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An integrated hydrogeophysical and hydrogeological approach to underpin the long-term water security of a remote tropical island

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SUMMARY

Groundwater resources that sustain small Indigenous communities in remote parts of northern Australia are often poorly characterised, in part due to their remoteness and the economics of undertaking field investigations. The Warruwi community on South Goulburn Island in the Northern Territory is completely reliant on groundwater for its livelihood. Recent consecutive poor wet seasons highlighted both: (i) the sensitivity of the island's water resources to short-term rainfall variability, and (ii) the inadequacy of the island's water infrastructure for meeting water demand during dry periods. An integrated approach was taken to underpin the longer-term water security for the community and to better characterise and quantify the island's water resources and infrastructure requirements. This involved: an airborne electromagnetic (AEM) survey supported by ground geophysics; a hydrogeological survey including environmental tracer analysis; and a desktop study including an annual groundwater balance. Spatial analyses of the AEM data, lithology, groundwater levels and salinity identified a thin (~20m), storage-limited unconfined freshwater 'lens' system overlying a regional aquitard. Groundwater level analyses combined with tracer interpretation characterised a hydrodynamic flow system with short flow paths (<2.5 km) and short mean residence times (MRTs) of ~15 years. A groundwater balance for the freshwater system confirmed that community water demand can be met with the existing resource, although additional water infrastructure and a more strategic management approach was required to better utilise the resource.

Key words: Freshwater lens, airborne electromagnetics, environmental tracers, groundwater balance

INTRODUCTION

Groundwater sustains the livelihood of many remote Indigenous communities in Australia from the arid deserts to islands off the tropical north coast. South Goulburn Island ('the island') is situated in the Arafura Sea in tropical northern Australia (**Error! Reference source not found.**) and is home to the Aboriginal community of Warruwi ('the community'). The island has two distinctive seasons: a warm dry season and a hot wet season. Mean annual rainfall is high (1133 mm) but variable (417 to 2194 mm) depending on the intensity of the northern Australia monsoon. A thin (~20 m), regional scale, shallow unconfined aquifer featuring low permeability is the only source of water on the island. Ageing water infrastructure (~30 years old) coupled with increasing water demand and high rainfall variability has resulted in recent water supply issues. In addition, an aquifer storage and recovery scheme (ASR) operated in a thin but localised deep (>100 m) confined aquifer has also suffered challenges. An improved understanding of the hydrogeological framework for the island as well as quantification of freshwater was required to assess the available water resource and optimise water infrastructure. Here the results of three phases of investigations to re-evaluate the potential available water resource and assess the suitability of the water infrastructure for meeting current and future water demand are summarised.

AIRBORNE AND GROUND GEOPHYSICS

An island-scale AEM survey was flown in September 2017 with a heliborne SkyTEM312 time domain electromagnetic system. The survey included 332 line-kms flown at 200 m spacing, with flight lines oriented east to west (**Error! Reference source not found.**). These data were inverted using a 1-D smooth model layered earth inversion (LEI) using the AarhusInv code (Auken et al. 2015). A series of down-hole and ground-based geophysical measurements were also acquired. Down-hole inductive conductivity logging was conducted at nine bores, TDEM soundings were conducted at 23 sites, and surface nuclear magnetic resonance (SNMR) measurements were obtained at 11 locations (**Error! Reference source not found.**). Down-hole and ground-based conductivity measurements were compared with bulk conductivity values estimated from the AEM survey. This provided confidence in the inverted AEM data. SNMR measurements were used to characterise hydraulic properties of aquifers including permeability and water content. This allowed effective porosity and pore size distributions to then be inferred.

