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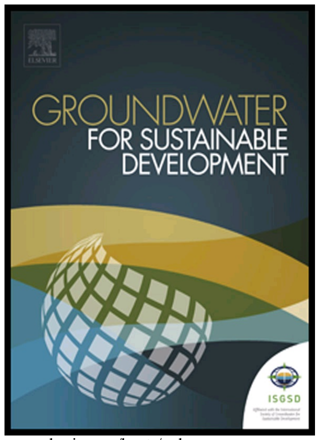

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Hydrogeological characterisation and groundwater exploration for the development of irrigated agriculture in the West Kimberley region, Western Australia

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Abstract

This work presents findings from an exploration programme aimed at identifying new sources of groundwater for irrigated agriculture in the West Kimberley region of Western Australia. The investigation combined drilling, geophysics, hydraulic tests, and water-quality data to improve the understanding of the aquifers' system. Geologically, the area was interpreted as part of an asymmetric syncline trending northwest towards the coast. Fractures and lineaments are largely concealed but they might disrupt the continuity of the aquifers at certain locations. Groundwater lies primarily in Mesozoic sediments of the Wallal Sandstone, and in the lower section of the Erskine Sandstone underneath. Pollen analysis casts doubt on the age of the Wallal Sandstone, which could actually correspond to a sequence not previously recognised in the area. Concentrations of major ions indicate that for the most part, waters are fresh and suitable for irrigation. The most productive zone for water abstraction locates in western outcrops of the Wallal Sandstone, where bore yields exceed 60 L/s. The northern flank of the syncline is also favourable for pumping the Erskine Sandstone although, fine-grained sediments make the aquifer less productive. The main source of groundwater recharge is rainwater. Chloride concentrations suggest that groundwater replenishment would range between 1 % and 3 % of the average annual rainfall. The safe yield has been estimated at 4.5 GL/year and 8.7 GL/year for the Wallal and Erskine aquifers respectively. Though several uncertainties remain to be addressed, the study contributes to future planning and a sustainable use of the groundwater resource.

Keywords: groundwater; hydrogeology; exploration; irrigation; West Kimberley

1. Introduction

Groundwater is one of the most precious resources for human consumption, industrial activities, and irrigated agriculture (Li et al. 2018). This is especially relevant to the West Kimberley, an area that covers more than 100,000 km^2 in the northern fringes of Western Australia (WA). Limited surface water and the uneven distribution of precipitation mean that water supply greatly depends on groundwater, locally stored across a few aquifers of the region. Rainfall occurs mostly between December and March, followed by a dry season lasting up to 9 months of the year. During this time, ephemeral creeks dry out, and cattle is forced to migrate to more fertile pastures near stock bores.

Due to the water shortage, population remains scarce and economic opportunities limited. In 2014, the population of the Kimberley was estimated to be around 39,000 people, almost 44 % of them indigenous Australians living in remote communities (Kimberley Development Commission, 2018). As an average, the proportion of aboriginal people engaged in full time employment, education or training in WA is less than half than non-aboriginal people (Australian Bureau of Statistics, 2016). In this regard, substantial efforts are being undertaken to stimulate investment and economic development through intensive irrigated agriculture in the Kimberley. That is expected to assist producers to lift productivity and to respond to the increasing food demand in Australia and Asia, resulting at the same time in jobs creation and new economic opportunities for local communities. Planning to increase water exploitation and expanding irrigated agriculture require a comprehensive understanding of how much water is available, host aquifers' characteristics, and what components must be taken into account for a sustainable management of the resource. The geological complexity of the area indicates that simple rules of thumb are not enough to locate sites adequate for water supply, and random boreholes commonly result in failure. Furthermore, the delicate balance that supports groundwater dependant ecosystems (GDEs), potential desiccation of permanent pools, and the presence of numerous sites of cultural significance precludes the use of groundwater in an unplanned manner.

