (C) shows how extraction of any significant proportion of recharge and/or discharge from the Tindall Limestone would reduce flux rates to GDEs (e.g., the Roper River and Mataranka Springs), without necessarily reversing the flow direction or breaching water level thresholds required to sustain these sites. Locations of a) and c) correspond approximately to north Larrimah to Mataranka (red line on Fig. 11); b) approximately from the CLA west of Tennant Creek to Daly Waters (Black line, Fig. 11). Figures not to scale. More precise field data & modelling are required to predict the spatial and temporal consequences of groundwater extraction at different rates in different regions accurately.

A comparison of volumes of extraction that could be permissible under the Arid Zone rules to annual recharge rate (as per the data in Tables 2 and 3) indicates that in the Georgina basin, permissible extraction over a 100-year period would represent between approximately 60 to 400 times the volume of recharge expected over this timeframe. In the Daly Basin (where storage capacity is estimated to be lower and recharge rate higher), extraction volumes would approximately correspond with (or exceed) the estimated rate of recharge over 100 years, which is likely to substantially reduce flows to GDEs (Fig. 15).

Consideration of climate change impacts on recharge and aquifer storage

Much of the recharge in CLA emanates from annual rainfall. As with other regions, groundwater across the CLA will continue to respond to the impacts of climate change through changes in the characteristics of rainfall (e.g., intensity, seasonality). The negative trends in annual recharge between 2003 and 2016 in some critical areas of the CLA (Fig 4b) highlights this further, suggesting that slight changes in the intensity of annual rainfall and/or increased evapotranspiration rates could create a water budget deficit, affecting rainfall-based storage contributions to the aquifer. Recharge may be significantly less in some years compared to long term averages – the limited analysis of hydrographs conducted for the Georgina basin indicates that this is particularly true in this basin, where substantial recharge appears to have only occurred once in a few decades. Groundwater extraction at rates that exceed recharge even temporarily (due to its episodic nature) could coalesce with prolonged droughts, to deplete storage faster than expected, lowering the water table and ultimately damaging GDEs and their unique biodiversity. Damaging impacts of severe dry conditions on hydraulic properties (e.g., transmissivity of karst aquifers in France), which may not be readily reversible, have been documented elsewhere (Green et al. 2011).

Threats to environmental and cultural values sustained by groundwater if groundwater extraction rates representing a substantial fraction of storage and/or recharge are permitted

As outlined above, the use of Arid Zone contingent rules or other storage-based method to calculate sustainable yield for groundwater extraction from the CLA would pose a high risk of damaging sites dependent on groundwater discharge from the aquifer. Extracting up to 80% (as permitted under the current contingent rule) or 40%, as suggested by APPEA (2020) would pose a very high risk of damaging sites and values dependent on groundwater from the CLA e.g., through reversing hydraulic gradients away from GDEs, breaching key groundwater level thresholds for these, and/or compromising throughflows between different regions. Extraction of substantially lower proportions of storage would still pose significant risks to GDEs, through capture of flows to the surface and/or root zone (see section 2).

The extraction of a large fraction of recharge - e.g., 40% of the estimated average recharge, as proposed in the current draft Georgina-Wiso Water Allocation Plan, may similarly pose risks to multiple values sustained by CLA groundwater. Important considerations regarding the proposed adoption of an estimated sustainable yield of approximately 260 GL/year in this plan (as per the current draft) include:

1. Estimates of recharge rates within the Georgina and Wiso basins remain uncertain, with conflicting values derived from different methods (e.g., Table 1 of the Draft WAP Background report – Northern Territory Government, 2022b). The model-derived estimates of recharge used to calculate the 40% fraction of recharge are almost double the previous recharge estimate using the same model. From review of the reporting it appears that the major difference is a shortening of the period used to model recharge compared to the previous model run (Knapton, 2020). This means that the volume currently estimated to be 40% of average recharge, may not actually represent this fraction of the true recharge. Under the previous modelling (Knapton,

2020), the proposed ESY would represent more than 75% of long-term averaged recharge to the Georgina Basin. If the use of a fraction of recharge is the approach preferred for calculation of an ESY in this region, then using the current minimum estimated recharge rate (and taking a fraction of this) would be a more conservative approach, given the current lack of data. Sound justification for the use of 40% of the recharge should also be provided.

2. Recharge to the CLA is thought to be very infrequent in the region covered by the draft WAP (Georgina and Wiso basins). As discussed in Tickell and Bruwer (2017), it is likely there have only been a small number (three or four) of unusually wet climatic periods since monitoring began in the early 1900s, in which effective recharge to the Georgina Basin CLA has taken place. Extracting a substantial proportion of the long-term averaged recharge each year would therefore mean extraction would far exceed recharge in most years, excluding these episodic recharge events (in which recharge would far exceed extraction). If there are many years or decades between substantial recharge events - as occurred for nearly four decades between the 1970s and early 2010s, the level of yearly extraction proposed along with limited recharge would result in effective mining of aquifer storage between recharge events, causing substantial reductions in groundwater levels (drawdown) and fluxes during these periods. Better understanding of the importance of maintaining groundwater levels for protecting stygofauna communities (e.g. Rees et al., 2021), throughflows to other parts of the CLA (Evans et al., 2020), water quality (Tickell and Bruwer, 2017) and ensuring structural integrity of the aquifer are required before such extraction rates - and the groundwater level reductions they would cause - can be said to be sustainable, i.e., protective of environmental, cultural and economic values.