HYDROGEOLOGICAL SURVEY

In 2018, groundwater levels were measured using a portable electric water level meter at 20 bores screened in the shallow unconfined aquifer (**Error! Reference source not found.**). Ten bores were sampled for ionic and metal chemistry and environmental tracers including: deuterium (^{2}H) , oxygen-18 (^{18}O), tritium (^{3}H), chlorofluorocarbons (CFC-11; CFC-12; CFC-113), sulfur hexafluoride, bromotrifluoromethane, carbon-13, carbon-14 and the stable noble gases helium, neon, argon, krypton and xenon. Sampled bore locations were distributed across recharge, throughflow and discharge areas, including near the freshwater–saltwater interface (FWSWI). Tracer concentrations were interpreted in a variety of ways, including comparisons to temporal variations in both rainfall and atmospheric values, and to expected solubility equilibria of noble gases. MRTs for groundwater flow were estimated using lumped parameter models (LPMs). These were the piston-flow model (PFM), which assumes zero mixing along groundwater flow paths (Jurgens, et al. 2012), and the exponential mixing model (EMM), where residence times increase logarithmically from the watertable to the aquifer base (Appelo and Postma 1996, Vogel 1967). Both LPMs are appropriate for characterising flow in an unconfined aquifer and assume advective flow only and a simplified aquifer geometry.

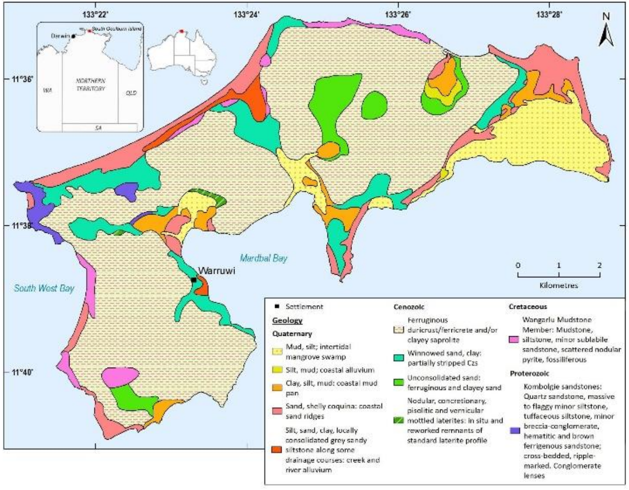

Figure 1. Surface geology of South Goulburn Island

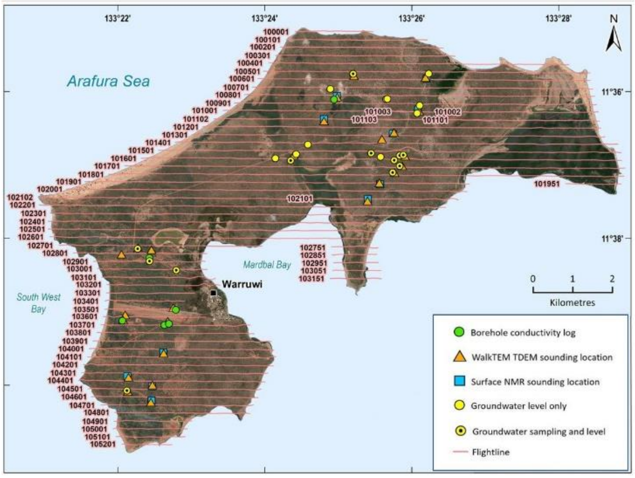

Figure 2. AEM survey extent, downhole and ground-based geophysical measurement locations, and groundwater sampling and level measurement locations

DESKTOP ANALYSES

A desktop assessment involved the collation and interpretation of lithological logs. These were then combined with AEM, down-hole conductivity, TDEM, and SNMR measurements to further characterise the island's hydrogeological framework. Historical groundwater level, salinity and ionic and metal chemistry data were examined with geophysical and tracer data to refine the hydrogeological conceptual model for the shallow unconfined aquifer. An arithmetic annual groundwater balance for the shallow unconfined aquifer was derived using estimates of net recharge, groundwater extraction and coastal submarine discharge (CSD). Net recharge was estimated by: (i) the chloride mass balance (CMB) method (Erickson and Khunakasem 1969); and (ii) MRTs derived from tracer interpretation (Cook and Bohlke 2000). Groundwater chloride concentrations were collated from data provided by DENR and PWC (DENR 2020, PWC 2020), along with measurements from the 2018 field sampling. Metered records provided estimates of groundwater extraction for community water supply. Rainfall chloride concentrations were obtained from a national-scale interpolated dataset (Davies and Crosbie 2018). MRTs derived from ^{3}H and CFC-12 samples were preferred for recharge estimation, as their concentrations were unaffected by degradation or contamination. Aquifer effective porosities were obtained from previous hydrogeological investigations (Power 1981, Yin Foo 1987, Yin Foo and Moretti 1991). The mean annual CSD flux was calculated by difference, as the discrepancy between mean annual net recharge and groundwater extraction fluxes. The ratio of water demand to net recharge was used to evaluate the potential available groundwater resource in the absence of a numerical groundwater flow model.