The groundwater potential in the nearby Derby Peninsula was first investigated by Leech (1972), who provided useful insights into aquifers in the area. However, some of the interpretations were speculative and could not be quantified with confidence. Due to the steady increase in the town water-supply, Laws and Smith (1988) carried a more in-depth study to assess groundwater resources that could be exploited for Derby and the immediate environs. The authors identified two major aquifers which contain high-quality water and could be utilised to address the increasing demand. Nonetheless, saline intrusion was deemed to be a potential problem for intensive groundwater abstraction. Allen et al. (1992) considered the Fitzroy River alluvium to be an additional groundwater source for the region. However, there are no records of further investigations for more than a decade, when Lindsay and Commander (2005) assessed the potential of the resource and modelled the likely drawdown of a hypothetical borefield. Their theoretical exercise simulated abstraction on a seasonally adjusted schedule from a line of equally spaced bores along the floodplain of the Fitzroy River, indicating possible yields up to 200 gigalitres (GL) from a stretch of 275 km of alluvium. Little work has been completed since then, typically undertaken by government agencies aiming at resolving a specific issue. As such, recent studies mostly focused on the surface – groundwater interaction in the lower reaches of the Fitzroy River. Fitzpatrick et al. (2011) employed geophysical interpretation, whilst Harrington et al. (2011) combined hydrogeological mapping with isotopic analyses to better understand the interrelationship between groundwater and surface water in this part of the catchment. A comprehensive synthesis of the latest findings and a review into the groundwater resources of the region has been presented by Harrington and Harrington (2015), who concluded that there are many knowledge gaps that need to be addressed to give potential investors confidence about the groundwater resource availability, and to enable the determination of sustainable extraction limits. Thus, there is still a substantial lack of data to broadly delineate groundwater potential zones, and even less information to make quantitative estimates of the resource across the West Kimberley. In this context, and as part of the WA State's initiative to support the expansion of agricultural activities in the far north, a hydrogeological investigation was carried out east of Derby to get a better understanding of the geologic environment and to identify areas with potential for groundwater supply. The study also aimed to characterise some of the main aquifers in the region, and to elucidate the mechanisms that control the storage and movement of water in the subsurface. While similar groundwater exploration programmes have been carried out in eastern Australia (e.g. Inverarity et al.

2011; Ross, 2014), and throughout the world (e.g. Ramesh and Mahesha, 2006; Moussa et al. 2017; Saha et al. 2018; Iqbal et al. 2018; and many others), our work is critical to support agricultural investment in northern Australia. Thus, it constitutes a step forward in the economic development of disadvantaged, remote communities. Simultaneously, the expected increase in groundwater demand requires to safeguard the sustainability of the resource and to protect the water-dependent environment. Accordingly, the investigation provides comprehensive information that will assist regulation authorities to establish water allocation limits and manage the resource in relation with anthropogenic stresses and climate change.

2. Study area

2.1 General Characteristics

The study area covers approximately 300 km^2 within the Fitzroy Valley, in the West Kimberley region of WA. Geographically, the area stretches from the town of Derby and the May River in the north, to the vicinities of the Great Northern Highway in the south. To the west, the area is limited by the Indian Ocean whilst, it extends about 60 km inland to the east (Figure 1). The land surface is a vast grazing area, with low relief and a general slope northward. In this regard, the southeast region reaches an elevation close to 130 m above the Australian height datum (AHD), but it lies close to the sea level near the coast. The May River constitutes the main surface feature in the area of interest. South of the investigation area, the Fitzroy River is one of the most significant rivers of northern Australia, with a length exceeding 700 km and a mean annual discharge of about 7,000 GL (Centre of Excellence in Natural Resource Management, 2010). Given the ecological, cultural, and historical value of the Fitzroy River, no works were undertaken near the watercourse or its area of influence. The climate of the region is the tropical monsoon type, characterised by a distinct hot, wet season from November to March, followed by a dry, warm period between April and October. As an average, precipitation ranges from 770 to 820 mm/year, most of it falling during the wet season. The mean annual areal potential evapotranspiration (APET) is 1,980 mm (CSIRO, 2009). Since APET is greater than rainfall, and rainfall only exceeds APET for short periods during the wet months, the Fitzroy region is considered to be water limited (Harrington and Harrington, 2015).

2.2 Geological Framework

The project lies within the Fitzroy Trough subdivision of the northern Canning Basin, a northwest-southeast trending depocentre bounded to the north by the Lennard Shelf, and containing carbonate and clastic rocks from the mid-Carbonaceous to the mid-Triassic (Mory and Hocking, 2011). The sediments themselves are predominantly sandstones and shales of shallow marine, deltaic and fluvial origin, with a thickness ranging from 3,000 m on the Lennard Shelf, up to about 8,000 m beneath Derby (Guppy et al. 1958).

