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REPORT

Field investigation of potential terrestrial groundwater-dependent ecosystems within Australia's Great Artesian Basin

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Abstract

Quantitative field methods were used to refine eco-hydrogeological conceptual models of terrestrial groundwater dependent ecosystems (GDEs) in the Great Artesian Basin (GAB), Queensland, Australia. There are few studies which report on the effectiveness of published methods to ground truth the occurrence of assumed GDEs, particularly in areas subject to coal seam gas development. Using a combination of methods, a field investigation was completed at four sites in vegetation communities dominated by river red gum (*Eucalyptus camaldulensis*) in areas overlying the GAB. Multiple lines of evidence determined the predominant source of water utilised by large trees at each locality to assess if the terrestrial ecosystems were dependent on the presence of groundwater. Methods included soil coring to observe tree rooting depth and underlying hydrogeological conditions, matching of soil moisture with leaf water potential, and analysis of naturally occurring stable isotopes of hydrogen and oxygen found in tree xylem, soil moisture and groundwater. Results indicate that despite study locations being conceptually mapped as GDEs, trees located within at least three of the four assessed sites were predominantly utilising shallow sources of soil moisture located above the regional water-table aquifer. Also, rooting depths of targeted tree species were consistently much shallower (maximum depth 7.6 mbgl) than what is commonly reported in literature (12–22.6 mbgl). The findings highlight the importance of ground-truthing to refine the eco-hydrogeological conceptual models of GDEs using a combination of methods to create a holistic understanding of water sources for terrestrial vegetation communities in areas vulnerable to groundwater abstraction.

Keywords Groundwater dependent ecosystems · Stable isotopes · Groundwater monitoring · Drilling · Australia

Introduction

Groundwater dependent ecosystems (GDEs) are important biotic elements of the landscape that require access to groundwater to sustain their ecological function, health and vigour (Eamus 2009) and form unique habitats critical to the survival of a range of terrestrial flora and fauna species. GDEs are widely distributed across Australia, and in some cases exist over shallow coal measures in Queensland. There are two major GDE types currently defined in the literature, being (1), those that rely on surface expression of groundwater (e.g. springs, wetlands and rivers) and (2), those that rely on

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subsurface expression of groundwater, in particular possessing tree root systems that interact with the saturated zone and associated capillary fringe (Doody et al. 2018; Richardson et al. 2011). For systems that rely on the subsurface expression of groundwater, the withdrawal of groundwater from the rooting zone has been shown to have a detrimental impact on the ecosystem's capacity to function (Kath et al. 2014). Historically, research into GDEs in Australia's Great Artesian Basin (GAB) has focused on the surface expression of groundwater, such as artesian mound springs (Fensham and Fairfax 2004; Fensham et al. 2004; Powell et al. 2015). Limited investigation has been directed toward validating subsurface water sources utilised by vegetation in areas mapped as terrestrial GDEs, thereby disregarding the feedback necessary to verify or dispute conceptualisations undertaken by government agencies (DSITIA 2015; DES 2017; Bureau of Meteorology 2017).

The coal seam gas (CSG) industry is prevalent in the Surat Basin due to the widespread presence of the Walloon Coal Measures, with adequate gas saturation levels and with permeability to support viable gas extraction. The production of CSG involves abstraction of groundwater from coal seams, which reduces formation pressure and liberates gas, allowing it to be captured for processing. Groundwater abstraction has been demonstrated to cause hydraulic drawdown in groundwater associated with coal seams, thereby reducing the volume and potentially the quality of available groundwater (DNRME 2016). In Australia, federal-government-issued environmental conditions of approvals for large-scale resource activities often require assessment of potential for groundwater drawdown and its impact on GDEs (Commonwealth of Australia 2015). Both nationally and internationally, landscape-scale studies have been undertaken to identify and map the location of GDEs, based on predictive modelling (DES 2017; BoM 2017; Jeanette and Matt 2010). These studies have utilised informed assumptions on ecohydrological processes and vegetation response to groundwater availability and groundwater regimes while also incorporating mapping tools such as satellite observations, interrogation of GIS databases and other remote sensing data (Gow et al. 2016; Huntington et al. 2016; Barron et al. 2014; Gou et al. 2015; Jeanette and Matt 2010; Orwig 2015; Eamus et al. 2015). Within Australia, this approach has progressed further by integrating diverse data and expert opinions to develop rules of GDE dependency which are then fed back into the mapping process (Moody et al. 2017). Government agencies have developed landscape-scale mapping procedures to delineate the inferred spatial extent of GDEs (DES 2017; BoM 2017), primarily as a risk management tool.

While the application of these broad-scale studies provides a robust system for the initial identification of the location of potential GDEs, the need still exists for a structured process with technically sound assessment methods to validate the regional mapping and confirm the presence of GDEs at a local scale. Within the GAB, there have been few studies that suit this purpose, with most of the literature focused on characterisation of GDEs in the Murray Darling Region, Western Australia and other regional areas (Doody et al. 2015; Lamontagne et al. 2005; Froend and Sommer 2010; O'Grady et al. 2005). The assessment of stand condition in river red gum in response to historical groundwater drawdown on the Condamine River Flood Plain, located within this study area, provides one of the few assessments of GDE function with the GAB (Kath et al. 2014; Reardon-Smith 2011). However, these studies do not attempt to physically identify tree rooting depth and mechanisms of tree root interaction with groundwater, focusing instead on the measured responses in vegetation condition that have been inferred from documented historical groundwater drawdown.

The objective of this study is to provide an insight into the physical functioning of selected areas mapped as GDEs in predictive mapping databases (DES 2017; BoM 2017) and to provide a refined eco-hydrogeological conceptual model. Specifically, this study will determine whether the target areas meet the traditional definition of a GDE, identify the predominant source of water usage for constituent GDE species and provide a technically sound field assessment method to identify the source of water usage by trees in areas conceptually mapped as terrestrial GDEs. A detailed field investigation has been undertaken at four locations within the Surat Basin region of the GAB in Queensland (Fig. 1) to understand if terrestrial GDEs identified in conceptualisations are dependent on the subsurface presence of groundwater. The insights, methods and approach are transferable, with site-specific modifications, to areas mapped as GDEs in the broader GAB.

Ecological characterisation of GDEs in the study area

Current GDE distribution mapping in Queensland is generated by government agencies including the Queensland Herbarium (DES 2017) and Bureau of Meteorology (BOM 2017). In these databases, GDEs are commonly mapped as potentially occurring based on the presence of characteristic riparian and floodplain vegetation, commonly where species that known to utilise groundwater, particularly 'keystone species' such as river red gum (*Eucalyptus camaldulensis*), are dominant. River red gum is the most widely distributed eucalyptus species in Australia and is almost universally associated with watercourses and wetlands throughout much of inland Australia (Doody et al. 2015). River red gum is an adaptable species demonstrating considerable adaptability and plasticity in response to water availability from varying sources (Doody et al. 2015; ANBG 2004; Mensforth et al. 1994). The species has a layered, dimorphic root system, which consists of

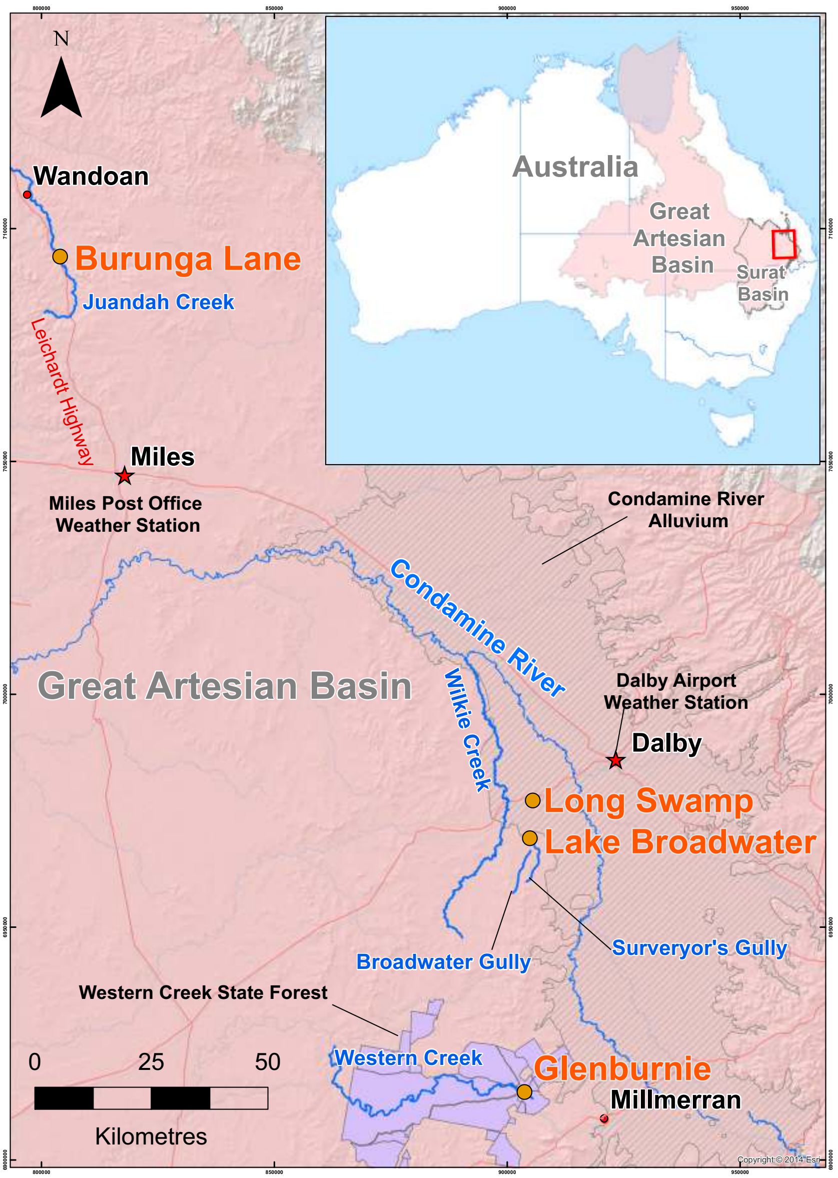


Fig. 1 Location of groundwater dependent ecosystem (GDE) assessment sites (orange circles) in relation to the Great Artesian Basin (GAB, extent shown in pink)

shallow roots to improve stability, nutrient uptake, and rapid uptake of surface soil water after rainfall events, and deeper "sinker" roots that can access the capillary fringe of groundwater (Eamus et al. 2006a; Pinto et al. 2014). The species is considered a facultative phreatophyte being a species which utilises groundwater when it is available (Pettit and Froend 2018). However, the absence or temporal withdrawal of groundwater from the rooting zone does not necessarily affect the fecundity of the species or its' persistence in an ecosystem (Eamus et al. 2006a; Mensforth et al. 1994; Thorburn and Walker 1994; Hatton and Evans 1998). A number of case studies indicate that river red gum, and other eucalyptus species that dominate the riparian corridors within the GAB, are adept at utilising a combination of groundwater, surface water and soil moisture depending on source availability (Doody et al. 2015; Zolfaghar 2013). Thorburn et al. (1994) and Mensforth et al. (1994) suggest river red gum will preferentially use groundwater over in-stream water sources when groundwater is accessible.

The maximum potential rooting depth of river red gum is subject to considerable conjecture in current literature, although it is widely accepted that the species has capacity to access deep groundwater sources (Eamus et al. 2006a). Based on observations of the health of riparian vegetation and knowledge of historical groundwater drawdown in the Condamine River Alluvium (CRA) aquifer which overlies GAB formations, Kath et al. (2014) predicted a 'stand condition threshold response' to groundwater drawdown, being the level of groundwater drawdown that would initiate a response through decline in vegetation health. From these studies a predicted a rooting depth of between 12.1–22.6 m below ground level (mbgl) was identified for river red gum. In a related assessment, Reardon-Smith (Reardon-

Smith 2011) concluded rooting depths of 13–16 mbgl based on observations of severe dieback in riparian habitats on the Upper Condamine floodplain subject to groundwater drawdown due to agricultural abstractions. Similarly, Horner et al. (2009) found rooting depths at 12–15 mbgl based on observed mortality in plantation river red gum forests on the Murray River Floodplain. In Queensland, the government authority on GDE mapping, being the Department of Natural Resources, Mines and Energy (DNRME 2013) uses 20 mbgl as the threshold point below which tree roots/groundwater interaction is unlikely to occur. Kallarackal and Somen (1998) showed that excavations in 20-year-old plantation forests of the ecologically similar *Eucalytpus tereticornis* found that roots were traceable to depths of 9.3 mbgl. Similarly, Mensforth et al. (1994) reported lateral root extension of at least 15 m for trees growing adjacent to permanent watercourses, which they considered a suitable surrogate for rooting depth. While there are numerous studies suggesting the maximum rooting depth of river red gum, there is little agreement on maximum rooting depth (depths range from 12 to 22.6 mbgl) and there is a lack of published studies providing localised data on river-red-gum-rooting depth in the GAB which comprises consolidated rock formations, rather than the unconsolidated alluvium aquifers described in many studies. This is an important consideration, as local site conditions will likely provide an over-riding control on maximum potential rooting depth including geology, soil characteristics and depth to groundwater (Eamus et al. 2006a). Eamus et al. (2006b) suggest that root penetration will be arrested somewhere between the upper level of the capillary fringe and the phreatic zone in unconfined alluvial aquifers and hence depth to the regional water table will be a major control on tree-rooting depth. Site specific geology will also play a major role including substrate (Dupuy et al. 2005) and possibly the degree of bedrock fracturing although no studies have been identified which address this scenario.