RESULTS

Hydrogeological framework

A conductivity-depth section from the AEM survey and intersecting the ASR scheme in the south-west of the island is shown in Figure 3. Resistive (10 to 60 mS/m) surficial sediments comprised of ferricrete, saprolitic clay and laterite were identified in the shallowest part of the depth section, at 20 to -10 metres Australian Height Datum (mAHD). Underlying these weathered sediments is the regionally extensive conductive (~400 to 800 mS/m) unweathered mudstone aquitard. This is more than 120 m thick in the south-western part of the island (NTLIS 2020). Relatively more resistive (~200 mS/m) sandstones underlie the mudstone at depths greater than -80 mAHD. These include the target aquifer for ASR injection – Marligur Sandstone and the basement (Kombolgie Sandstone). Conductivity logs for bores RN032759 and RN032932 were in agreement with the conductivity structure defined from inverted AEM data.

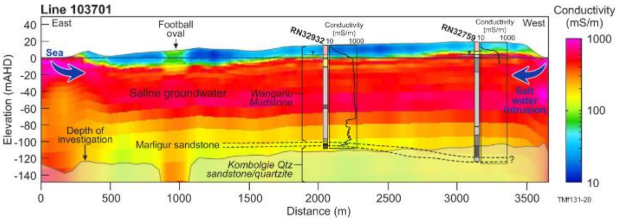

Figure 3. Conductivity depth section for flight line 103701 (see Figure 2 for flight line location). *Lithology log of bores RN032932 and RN032759 superimposed, with inductive conductivity logs (black traces) and indicative groundwater hydraulic heads (nabla symbol over dashed line)*

Intertidal mangrove swamps, coastal muds and alluvium occur in conjunction with surficial laterite at low elevations (~5 mAHD) in the centre and north of the island (Figure 4). Here, the FWSWI in the shallow unconfined aquifer can intrude up to 2 km inland. A conductivity-depth section from the AEM survey of 10 to 15 m below ground surface in the central part of the island is shown in Figure 4. The spatial extent of high conductivity (>400 mS/m) zones associated with inland saline coastal flats is apparent. Also visible is the position of the FWSWI relative to bores in the shallow unconfined aquifer. Inland migration of the FWSWI was attributed to over three decades of groundwater pumping at bores RN008708, RN008709 and RN025737. Historical water quality data confirmed the marginal to brackish water quality (1000 - 3000 mg/L TDS) present at this location.

Freshwater extent of the shallow unconfined aquifer

AEM-derived bulk conductivity values ranging between 2 and 100 mS/m at depths of 4 to 18 m below ground surface were used to delineate the freshwater extent of the shallow unconfined aquifer (Figure 5). This resulted in an estimated cumulative spatial extent of freshwater in the shallow aquifer of 28.7 km^2. Historical water quality data for the aquifer (DENR 2020, NTLIS 2020, PWC 2020) indicated high spatial correlations between (i) areas of mapped freshwater and low bulk conductivities, and (ii) areas of brackish to saline water and high bulk conductivities.

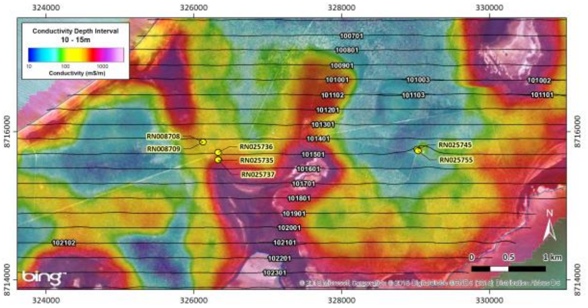

Figure 4. Gridded conductivity depth sections at depths of 10 to 15 m below ground surface in the central part of the island (see Figure 2 for flight line locations).