The main regional structure is an elongated syncline that plunges northwest and propagates beneath the Derby peninsula (Figure 2). Furthermore, the folds are cross cut by numerous north-northwesterly transverse faults that create a trellised drainage system (Gibson and Crowe, 1982). Laws and Smith (1988) also reported the existence of two major fault systems trending northwest, which put Triassic rocks in contact with underlying units. All of these structures would have dislocated a series of blocks hence, producing additional discontinuities in the stratigraphy and affecting the hydrogeological configuration of the system. The Blina Shale, from the lower Triassic, lies at the base of the sequence of interest (Table 1). The formation has a maximum thickness of 403 m and it is dominated by claystones, sandy siltstones, and fine-grained sandstones with ripple marks and bioturbation (Mory, 2010). The shales are overlain by a succession of very fine sandstones and siltstones from the Erskine Sandstone. Drilling data indicates that the thickness of the Erskine Sandstone would exceed 150 m along the axis of the syncline whilst, Laws and Smith (1988) interpreted it to be 265 m thick in bores east of Derby. In this context, the town of Derby is entirely dependent on this unit for its water supply. In here, groundwater is sourced from the Lower Erskine Sandstone which is considered to be a confined aquifer system, situated at a minimum depth of approximately 200 m from the surface (Department of Water, 2008). Nonetheless, the unit outcrops extensively across the east-southeast corners of the project area, where it constitutes an unconfined aquifer. Due to the complex geological structure and possible faulting, there might be some lateral compartmentalisation of the succession which in turn, would influence hydraulic connections and the groundwater circulation. Hydraulic conductivities in the Erskine Sandstone range from 1.5 to 3 m/day, whilst its storage coefficients would be in the order of 5×10^{-5} to 7×10^{-7} (Laws and Smith, 1988). The hydraulic conductivity would increase towards the base of the aquifer along with an increase in the sand content.

A succession of multi-coloured mudstones referred as the Munkayarra Shale, overlies the Erskine Sandstone. The sequence consists of indurated clays and minor coal, arguably indicative of cyclic deposition both, under shallow waters and subaerial conditions. The unit constitutes the main confining body in the area, and where present, it separates the Erskine Sandstone from sediments near the surface.

Sediments currently attributed to the Wallal Sandstone are widespread around Derby and the coastal area. Regionally, the unit outcrops in a fan-like pattern than spreads outward from the nose of the aforementioned syncline, and dips gently westwards in line with the morphology of the terrane. The sequence is characterised by a high degree of heterogeneity, mostly composed of laminated pink and white, fine to very coarse sandstones, with local intercalations of siltstones and conglomerates. It has been assigned to the Late Jurassic (Leech, 1979). However, the relationships thus far recognised do not seem to agree with findings from the present investigation, which suggest a possible Cainozoic age for the sediments. For practical purposes and until the stratigraphic relations are clarified, the present work will still refer to the unit as the Wallal Sandstone. With a thickness of approximately 90 m, the formation is an unconfined aquifer capable of yielding large volumes of water to wells. At present, the aquifer is mainly used for stock and domestic purposes, although pumping rates over 65 L/s have been recorded at an irrigation bore within the Mowanjum pastoral station, approximately 20 km south of Derby. According to Smith (1988), hydraulic conductivities would range from 0.8 to 16 m/day, with values as high as 44 m/day in some locations (Rockwater, 1987; Global Groundwater, 2015). The floodplains of the May River are commonly covered by a layer of alluvial deposits of Quaternary age. The beds are up to 30 – 40 m thick, and composed of basal sand gravel representing the river bed loads, overlain by up to 10 m of silt/clay overbank deposits (Lindsay and Commander, 2005). These deposits are partially unsaturated, show considerable lateral variations and have limited thickness, which in a broad sense, render them poorly productive for commercial abstraction.