While there have been studies that qualitatively assess the relationship between river red gum and groundwater depth in riparian communities across eastern Australia (Kath et al. 2014; Cunningham et al. 2007), there is a lack of published data characterising tree-rooting depth or source water utilisation by river red gum and other deeper-rooted vegetation in the Surat Basin, an area where aquifers are subject to considerable extractions for CSG, agriculture and other industries. Providing data which characterises the idiosyncratic elements of GDEs in an area susceptible to groundwater drawdown will allow for better informed conceptualisations of these systems and interpretations to support accurate impact assessment studies. The aim of this study is thus twofold—firstly, to provide a synoptic field-based approach to testing the validity of GDE conceptualisations and secondly, provide data on the rooting depth and water source utilisation of river red gum in a localised setting.

Based on a literature review related to maximum tree-rooting depths, knowledge of contemporary and historical depths to water table from groundwater bore baseline assessments, the maximum predicted rooting depth for river red gum was hypothesised to be 20 mbgl, which is the depth used by DNRME (2013) for regional GDE mapping. This depth is considered sufficiently conservative to allow for site specific variation across the range of geomorphic settings tested. Enough flexibility was however allowed for in the assessment methods to identify any deeper water use/root penetration at any of the GDE assessment sites.

Site selection and description

The study was conducted in the Surat Basin of western Queensland and sites were spread across a 250 km area spanning the town of Millmerran in the south and Wandoan in the north. The most northerly site lies on Juandah Creek, a tributary of the Dawson River with all other assessment localities being on tributaries of the Condamine River, part of the Murray River catchment. The Surat Basin is a subbasin of the GAB. The GAB is an iconic Australian Hydrogeological feature, covering more than 1.7 million km^2 and contains a vast volume of underground water—estimated at 64,900 million megalitres (ML)—and is the largest groundwater basin in Australia. Groundwater from the GAB is a vital resource for pastoral, agricultural, extractive industries, town water supply and springs, which support unique ecological communities (Ransley et al. 2015). The Walloon Coal Measures are a Jurassic sequence within the Surat Basin dominated by fine-grained sediments and coal seams which form resources for both coal mining and coal seam gas (CSG) extraction.

Local study sites were initially chosen based on a desktop review of GDE mapping databases produced by DSITI (2015) and BOM (2017) in areas where CSG activities are proposed. Site selection was further refined by the assessment of the likelihood that the component ecosystem may be dependent on groundwater, taking into consideration available groundwater level and pressure data, borehole logs and indicated stratigraphy (soil and lithology), site observations, and landscape position (as an indication of contributing hydraulic and geomorphic processes). All assessment sites are indicated in the Queensland (Qld) GDE mapping program (DES 2017) to be terrestrial GDEs with moderate to high confidence except for Long Swamp which is considered to be a 'low confidence' feature. Two of the selected sites (Burunga Lane and Glenburnie) also represent areas where the predicted rate of change in groundwater levels propagated by surrounding CSG activities, based on modelling, could result in an impact to the ecological function and composition of the terrestrial ecosystem if such ecosystems were dependent on the regional aquifer. Long Swamp and Lake Broadwater were assessed due to their listing as significant wetlands and references in CSG project approval conditions for further assessment by the federal government. The locations of the four GDE study sites in relation to the GAB are shown in Fig. 1.

Lake Broadwater is a naturally occurring, seasonal, shallow, freshwater wetland covering approximately 350 ha (ha) of the Lake Broadwater Conservation Park (DEHP 2012). Lake Broadwater is perched on a transitional landscape of Jurassic-age colluvium derived from the Westbourne Formation overlying lower Westbourne Formation regolith (DNRME 2018a, b). The lake system is mapped as a Wetland of High Ecological Significance (DEHP 2012) and is listed in the Australian Directory of Important Wetlands (Australian Government DEHA 2010). The sandy lake fringe is occupied by a well-developed woodland of river red gum. Queensland Groundwater Dependent Ecosystems Mapping (DES 2017) identifies Lake Broadwater as a "Derived Terrestrial GDE – High Confidence". The lake derives its water supply principally from rainfall entering the lake via two ephemeral streams (Surveyor's Gully to the south-east and Broadwater Gully in the south-west) and from overland flow (run-off) and possibly shallow infiltration from the surrounding sandy mantle during periods of lake recession (drying). The lake overflows to the north-west through the Broadwater Overflow into Wilkie Creek which drains northwards into the Condamine River (DEHP 2012).

Long Swamp is a broad, sinuous overland flow path that extends along the western margins of the Condamine River Alluvial plain for over 30 km before discharging into Wilkie Creek and then the Condamine River. Long Swamp represents a broad, shallow drainage depression with a central portion formed on highly vertic clay soils with a strong shrink-swell structure of hummocks and deep cracks. Vegetation on the swamp is largely native with a canopy formed by broadly spaced river red gum over a groundcover of native sedges and forbs. The Queensland Government maps Long Swamp as a "Wetland of High Ecological Significance" (DEHP 2012). Queensland GDEs Mapping (DES 2017) identifies Long Swamp as a "Derived Terrestrial GDE – Low Confidence". Long Swamp is fed directly by overland flow run-off from the surrounding Condamine River Alluvium (CRA) flood plain which is largely occupied by intensive cultivation.

The Burunga Lane study site is located on an alluvial terrace of Juandah Creek, which forms a sandy drainage channel approximately 20 m wide. It is incised to a depth of 3 m below an alluvial floodplain that extends to the west for over 500 m, where it meets with sedimentary hillslopes. The eastern alluvial flood plain is much narrower due to interaction with shallow surface rock. The channel benches are fringed by a line of mature river red gum. Surface geology mapping identifies the site as being located on a sinuous band of Quaternary age alluvium associated with the creek channel, confined between low hills of outcropping lower Springbok Sandstone formation and upper Walloon Coal Measures (DNRME 2018b). The creek channel was dry during the assessment period, despite some recent rainfall events. Queensland Groundwater Dependent Ecosystems Mapping (DES 2017) identifies Juandah Creek as a "Derived Terrestrial GDE – Moderate Confidence". The Office of Groundwater Impact Assessment (OGIA 2017) suggest that there is potential discharge of groundwater from the Springbok and Walloon Coal Measures into the Juandah Creek Alluvium, although most likely north of the Leichardt Highway (AGE 2005).

The Glenburnie study site lies on Western Creek, which presents as a dry (at the time of assessment) sandy creek channel with a narrow sinuous overflow flood terrace that has only limited alluvial development. The channel is weakly incised into weathered Springbok Sandstone formation regolith, which was noted to be outcropping in nearby exposed stream benches and subcropping beneath the sandy bedload of the channel floor. Vegetation within the riparian corridor was less developed than the other GDE study sites, with only scattered mature river red gum fringing the stream banks. Queensland Groundwater Dependent Ecosystems Mapping (DES 2017) identifies Western Creek as a "Derived Terrestrial GDE – Moderate Confidence". At the assessment site, Western Creek represents a third order stream that flows intermittently in response to major rainfall events, fed from ephemeral drainage within the largely intact Western Creek State Forest.

Although the current groundwater regime is unknown, registered groundwater bore RN No.32726A located approximately 1 km to the west of the study site indicates groundwater levels in the underlying Walloon Coal Measures were 14.6 mbgl in 1969 and had dropped to 23.5 mbgl in 1983 (Queensland Groundwater Database).

All sites were located adjacent to ephemeral surface water bodies. With the exception of Lake Broadwater, all were dry at the time of field assessment. Lake Broadwater is an evaporative system, with the lake recorded to dry out completely during prolonged (multi-year) dry periods (DEHP 2012). Burunga Lane and Glenburnie are situated adjacent to ephemeral streams. Long Swamp is an overland flow path which flows only during flooding events.

Climate

The climate of the region is characterised as warm and seasonally wet or dry, with long hot summers and mild winters. Average temperatures at Dalby (Dalby Post Office, 1992–2019) range from 11.9 to 26.9 °C (BoM 2019a) and 12.2 to 27.1 °C at Miles (Mile Post Office, 1885–2019). The average rainfall is dominated by summer events although heavy rainfall can occur throughout the year with the driest months typically April through to August. The region follows a trend of decreasing rainfall and consistent with much of eastern Australia, is in a period of declared drought (BoM 2019b) The rainfall is summer-dominant although significant rainfall events can occur at any time of the year. Rainfall records from January 2016 to February 2018 (following the second survey event) are presented in Fig. 2a for the Dalby Airport recording station and Fig. 2b for the Miles Post Office recording station. For the 2 years preceding the 2017 assessment event, rainfall was well below the long-term average at the Miles Post Office with 524.4 mm falling in 2016 and 464.6 mm in 2017 compared to the long term mean rainfall of 645.8 mm (Fig. 2a). The Dalby Airport recording station received 486 mm of rainfall in 2016 compared to the long-term mean of 603.1 mm. The months preceding the late 2017 assessment event were considerably wetter with slightly above average rainfall (622 mm) falling in 2017 (Fig. 2b). Plant growth in the region is strongly limited by moisture rather than temperature (Hutchinson et al. 1992). This is reflected in evapotranspiration rates measured at the Dalby Airport which exceeds rainfall in most months and annual water loss through evapotranspiration significantly exceeds annual rainfall (BoM 2019c; Fig. 2c).

Methods

Assessment timing

Assessment of Long Swamp and Burunga Lane were completed from 8–15 December 2017 and Lake Broadwater and Glenburnie sites completed from 14–18 February 2018. Data from the nearest reliable weather recording stations to each assessment site were sourced from the Bureau of Meteorology website (Australian Government; BoM 2019a). The month of October 2017 was extremely wet with 120.6 mm recorded compared to a long-term monthly average of 63.1 mm. November recorded well below average rainfall with 10.6 mm falling compared to a long-term average of 71.0 mm. Prior to drilling Long Swamp, 21.4 mm of rainfall fell in a storm on the 3rd of December. A further 20.6 mm fell on the 9th of December the day before drilling commenced.

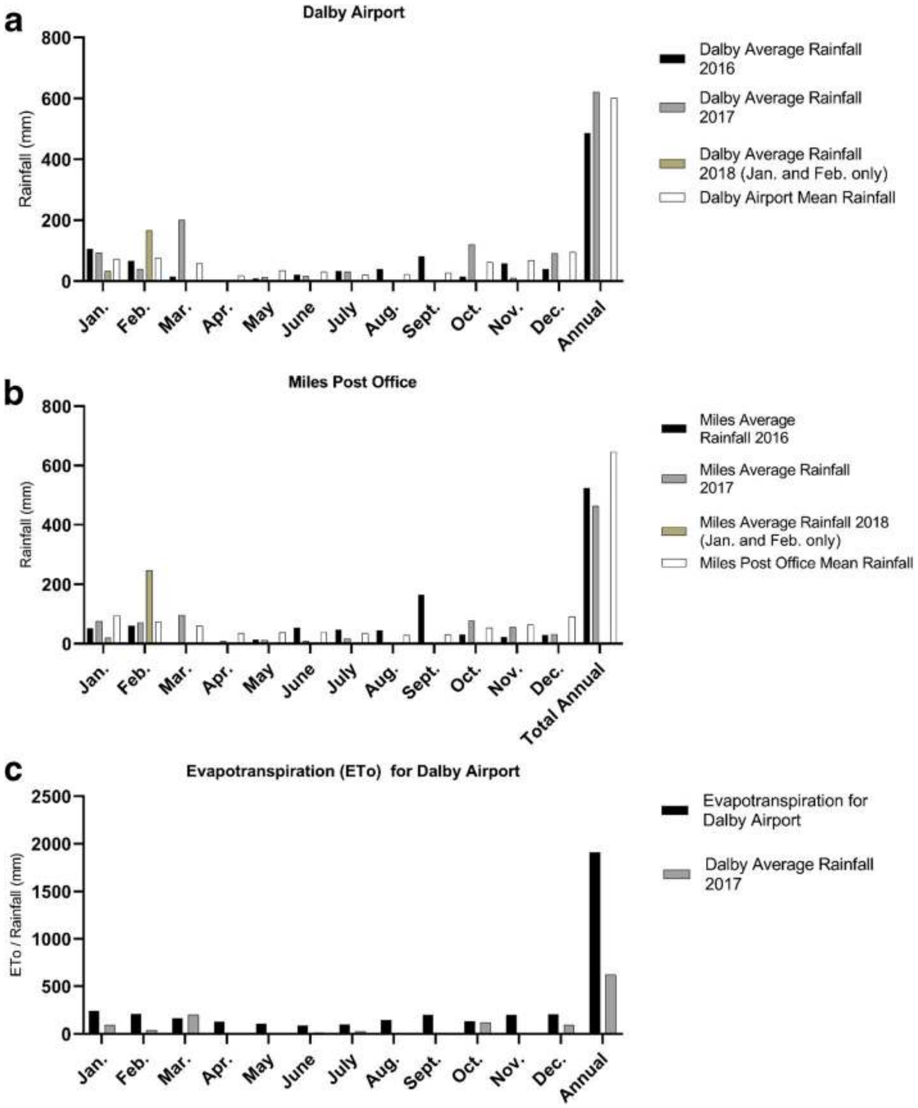


Fig. 2 **a** Mean annual rainfall (mm) recorded at Dalby airport for 2016, 2017, 2018 and combined mean rainfall across all years. Data sourced from BOM (2019a). **b** Mean annual rainfall (mm) recorded and Miles Post Office for 2016, 2017, 2018 and mean rainfall across all years. Data sourced from BOM (2019a). **c** Mean evapotranspiration rate (mm) recorded between January to December 2017 at Dalby Airport (BOM 2017) plotted with mean annual rainfall (mm) recorded at Dalby Airport in 2017 (BOM 2017)

Maximum temperatures recorded during the drilling of Long Swamp ranged from 30.0 °C on the 11th of December to 32.6 °C on the 9th with a relative humidity of 31% at 3 pm.