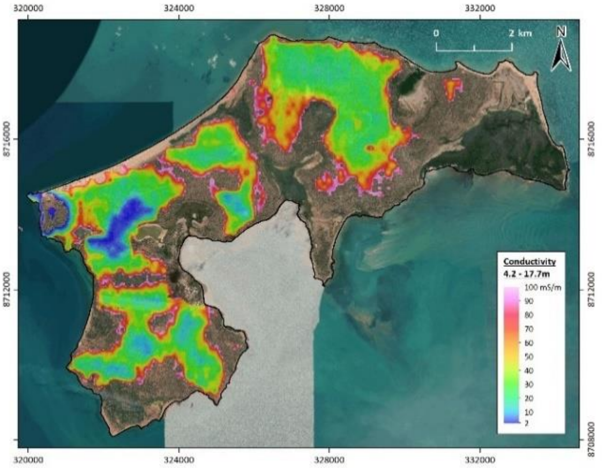

Figure 5. Bulk conductivity at depths ranging between 4 and 18 m below the surface

Groundwater flow processes

Hydrographs derived from pressure loggers installed in the shallow unconfined aquifer indicated typical annual watertable fluctuations of 5 to 7 m after good wet seasons (2017/2018) and 2 to 3 m after poor wet seasons (2015/2016) (Figure 6). Large increases in watertable elevation generally occurred after 500 mm of rainfall (observed over the preceding one to three months). This volume is required to satisfy the soil moisture deficit at the end of the dry season, after which groundwater recharge commences. Peak groundwater levels occurred at a variety of times during the wet season. Declines in groundwater levels during the dry season are consistent with horizontal movement of groundwater towards the FWSWI, with groundwater levels equilibrating just below MSL (-1 to -2 mAHD) at the end of the wet season.

Stable isotope samples from the shallow unconfined aquifer featured limited variability and were depleted in comparison to rainfall (Figure 7). Deuterium values ranged from –48.3 to –44.4‰ VSMOW, while delta-^{18}O values ranged from –7.3 to –6.6‰ VSMOW (n=10). Groundwater samples plotted either on or just below the Darwin local meteoric water line (IAEA/WMO 2020) and exhibited very little evaporative enrichment. This isotopic composition was consistent with highly depleted, large magnitude wet season rainfall events. For example, monthly rainfall totals exceeded 500 mm as shown by the amount-weighted monthly mean (AWMM) isotopic compositions. This finding is consistent with recharge responses observed in groundwater hydrographs.

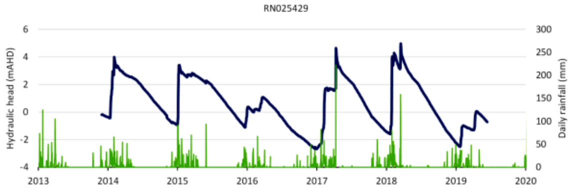

Figure 6. Hydraulic head and daily rainfall values for a monitoring bore in the shallow unconfined aquifer. *Data sources: Hydraulic head data – (PWC 2020); rainfall data – (BOM 2020)*

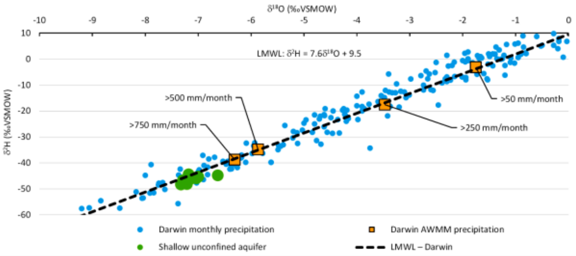

Figure 7. Stable hydrogen and oxygen isotope composition of groundwater samples from (i) the shallow unconfined aquifer and (ii) the Kombolgie sandstone aquifer versus Darwin rainfall samples. *Data source: ^{2}H and ^{18}O data for rainfall – (IAEA/WMO 2020)*

Groundwater ^{3}H and CFC-12 concentrations are plotted versus depth below the watertable in Figure 8. Also shown are equivalent values derived from selected PFM and EMM lumped parameter models. Due to the limited thickness of the shallow unconfined aquifer, ^{3}H and CFC-12 values did not vary considerably with depth. For the same reason, they were not consistent with either the PFM or EMM lumped parameter models. Groundwater ^{3}H and CFC-12 values were considered relatively high with respect to the isotopic composition of rainfall (for ^{3}H) and atmospheric concentrations (for CFC-12), indicating relatively short MRTs. MRTs estimated using the PFM and EMM lumped parameter models were ~15 years for flow paths <2.5 km.