3. Groundwater discharge mechanisms from the Wiso and Georgina basins are poorly understood. It is questionable to believe that there is little or no groundwater discharge from these basins currently occurring – as appears to be assumed in the draft WAP (e.g., Table 1 of Northern Territory Government, 2022a). Outflow of groundwater is likely to be occurring at rates of similar order to the estimated long-term average recharge – in line with general steady-state conditions typically encountered in relatively un-developed aquifers (Alley et al, 1999). The outflow/discharge of groundwater is likely to be occurring either through evapotranspiration, flow to springs (such as those on the west of the Wiso basin that are currently poorly understood), groundwater throughflow to other regions (which has been considered but may be under-estimated), and/or inter-aquifer leakage. The large imbalance between estimated recharge and outflow/discharge currently reflected in the draft WAP may well reflect limited data currently available to quantify groundwater outflows rather than an actual large imbalance between inflows and outflows.

Ultimately, the extraction of the volumes of water proposed each year in the draft Georgina Wiso WAP would likely have flow-on effects for the rest of the CLA water balance and associated values. As discussed in section 3, 40% of the long-term average annual recharge is at the high end of typical fractions of recharge used to calculate estimated sustainable yields in other jurisdictions, such as the SDLs determined for Murray Darling Basin catchments (Walker et al., 2020). Without addressing the issues described above, the adoption of the proposed ESY/extraction rates in the draft WAP may seriously jeopardise environmental and cultural values. Of further considerable concern is the fact that cultural and environmental values supported by the CLA groundwater in this region (encompassing appropriate stakeholder engagement) appear not to have been effectively documented and considered in the setting of the ESY, and this is not proposed to be addressed until halfway through the life of the plan. This runs counter to best practice water management approaches, which ensure that stakeholder management occurs early and frequently in the determination of water plan rules (e.g., Thomann et al., 2020 and further discussion in Section 3).

In the Daly Basin, the sites most at risk from excessive extraction of CLA groundwater would be the Roper River and Mataranka Springs (on the east), and to the west, Flora River and its associated springs. It is well established that these sites are strongly dependent on groundwater discharge from the Tindall Limestone aquifer. If extraction rates within the Daly Basin (e.g. Flora Tindall and Mataranka WAP areas) allow for a significant percentage of storage depletion, then these sites would be at high risk of harm. Even if significant extraction rates are permitted a long distance from the GDEs (e.g. groundwater extractions focused near Larrimah, or Daly Waters, above the Beetaloo sub-basin), the most likely *long-term* consequence of increasing groundwater extraction rates within the Daly basin is the capture of discharge that ultimately sustains these critically important GDEs (Ponce, 2007). Further, the depletion of storage in the Georgina and/or Wiso basins to the south would result in throughflow from these basins no longer sustaining the Tindall Limestone, and (as shown in Fig. 15b) a change to a net <u>loss</u> of groundwater throughflow, with groundwater from the Tindall Limestone instead flowing back towards the Gum Ridge Formation.

Ecohydrological and modelling studies have yet to (as far as we are aware) determine the threshold groundwater elevations required to sustain the Mataranka springs, Roper River and other springs and groundwater dependent streams and vegetation above the CLA, nor have they determined the extent of reduction in baseflow and/or associated environmental impacts that would likely be caused at different extraction rates in different areas. Some estimates using numerical modelling, examining potential impacts of extraction at different rates on baseflow to the Roper River have been documented; for example, Bruwer and Tickell (2015) modelled the effect of extracting 20% of estimated recharge of the Tindall Limestone via a wellfield near Larrimah, finding that this would result in a reduction in baseflow to the Roper River of approximately 20% in the long-term. The environmental consequences of such a reduction (i.e., extent to which the values described in section 1c would be harmed) are not known, although they have been explored in Jolly et al. (2004) to some extent. Reductions in flow to springs and/or baseflows in the Roper would cause corresponding declines in river flows downstream. Thus, as well as groundwater dependence of Mataranka Springs and Roper River from the CLA in its upstream sections, downstream sections of the Roper are vulnerable to saltwater intrusion if flows decline below certain thresholds. In the 1950s and 60s, substantial reductions in flow along the Roper caused the loss of the water supply for the Ngukurr Aboriginal community (Zaar, 2009).

It is currently unclear what the major groundwater discharge mechanisms for the Georgina and Wiso basins are; throughflow to the Daly Basin is clearly one component, and discharge to springs a probable additional component (Evans et al., 2020), but it is not clear where or how much discharge takes place, or what the ultimate fate of much of the CLA groundwater flowing through these basins is. This may encompass cross-flow to other aquifer units and/or diffuse evapotranspiration (including by GDEs that are not well documented). As such, the consequences of pumping at rates that deplete storage, and thus reduce groundwater discharge significantly, are not well understood. Stygofauna communities identified in the CLA by Rees et al., (2020) would be at high risk of losing their habitat if a significant proportion of storage was depleted in these basins, due to the low recharge rates - which would mean extensive drawdown would occur over wide areas, with limited recovery of water levels for a long period of time. Irreversible aquifer compaction, development of surface collapse structures and/or reductions in groundwater quality (e.g. increasing salinity due to enhanced leakage from low-quality water bodies) also cannot be ruled out.

3. Advise on how an "estimated sustainable yield" should be calculated for the purposes of water allocation plans in the Beetaloo Basin to safeguard against risks to dependencies (particularly Mataranka springs and Roper River).