Prior to installation of the Burunga Lane monitoring bore, 79.1 mm of rainfall fell in October, which was above the long-term average for the month of 53.6 mm, while 56.6 mm fell in November compared to a long-term average of 64.4 mm. Rainfall of 12 mm was recorded on the 9th of December 3 days prior to bore installation. Maximum temperatures during the assessment ranged from 32 °C on the 11th of December to 36.0 °C on the 15th.

Prior to installation of Long Swamp 31 monitoring bore on the 14th–15th February, 34.4 mm of rainfall was recorded at the Dalby Airport (26 km NE of the assessment site) in January, well below the long-term average of 76.1 mm for the month. A total of 48.8 mm fell in storms on the 2nd, 3rd and 4th of February, several days prior to bore installation. The highest temperature recorded during the assessment reached 34.9 °C on the 14th of February coupled with a low relative humidity of 39.7% at 3 pm.

There are no reliable weather stations near the Glenburnie GDE assessment site. The Dalby Airport site 76 km north of the site recorded maximum temperatures of 33.6 °C on the 18th of February with a humidity of 27% at 3 pm. An estimated 15–25 mm of rainfall fell at the site on the 17th of February, which temporarily saturated soils at the surface. There was limited evidence in drill core of any significant percolation of rainfall and ground conditions dried rapidly, although surface runoff was noted to have channelled into the sandy creek bed.

General study approach

This study utilised a combination of published recommended methods (e.g. Eamus et al. 2006a; Richardson et al. 2011) and additional methods tailored to site-specific conditions to investigate shallow sources of moisture and groundwater present in the shallow subsurface (upper 30 m), and likely vegetation interactions with these water sources. Adopted methods included (1) utilisation of drill core to provide evidence for tree-rooting depth and characterise the local hydrogeological conditions; (2) installation of groundwater monitoring bores; (3) soil-moisture potential measurement, (4) leaf-water-potential measurement, (5) stable isotope analysis of xylem water, soil moisture and groundwater, and (6) groundwater chemical characterisation and monitoring. Detailed assessment methods were focused around target trees species which were chosen to be representative of the potential deeper-rooted species at each site, the majority of which were mature river red gum.

Geological coring

Geological coring was completed utilising a Commachio MC900 sonic drilling rig. The sonic rig enabled recovery of an almost continuous, relatively undisturbed 90-mm lithology core in both consolidated rock and unconsolidated soils. Two to four core holes were drilled at each site at the base of target trees to a maximum depth of 30 m and a minimum depth of 20 m (Lake Broadwater), which is well below the maximum anticipated tree-rooting depth. At least one core hole at each site was angled under the target tree (Fig. 3), except Lake Broadwater where access for the drill rig support truck was extremely limited due to the density of vegetation. The angled hole targeted the intersection of the water table directly beneath the tree centreline to maximise the potential for intersection of root material likely located within the capillary fringe (Pettit and Froend 2018), or the zone of moisture identified during coring of the previously drilled vertical core hole. Additional vertical core holes were drilled around the circumference of the tree beneath the canopy and as close as possible to the tree itself to provide additional locations for the intersection of tree roots.

The premise of coring to intersect root material was that root material would spread laterally and be thickened upon intersection with the capillary fringe or where significant soil moisture or groundwater was present (Eamus et al. 2006a; Pettit and Froend 2018), and thus would be most concentrated in the zone of predominant moisture uptake. Therefore, it is surmised that coring would likely intersect this root material in one or more of the cores drilled under the tree trunk (angled) and canopy (verticals). While it is acknowledged that deeper roots may exist below the maximum observed root depth, it is hypothesised that coring should intersect some root material in the zone/s of predominant moisture uptake where the tree root mass would likely be most concentrated.

This assumption is based on observations from phreatophytic species which often develop a dimorphic root system with a zone of high root density in the upper soil profile, and a second zone of high rooting density in the zone immediately above the water table (Orellana et al. 2012). In such cases, tap roots would serve to place root matter within the zone/s of high water availability. It is acknowledged however that studies of river-red-gum-root architecture, particularly in the GAB setting, are very limited.

Other lines of evidence for the presence of a significant water sources in such horizons during coring such as observations of increased moisture/saturation, and lithology in undisturbed core, were combined to provide a complementary visual data-set, while also allowing the collection of samples for additional analyses to assess water source hypotheses. Furthermore, a positive observation of root material in measured drill core allows a reliable finding ("roots must be at least as deep as the depth of root material observed")

Fig. 3 Angled core hole being drilled at the Glenburnie GDE assessment site

justifying the exercise without speculation associated with the less absolute data sets, also provided here to complement physical identification and provide some study conservatism. Significant care was taken during drilling to observe for the presence of shallow saturated zones, subtle changes in moisture within the drill core, and evidence of free water draining into the core hole. Drilling was completed without water in all holes except in the Long Swamp site where it was necessary to run a second string of casing (using water) to stabilise a collapsing zone of loose alluvium prior to construction of the monitoring bore. Sampling of core material could however be taken from several holes at each site so that representative uncontaminated core could be collected for most soil depth intervals.

Observations and sampling of root material in the drilling core was undertaken by an ecologist/geologist at the drilling site during sampling for stable isotope and soil-moisture potential with the aid of a hand lens. Two intact drill cores from each assessment site were transported back to a laboratory for detailed examination of root material with the aid of a binocular microscope. Detailed examination of the drill core, specifically to identify root material, included sifting, crushing, breaking along fracture planes along the length of the drill core to a maximum depth of 20 m. Laboratory examination of drill cores allows for greater identification of root material compared to field examination alone. Where root material was recorded, rooting depth, diameter and other root structural observations were recorded in drilling logs.

Deeper underlying formations and regional aquifers at depths considered inaccessible to trees (>20 m) were targeted by the drilling and construction of deeper aquifer groundwater monitoring bores within a related and complementary drilling campaign. This deeper drilling programme allowed further coring and assessment of geological conditions and potential interconnectivity between intervening geological horizons. Deeper groundwater monitoring bores were installed within underlying aquitards and aquifers potentially subject to CSG depressurisation. Further details of the deeper groundwater monitoring bore drilling programme are reported in Arrow (2018).

Due to the larger footprint of the water bore drilling rig used for the deeper monitoring bore drilling, drilling sites were not able to be located immediately adjacent to the shallow GDE study sites drilled with the sonic rig in sensitive settings, and were typically located 50–475 m from the study sites.

Groundwater monitoring bore installation

A vertical core hole was selected for construction of a groundwater monitoring bore at each study site, and all other holes not utilised for monitoring bore construction (i.e. cored to inspect for the presence of tree roots on multiple sides of the tree) were grouted from total depth (TD) to surface with a bentonite/cement grout mix. Each monitoring bore was installed to a depth and screened across the most likely source of soil moisture for vegetation at each GDE assessment site. This was determined based on observed tree root material, and depth to intersected groundwater or where soil moisture increased. The rationale of the depth of each groundwater monitoring bore installed for this study is provided in the following:

1. Burunga Lane monitoring bore (BL182) constructed at 7.1 mbgl, screened from 4.1–7.1 mbgl across the interface between the unconsolidated alluvium, conglomerate (which contained minor free perched water during drilling) and the highly weathered upper fringe of weathered fine sandstone regolith.
2. Long Swamp monitoring bore (LS35; Fig. 3) installed to a depth of 18 mbgl which coincides with the vertical extent of an observed seepage zone and approaching the maximum likely rooting depth for GDE vegetation. Screened from 15 to 18 mbgl across a predominantly dry sand unit with minor groundwater perched above the underlying clays and silts.

3. Lake Broadwater monitoring bore (LS31) installed to a depth of 3 mbgl at the interface between plastic clays and overlying sandy alluvium where a zone of perched groundwater was intersected.
4. Glenburnie (GB20) installed at a depth of 18 mbgl with the interval from 10 to 18 mbgl screened to monitor a seepage zone observed during drilling.

Groundwater sampling

Prior to both development and sampling, depth to the standing water level was measured with a 9 V electrical water level meter in each bore. Development of groundwater monitoring bores was undertaken by removal of a minimum of 5–7 bore volumes utilising an electric submersible pump for higher yielding bores, and by hand bailing for lower yielding bores until field groundwater quality parameters stabilised. Field parameters measured included pH, redox potential (Eh), electrical conductivity (EC), total dissolved solids (TDS), temperature, and dissolved oxygen (DO). Groundwater sampling followed methods described in *Geosciences Australia Groundwater Sampling and Analysis: A Field Guide* (Sundaram et al. 2009). Prior to sampling, bores were purged using the same equipment utilised for bore development until a minimum of 3 bore volumes were removed or groundwater quality parameters stabilised. The "low flow" method utilising an electrical submersible pump (low flow) and minimising groundwater level drawdowns was applied in almost all bores with the exception of very low flow bores where bores were hand bailed and sampled the following morning.

Samples were collected directly from disposable bailers (low yielding bores) and disposable discharge tubing above the electrical submersible pumps (higher yielding bores) which were installed into the screened interval of the bores. Samples were dispatched to ALS Laboratories for a comprehensive geochemical characterisation suite. The majority of analytical parameters, while useful for refining the broader hydrogeological conceptualisation, are not directly relevant to this study scope and therefore have not been reported here. Relevant hydrochemistry findings are discussed in the section 'Results'. Samples for analysis of relevant isotopes were sent to Rafter Radiocarbon Laboratories (NZ) for analyses of ^{13}C and ^{14}C isotopes; and Australian National University (ANU) for analyses of stable isotopes of oxygen and deuterium.

Soil-moisture potential measurement

Returned drilling cores were sampled for the analysis of soil-moisture potential at surface, 0.2 and 0.5 mbgl after which samples were collected at 0.5-m intervals down to a depth of 18 mbgl. Samples were cut from the central portion of the core to minimise the risk of contamination from clay smearing, introduced drilling water (if used), or excessive drying. Two samples were taken from each interval with approximately 200-mm sections of soil collected. Samples were then immediately sealed in clip-seal bags and placed on ice. For each interval sampled, one sample was dispatched to the Australian National University (ANU) Stable Isotope Laboratory (Farquhar Laboratory) for the analysis of the naturally occurring stable isotopes of hydrogen and oxygen within soil moisture, while the second sample was retained for the measurement of laboratory tested soil-moisture potential.

Soil-moisture potential, which includes the matric and osmotic potential, is a measure of the energy required to extract moisture from soil. It is widely agreed in ecohydrology and plant physiology fields, that large, mature trees are unable to extract moisture from regions in the soil profile where the total soil-moisture potential is significantly below leaf water potential measured in predawn leaf material (Feikema et al. 2010; Lamontagne et al. 2005; Thorburn et al. 1994; Mensforth et al. 1994; Doody et al. 2015).

For crops, the maximum suction roots can apply to a soil/rock before a plant wilts due to negative water supply is approximately −15 bars or −1.5 MPa (or −217.55 psi). This wilting point is considered relatively consistent between all plant species (McKenzie et al. 2004), although many Australian plants have adapted to conditions of low water availability and can persist strongly in soil conditions where soils moisture potential is below standard wilting point (Eamus 2009). As a general measure however, where measured leaf water potential is below standard wilting point, it indicates a plant water deficit and the tree is unlikely to be supported by a saturated water source.

The measurement of soil-moisture potential was completed in the laboratory by a portable Dew Point PotentioMeter (WP4C; Meter Group Inc. 2017). The WP4C meter uses the chilled mirror dew point technique with the sample equilibrated within the headspace of a sealed chamber that contains a mirror and a means of detecting condensation on the mirror. Soil-moisture potential samples were measured in megapascal pressures units (MPa). In accordance with Australian Standard Test Method (ASTM) D5298–16 and to eliminate the potential for user error associated with measurement using filter paper, a single 7-ml soil sample was inserted into the WP4C meter using a plastic measuring tray with a stainless-steel base.

Leaf water potential measurement

The leaf water potential of selected trees was measured before dawn between 0430 to 0500 h. Samples were taken predawn before transpiration commenced, consistent with standard methods (Richardson et al. 2011) when trees are in equilibrium with the soil-moisture potential with their predominant source of moisture in the soil profile (Eamus et al. 2006a).

Leaves were collected by use of a 7.5-m extension pole fitted with a lopping head. Canopy leaves were collected from the target tree at each site, plus a selection of adjacent trees to assess variability in leaf water potential between tree size classes and species. Individual leaves were removed from branch material via cutting of the petiole. Excised leaves were then sealed into a Model 3115 Plant Water Status Console (Soil Moisture Equipment Corp 2006). Once sealed, the chamber was gradually pressurised until the first drop of leaf water emerged from the petiole a recording of pressure (MPa) was taken (Fig. 4). Three readings of leaf water potential (different leaves) were recorded per tree at each site, to calculate the mean reading of each tree sampled. Measurements of trees that were adjacent to the target tree were also generally tested with 1–2 measurements.