3. Methods and materials

The investigation commenced with a comprehensive review of available information such as reports, maps, lithological descriptions, and geophysical surveys. Additionally, well logs and groundwater records were extracted from the Department of Water and Environmental Regulation of Western Australia (DWER) WIN database, and the Department of Mines and Petroleum of Western Australia's GeoView index. The database returned a wide distribution of bores, although the quality of the data was often poor. Furthermore, the density of points was not uniform, decreasing substantially away from Derby. Data from a field programme carried out by the DWER in early 2015 provided valuable information about the Wallal Sandstone in the region. The programme involved 730 m of drilling across 8 sites, and the successful completion of 2 production bores that currently support a 38 hectare centre-pivot irrigation system at the Mowanjum pastoral station. In addition, an airborne electromagnetics survey (AEM) was carried out by the DWER and Geoscience Australia across the region in September 2015. The survey comprised over 5,000 km of flown lines collected with the SkyTem 312 system. The automated laterally constrained inversion (ALCI) algorithm was used to delineate conductivity gradients and produce spatial images for each individual flight line. This data contributed significantly to initially define areas favourable for groundwater occurrence and to target new sites for exploration. In this context, 14 sites were selected for additional drilling and installation of 100 mm, PVC monitoring bores (refer to Figure 1). The boreholes were mostly drilled by air core methods and sediment cuttings sampled every 2 m. Selected intervals were tested for soil particle distribution so as to design the filter pack and screen aperture of future production bores. Additionally, discharge rates, water electrical conductivity, and pH were regularly measured on site to construct a flow and water-quality profile. Drilling through unconsolidated sands was commonly hindered by ground instability and severe caving requiring thus, the use of mud-rotary techniques at some sites. Downhole gamma and resistivity logging (16" – 64") were conducted at the end of drilling at each location to assist with the geological interpretation and guide the bore construction. Following installation of the casing, the bores were developed by screen jetting and airlift until flow rates and standard parameters (i.e. electrical conductivity, pH, and temperature) stabilised, and turbidity was deemed to be minimum. Groundwater unfiltered samples were collected in 1-litre Nalgene® bottles for the analysis of major cations and anions (i.e. K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-) whilst, 250 ml containers were used for the determination of total nitrogen. Additional samples were collected in 125 ml bottles for the analysis of trace metal ions, although they were excluded from the discussion as their concentrations are generally negligible. Samples were chilled at 4 ºC, except for the 250 ml containers which were frozen immediately after collection. Major ions were analysed by chromatography methods at the Australian Government National Measurements Institute, in Perth. Nitrate contents (largely non-detectable) were estimated in the field by colorimetric titration. Ultimately, the accuracy of the chemical analysis was assessed by an ion-balance computation. Cumulative rainfall samples were collected over the wet season using oil-type collectors. A layer of paraffin oil at the bottom of the collection container inhibited evaporation and prevented fractioning of the incoming waters. After analysis, rainfall chemical concentrations were compared to groundwater contents from selected locations to estimate recharge rates into the aquifers. Rising-head slug tests were also undertaken to examine aquifer properties at a minimal cost In this regard, the bores were airlifted using a 5-cm diameter polyethylene pipe to rapidly remove a noticeable volume of water and to induce a decline in the static water level. Immediately afterwards, the water level was monitored both manually and by the use of a Level Troll 400 data logger until about 2/3 of the initial drawdown recovered. Hydraulic conductivity values were then estimated using the Hovrslev mathematical solution (Hovrslev, 1951). While intended for confined aquifers, the method can also yield appropriate estimates in unconfined aquifers as long as the well screen is not too close to the water table (Butler, 1998).

Upon gaining a basic understanding of the hydrogeological system, a 250 mm diameter steel-bore was constructed at one of the most prospective groundwater sites in the Erskine Sandstone to better determine the hydraulic properties of the formation. A Grundfos SP95-5 electric submersible pump was installed with the inlet at a depth of 72 m below ground level (m bgl), and connected via a 100 mm fibre-reinforced plastic (FRP) rising main. Two polyethylene pipe dip tubes were attached and strapped to the rising main to allow for the installation of a Level Troll 400 data logger, and for the manual dipping of water levels during the test. The discharge rate was regulated using a geared butterfly valve, and monitored using 2 calibrated 100 mm magnetic flow units (Resource Water Group, 2016). A step-test comprising 5 increasing abstraction rates (2, 3, 4, 5, and 6 L/s) of 100 minutes each was first conducted to establish optimum discharge rates and the efficiency of the bore. The test was followed by a constant-rate pumping test that extended for 6 days at the maximum sustainable discharge rate of 5 L/s. Drawdown and recovery water-levels were measured both at the test bore and in one of the newly constructed monitoring bores, approximately 40 m apart. The results were finally interpreted by the use of available commercial software.