In line with the discussion above, current groundwater management rules in the Northern Territory should be urgently updated, so that they ensure protection of the groundwater dependent values sustained by the CLA and any other groundwater resources. Updated groundwater management rules set out in the WAPs currently being developed should firstly outline clearly the key groundwater dependent values of each region, and/or the connectivity between extraction within the relevant plan area, and other regions of the CLA where the groundwater sustains key values. Secondly, the WAPs should document how adverse impacts to these values are to be monitored and prevented, informed by rigorous baseline studies and modelling - e.g., to determine minimum groundwater levels and flow rates (as well as quality) required to sustain river baseflow, springs, stygofauna, groundwater dependent vegetation, and access to groundwater and surface water for other purposes/users. This must include thorough scientific work to address knowledge gaps regarding the ecological, cultural and water use values sustained by CLA groundwater in the Georgina and Wiso Basins, where data and knowledge are to date relatively lacking. The following is a brief review of groundwater management approaches adopted elsewhere in Australia to provide context in support of the proposed updated management regime outlined below ('A path to sustainable groundwater management in the CLA'):

Approaches to sustainable groundwater management

Approaches to groundwater management in Australia and internationally vary considerably (Cook et al., 2023); however, many jurisdictions set regional and/or local caps on extraction volumes from a given aquifer, terming this a 'sustainable yield' or some variation (e.g., 'Permissible consumptive volume' in Victoria). Approximately half of the groundwater management areas declared in Australia adopt a limit on volumetric extraction rates of this kind (Barnett et al., 2020). In many of these districts, water trading is also permitted between users within the groundwater management area, provided total extraction rates stay below the overall cap for the aquifer. In some regions (such as the Lower Burdekin in Queensland), extraction rate limits can change depending on other variables – such as the salinity of groundwater, to mitigate the risk of saline intrusion (Thomann et al., 2020). Water trading may also be used as a mechanism to encourage water use away from areas where it may risk causing adverse consequences, into areas considered low-risk (e.g. Southern Rural Water, 2010).

The determination of extraction cap limits within different groundwater management areas relies on different approaches, depending on jurisdiction (Cook et al., 2023). Many states (such as NSW, Victoria and WA) have commissioned state-wide reviews into appropriate sustainable yields for different aquifer systems and have used these as the basis for setting or adjusting extraction rate limits. In some areas where groundwater extraction is already intensive, and there are significant values at stake (such as groundwater flows to surface water), numerical modelling is used to determine allocation rates, such as for the Namoi alluvial aquifer, one of the most intensively utilized groundwater resources in Australia (NSW Government, 2019). The region with the greatest number of groundwater management areas (and greatest cumulative extraction volumes) in Australia is the Murray Darling Basin. According to the methodology adopted by the Murray Darling Basin Authority in its 2012 Basin Plan, caps on rates of groundwater extraction - termed Sustainable Diversion Limits (SDLs) within sub-regions of the basin, are set based on an analysis of the rate of diffuse groundwater recharge, and analysis of the risks of extracting different fractions of this recharge on aquifer integrity, baseflow to streams, groundwater quality, and GDEs. In areas where these risks are deemed high, sustainable yields/SDLs are set at 5% of recharge or less – in other ‘low risk’ areas, the fraction may be as high as 70%, but this is rare (Walker et al., 2020).

Alternative or complementary groundwater management rules (in addition to volumetric extraction rate caps) include the use of trigger levels, whereby the management objective is to maintain groundwater levels in an aquifer above a threshold required to protect certain values. This is usually designed to achieve either protection of environmental assets (such as groundwater discharge to rivers or springs) or prevent bore interference and loss of access to the resource. A combination of a cap on yearly extraction volumes within a district, plus trigger-based rules which result in a cut to the volumetric extraction cap if levels fall below a certain value, are used in some groundwater management areas to address concerns over both access to the resource, and flow of groundwater to the surface or other aquifers (e.g., Katunga WSPA in Victoria, see Goulburn Murray Water, 2017). There are also examples where conjunctive groundwater-surface water management rules are implemented – e.g., limits on groundwater pumping depending on the distance to a stream (i.e., buffer zones around the stream), and pumping limits that change seasonally to correspond with periods of higher/lower streamflow and thus limit stream depletion (Goulburn Murray Water, 2012). These approaches hold significant potential, when combined with a sustainable yield cap, to balance a desire for groundwater development to support agriculture or other industries, the needs to ensure ongoing access for domestic and stock users, and the health of groundwater dependent surface waters and GDEs.

The Northern Territory’s Arid Zone contingent allocation rule appears to be one of the only cases in Australia where a storage-based approach is applied to the determination of a ‘sustainable’ yield. This may reflect the knowledge that Alice Springs’ town water supply requires far greater rates of extraction than the natural recharge rate (DLRM, 2016), to supply a fundamental need for the township. If this is the rationale for the Arid Zone contingent rules remaining in place in the NT, then it would be straightforward to ratify the Alice Springs Water Control District as exempt from management rules that prevent over-extraction, and allow for continued pumping at greater than the recharge rate in this zone (ideally on a temporary basis while alternative sources are developed). Allowing extraction that depletes aquifer storage to supply adequate drinking water to a major town (a fundamental human need) is very different to allowing such extraction in new areas to supply water for private industry.

The use of the Arid Zone contingent rules or other method that uses a fraction of the total storage volume of the aquifer will not provide the necessary protection required to sustain the ecological and cultural values supported by groundwater in the CLA (as discussed in Section 2) and would lead to damage or (potentially) complete loss of GDEs and access to the resource for existing water users. In the case of the Georgina-Wiso Water Allocation Plan, the current proposal to allow yearly extraction of 40% of the (poorly constrained) long-term average recharge would effectively allow ongoing depletion of aquifer storage in this system, due to the highly episodic nature of recharge. The associated impacts of such depletion (which could be expected to continue for years or decades between significant recharge events) have not been addressed in the draft WAP.

Due to the relatively sparse population and infrastructure in the Georgina and Wiso basins, it is probable that groundwater extraction for irrigation, oil and gas development would be initially concentrated in particular geographic areas, e.g., where road infrastructure allows easy access. Hence, the extraction of groundwater under the ESY proposed in the draft plan would be unlikely to be evenly distributed throughout the WAP area. Modelling the extent of drawdown and the localized impacts of this (such as loss of stygofauna, subsidence and migration of saline groundwater) in scenarios where the ESY rates are concentrated in particular zones should form part of the analysis of the suitability of the ESY, considering this.