Stable isotope analyses

The isotopic composition of soil moisture and twig xylem was assessed for target trees at each study site. The sampling intervals for soil-moisture isotope analyses mirrored that of sampling for soil-moisture potential. Approximately 200 ml of soil was collected for isotopic analysis from the central portion of the drill core to minimise potential for contamination, preferentially from bores drilled without the introduction of water. Where drilling used injected water (e.g. Long Swamp site) and there was no alternative sample from that could be obtained from an adjacent drill hole, samples were obtained from the central portion of the core only where it could be confirmed that contaminated water had not penetrated. Twigs were collected for stable isotope analysis from branches of the same target trees sampled for leaf water potential. Duplicate samples prepared from each harvested branch for isotopic analysis. Stem material was cut using clean secateurs to approximately 10–15 mm (mm) and placed in 125-ml-wide-mouth sample containers with leakproof polypropylene closure and placed in an iced storage vessel prior to dispatch to the ANU stable isotope laboratory. Upon receipt at ANU, both soil and twig samples were snap frozen at −18 °C until analysis.

To measure the $\delta^{18}O$ and $\delta^{2}H$ isotopic composition of water in plants, water within twig xylem was extracted from each sample by cryogenic distillation using a vacuum system. The water extracted from the stems and the source water was analysed for $\delta^{18}O$ and $\delta^{2}H$ using a Cavity Ring-down Spectrometer (Picarro L2140-I, Santa Clara, California, USA). Samples were analysed directly against two calibrated laboratory standards including water and clay with known isotopic composition (including Vienna Mean Standard Ocean Water, VSMOW) to correct for drift.

For each tree sampled, the value of the lowest (least enriched) sample was used as a reference isotopic value for the GDE assessment site. This is due to the potential for considerable partitioning of isotope ratios across a twig section and as it is not always possible to sample the same region of a twig consistently when multiple samples are analysed. There is potential for fractionation of stable isotope values during movement of water through the xylem from roots to leaves (Evaristo et al. 2017; Pettit and Froend 2018) and as

Fig. 4 **a** Completed groundwater monitoring bore with protective monument cover next to target river red gum at Long Swamp 35 (Long Swamp); **b** The fringes of Lake Broadwater (near monitoring bore Long Swamp 31 with river red gum on the sandy mantle. **c** The sandy channel of Juandah Creek near the Burunga Lane monitoring bore (Burunga Lane 182), and **d** The sandy channel of Western Creek near the Glenburnie monitoring bore (Glenburnie 20)

fractionation will result in isotopic enrichment rather than depletion, the least enriched sample from each tree is considered most likely to be representative of the soil moisture or groundwater source.

Results

In total, 15 trees were sampled for leaf water potential and stable isotope composition of xylem water across the 4 sites and 127 soil/core samples were analysed for stable isotope composition and soil-moisture potential. Assessment observations and measured parameters are reported separately for each study site. Geological and hydrogeological descriptions were recorded in detailed drilling logs. Key results are presented in the text related to each of the study sites, and further described in the discussion. For ease of presentation and to allow comparisons between study sites, groundwater radiocarbon age results are presented in a single table (Table 1), prior to the presentation of any other relevant groundwater chemistry results on a site-by-site basis. Radiocarbon age results are presented for each bore alongside the relevant aquifer each bore is tapping and the screened interval.

Results for Lake Broadwater

For Lake Broadwater (LS31a), approximately 3 m of loose sandy fluvially derived lacustrine alluvium was intersected above a sequence of massive plastic clays to a depth of 11 m which in turn overlay deeply weathered regolith of the Westbourne Formation comprising plastic clays, sandy clays and clayey sands from 13 m to the total depth of the core hole at 21 m. Shallow groundwater was intersected at 1.8 mbgl within the lacustrine sands, perched above an abrupt change into the plastic clay at 2.9 mbgl. The recovered core showed evidence for a moisture transition from moist to wet at approximately 18 m depth coinciding with a change from sandy clay to clayey sand. This transition was best described as a seepage horizon rather than a significant water strike. Very little free groundwater was noted entering the core hole during drilling beyond 3 mbgl; hence, a 100-mm-diameter groundwater monitoring bore was constructed at 3 mbgl, screened across groundwater perched in the sandy alluvium. Fine fibrous root material was recorded throughout much of the upper 2.9 mbgl of the core hole with the greatest concentration of root material recorded in the perched sand aquifer at the interface between the sand and underlying clay. Occasional tree roots were also recorded in sandy clay to a depth of 4 mbgl.

Soil-moisture potential analysis, in conjunction with results of stable isotope analysis of soil profiles, presented in Fig. 5, indicate that the highest moisture potential occurs at 2.7 m in the profile in medium to coarse quartz sand corresponding to the approximate position of a shallow perched water table. This also corresponds most precisely with the leaf water potential measured for trees 1 and 2 (see Table 2) and is inferred as the predominant zone of soil moisture uptake for those trees. Soil-moisture potential diminishes abruptly between 2.7 and 3 mbgl coinciding with a sharp change from sand to clay. The entirety of this clay horizon has a very low soil moisture potential (at or near standard wilting point).

The stable isotope profiles indicate moderate enrichment in δ^2H and δ^{18}O in the upper soil profile to a depth of approximately 3 m where a sharp transition to a more depleted isotopic signature occurs, corresponding with the sharp boundary between loose sand and plastic clay. The depleted signature is relatively consistent throughout the thick unit of heavy plastic clay with a slight enrichment occurring at approximately 11 m, at the lithological change from clay to sandy clay.

Table 1 Conventional radiocarbon age (CRA) results for water samples at each study site

Monitoring nest	Sample ID	CRA (years BP)	CRA error (years)	Aquifer	Screened interval (mbgl)
Lake Broadwater	Lake Broadwater	Modern	–	NA (lake water)	0
	Long Swamp 31	Modern	–	Alluvium	0.5–3
	Long Swamp 28	10,465	108	Westbourne	33–40
	Long Swamp 29	29,345	1,405	Springbok	103–111
Longswamp	Long Swamp 35	Modern	–	CRAl	14–18
	Long Swamp 32	3,204	35	Westbourne	31–38
	Long Swamp 33	25,030	808	Springbok	71–79
Burunga Lane	Burunga Lane	Dry	NA	Alluvium	3.1–7.1
	Burunga Lane 185	21,377	483	WCM-Macalister	19–27
	Burunga Lane 183	Background[a]	–	WCM-Macalister	33–40
Glenburnie	Glenburnie 20	39,91	38	Springbok	10–18

[a] Likely radiocarbon age >40,000 years. The sample is beyond accurate measurement by radiocarbon due to its older age. The sample is considered older than the ^{14}C internal sample used for reference in the laboratory

*BP*Before Present; *CRAl* Condamine River Alluvium; *WCM* Walloon Coal Measures; *mbgl* metres below ground level, *NA* not applicable

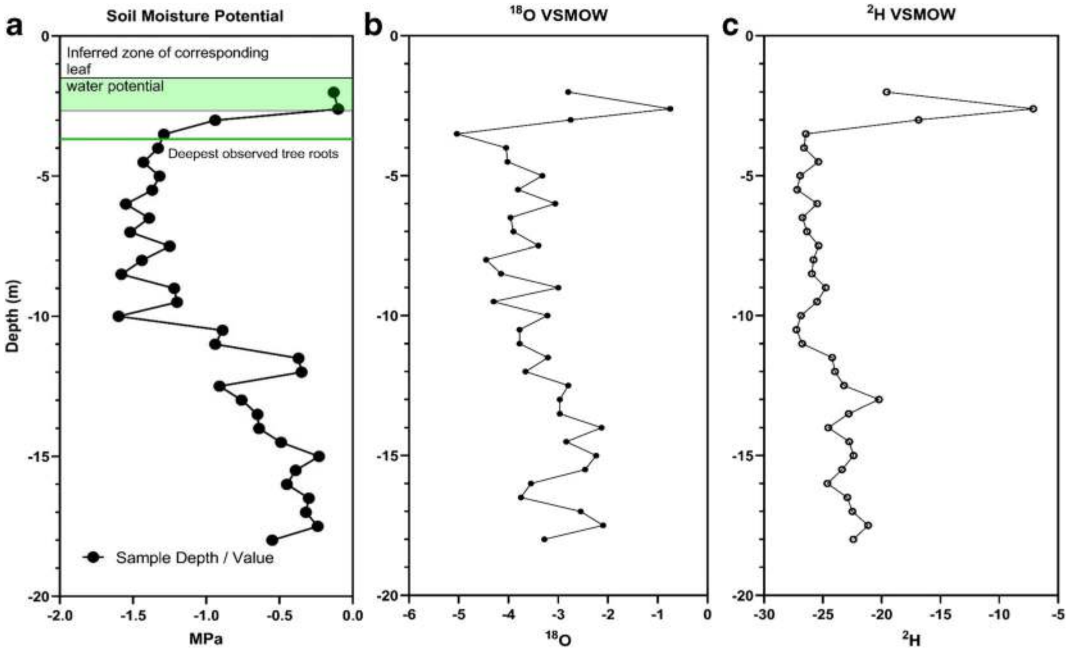


Fig. 5 **a** Soil-moisture potential (MPa) measured at depth (m) of drill cores at Lake Broadwater. Green shading indicates the zone of corresponding leaf water potential in tree 1. **b** Stable isotope of oxygen δ^{18}O measured at depth of drill core. **c** Stable isotope of hydrogen δ^{2}H measured at depth of drill core. Isotope results have been calibrated against Vienna Standard Mean Ocean Water (VSMOW)

Average leaf water potential for five measured trees at or surrounding the GDE assessment site is presented in Table 2. Mature river red gums on the margins of Lake Broadwater (trees 1 and 5) recorded the highest leaf water potential, matching soil-moisture potential measured at the interface between sand and clay at 2.6 mbgl. As a comparison to assessments for river red gum, it is indicated that other tested tree species including cypress pine (*Callitris glaucophylla)* and the rough-barked apple (*Angophora floribunda)*, located further from the lake edge had a much lower leaf water potential, indicating their source of soil moisture is from a much drier portion of the soil profile.

The stable isotopes of δ^{18}O and δ^{2}H analysed from soil samples, a groundwater sample from monitoring bore LS31a, and a sample of Lake Broadwater surface water were compared to isotopic ratios in water extracted from twig xylem in a bi-plot shown in Fig. 6. Tree 1 was directly on the margins of Lake Broadwater and tree 2 was located 100 m from the margins of the lake (Table 2).

Xylem water extracted from tree 1 overlaps with the isotopic signature for soil moisture at 2.6 mbgl, also corresponding to the area of observed high root density. Tree 2, located away from the lake margin overlaps with isotopic signatures recorded in the clay and sandy clay material that lies below the sand/clay interface at approximately 3 mbgl. The groundwater sample taken from monitoring bore LS31 (LS31_Well) has an isotopic fingerprint of the clay water rather than the overlying sand. The salinity of groundwater in the Long Swamp 31 (Lake Broadwater) monitoring bore was 6,050 μS/cm. The radiocarbon age of groundwater from the shallow perched aquifer was reported as being "Modern", considerably younger than the groundwater

Table 2 Structural attributes of trees and leaf water potential measurements at five trees assessed at the Lake Broadwater GDE assessment site

Tree ID	Species	Height (m)	DBH (cm)	Position	M1_MPa	M2_MPa	M3_MPa	Average
Tree 1	*Eucalyptus camaldulensis*	28	105	Sandy shoreline deposit on lake margins	−0.21	0.21	−0.17	−0.12
Tree 2	*Eucalyptus camaldulensis*	19	50	Approximately 100 m from lake edge on residual sand plain	−0.28	−0.31	–	−0.29
Tree 3	*Callitris glaucophylla*	17	45	Approximately 150 m from lake edge on residual sand plain	−1.17	–	–	−1.17
Tree 4	*Angophora floribunda*	21	68	Approximately 150 m from the lake edge on residual sand plain	−0.86	–	–	−0.86
Tree 5	*Eucalyptus camaldulensis*	27	110	Sandy shoreline deposit on lake margins	−0.14	–	–	−0.14

DBH diameter at breast height

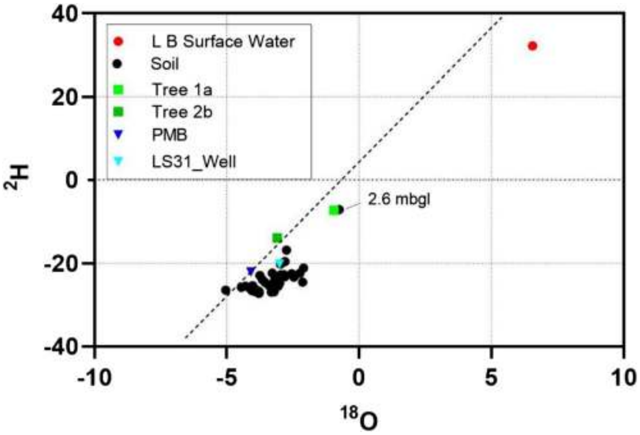


Fig. 6 Scatterplot showing the relationship of δ^{18}O and δ^{2}H among surface water at Lake Broadwater (LB surface water: red circles), water of soil (solid circle), water of trees (green squares), groundwater monitoring bore LS31 (light blue triangle). Dotted line indicates global meteoric water line (Craig 1961). Results indicate strong evaporative enrichment in Lake Broadwater surface-water samples and direct correlation between isotopic signature of twig xylem in tree 1 and soil sample at 2.6 mbgl corresponding with a shallow water table

from the underlying Westbourne and Springbok Sandstone Formations (>10,000 years BP).