4. Results

4.1 Geology

In agreement with regional information, deposits historically attributed to the Wallal Sandstone have been extensively identified in the west – northwest of the study area, in surroundings of Derby. The unit primarily consists of poorly to moderate-sorted coarse, vitric sands near coastal areas, laterally interfingering with silty sands and discontinuous clays that conform up to 50 % of the sequence to the east. The formation is structurally uniform and little disturbed. Its contact with the underlying Munkayarra Shale appears to be unconformable, with an increase in the clay content from approximately 80 m bgl. The Wallal formation has long been attributed to the Jurassic (Geoscience Australia, 2018). However, the detection of pollen assemblages from the Cretaceous in two specimens from the underlying Munkayarra Shale, opens the debate about the stratigraphic relationships and age of the sediments. In effect, identification of dinocysts from the Late Aptian – Cenomanian in the Munkyarra Shale (Backhouse, 2015), would indicate a probable Late Cretaceous or younger age for the sands above. In the absence of any known Cretaceous rocks nearby these estimations must be treated with caution although, the presence of a younger formation not previously recognised in the area could not be ruled out. The underlying Munkayarra Shale was mostly identified from the coastal plains south of Derby up to about 40 km inland, on the western sections of the Meda pastoral station. The sediments are generally indurated to moderately compacted, either massive or with thin clays and silts interbedded. The conspicuous presence of green and red beds suggests regular changes in the redox environment, fluctuating between shallow waters and subaerial conditions. Structurally, the formation mostly infills the centre of a syncline that trends towards Derby, after an extended period of erosion in the Middle Triassic – Middle Jurassic. Thus, the unit appears gently folded, plunging northwest but, tilted upward and dissected near the coast. The shales do not underlie the Derby Peninsula (Laws and Smith, 1988), although results from the present study suggest that they are present in Knowsley, approximately 10 km to the south.

The Erskine Sandstone has a widespread distribution over the study area, either underlying the Munkayarra Shale or beneath a thin cover of Holocene sediments. Overall, the formation consists of thin intercalations of micaceous very-fine sands, carbonaceous silts, and grey and multi-coloured claystones, all of which are part of the WNW – ESE syncline previously discussed. Drilling data suggests that the northern limbs of the fold dip more steeply than in the south. Erosion would have stripped the top of the sequence throughout much of the centre and northern flank of the syncline, but it remains well represented on the opposite side of the hinge. On the basis of lithology and field relationships, the Erskine Sandstone was subdivided into 3 major members of distinct characteristics. Thus, the upper member is about 80 m thick and crops out mainly in the southern part of Yeeda and Meda stations, and in vicinities of the Great Northern Highway. The material is mostly a mixture of fine to coarse sands, gravels, and minor clayey sands in a powdery matrix enriched in iron oxides. The deposits are largely unsaturated, except for a few possible lenses of water sitting above impermeable layers. On occasions, some of the beds appear to be leached, possibly due to the effect of percolating waters. This is consistent with Thomas (2012), who postulated that sections of bleached sandstones in the Erskine Formation may be a relatively common feature, only masked by the significant ferrugination of the outcrops.

Underneath, the Middle Erskine member is represented by a bed of dark, dry, and indurated siltstones, approximately 25 thick. This subunit was extensively intercepted across the area, except in vicinities of the Gibb River Road, where it has been significantly eroded by the Munkayarra Shale. The distinctive composition and wide geographical extent of the siltstone makes it a useful diagnostic horizon across the catchment. The bed resembles the shale layer "Marker III" (GCS, 2008) previously identified near Derby therefore, it has been informally named the "Siltstone Marker" in the present work. Black, carbonaceous and massive shales suggest deposition in a closed or nearly closed basin, possibly marginal to the marine shore (e.g. lagoon) or in swampy areas of a delta.

The Lower Erskine member comprises fine to very fine sands, silts, and laminated mudstones with a total thickness exceeding 150 m. The structural geometry of the area results in the member to be exposed along the fringes of the syncline, especially in locations close to the May River in the north, and near the Great Northern Highway to the south. Elsewhere, the unit deepens below the land surface, to reach maximum depths (> 200 m) beneath the axis of the structure. The mineralogical composition includes subrounded vitric quartz, muscovite flakes, and traces of coal in a clayey matrix typically grey in colour. A very characteristic feature of delta deposits is their lamination (Botvinkina and Yablokov, 1963). In this respect, the intricate interfingering of sands, silt, and organic clays might be the result of deposition in a deltaic environment under a humid climate. The sands would reflect the infill of braided streams in an estuary unlike finer sediments which, would spread out in front of the river mouth under lower velocities. Grey mudstones would have developed on the submerged parts of the delta whilst, minor iron staining would be the result of subaerial exposure. Finally, coal debris is explained as plant and organic remains in swamps. The Erskine Sandstone conformably overlies the Blina Shale, typically characterised by dark-grey mudstones with minor pyrite and usually high contents of organic matter. A few small, generally saline supplies have been developed from the shale in the Derby area (Lindsay and Commander, 2006). Due to its thickness and relative low permeability, the unit was considered the basement of the sequence of interest