A path to sustainable groundwater management in the CLA

The most effective way to manage groundwater to protect the environmental and cultural values sustained by the CLA in the Daly, Georgina and Wiso basins would be a combination of both volume and trigger-level based rules, that encompass:

1. **Volumetric extraction rate limits** which in the long-term ensure:
   a) groundwater flows do not decline in such a way as to compromise the health of the groundwater dependent ecosystems sustained by these flows. This requires careful analysis of recharge and discharge flux rates, environmental dependencies on these flows, and the extent of 'capture' by pumping at different rates in the different CLA basins. The connectivity of the CLA flows to rivers (e.g. the Roper, Flora and Daly) and throughflow across sub-regions and basin boundaries (e.g. the dependence of flows within the Daly basin on inflow from the Georgina and Wiso basins), must be properly considered in this process. Sustainable yields set within a given management area must be shown to be sustainable cumulatively, in conjunction with those set in adjacent WAP areas.

   b) the renewability of groundwater resources, preventing ongoing storage depletion and/or detrimental capture of surface flows, e.g., by not exceeding any significant fraction of the recharge/discharge, in recognition of the high value of groundwater to the maintenance of the Roper River, Mataranka springs and other GDEs and communities.

2. **Clearly defined and well monitored water level triggers/thresholds**, which are determined to be the groundwater elevations required to sustain environmental and cultural values of key groundwater dependent sites and ecosystems. When threshold levels are approached or crossed, reductions in groundwater pumping would be triggered, in line with level-based management approaches adopted in other parts of Australia and internationally. Trigger levels must be set at an appropriate distance from the environmental assets seeking to be protected, to account for time-lags between changes in extraction rates, hydraulic gradients and flow rates in an aquifer. Buffer zones around high value GDEs should be enacted, in which groundwater extraction is restricted and/or not permitted, to minimize the risk of short-term damage that may result from rapid drawdown and/or capture of fluxes near the point of extraction.

A mechanism to adjust the volumetric rates and trigger levels to consider climatic conditions - e.g., periods of unusually low rainfall and high evapotranspiration, following which groundwater levels and fluxes are likely to deplete more rapidly in response to extraction, should also be included. This would align with the intent of the National Water Initiative (Walker et al., 2021).

The setting of appropriate trigger levels requires in-depth eco-hydrological studies to determine the threshold groundwater levels required to maintain flows to springs and rivers, the viability of stygofauna, and access to groundwater by vegetation. Following these studies, a series of trigger levels at various distances from each GDE should be set, with clearly defined monitoring locations. If these threshold levels are approached or crossed, groundwater extractions should (according to management rules) be reduced or ceased until they stabilise or recover above the threshold. This approach should be conducted in conjunction with numerical or analytical modelling, to ensure the trigger points can provide sufficient early warning (incorporating time-lags in response to changes in extraction rates), to protect the GDE (Currell, 2016; Noorduijn et al., 2019). This combination of flux and trigger-based management values would align with current best practice for sustainable groundwater management (Thomann et al., 2020).

Proper determination of the appropriate extraction rate limits and triggers to satisfy both 1) and 2) in each WAP (and cumulatively), will require further scientific work, including both field studies and modelling, to establish and monitor:

- Recharge rates throughout the CLA and its sub-basins and zones (particularly where these are not already well constrained), including recharge from streams, lakes and karst structures
- Discharge fluxes from the aquifer to the surface, and between different basins (i.e., throughflow, which remains poorly constrained, and vertical inter-aquifer leakage)
- The environmental dependencies on water levels and discharge fluxes from the CLA (i.e., ecohydrological studies)
- How extraction at different rates, and in different regions, changes both groundwater levels and discharge fluxes, including the timescales and spatial distribution of these responses
- Different GDEs' tolerance for changes in both groundwater levels at different locations, and groundwater discharge fluxes (flow rates)

The combination of strategies and rules described above is the only clear path to sustainable aquifer management in the Cambrian Limestone Aquifer and Beetaloo sub-region.

Setting a sustainable yield for the Tindall Limestone aquifer

Under the current water allocation planning framework rules, the Tindall Limestone aquifer (which is critical for maintenance of the Mataranka Springs, Roper and Flora rivers and other GDEs) falls in the Top End zone, and as such, a default position for setting a volumetric cap on extractions would be 20% of the Basin's estimated recharge (i.e., approximately 66 GL/year). Bruwer and Tickell, 2015 conducted modelling of groundwater extraction from Daly Waters to Mataranka under this scenario, involving an additional 40 GL/year of extraction surrounding Larrimah, plus the existing 26 GL/yr of licensed extractions in the CLA to the north (predominantly near Mataranka). This modelling indicated that in the long term, the additional pumping would result in an approximately 20% reduction in flows in the Roper River, following an equilibration period of approximately 300 years. The environmental and cultural significance of these flow reductions was not assessed, and it has not been determined whether 20% reduction in baseflows, particularly during particularly dry years, could have significant detrimental impacts on ecological and/or cultural values of the Roper River. Analysis by Jolly et al., (2004) indicated that in years of below average rainfall, such reductions may jeopardise GDEs and cause significant saltwater ingress up the Roper River.

A previous draft of the Mataranka Tindall WAP from 2012 proposed the use of 15% of recharge as an extraction cap, which (if applied over the whole Tindall Limestone aquifer) would equate to approximately 50 GL/year. Determining the effect on baseflows to the Roper River, Mataranka Springs and other GDEs, and assessing the associated risk from ecological, cultural and water resources viewpoints, would be important to determine if this is an appropriate extraction cap. Should the dependence of ecological and cultural values of these sites during dry periods be put at risk, lower fractions of recharge should be considered.