Results for Long Swamp

The surficial geology of the Long Swamp study site comprised plastic clays with strong vertic structure at surface, underlain by sandy clays and clayey sands. Open fissures in the surface clay to a depth of at least 2.4 mbgl provide a pathway for surface-water infiltration into a moist clay-bound sand, with the sand content increasing with depth, and thus representing a noticeably moist vadose zone, approaching saturation. A feature of these open fissures (often also containing tree root material) was the presence of rounded clay "pebbles", likely due to the tumbling of surface clays down the open fissures during surface-water infiltration (Fig. 6). This may ultimately result in the eluviation of clays into lower sandy horizons (Fig. 7). An abrupt change into a dry loose sand, becoming gravelly at the base, was observed at 10.8 mbgl. This sand unit was noted to be moist to wet towards the base at approximately 15.1 mbgl, with water possibly perched above the underlying low permeability clays and silts. Groundwater, likely to be the regional aquifer, was intersected at the base of the underlying clay-rich sequences upon penetration into a loose to medium dense, very weakly consolidated sand at 26.5 mbgl, which was present to the total drilling depth of 30 mbgl. Tree roots were predominantly recorded throughout the upper 3.5 mbgl of the soil profile in fissures in vertic clays, although the deepest root material was recorded at 7.1 mbgl in borehole LS35c (angled hole). This depth corresponds with an observed increase in the moisture content of constituent sands. A 100 mm diameter groundwater monitoring bore (Long Swamp 35) was constructed at 18 mbgl, screened from 15 to 18 mbgl across a predominantly dry sand unit with minor groundwater perched above the underlying clays and silts. This was the only zone observed to contain free water above the maximum likely tree-rooting depth of 20 mbgl.

The salinity of groundwater measured in this bore was 4,480 µS/cm. The radiocarbon age of groundwater from the shallow perched aquifer was reported as being "Modern", considerably younger than the groundwater from the underlying Westbourne and Springbok Sandstone formations (>3,000 and >25,000 years BP respectively).

Soil-moisture potential analysis results, coupled with results of the stable isotope sampling in the core profile (Fig. 8), show that vertic clay in the upper soil profile has a low soil-moisture potential to approximately 0.5 mbgl with silty clays to 6.5 mbgl also falling below standard wilting point. Soil-moisture availability increases between 7 and 8 m depth (−0.73 MPa at 7.5 mbgl) in wet to moist clayey, silty sand and then again at 10.5 m (−0.61 MPa). Soil-moisture potential in the profile between 7.5 and 11.5 mbgl compares most consistently with leaf water potential measured in trees 1–3 (see Table 3) and this interval is considered to represents the predominant zone of moisture uptake for these trees. The stable isotope profile indicates minor enrichment in δ^{2}H and δ^{18}O in the upper portion of the soil to a depth of approximately 0.5 m consistent with evaporative enrichment in the upper soil profile. There is then a gradual decline in isotopic ratios with depth, particularly for δ^{2}H which declines more obviously than δ^{18}O. Leaf water potential for all trees measured at Long Swamp assessment site is provided in Table 3. Tree 2 is the largest and most mature of the measured trees and it recorded a higher leaf water potential than other trees measured in the locality. Leaf water potential for trees 1–3 (poplar box) correspond with soil-moisture potential measurements at depths between 7 and 10.5 mbgl. The brigalow (tree 4) has an extremely low leaf water potential indicating that the tree would be sourcing moisture from the upper soil profile where moisture availability in the heavy clay is extremely low.

Figure 9 provides a biplot demonstrating the relationship between δ^{18}O and δ^{2}H for soil-moisture samples collected from borehole LS35, with comparison to the isotopic composition of xylem water in trees 1 and 2. The groundwater sample (well LS35b) shows isotopic enrichment above any of the soil samples Isotopic signatures of both trees 1 and 2 (as per Table 3) are enriched above all soil samples except for the sample taken at 0.2 m depth.

Results for Burunga Lane

The surface geology comprised alluvial sand, silty sands and clays becoming more indurated towards a basal conglomerate

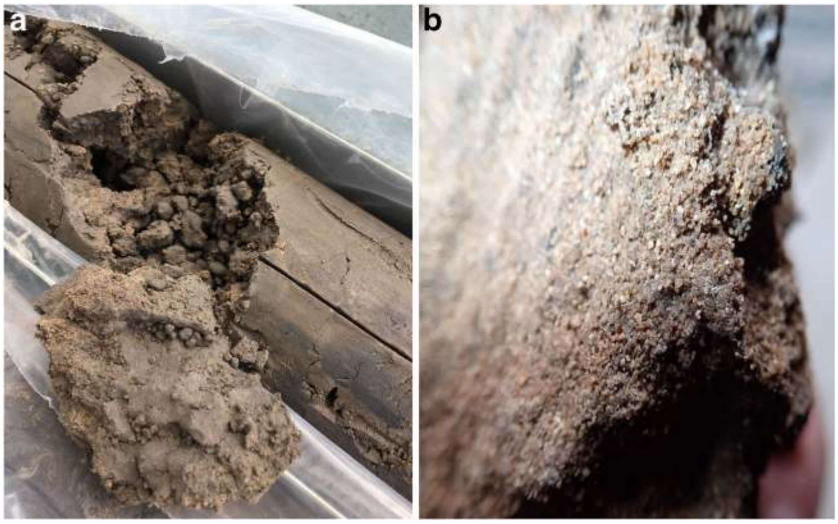


Fig. 7 **a** Clay "pebbles" in open fissures at 2 m (100 mm diameter core) demonstrating a preferential pathway for movement of water down into the underlying clayey sand; and **b** underlying clayey sand (×3 magnification) comprising a very moist vadose zone inferred to be the horizon of predominant soil moisture uptake by trees in Long Swamp

that was encountered at variable depths between 4.9 and 6.0 mbgl dependent of borehole location. The alluvium and conglomerate overlay a sequence of highly to completely weathered sandstones, siltstones and thin coal seams of the Walloon Coal Measures present to the total drilled depth of 14.5 m. Increased soil moisture was apparent at the alluvium/conglomerate interface although the first noticeable true groundwater strike occurred at 13.5 m within a thin coal seam, the inferred position of the regional aquifer. The groundwater level rose under subartesian pressure to approximately 7.5 mbgl. Root material was intersected in the upper 0.5 m of the soil profile with further concentrations of tree roots recorded between 3.8 and 4.5 mbgl. Maximum tree-rooting depth recorded was 6 mbgl in drill core BL182b where a 1.5-mm tree root was recorded in a conglomerate band.

Soil-moisture potential analysis along drill sections presented in Fig. 10 demonstrate an extremely dry subsurface profile between 0.5 and 2.0 mbgl, corresponding with unconsolidated silty sand (alluvial) where soil-moisture potential falls considerably below standard wilting point (−1.5 MPa). The zone with the highest soil-moisture potential occurs between 4.5 and 6.5 mbgl, corresponding with a horizon of moist sand above the conglomerate band surface and weathered basement rock. Leaf water potential sampling was undertaken on a mature river red gum (tree 1) adjacent to the upper creek bank, plus a smaller regrowth tree in an open paddock 20 m to the west of tree 1. At tree 1, the measured soil-moisture potential was −0.43 MPa (based on an average of three readings) and for tree 2 relatively consistent at

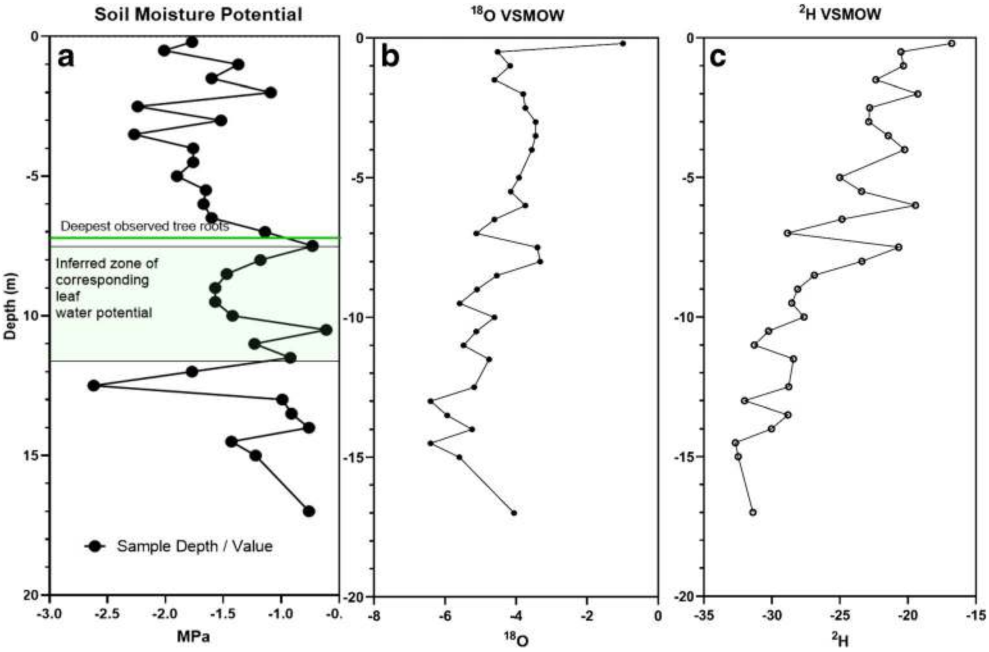


Fig. 8 **a** Soil-moisture potential (MPa) measured at depth (m) along drill core from Long Swamp 35b. Green shading indicates zone where leaf water potential measured in tree 1 and tree 2 corresponds most closely with soil-moisture potential in the profile. Solid green line shows depth (m) of deepest observed tree roots. **b** Stable isotope of composition δ^{18}O measured at interval along depth of drill core. **c** Stable isotope of hydrogen δ^{2}H measured at depth along drill core. Enrichment of both δ^{18}O and δ^{2}H gradually declines at depth in profile. VSMOW Vienna Standard Mean Ocean Water (used for calibration)

Table 3 Structural attributes of trees and leaf water potential measurements of four trees assessed at the Long Swamp GDE assessment site

Tree ID	Species	Height (m)	DBH (cm)	Position	M1_MPa	M2_MPa	M3_MPa	Average
Tree 1	*Eucalyptus camaldulensis*	19	55	At GDE site as central point in swamp	−1.10	−1.10	−0.39	−0.99
Tree 2	*Eucalyptus camaldulensis*	24	80	At GDE site as central point in swamp	−0.80	−0.30	−0.39	−0.49
Tree 3	*Eucalyptus populnea*	19	60	On upper margins of swamp above region of flood inundation	−0.99	−0.99	0.99	−0.99
Tree 4	*Acacia harpophylla*	12	26	On margins of swamp slightly above region of flood inundation	−2.29	–	–	−2.29

−0.49 MPa. (see Table 4). This corresponds to an inferred zone of water uptake for the two trees between 4.5 and 6.5 mbgl. The isotopic composition of extracted soil moisture is plotted against sample depth for borehole BL182b in Fig. 10b, c. The profile indicates relative isotopic enrichment at the surface (0.2 mbgl) with an enriched horizon also located at 3.0 mbgl, corresponding with a change in lithology from silty sand to sandy clay. There is a very gradual decline in isotopic ratios with increasing depth in the soil profile.

Figure 11 provides a biplot demonstrating the relationship between $\delta^{18}O$ and $\delta^{2}H$ for soil-moisture samples collected from borehole BL182b, with comparison to the isotopic composition of xylem water (trees 1 and 2 as per Table 4). Both trees align more closely to enriched zones of soil moisture collected at the surface (0.2 and 3.0 mbgl) although demonstrate a greater degree of $\delta^{18}O$ enrichment than all but the shallowest soil samples with $\delta^{2}H$ showing considerable scatter.

Results for Glenburnie

The surface geology comprised loose, alluvial sands to 2.5 m depth which overlay increasingly carbonaceous and less weathered sequences of fine-to-coarse sandstones which were present to the total depth of drilling (30 m in GB20a). The shallow depth to sandstone bedrock was confirmed through the presence of nearby outcrop, and through hand augering within the sandy dry bed of Western Creek adjacent to the drilling site. Weathered sandstone was present at 0.7 m depth, demonstrating a very thin drape of sand and a shallow bedrock base which will temporarily support the perched flow and pooling of shallow groundwater after significant rainfall events.