4.2 Hydrogeology

Results indicate that both the Wallal Sandstone and the Erskine Sandstone constitute the main aquifers hosting the bulk of groundwater in the study area. In consequence, the character of these units and the relationship between them directly influence the groundwater potential of the system. The Wallal Sandstone is an unconfined aquifer that represents a significant, if not the most significant, source of water supply near the coast. In general, the regional flow is to the northwest. Groundwater levels largely mimic the land surface, ranging from about 16.5 m AHD (48 m bgl) in the east, to less than 4 – 5 m AHD (~ 5 m bgl) in the littoral zone (Figure 3). Rainfall would be the primary source of recharge as the aquifer is unconfined and mostly subcropping under a thin cover of highly permeable Pindan soils. In contrast, evapotranspiration and seepage into the ocean would constitute the main mechanisms of groundwater discharge. Upward leakage from the underlying Erskine Sandstone is also known to occur where hydraulic connectivity is present (Laws and Smith, 1988). No evidence of connection was observed between the Wallal and the Erskine Sandstone in the project area therefore, it is argued that any direct contact between the aquifers is likely restricted to the Derby Peninsula. Specific yields from disturbed samples of the Wallal Sandstone were estimated at 0.28 (Leech, 1972). Based on a series pumping tests at 16 sites within the West Canning basin, Leech (1979) also estimated the aquifer transmissivity to average 340 m^2/day, with a mean hydraulic conductivity of 18.5 m/day. Similarly, Smith (1988) postulated that transmissivity values for the Wallal Sandstone range between 60 and 500 m^2/day whilst, the hydraulic conductivity is between 0.8 and 16 m/day. These results are in agreement with the interpretation of a 7-days pumping test performed at Mowanjum. Based on the Neuman solution for unconfined aquifers (Neuman, 1974), the transmissivity of the aquifer was estimated to be in the order of 273 m^2/day, which results in an average hydraulic conductivity of 4.8 m/day at the investigation site (Table 2). In spite of appearing to be too high, transmissivity values up to 2,500 m^2/day and therefore, a maximum average hydraulic conductivity of 43.9 m^2/day is not entirely ruled out in some parts of the aquifer (Global Groundwater, 2015). The high potential of the groundwater resource is further confirmed by airlift yields over 10 L/s in monitoring bores, and pumping rates over 60 L/s in large-diameter production bores. Groundwater samples from the Wallal Sandstone were categorized mainly as Na-Cl type, with a uniform character and composition across the area (Figure 4). In addition, the waters are essentially fresh, with an average electrical conductivity of 440 µS/cm, and pH values between 6.3 and 7.2. Low ionic contents suggest a limited rock-water interaction, possibly due to the relative low solubility of the host sandstones, rapid flow circulation and consequently, short groundwater residence times in the aquifer. The suitability of groundwater for irrigation is conditional on the effects of mineral constituents of water on both the plant and soil (Aksever et al. 2016). On average, the groundwater chemical composition falls within the ANZECC (2000) recommended levels for irrigation in Australia. For instance, the guidelines indicate that trigger values for chloride with respect to foliar injury and increased cadmium uptake from soils should be in the order of 175 mg/L. Concentrations below 90 mg/L indicate thus, high tolerance of crops to the Wallal Sandstone' waters. Similarly, groundwater sodium concentrations below 150 mg/L are expected to have no toxicity effects on soils or crop yields. Nevertheless, the development of an irrigation scheme should be assessed on a case by case basis and on site-specific conditions as several other factors such as the type of crop, soil adsorption ratios, and soil management and water management practices still play a critical role.

The Erskine Sandstone is another aquifer usually confined, but becoming phreatic when the formation comes close to the surface in the east. Regional folding controls the geometry of the deposits, which in turns influences the dip and thickness of the aquifer. Well-log data was insufficient to confirm the presence of linear structures. However, boreholes correlation and the electrical resistivity distribution underlined the occasional dislocation of strata hence suggesting, local offsets and the consequent discontinuity of the aquifer. The depth of the water table is approximately 75 m bgl (~48 m AHD) in bores close to the Great Northern Highway, up to about 5 m bgl (~4 m AHD) near the May River. This implies that the hydraulic gradient is south-southeast to north-northwest, which in a general sense is coincident with the slope of the land surface. The Siltstone Marker represents an impermeable aquitard of little importance for water abstraction but, it is a diagnostic horizon to guide the search of the water-bearing beds underneath. The Lower Erskine member is fully saturated, recharged by direct infiltration where the aquifer outcrops, and possibly by leakage through the siltstone in the confined sections. Vertical leakage could also be enhanced in the north of the study area due to the gradual thinning of the confining aquitards. A major part of the flow is intercepted by the May River which would constitute thus, the main area of interaction between the surface and groundwater systems.