One way to help determine appropriate sustainable yields is through numerical modelling, noting that Knapton (2020) completed major FEFLOW-MIKE11 coupled groundwater/surface modelling of the CLA, designed to aid current and future assessment of groundwater abstraction scenarios. The impetus for the modelling was the recommendations of the Pepper Inquiry, including that there was a need for "development of a regional groundwater model to assess the effects of proposed water extraction of the onshore shale gas industry on the dynamics and yield of the regional aquifer system." A key aspect of the modelling was also to enable water planning to conduct predictive uncertainty analysis to help determine the level of confidence with which the impacts of extraction at given rates could be made.

The draft Georgina Wiso WAP appears to have involved further modelling, based on the work of Knapton (2020), to inform the recharge rate used to calculate the proposed ESY. The precise changes to the previous model and/or updates in modelling assumptions are not clear from the plan's documentation.

It should be noted that numerical modelling is only as robust as the field data used to develop its conceptual elements and parameters. Most of the key knowledge gaps discussed above and below in this report still require additional field studies, before modelling can be considered reliable to predict impacts within acceptable ranges of uncertainty. This is important due to current limitations acknowledged in the modelling – e.g., it is based on conventional porous media flow, whereas it is known that flow in the CLA is predominantly through secondary porosity, and water balance/budget estimates and inter-aquifer connectivity remain relatively poorly constrained through most of the region (Knapton, 2020).

Sustainable management regimes for other management zones in the CLA
Key considerations in the setting of extraction caps in the southern CLA basins – i.e., Georgina Basin and Wiso Basin, are:

a) Current uncertainty in the recharge rates for these basins (the rates are not well constrained and there is evidence recharge may occur by both diffuse and preferential mechanisms – see Deslandes et al., 2019; de Caritat et al., 2019).
b) Lack of understanding of the major groundwater discharge mechanism(s) in these basins (e.g. spring discharge, diffuse ET losses, inter-aquifer leakage). These discharges are likely to be significantly changed by a large increase in groundwater extraction rates - as the capture of discharge is often the dominant long-term consequence of groundwater extraction. The environmental, social, cultural and economic consequences of increases in extraction can't be determined until the pre-existing baseline, and changes to this are properly understood.
c) Uncertainty over the extent of throughflow from the two basins into the Daly Basin (Tindall Limestone) and likely flow-on effects to GDEs in the Tindall Limestone if these throughflow volumes decline and/or reverse over time.
d) The potential for irreversible loss of storage and/or reductions in aquifer transmissivity, causing subsidence and aquifer compaction, if groundwater levels substantially decline.
e) The extent of damage to stygofauna communities (e.g., Oberprier et al., 2021) that may occur under different levels of drawdown in these basins.
f) The likelihood of migration of saline groundwater into areas of fresher groundwater under the influence of intensive groundwater extraction in particular areas.

Mechanisms to ensure the following are also critical to ensure rigor and trust in groundwater management processes:

- The scientific basis for the setting of sustainable yields, trigger levels and any other groundwater management rules must be clear and transparent, and any supporting datasets and modelling made publicly available.
- Ample opportunities for input to the design of the management rules from the public and key stakeholder groups, e.g., Traditional Owners and conservation groups who can speak to the value of the ecosystems and waters sustained by the aquifer(s) and what is at stake if these are lost.
- Participation of independent scientific and water policy experts in the process of reviewing and developing science-based management rules to protect values identified as being in need of protection.

4. Identify key gaps, misinterpretations and inconsistencies in the existing data, science, interpretation, analysis, modelling and conclusions Identify the critical science requirements for robust water allocation.

As discussed above, the setting of new/updated groundwater management rules that can ensure protection of the values sustained by the CLA requires a significant amount of scientific data and analysis, to address current knowledge gaps. In response to the Pepper Inquiry's recommendations, a program of scientific work – the Strategic Regional Environment and Baseline Assessment (SREBA), has been underway since 2018, attempting to address knowledge gaps raised in the inquiry and those highlighted in this report (Table 5):

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 5: Hydrogeological knowledge gaps identified in the SREBA review, as of 2021 (Northern Territory Government, 2021).

Key gaps requiring additional data and knowledge, which (according to the above) are currently being addressed through ongoing studies include:

- More detailed quantification of groundwater recharge and its mechanisms/processes in the three CLA sub-basins
- Better understanding of inter-aquifer connectivity and likely fluxes between different layers and units within and across the three CLA Basins.
- Further data characterising aquifer and aquitard hydraulic properties
- A greatly improved monitoring network for both water quality and quantity, encompassing nested sites allowing for analysis of inter-aquifer connectivity.

Scientific work is also required to address further issues identified in this review, in order to implement a robust groundwater management regime. It is unclear to what extent the SREBA or other programs are going to address these:

- Eco-hydrological studies to determine threshold groundwater levels and flow gradients required to sustain discharge flows to the Roper River, Mataranka Springs, Flora River springs and other GDEs – such as vegetation sustained by permanent access to shallow groundwater. Such studies are required both to inform details of updated groundwater management rules, and to establish appropriate monitoring programs that can document changes to GDEs and allow for informed actions to protect these.

- More data and information about the springs of the Flora River and those on the western margin of the Wiso Basin (Top Springs), e.g., documenting rates of discharge, source aquifer(s) and vulnerability to depletion due to up-gradient groundwater extraction.

- A more in-depth analysis of the major current mechanism(s) of groundwater discharge from the Georgina and Wiso basins (encompassing the above, as well as diffuse inter-aquifer leakage, ET by vegetation communities and un-documented springs and stream baseflow), to determine what the likely long-term impact of increased groundwater extraction is within these relatively under-characterised aquifer systems.