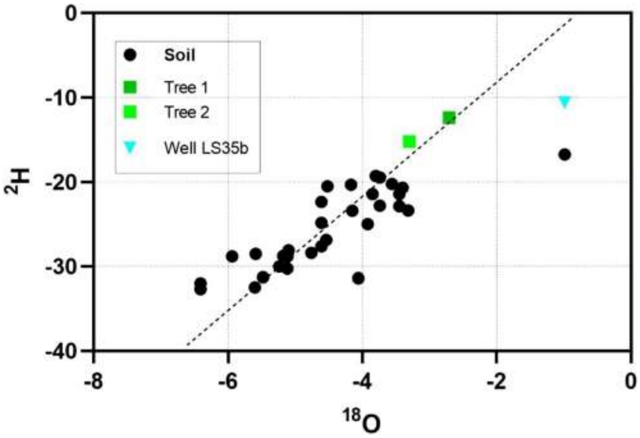


Fig. 9 Scatterplot showing the relationship of $\delta^{18}O$ and $\delta^{2}H$ in extracted soil moisture (solid circle), xylem water from sampled trees (green squares) and water from monitoring groundwater bore (LS35b). Dotted line indicates Global Meteoric Water Line (Craig 1961)

Considerable soil moisture was noted in seepage zones between 11 and 18 m above a transition into a carbonaceous sandstone rich in reworked coal fragments, other carbonaceous clasts and dark grey siltstone lenses. This change in lithology is considered to represent the top of the Walloon Coal Measures (Arrow Energy Pty Ltd., personal communications and unpublished geological cross section correlations, 2018). The regional aquifer was encountered at a depth of approximately 27 m in a fine-to-medium quartzose sandstone which became stronger, less weathered from 28.9 m. The groundwater level from this water strike rose under subartesian pressure to approximately 14.4 m. This aquifer was much deeper than the maximum likely tree-rooting depth of 20 m. The Glenburnie assessment site was geologically different to other GDE assessment sites due to the very shallow presence of weathered bedrock intersected within 1.5 m of the ground surface. Root material was recorded in weathered bedrock at a number of depths in the core hole with an extremely fragile rootlet with pronounced xylem vessels (Fig. 12) recorded at 7.6 m depth in the angle hole (GB20c) and a large (1 cm wide) tree root recorded along a bedding plane at 4.5 m depth (Fig. 13). This former example, which had penetrated the rock matrix, had an extremely open vessel structure.

A 50-mm-diameter groundwater monitoring bore was constructed at 18 m depth, screened from 10 to 18 m across a noted seepage zone within fine-to-coarse-grained sandstones. This was the only zone observed to contain free water (saturated) above the maximum likely tree-rooting depth of 20 m. Groundwater noted at 11–18 m did not flow rapidly into the bore during drilling, but rather entered slowly overnight as seepage rising 0.3 m in 13 h from 18 m. Hydrographs

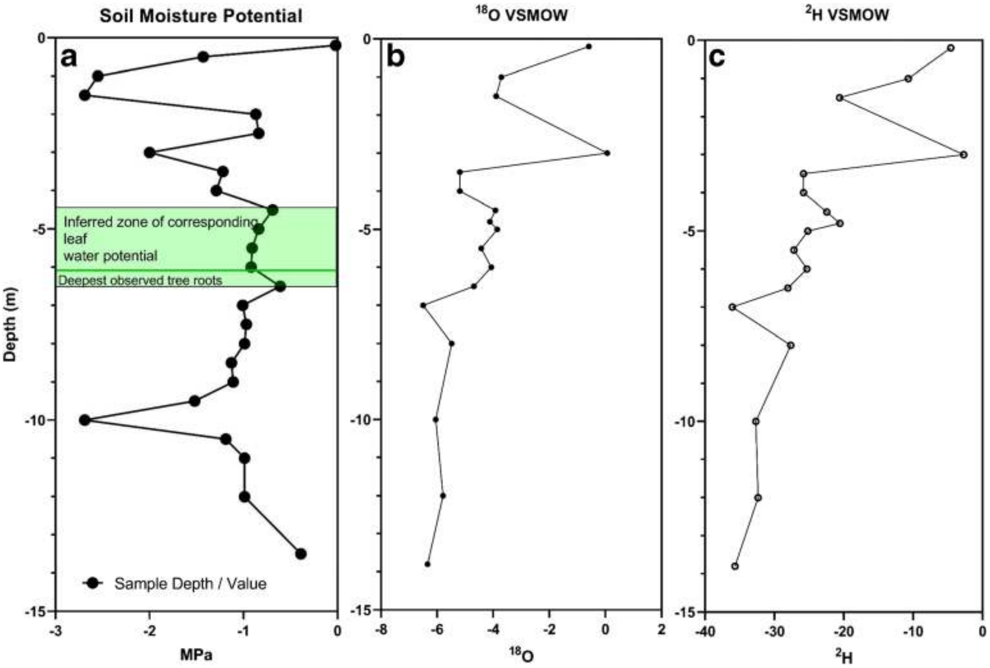


Fig. 10 **a** Soil-moisture potential (MPa) measured at depth (m) along drill core at Burunga Lane (Burunga Lane 182). Green shading indicates zone where leaf water potential in trees 1 and 2 correspond most closely with soil-moisture potential. Solid green line shows depth (m) of deepest observed tree roots. **b** Stable isotope of oxygen δ^{18}O measured at depth along drill core. **c** Stable isotope of hydrogen δ^{2}H measured at depth through drill core. Enrichment of both δ^{18}O and δ^{2}H decline with depth along drill core. VSMOW Vienna Standard Mean Ocean Water

from the pressure transducer installed after drilling shows that the bore took approximately 4 days to reach 90% recovery.

Soil-moisture potential analyses completed on soil and weathered bedrock samples from drill hole GB20b indicate that soil-moisture potential was extremely low for the top 8 m (see Fig. 14) of the hole within weathered sandstone, considerably lower than standard wilting point. The major zone of available soil moisture occurred between 9 and 11.5 m where soil-moisture potential rises to −0.049 MPa at 10.5 mbgl. A deeper zone of high water potential occurred from 14.5 m depth down to the base of the bore hole at 18 m. The leaf water potential for the three eucalypts measured (Trees 1, 2, and 4) shown in Table 5 all suggest that the trees have equilibrated with soil moisture at depths below 8 m in the profile, largely consistent with the deepest recorded tree roots at 7.6 m depth. The cypress pine (tree 3) has a much lower leaf water potential than the eucalypts, which may indicate that the predominant zone of moisture extraction is at shallower depths where there is limited water availability.

The isotopic composition of extracted soil moisture is plotted against sample depth for borehole GB20b in Fig. 14b for δ^{18}O and Fig. 14c for δ^{2}H. The trend shows strong enrichment of both δ^{18}O and δ^{2}H in the upper 1 m of the soil profile before trending to a gradual decline in isotopic enrichment below 2.5 mbgl.

A biplot providing a comparison between measured δ^{18}O and δ^{2}H composition for soil-moisture samples collected from borehole GB20b, isotopic composition of xylem water (trees 1 and 2) and groundwater from sampling of monitoring bore GB20 is provided in Fig. 15. Isotopic signatures of both trees 1 and 2 are enriched above the majority of soil samples with the exception of tree 2. The isotopic signature of tree 2 is similar to the soil sample from the upper soil profile (0.2 mbgl) and samples collected in shallow auger holes (sampled to a depth of 0.5 and 0.75 mbgl) than samples taken at greater depth or from groundwater sampled in the monitoring bore GB20a.

A summary of results of the assessment for each of the four GDE assessment sites has been prepared in Table 6 which presents the results of several key parameters assessed in this study, including (1) maximum observed rooting depth, (2) the zone of soil-moisture uptake by trees at each locality inferred from soil-moisture potential results, (3) any observed zone of shallow saturation or seepage within the assessed soil profile, (4) indications of groundwater sources from stable isotope data and (5) the observed depth to the regional aquifer.

Table 4 Structural attributes of trees and leaf water potential measurements of two trees assessed at the Burunga Lane GDE assessment site

Tree ID	Species	Height (m)	DBH (cm)	Position	M1_MPa	M2_MPa	M3_MPa	Average
Tree 1	*Eucalyptus camaldulensis*	24	120	6 m west from the immediate upper bench of the stream channel	−0.47	−0.42	−0.41	−0.43
Tree 2	*Eucalyptus camaldulensis*	12	30	30 m west from tree 1 on alluvial flood plain	−0.48	−0.48	−0.51	−0.49

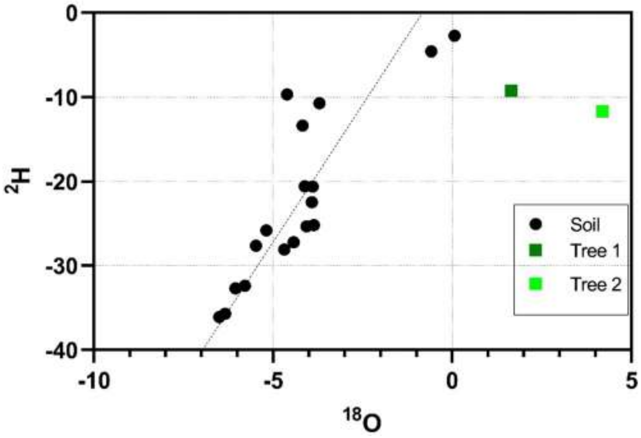


Fig. 11 Scatterplot showing the relationship of δ^{18}O and δ^{2}H among water extract from soil (solid circle), trees (green squares) at Burunga Lake. Dotted line indicates global meteoric water line (Craig 1961). There is considerable divergence of δ^{2}H values away from trend in both trees 1 and 2

Discussion

Multiple lines of evidence were applied to determine the likely source of water for riparian vegetation that has been identified as being potentially groundwater dependent. The outcomes of these assessments for each of the four study sites is discussed. Diagrammatic representations of the conceptual eco-hydrogeological models for each site are also presented to assist with communicating key aspects of the study findings (Figs. 16, 17, 18 and 19).

Lake Broadwater

Analysis of leaf water potential, soil-moisture potential and stable isotopes of δ^{18}O and δ^{2}H indicates that the target trees closest to the lake edge (trees 1 and 5) are predominantly utilising water from a shallow water table perched at the interface of sand and plastic clay at approximately 2.6 mbgl. Moving back from the lake edge, the same parameters indicate trees (including trees 2, and 4) show increasing reliance on unsaturated soil moisture contained within the soil profile. Tree roots were recorded to a depth of 4 mbgl within the upper surface of the clay profile. The extremely low soil-moisture potential of the clay (at or below standard wilting point of −1.49 MPa) coupled with the massive nature of the clay horizon with no visible voids or fissures would provide an extreme physical barrier to root penetration. As the regional aquifer was not intersected during drilling of the core hole to 21 mbgl, it is considered unlikely that trees could be accessing a deeper aquifer source through development of a tap root. Dupuy et al. (2005) considers that clay does not provide a favourable substrate for tap root development. The unconsolidated sand in the upper 3 m of the soil profile would have no capacity to support strong wind loads on a tall spreading red gum. Therefore, the surficial penetration of tree roots into the clays is considered a possible anchorage adaption to maintain the structural integrity of the tree (Dupuy et al. 2005; Fourcaud et al. 2008; Stubbs et al. 2019) as well as a possible source of residual soil moisture in wet sandy clays at the interface with sand during periods of sustained drought. This is consistent with observations of toppled red gum on the lake margins that show little evidence of a developed tap root system.

The salinity (6,050 µS/cm) and the young radiocarbon age of groundwater sampled from the shallow monitoring bore (LS31a) installed within river-red-gum-dominanted fringing forest confirmed the conceptualisation of an ephemeral perched evaporative lake connected to shallow groundwater within the sandy lake fringe and disconnected from underlying aquifers (groundwater radiocarbon age >10,000 years BP). Eamus et al. (2006b) identifies river red gum as being a relatively salt-tolerant species, growing well in soil salinities of almost 1,500 µS/cm. In addition, Mensforth et al. (1994) identified that river red gum will continue to utilise groundwater with salinity as high as 40,000 µS/cm in the absence of a fresh source of soil moisture, although higher levels of tree stress

Fig. 12 **a**–**b** Open vessel structure of tree roots recorded at 7.6 m in weathered Springbok Sandstone. Note water or resin droplets present within xylem (**b**). Largest vessel 0.5 mm diameter

Fig. 13 Large tree roots recorded penetrating along bedding planes in sandstone at 4.5 mbgl in GB20a

and lower growth rates are recorded. Hence, while the shallow perched water table at Lake Broadwater is considered moderately saline, it does not preclude it's use by river red gum, where other sources of freshwater are not available. It is expected that during high stand levels in Lake Broadwater, freshwater will replenish the shallow aquifer and the GDE system will respond with increased vigour and foliage growth. The well-developed riparian vegetation dominated by river red gum that fringes Lake Broadwater is considered to represent a GDE, although the groundwater source is a shallow unconfined aquifer with inputs of water provided during periods of high lake levels and recharge through direct infiltration.

Long Swamp

Comparison of leaf water potential and soil-moisture potential for the Long Swamp GDE investigation site indicate that the predominant source for soil moisture for river red gums in the central portion of the swamp is likely to occur at a depth range from 8 to 11.5 mbgl in a moist sandy clay merging to clayey sand. This is marginally below the maximum tree root depth of 7.1 mbgl that was observed in drill core. Borehole LS35 remained dry during coring to a depth >14 mbgl, and extremely low soil-moisture potential (−2.62 MPa) was recorded in a dry sand horizon between depths of 12 and 13 mbgl. This extremely dry sandy horizon would present a major impediment to penetration of tree roots below 11.5 mbgl. Analysis of stable isotopes of δ^{18}O and δ^{2}H suggests a mixed source of soil moisture for river-red-gum canopy trees within the swamp, potentially influenced by evaporatively enriched surface moisture that percolates into fissures within the vertic clay profile. Possible reasons for the disparity between physical parameters such as leaf and soil-moisture potential and stable isotope results are provided in following sections, although for Long Swamp, there is no support in the isotopic data or any other parameter that trees are utilising a deeper source of groundwater.