The upper part and the lowermost section of the Lower Erskine Sandstone normally contain a higher proportion of sands and show a higher degree of sorting. Thus, they are relatively more permeable than other parts of the unit (Figure 5). The thickness of these confined and productive layers is about 45 m for the upper segment, and up to 55 m at the base of the aquifer. Yet, a thickness of 10 – 25 m is usually more frequent in the basal section. The highest yields were obtained along a northwesterly belt from the vicinities of the Gibb River Road up to the May River. In there, potentiometric heads are the highest (6 – 17 m bgl) and airlift yields in 100 mm-diameter bores reached a maximum of 11 L/s. Nevertheless, the 250 mm-diameter production bore placed at one of the sites yielded less than 5 L/s, which is considered to be the maximum rate that the aquifer could withstand over extended pumping periods. This decline in well yields is attributed to smaller screen slots (0.4 mm) and a tighter filter pack (0.5 – 1 mm), which in this case were specifically tailored to the aquifer materials. The transmissivity of the aquifer was obtained from a 6-days pumping test at the aforementioned production bore. Based on the Theis recovery solution (Theis, 1935), the bulk aquifer transmissivity in the confined section of the Erskine Sandstone would be approximately 260 m^2/day, and the storativity about 2.6 x 10^{-4} (RWG. 2016). This translates into an approximate average hydraulic conductivity of 3.6 m/day. Results from the rising-head slug tests indicated that hydraulic conductivity decreases to about 1 m/day towards the syncline axis. This is consistent with Laws and Smith (1988), who reported hydraulic conductivities from slug tests to range from 0.02 to 1.2 m/day. Thus, the complex intercalation of clayey lenses, and the fine-grained size of the arenaceous beds would severely reduce the ability of the formation to transmit water, making the aquifer throughout much of the centre and south of the study area poorly productive.

A section of the basal Erskine Sandstone outcrops south of the Great Northern Highway. Groundwater in this area is generally unconfined, with a water table at approximately 20 m bgl, and a total saturated thickness up to about 30 m. Both the soils and the underlying materials are highly permeable, confirming that rainfall contributes appreciably to groundwater recharge. Aquifer parameters at that location were obtained from a 7.5-hr single-well test using the Theis solution with drawdown correction (Jacob, 1944), as discussed by Kruseman and de Ridder (1990). The assumptions of the method were satisfied by the small relative drawdown and absence of a true delayed water table response during the test (Figure 6). The calculated transmissivity averaged 570 m^2/day, resulting in a hydraulic conductivity as high as 23 m/day. This much greater transmissivity value at that location is explained by the increase in sand contents and the effects of more homogeneous sediments on the effective porosity of the unit.

From the chemical point of view, groundwater in the Erskine Sandstone exhibits higher levels of mineralisation, although waters are largely suitable for irrigation (Table 3). The majority of the samples showed TDS values below 500 mg/L, falling within the "fresh water" category as defined by Freeze and Cherry (1979). The waters are neutral to mildly alkaline (pH 7.5 – 8.2), typically of the Na–Cl to Na–Cl–HCO_3^- type in the confined sections. Critical components such as sodium and chloride mostly remain within acceptable levels for irrigation and should be satisfactory for most salt-tolerant crops. No trigger value is recommended for bicarbonate in irrigation waters (ANZECC, 2000). However, higher concentrations of this element were measured in a few bores to the south, making groundwater in this area less desirable for irrigation equipment and soil structure.