- Determining hydrological and water quality requirements of stygofauna, and analysis of the extent to which these subterranean ecosystems may be impacted by groundwater extraction at different rates in different regions
- The likely time scales of the responses of aquifers to extractions at different rates and locations, and how the response evolves through time (e.g. proportions of storage depletion vs stream/spring depletion caused by pumping, and how this changes through time)
- The importance of episodic recharge, particularly in the southern CLA basins, and the likely recurrence interval for major recharge events, which provide the majority of water to the aquifers over the long-term.
- The likely impact of climate change on groundwater recharge rates and mechanisms, groundwater discharge (e.g., via evapotranspiration) and flow-on effects to GDEs.

At present, existing knowledge gaps prevent a comprehensive analysis of the likely impacts of groundwater extraction from the CLA at different rates and in different areas on the key environmental and cultural values the aquifer sustains, or the adoption of appropriate caps on groundwater extraction rates and trigger levels to protect GDEs and river baseflows. Finalising the CLA / Beetaloo WAPs, and making future groundwater licensing decisions in a manner that is scientifically robust, will require these gaps to be (urgently) addressed.

References

Ah Chee, D., 2002. Kwatye, Indigenous peoples connection with kwatye (water) in the Great Artesian Basin. Environment SA 9: 20-25

Alley, W.M., Reilly, T.E., Franke, O.L. 1999. Sustainability of Ground Water Resources. USGS Circular 1186.

Alley, W.M., Healy, R.W., LaBaugh, J.W., Reilly, T.E., 2002. Flow and storage in groundwater systems. Science 296: 1985-1990.

APPEA (Australian Petroleum Production & Exploration Association), 2020. Claim vs Fact. Energy Information Australia: https://energyinformationaustralia.com.au/wp-content/uploads/2022/08/EIA_claimvsfact_beetaloo.pdf

Barber, M. and Jackson, S. 2011. Indigenous water values and water planning in the upper Roper River, Northern Territory. CSIRO: Water for a Healthy Country National Research Flagship.

Barber, M. and Jackson, S. 2012. Indigenous water management in the upper Roper River, Northern Territory: history and implications for contemporary water planning. CSIRO, Darwin

Barnett, S., Harrington, N., Cook, P., Simmons, C.T., 2020. Groundwater in Australia: Occurrence and management issues. In: J.-D. Rinaudo et al. (eds.) *Sustainable Groundwater Management: A Comparative Analysis of French and Australian Policies and Implications to Other Countries.* Global Issues in Water Policy 24: Springer, pp.109-127.

Bierkens, M., Wada, Y. 2019. Non-renewable groundwater use and groundwater depletion: a review. Environmental Research Letters 14: 063002.

Bredehoeft, J., Durbin, T., 2009. Ground water development – the time to full capture problem. Groundwater 47: 506-514.

Bruwer, Q., Tickell, S.J., 2015. Daly Basin Groundwater Resource Assessment – North Mataranka to Daly Waters, Department of Land Resource Management, Water Resources Report Number 20/2915D.

Chen, J.L., Wilson, C.R., Tapley, B.D., et al., 2016. Long-term groundwater storage change in Victoria, Australia from satellite gravity and in situ observations. Global and Planetary Change 139: 56-65. https://doi.org/10.1016/j.gloplacha.2016.01.002.

Crosbie, R.S., Rachakonda, P.K., 2021. Constraining probabilistic chloride mass-balance recharge estimates using baseflow and remotely sensed evapotranspiration: the Cambrian Limestone Aquifer in northern Australia. Hydrogeology Journal 29, 1399–1419

Currell, M.J. 2016. Drawdown “triggers”: a misguided strategy for protecting groundwater-fed streams and springs. Groundwater 54(5): 619-622

Currell, M.J., Gleeson, T.P. Dahlhaus, P.D., 2016. A new assessment framework for transience in hydrogeological systems. Groundwater 54(1): 4-14.

De Caritat, P., Bastrakov, E.N., Jaireth, S., English, P.M., Clarke, J.D.A., Mernagh, A.S., Wygralak, A.S., Dulfer, H.E., Trafford, J. 2019. Groundwater geochemistry, hydrogeology and potash mineral potential of the Lake Woods region, Northern Territory, Australia. Australian Journal of Earth Sciences, 66: 411-430.

Deslandes, A., Gerber, C., Lamontagne, S., Wilske, C., Suckow, A. 2019. Environmental Tracers in the Beetaloo Basin. Aquifer and groundwater characterization. CSIRO, Australia.

DLRM, 2016. Alice Springs Water Allocation Plan 2016-2026. Northern Territory Department of Land Resource Management, Report No. 01/2016A

Doody TM, Hancock PJ, Pritchard JL 2019. Information Guidelines Explanatory Note: Assessing groundwater-dependent ecosystems. Report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment and Energy, Commonwealth of Australia 2019

Duong, A., Stokeld, D. 2021. Mapping the Future Project - Larrimah Biodiversity assessment of the Larrimah area. Technical Report 13/2021. Department of Environment, Parks and Water Security, Darwin, Northern Territory.

Evans TJ, Radke BM, Martinez J, Buchanan S, Cook SB, Raiber M, Ransley TR, Lai ÉCS, Skeers N, Woods M, Evenden C, Cassel R and Dunn B (2020) Hydrogeology of the Beetaloo GBA region. Technical appendix for the Geological and Bioregional Assessment: Stage 2.Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia

Frery, E., Byrne, C., Crosbie, R., et al., 2022. Fault-related fluid flow implications for unconventional hydrocarbon development, Beetaloo sub-basin (Northern Territory, Australia). Geosciences 12: 37, https://doi.org/10.3390/geosciences12010037

Fulton, S., Knapton, A. 2015. Water table contours and flow direction arrows from water table mapping for the cambrian limestone aquifer used in Beetaloo hydrogeological assessment Hydrogeology of the Beetaloo GBA region.