The relatively young radiocarbon age ("Modern") of groundwater sampled from the shallow groundwater monitoring bore supports the conceptualisation of this as a perched seepage zone disconnected from the underlying Westbourne and Springbok Sandstone aquifers (>3,000 and >25,000 years BP respectively). Based on multiple lines of evidence, the Long Swamp GDE assessment site is not considered to be a

Fig. 14 **a** Soil-moisture potential (MPa) measured at depth (m) along drill core at Glenburnie 20a. Green shading indicates zone where leaf water potential corresponds most closely with soil-moisture potential measured. Solid green line shows depth (m) of deepest observed tree roots. **b** Stable isotope of oxygen δ^{18}O measured at depth through drill core. **c** Stable isotope of hydrogen δ^{2}H measured at depth through drill core. VSMOW Vienna Standard Mean Ocean Water

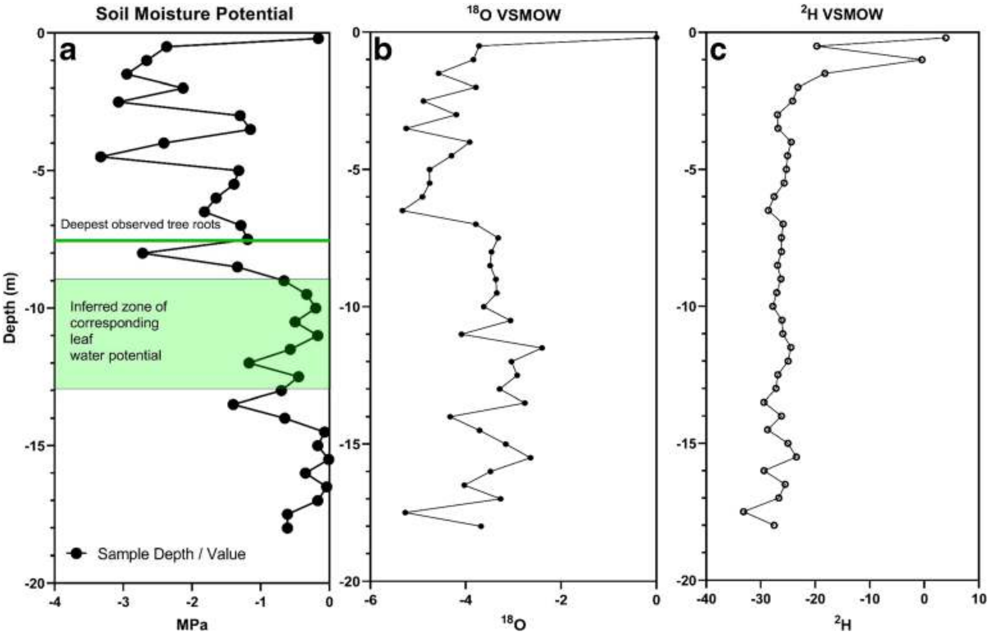


Table 5 Leaf water potential measurements of trees at the Glenburnie GDE assessment site

Tree ID	Species	Height (m)	DBH (cm)	Position	M1_MPa	M2_MPa	M3_MPa	Average
Tree 1	*Eucalyptus camaldulensis*	24	80	At the overlap zone between the narrow alluvial flood plain and colluvium from sandstone	−0.47	−0.52	−0.62	−0.63
Tree 2	*Eucalyptus camaldulensis*	19	40	On a narrow alluvial terrace adjacent to the stream channel of Western Creek	−0.39	−0.29	−0.35	−0.35
Tree 3	*Callitris glaucophylla*	17	45	At the overlap zone between the narrow alluvial flood plain and colluvium from sandstone.	−1.24	−0.89	−1.34	−1.15
Tree 4	*Corymbia tessellaris*	21	55	At the overlap zone between the narrow alluvial flood plain and colluvium from sandstone.	−0.29	−0.62	–	−0.51

GDE and river red gum at this location are sourcing their water requirements entirely from moisture stored in the soil profile.

Burunga Lane

Measurements of leaf water potential and soil-moisture potential from samples collected at Burunga Lane identified a likely source of soil-moisture uptake between 4.5 and 6.5 mbgl. This depth corresponds with a broad zone of relatively high moisture availability coincidental with the interface between predominantly unconsolidated alluvial sediments and weathered Walloon Coal Measures. Below 6.6 mbgl, soil-moisture availability decreases significantly to a depth of 10 mbgl where the lowest soil-moisture potential of −2.68 MPa was recorded, which would provide a barrier to deeper penetration of tree roots. Stable isotope analysis indicates that isotopic enrichment of water extracted from tree xylem is closest to the isotopic composition of soil moisture in the upper 0.2 mbgl of the soil profile.

The aquifer intersected at 13.5 mbgl within the Walloon Coal Measures is below the depth of inferred water uptake (up to 6.5 mbgl) and there is no indication that tree roots are tapping this water source. The shallow groundwater monitoring bore remained dry during drilling to the depth of the regional aquifer and was dry in the follow up sampling event.

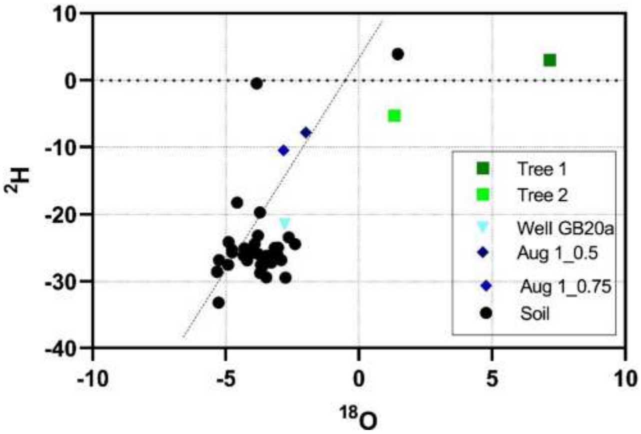


Fig. 15 Scatterplot showing the relationship of δ^{18}O and δ^{2}H from water extracted from soil (solid circle) and samples from shallow auger holes (diamond), xylem from trees (green squares) and groundwater from monitoring bore GB20a. The dotted line indicates global meteoric water line (Craig 1961)

Glenburnie

Through comparisons of soil-moisture potential and leaf water potential measured in river red gum at the Glenburnie site, the zone of predominant water uptake is interpreted to lie between 9 and 11.5 mbgl. Within this zone, soil-moisture potential ranges from −0.68 to −0.51 MPa and overlaps with the upper limits of a series of seepage zones that were intersected in drill core between 11 and 18 mbgl. The deepest root material identified in the Glenburnie drill core was at 7.6 mbgl which adds confidence to the interpretation that tree roots are not penetrating to depths significantly below these seepage zones.

Stable isotope signatures from twig xylem water are considerably enriched which suggests trees are accessing an evaporatively enriched source of soil moisture and the only comparable isotopic signatures in analysed soils occurs at 0.2 m depth in the upper soil profile. There is potential that isotopic results have been influenced by the preceding heavy rainfall event although similar trends have been reported in Feikema et al. (2010) where the stable isotopic composition of eucalypt twigs was correlated most closely with a moisture source in the shallow soil profile to a depth of 0.25 mbgl. Despite the lack of a definitive source of water for transpiration identified in the stable isotope analysis, at the time of assessment, there was no indication that mature trees at the Glenburnie site were utilising significant amounts of water from sources deeper in the soil profile, which includes saturated seepage zones between 8 and 11 mbgl and the deeper subartesian aquifer that lies at approximately 27 mbgl. Based on the previously described multiple lines of evidence, vegetation at the Glenburnie GDE assessment site is not considered to represent a GDE.

Sampling considerations

While analysis of δ^{18}O and δ^{2}H in twig, soil and groundwater samples supports a shallow groundwater source of moisture

Table 6 Key parameters for GDE Assessment for each GDE assessment area

Study site	Maximum observed root depth (m)	Inferred zone of soil-moisture uptake (m)	Observed zone of shallow saturation/ perched aquifer (m)	Stable isotope analysis: indicated zone of water uptake (m)	Observed depth to regional aquifer (m)
Lake Broadwater	4	1.8–3	1.8–3	2.6	>18 (Westbourne)
Long Swamp	7.1	7.5–11.5	14.7–17.4	0–7.5	26.5 (Westbourne)
Burunga Lane	6	4.5–6.5	4.9–6	0–3.0	13.5 (WCM)
Glenburnie	7.6	9–11.5	13.5–18	0–0.2 m	27 (WCM)

for trees at the Lake Broadwater (LS31) GDE assessment site, the results at other assessment localities are less definitive. The Glen Burnie and Long Swamp sites may have been influenced by preceding rainfall events with mixing of rainwater with isotopically enriched portions of the upper soil profile to cause scatter, particularly in δ^2H values creating a nondistinctive δ^2H signature in surficial soil moisture which was possibly then harvested by lateral tree roots in the upper soil profile (Feikema et al. 2010).

The strong enrichment of δ^{18}O in xylem samples above soil-moisture samples may also have been influenced by isotopic fractionation within tree xylem which has potential to confound the results of isotopic analysis (Pettit and Froend 2018; Singer et al. 2014). Isotopic transfer may also occur between semi-permeable barriers of the phloem and xylem, especially in stored samples, or the Peclet effect ,whereby diffusion of enriched water from the site of enrichment (i.e. the leaves) against the physical flow of water (H. Stuart-Williams, Farquhar Laboratory, personal communication, 2018). Confounding sources of error may have occurred which include sampling in conditions of extreme heat which may have facilitated isotopic fractionation in the xylem water and soil, plus the fact that any handling of samples during extremely hot conditions will exacerbate the tendency for fractionation due to evaporative loss (Pettit and Froend 2018). It is noted that all sampling events were completed under hot conditions.

While Pettit and Froend (2018) consider stable isotope analysis a powerful tool, they state that it is often not enough to disentangle complex ecological interactions. Due to a

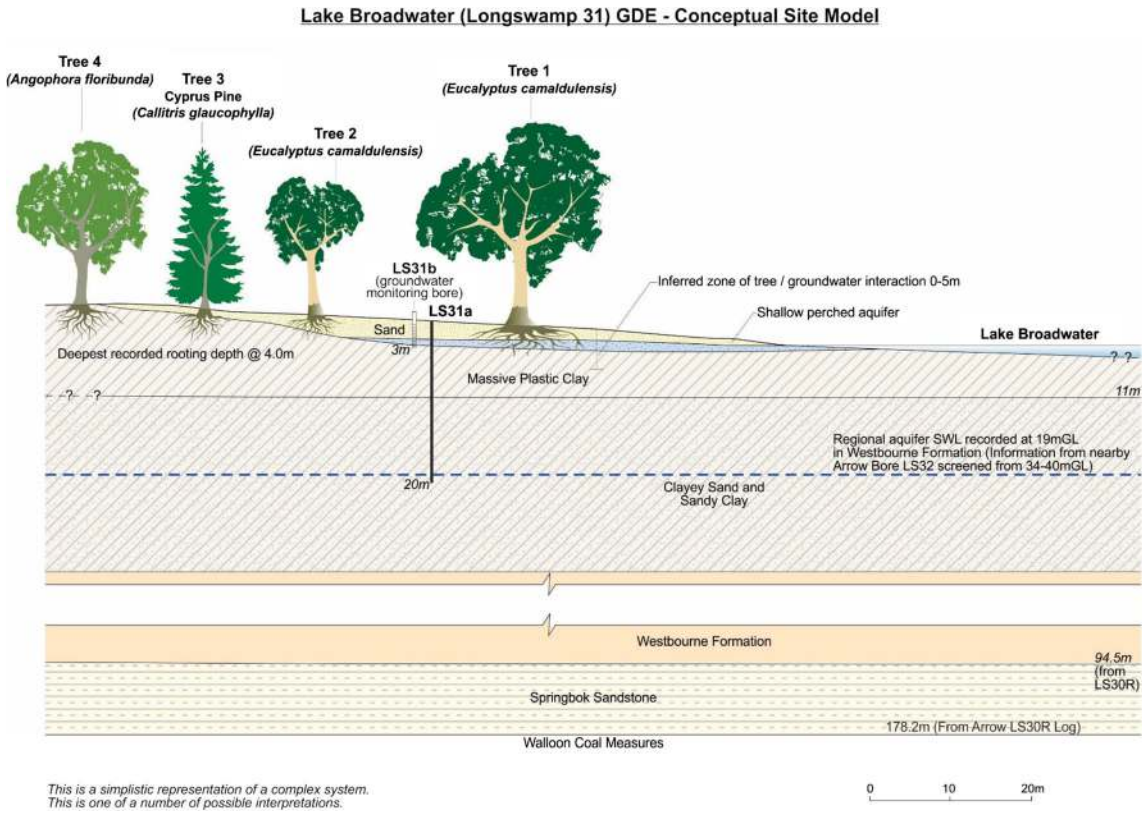
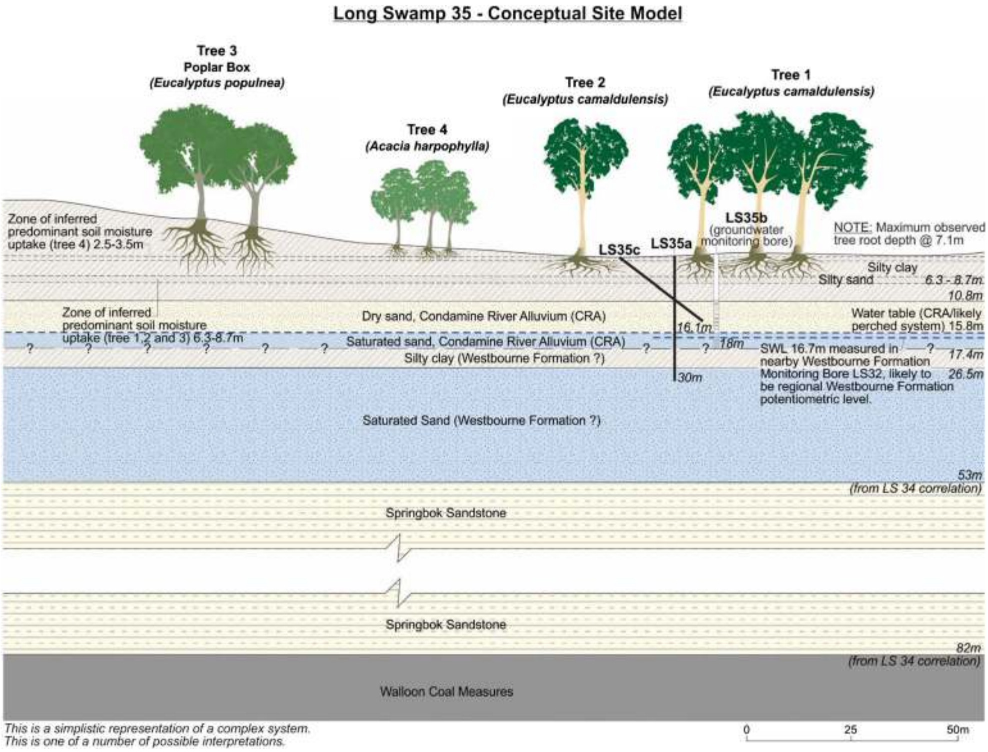