Annual groundwater balance

Components of the annual groundwater balance for the shallow unconfined aquifer are summarised in Table 1. Mean annual net recharge values estimated using the CMB method ranged from 40 to 160 mm (median=70mm; n=51), whereas values estimated from tracers ranged from 5 to 60 mm (median=25mm; n=10). Differences in estimates between the two methods were attributed to differences in (i) underlying assumptions and (ii) spatial and temporal scales of sampling. CMB-based estimates of net recharge were adopted for groundwater balance calculations as they represented a relatively larger aquifer area. The product of the median CMB-based net recharge rate (70 mm) and the total spatial extent of freshwater aquifer lenses (28.7 km^2) equated to an annual net recharge volume of 2 GL. Annual metered groundwater extraction ranged from 0.08 to 0.20 GL with a median value of 0.14 GL (PWC 2020). A CSD flux of 1.86 GL was calculated by difference assuming pseudo-equilibrium conditions existed, as supported by observed trends in groundwater hydrographs.

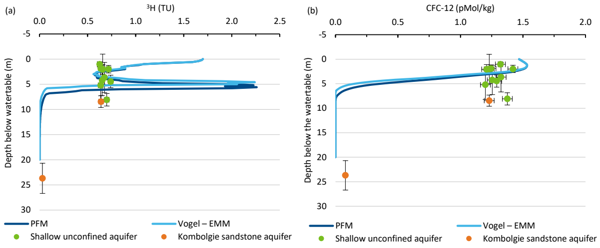

Figure 8. Concentrations of (a) ^{3}H and (b) CFC-12 in the shallow unconfined aquifer versus depth below watertable
Solid lines represent predicted composition of groundwater from lumped parameter models assuming a recharge temperature of 30ºC and an effective porosity of 0.05. Dark blue line represents the PFM; light blue line represents an EMM.

Table 1. Summary of pseudo-steady-state annual water balance components for the shallow unconfined aquifer

Component	Estimated value (GL)	Lower limit (GL)	Upper limit (GL)
Net recharge	2.00	1.00	5.00
Groundwater extraction	0.14	0.08*	0.20*
Coastal/submarine discharge (CSD)#	1.86	N/A	N/A
Change in storage	~0	N/A	N/A

**uncertainty range based on the variability of metered groundwater extraction, #calculated by difference, as opposed to estimated directly*

CONCLUSIONS

Island-scale AEM and ground-based geophysical surveys, combined with a spatial study of lithology, groundwater levels and salinities informed a refined hydrogeological framework for the island. It defined a thin (~20m) storage-limited unconfined aquifer hosting a discontinuous but intermediate- to regional-scale freshwater 'lens' system overlying a regional-scale aquitard. Prospective areas for the installation of additional water infrastructure in both shallow and deep aquifers were also determined. A combination of groundwater hydrograph analyses and environmental tracer interpretation identified relatively short flow paths (<2.5 km) and short MRTs (~15 years) in the shallow unconfined aquifer. Due to the limited weathering below MSL and limited vertical fluxes through the underlying mudstone aquitard, the freshwater lens is inconsistent with the principles of the Ghyben–Herzberg ratio (Ploessel 1984). The mean annual groundwater balance for the revised extent of the freshwater lens system estimated that current and projected community water demand represent 7 and 13% respectively of the mean annual net recharge volume. However, further work on the water balance is required using additional ion chemistry and environmental tracer sampling. This study found that community water demand can be sustained using the existing groundwater resource. However, the total annual volume of groundwater extraction should be limited to a maximum of 20% of annual net recharge, in order to: (i) satisfy the evapotranspiration demand across the aquifer; (ii) replenish permanent aquifer storage, to maintain groundwater levels at or above MSL; and (iii) maintain sufficient CSD to avoid or limit encroachment of the FWSWI inland. The study provided a number of suggestions for improvement of groundwater monitoring and management. These included the installation of additional water infrastructure in unexploited areas of the freshwater system, to increase the sustainability of the resource and thereby improve water security. Improved monitoring of groundwater levels and salinities can be used to inform an adaptive groundwater extraction strategy. The development of a three-dimensional numerical flow and transport model would enable higher resolution evaluations of aquifer vulnerability to depletion and saltwater intrusion.

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