Gleeson, T., Alley, W.M., Allen, D.M., Sophocleous, M.A., Zhou, Y., Taniguchi, M., VanderSteen, J. 2012. Towards sustainable groundwater use: Setting long-term goals, backcasting, and managing adaptively. Groundwater 50: 19-26.

Goulburn Murray Water, 2012. Upper Ovens Water Supply Protection Area. Water Management Plan.

Goulburn Murray Water, 2017. Groundwater Management Plan for the Katunga Water Supply Protection Area.

Green, T.R. Taniguchi, M., et al., 2011. Beneath the surface of global change: Impacts of climate change on groundwater. Journal of Hydrology 405: 532-560,

Hatton, T., Evans, R., 1998. Dependence of ecosystems on groundwater and its significance to Australia. LWRRDC Occasional Paper No 12/98.

Healy, R., 2010. Estimating Groundwater Recharge. Cambridge University Press.

Holzapfel, C. 2008. Deserts. In: Jorgensen, S.E., Fath, B.D. 2008. *Encyclopedia of Ecology.* Elsevier.

Jackson, S., Barber, M. 2013. Recognition of indigenous water values in Australia's Northern Territory: current progress and ongoing challenges for social justice in water planning. Planning Theory & Practice 14: 435-454.

Jolly, P., Knapton, A., Tickell, S. 2004. Water availability from the aquifer in the Tindall Limestone south of the Roper River. Northern Territory Government Department of Infrastructure, Planning and Environment, Report No. 34/2004D.

Karp, D., Surface and groundwater interaction the Mataranka Area. Department of Natural Resources, Environment, The Arts and Sport. Report No. 17/2008D.

Knapton, A. 2004. Modelling of Water Extraction at the Shenandoah Station, Georgina Basin and Effects on Base Flows in the Roper River. Department of Infrastructure, Planning and Environment, Natural Resources Division, Report No. 31/2004.

Knapton, A. 2006. Regional Groundwater Modelling of the Cambrian Limestone Aquifer System of the Wiso Basin, Georgina Basin and Daly Basin. Department of Natural Resources, Environment and the Arts (Northern Territory), Alice Springs.

Knapton, A. 2009. Gulf Water Study. Integrated Surface – Groundwater Model of the Roper River Catchment. Part A: Coupled Surface – Groundwater Model. Department of Natural Resources, Environment, The Arts & Sport, Technical Report 15/2009D.

Knapton, A. 2020. Upgrade of the Coupled Model of the Cambrian Limestone Aquifer and Roper River Systems. WRD Technical Report 57/2020.

Konikow, L., Leake, S.A., 2014. Depletion and capture: Revisiting "The source of water derived from wells". Groundwater 52: 100-111.

Lamontagne, S., Suckow, A., Gerber, C., Deslandes, A., Wilske, C., Tickell, S. 2021. Groundwater sources for the Mataranka Springs (Northern Territory, Australia). Scientific Reports 11: 24288.

Lamoureux, S.C., Veneklaas, E.J., Poot, P. 2016. Informing arid region mine-site restoration through comparative ecophysiology of *Acacia* species under drought. *Journal of Arid Environments* 133: 73-84.

Laroque, M., Mangin, A., Razack, M., Banton, O., 1998. Contribution of correlation and spectral analyses to the regional study of a large karst aquifer (Charente, France). Journal of Hydrology, 205: 217–231.

Lee, C. H. (1915). The determination of safe yield of underground reservoirs of the closed-basin type. Transactions, American Society of Civil Engineers, Vol. LXXVIII, Paper No. 1315, 148-218.

Marshall, V. 2017. Overturning *Aqua Nullius*: Securing Aboriginal Water Rights. Aboriginal Studies Press.

Merlan, F. 1982. "A Mangarrayi representational system: environment and cultural symbolisation in Northern Australia." American Ethnologist 9(1): 145-166.

Moggridge, B. J., 2020. Aboriginal People and Groundwater. Proceedings of The Royal Society of Queensland, 126, 11–27.

Northern Territory Government, 2021. SREBA Water Quality and Quantity studies (Project 1) Water Resources Division Report Number 18/2021v

Northern Territory Government, 2022a. Draft Georgina Wiso Water Allocation Plan 2022 – 2030.

Northern Territory Government, 2022b. Draft Georgina Wiso Background Report 2022 – 2030.

NSW Government, 2016. Water Sharing Plan for the North Coast Fractured and Porous Rock Groundwater Sources

NSW Government, 2019. Namoi Alluvium Water Resource Plan. Groundwater Resource Description. NSW Department of Industry.

Noorduijn, S.L., Cook, P.G., Simmons, C.T., Richardson, S.B., 2019. Protecting groundwater levels and ecosystems with simple management approaches. Hydrogeology Journal 27: 225-237.

Oberprieler, S. et al., (2021). Connectivity, not short-range endemism, characterizes the groundwater biota of a northern Australian karst system. Science of the Total Environment 796: 148955.

O'Donnell, E., Jackson, S., Langton, M., Godden, L. 2022. Racialized water governance: the 'hydrological frontier' in the Northern Territory, Australia. Australasian Journal of Water Resources, 26: 59-71.

Ojha, C., Werth, S., Shirzaei, M., 2019. Groundwater loss and aquifer system compaction in San Joaquin Valley during 2012-2015 drought. Journal of Geophysical Research Solid Earth 124: 3127-3143.

Pierce, S.A., Sharp Jr., J.M., Guillaume, J.H.A., Mace, R.E., Eaton, D.J., 2013. Aquifer-yield continuum as a guide and typology for science-based groundwater management. Hydrogeology Journal 21: 331-340.