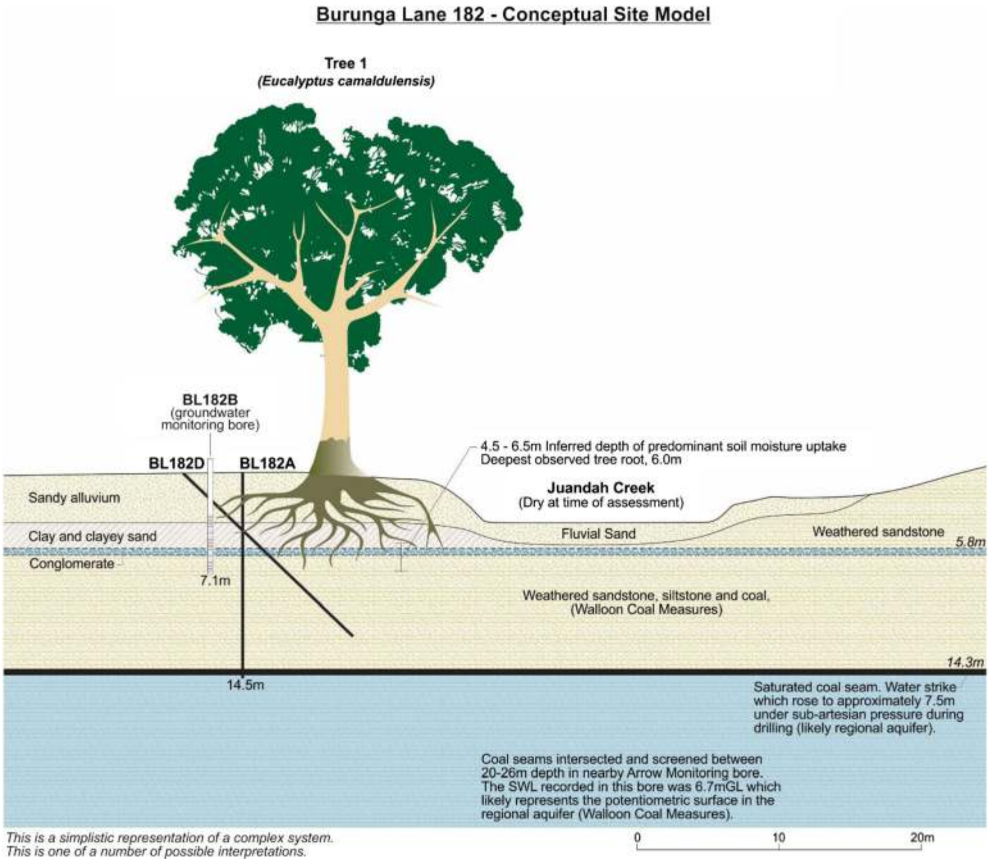
Fig. 16 Conceptual site model of the Lake Broadwater GDE Assessment Site

Fig. 17 Conceptual site model for the Long Swamp GDE Assessment Site



variability in the isotopic composition of xylem water which responds to climatic variables, they recommend isotopic sampling over an extended time frame to account for seasonality. Hence, the one-off sampling event undertaken during

Fig. 18 Conceptual site model for the Burunga Lane GDE Assessment Site



this study is unlikely to have provided sufficient temporal context to allow the results of isotopic sampling to be interpreted with confidence. Ongoing monitoring of all sites, focusing on extremely dry periods when trees are most likely to be utilising groundwater, is required before conclusive statements can be made on groundwater usage by plants based on isotopic signatures alone. Similar statements can apply to measurement of leaf water potential which may be subject to considerable variation as a result of localised rainfall events following which opportunistic harvesting of surface water may occur.

Despite these limitations, the combination of multiple lines of evidence including drilling to gather information on the local groundwater regime, identify likely maximum tree-rooting depth plus measurement and comparison of soil and leaf water potential reinforce conclusions made on groundwater use by plants at the selected study sites. There is strong, corroborating evidence that trees are not utilising deeper regional aquifers at any of the GDE investigation sites and that soil moisture is the primary source of water sustaining mature vegetation. Vegetation at Lake Broadwater is an exception, where multiple lines of evidence indicate that mature red gum fringing the lake are meeting their water requirements from a shallow perched, moderately saline aquifer contained within sandy lacustrine shoreline deposits. The Lake Broadwater site would therefore meet the definition of a GDE.

At other sites including Long Swamp and Glenburnie, the regional aquifer is well below the maximum likely tree-rooting depth (e.g. 26.5 m at Long Swamp and 27 m at Glenburnie), suggesting river red gum and other tree species are not dependent on the regional aquifer as a source of water to maintain physiological function. Trees are instead likely to be utilising shallow soil moisture or a perched water table consistent with findings of Mensforth et al. (1994), Zolfaghar (2013) and Doody et al. (2015) who identify that river red gum can obtain water from multiple sources including fresh to moderately saline groundwater, episodic overbank flooding, lateral bank recharge and surface flows associated with localised and regional rainfall events. In some circumstances, stand condition of river red gum can be maintained by flooding regimes that recharge soil moisture reserves over a time interval that extends to as much as 10 years (Doody et al. 2015).

It is postulated that river red gum and possibly other deep-rooted eucalyptus species at Long Swamp, Glenburnie and Burunga Lane are potentially tapping downward-percolating

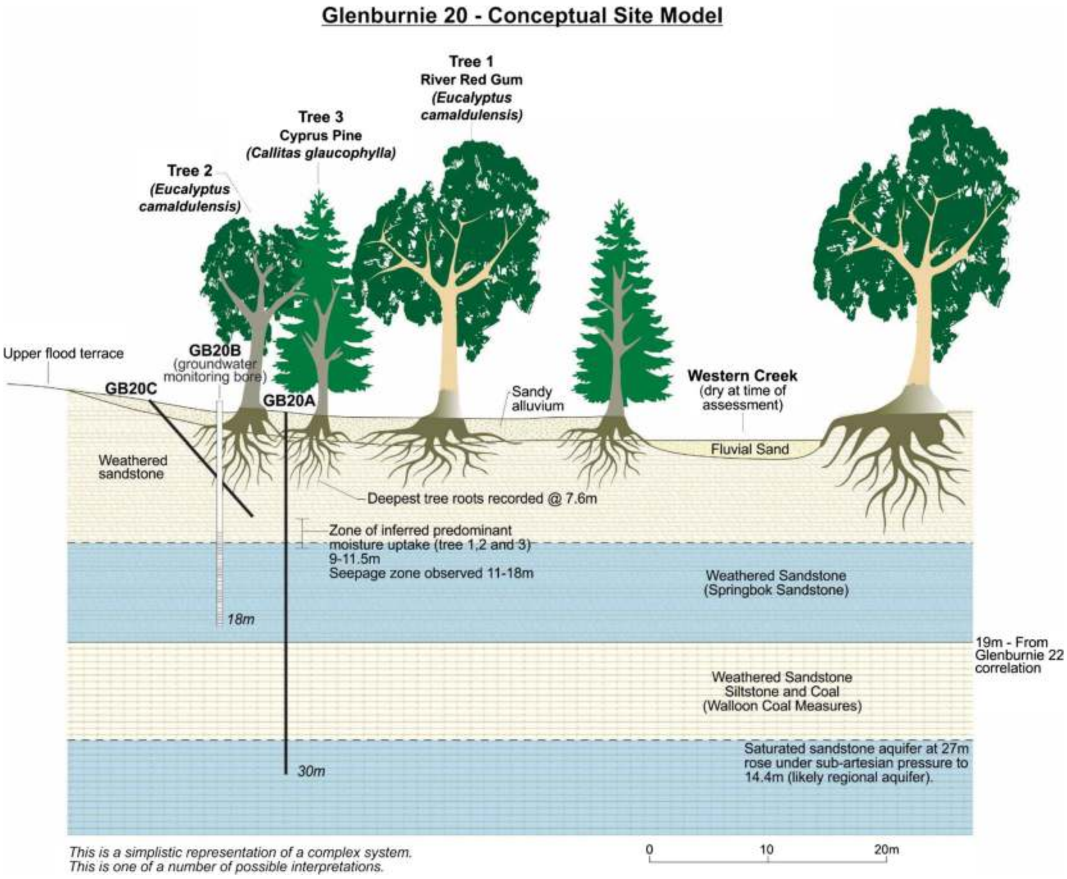


Fig. 19 Conceptual site model for the Glenburnie GDE Assessment Site

water moving under gravity through a near-saturated vadose zone. The water in the vadose zone exists in a transient state of near-saturation to saturation and is moving within a permanent to near-permanent wetting front associated with overlying ephemeral surface-water bodies which temporarily channel and hold water for extended periods. This is supported by the very limited presence of such species away from riparian corridors. Trees such as river red gum appear to be tapping the near permanent sources of moisture described previously, which is available in horizons containing a balanced matrix of grain-sizes, with coarser fractions providing enough permeability for the high transpiration rates required for such trees, but also enough fine material to slow and hold water between wetting events (recharge), and hence buffer the effects of tree stress that would be caused by pronounced drought. Due to the relatively shallow regional piezometric surfaces (<10 mbgl) observed at the Burunga Lane site (see Fig. 18), further assessment and groundwater monitoring will assist with validating the conceptual eco-hydrogeological model at this site.

As noted in Table 6, another key finding is the relatively shallow maximum tree root depths observed compared with the maximum anticipated depth range of 12–23 mbgl based on literature studies (Kath et al. 2014). Although root observations in drill core cannot be considered a conclusive indication of maximum tree root depth, the consistent maximum observed tree root depth of 6–8 mbgl or shallower (e.g. Lake Broadwater site) overlaps with zones of predicted moisture uptake from soil moisture and leaf water potential readings. This finding should be considered strong evidence that the bulk of the tree root mass occurs within the zone of predominant moisture uptake that was observed in drill core. While it is not possible to rule out the occurrence of deeper root material, the lack of observed tree root mass in multiple drill holes that intersected the capillary fringe of the shallow perched aquifer at Glenburnie (top of saturated zone at 13.5 mbgl) or in the confined aquifer associated with coal seams at the Burunga Lane site (top of regional aquifer at 13.5 mbgl) indicates that these saturated zones or aquifers are unlikely to be the predominant source of moisture for trees at these assessment localities. Given the variability of landscape setting the river red gum has been observed in, it is problematic to generalise rooting depths for such a widely distributed species occurring across a range of geologic, geomorphic and hydrologic settings. This study provides a robust data collection process with capacity the be modified to site-specific settings and applied in field and desktop assessments for similar locations within the GAB. This assessment provides the basis for further studies to quantitatively assess river red gum's dependence on the regional aquifer as a water source with methods that are broadly transferable across other regions of the GAB that display similar site settings to those depicted in this study.

Conclusions

The study's outcomes demonstrate the applicability of a series of complementary assessment methods which provide multiple lines of evidence for the revision of existing generalised and simplistic conceptual models of terrestrial GDEs in the Surat Basin and broader GAB. The study has resulted in a more robust understanding of the range of potential sources for moisture uptake by dominant deep-rooted tree species and provides additional context to the generally simplistic understanding of terrestrial GDEs in the GAB. Direct evidence is also provided for the ability of tree species that typically form GDEs in the GAB to source water from the most accessible source of available soil moisture which is not always the regional water table aquifer.

This study has shown that eco-hydrogeological relationships are complex and varied, with significant differences in water use inferred within the four case study areas. It is anticipated that the findings of the field investigations, including shallower than expected tree-rooting depths and dependency on soil moisture and/or perched water, will serve as useful case study conceptualisations for comparison with future assessment of other potential terrestrial GDEs and the risks to such ecosystems due to aquifer drawdown impacts from cumulative CSG production in the Surat Basin. Acknowledging that tree water usage may change in response to seasonal water availability, a comprehensive surface water, multi-aquifer groundwater and ecological monitoring programme has commenced and results from the programme comprise the basis of a future publication.

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