Ponce, V. (2007) Sustainable Yield of Groundwater. California Department of Water Resources. http://gwsustainability.sdsu.edu

Rateb, A., Scanlon, B. R., Pool, et al., 2020. Comparison of groundwater storage changes from GRACE satellites with monitoring and modeling of major U.S. aquifers. Water Resources Research, 56, e2020WR027556. https://doi.org/10.1029/2020WR027556

Rees GN, Oberprieler S, Nielsen D, Watson G, Shackleton M, Davis JA (2020). Characterisation of the stygofauna and microbial assemblages of the Beetaloo Sub-basin, Northern Territory. CSIRO, Australia.

Rossini, RA, Fensham, RJ, Stewart-Koster, B, Gotch, T, Kennard, MJ. 2018. Biogeographical patterns of endemic diversity and its conservation in Australia's artesian desert springs. Diversity and Distribution. 24: 1199– 1216.

Sanford, W. 2002. Recharge and groundwater models: an overview. Hydrogeology Journal 10: 110-120.

Scanlon, B., Healy, R.W., Cook, P.G. 2002. Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeology Journal 10: 18-39.

Seward, P., Y. Xu, and L. Brendock. (2006). Sustainable groundwater use, the capture principle, and adaptive management. Water SA, Vol. 32, No. 4, October, 473-482.

Short, M.A., 2020. Mapping potential groundwater dependent ecosystems using Landsat imagery: Mataranka Tindall Limestone Aquifer. Technical Report 53/2020. Department of Environment, Parks and Water Security (Water Resources Division), NT Government.

Southern Rural Water, 2010. Groundwater Management Plan, Koo Wee Rup Water Supply Protection Area.

Theis, C. V. 1940. The source of water derived from wells: Essential factors controlling the response of an aquifer to development. Civil Engineering, Vol 10, No. 5, May, 277-280.

Thomann, J.A., Werner, A.D., Irvine, D.J., Currell, M.J., 2020. Adaptive management in groundwater management: A review of theory and application. Journal of Hydrology, 124871

Tickell, S. J. and Bruwer, Q. 2017. Georgina Basin Groundwater Assessment: Daly Waters to Tennant Creek, Technical Report 17/2017 (Version 2, April 2019), Northern Territory Department of Environment and Natural Resources. Northern Territory Government, Australia.

Tickell, S.J., 2007. Daly Basin Aquifers, Hydrogeological Map Sheet. Northern Territory Government.

Todd, D. K. (1959). Ground Water Hydrology. John Wiley and Sons.

Walker, G., Barnett, S., Richardson, S. 2020. Developing a Coordinated Groundwater Management Plan for the Interstate Murray-Darling Basin. In: J.-D. Rinaudo et al. (eds.) *Sustainable Groundwater Management: A Comparative Analysis of French and Australian Policies and Implications to Other Countries.* Global Issues in Water Policy 24: Springer, pp. 143-161.

Walker, G.R., Crosbie, R.S., Chiew, F.H.S., Peeters, L., Evans, R. 2021. Groundwater impacts and management under a drying climate in southern Australia. Water 13: 3588; https://doi.org/10.3390/w13243588

Woinarski, J. C. Z., C. Brock, et al. (2000). "Bird distribution in riparian vegetation in the extensive natural landscape of Australia's tropical savanna: a broad-scale survey and analysis of a distributional data base." Journal of Biogeography 27(4): 843-868.

World Commission on Environment and Development (The Brundtland Commission). (1987). Our Common Future. The United Nations, New York.

Appendix A: List of questions/topics to address in this report (Environment Centre NT)

1. **Using publicly available scientific reports (which have been collated by the Environment Centre NT and will be provided to you) develop a conceptual understanding of the Cambrian Limestone aquifer, including:**

   a. The hydrogeological structure of the Cambrian Limestone Aquifer (including the configuration, geometry and hydraulic properties);

   b. The water balance components and their dynamics for key groundwater systems, including inputs (eg recharge from rainfall events or leakage from rivers, groundwater inflows from other aquifers), through-flow (eg definition of groundwater flow paths, watertable and groundwater level contours) and outputs (eg spring discharge, baseflow to rivers, evapotranspirative use by vegetation, outflow to other aquifers, groundwater pumping); and

   c. The dependencies on the key groundwater systems from the hydrological perspective (eg groundwater discharge maintaining river flows), environmental perspective (ie ecosystems reliant on groundwater such as vegetation accessing shallow groundwater, aquatic ecosystems in springs and groundwater-fed rivers) and cultural perspective.

2. **Advise on the risks to dependencies (particularly the Mataranka springs complex and the Roper River) of utilising:**

   a. the Arid Zone contingent allocation rules in the NT Water Allocation Planning Framework as the basis for establishing an "estimated sustainable yield" in the Beetaloo Basin (with specific reference to the proposed Mataranka Tindall Water Allocation Plan and the Georgina Basin Water Allocation Plan);

   b. an "estimated sustainable yield" based on a significant proportion of storage of the Cambrian Limestone Aquifer or its constitutive aquifers (with specific reference to the asserted estimated sustainable yield of 40% of the storage of the Gum Ridge Formation identified in the APPEA fact sheet).

3. **Advise on how an "estimated sustainable yield" should be calculated for the purposes of water allocation plans in the Beetaloo Basin** to safeguard against risks to dependencies (particularly the Mataranka springs complex and the Roper River).

4. **Identify key gaps, misinterpretations and inconsistencies in the existing data, science, interpretation, analysis, modelling and conclusions**. Identify and prioritise the key sources of uncertainty relating to the hydrogeological architecture, water balance, groundwater dependencies and risks from existing and potential resource development, and the science needs to reduce these uncertainties. Identify the critical science requirements for robust water allocation.