5. Discussion

Findings from the study indicated that the western outcrops of the Wallal Sandstone, and the base of the Erskine Sandstone represent the primary sources of groundwater in the area. With a saturated thickness of 60 – 80 m, high transmissivity, and low salinity, the shallow sediments of the Wallal Sandstone between the Derby Highway and the 585,000E meridian (GDA94 MGA Z51) appear to be the most prospective for water abstraction (Figure 7). The potential of the aquifer is further confirmed by irrigation at the Mowanjum pastoral station, which resulted in bore yields above 60 L/s and minimum drawdowns. Rates as much as 150 L/s have been also reported at a nearby bore close to the Derby Highway (Global Groundwater, 2014). However, these values could be influenced by local conditions and are unlikely to be sustainable over the long-term. The thickness of the Wallal Sandstone reduces eastward, grading laterally into more clayey materials that restrict the water availability. Planning for future irrigation should also be accompanied by an assessment of impacts from the development. Hereof, the design of an optimal pumping scheme remains challenging. The aquifer already supplies dozens of domestic users around Derby and going forward, growing population and urbanization of the Derby Peninsula are expected to put further pressure on the resource. To make matters worse, climate change in northern Australia is accelerating at an increasing rate, with the first decade of 2000 – 2010 being the hottest on record (City of Darwin, 2011). Saline water intrusion is not only caused by a decrease in groundwater levels but also by rises in the sea level (Tularam and Krishna, 2009). Thus, potential seawater intrusion restricts pumping near the coast, and the severity of the threat needs to be evaluated in the context of climate change predictions for the region. Extensive outcrops of Wallal Sandstone were also identified on the low-lying plains north of the Gibb River Road. In here, there are several wells randomly drilled by land owners, but the information is limited. Thus, the groundwater availability in the area remains unclear, although extrapolation of this study's results suggests that the aquifer could produce good yields. Again, the proximity to Derby and the presence of drainage channels near the coast greatly reduce the potential of finding suitable sites for irrigated agriculture, but a closer examination is still required to verify these assumptions.

Due to the sediments' heterogeneity and predominant fine lithology, the Erskine Sandstone is considered to be a moderate to poorly productive groundwater unit. In general, only the uppermost segment and the basal sections of the Lower Erskine member emerge as relatively prospective aquifers, with typical discharge rates in the order of 5 L/s. As previously discussed, the Erskine Sandstone is part of a regional synclinal whose core separates 3 major hydrogeological zones: a) a shallow (< 100 m), moderately productive (~ 5 L/s), confined aquifer in the northern flank of the structure; b) a deeper (> 120 m), poorly productive unit (~ 2 L/s), beneath the Siltstone Marker throughout much of the southern flank and; c) an unconfined, productive (> 5 L/s) aquifer on the fringes of the southern flank, close to its contact with the Blina Shale. As such, the highest piezometric heads (6 – 17 m bgl) were measured in the north, indicating a component of groundwater discharge into the May River. In view of these shallow heads, the greater proportion of sands, and generally low TDS contents (< 350 mg/L), the area is considered to be a suitable target for the development of a rural water-supply scheme. A shallow aquifer reduces the depth of the wells to be installed and would replenish more rapidly, making the resource more desirable for abstraction. Concurrently, additional pumping will also intercept northern groundwater flows to the May River therefore, any irrigation development must be preceded by an assessment of the river – aquifer interaction and potential detrimental impacts on associated ecosystems.

Indurated and fairly impermeable siltstones overlie the Erskine Sandstone near the axis of the syncline. In here, the aquifer is at its deepest, at more than 140 m bgl. In terms of lithology, the sediments exhibit similar proportions of very fine sands and silts, often intercalated with clayey materials and carbonaceous shales that difficult the identification of distinct aquifer zones. Piezometric heads were observed to reach up to approximately 45 m bgl however, the high content of fine materials, reduced hydraulic conductivities (~ 1 m/day), and the depth and cost to access the resource make the locality poorly prospective for groundwater supply.

Complete sections of the Erskine Sandstone have been recognised on the southern flank of the fold (i.e. north of the Great Northern Highway), as the elevation of the terrane increases. The uppermost members are largely unsaturated hence, irrelevant as a water resource. At a minimum depth of 70 – 100 m bgl, the Lower Erskine member shows similar characteristics to its counterpart in the north. Airlift rates revealed that the aquifer at the location is generally low yielding (< 3 L/s), possibly due to unnoticed higher clay contents, and structural control. There is no conclusive evidence about the presence of faults or structural lineaments, although it is argued that fracture zones might be concealed and would not easily be identified. This could cause the compartmentalisation of major portions of the aquifer and the consequent disruption of the groundwater flow. It is important to realise that groundwater characteristics will most likely be different among structural blocks, due to changes in recharge and discharge areas, duration of groundwater flow, and the location, continuity, and hydrologic connectivity of lineaments (Hanich et al. 2011). Thus, water-quality variations in bores at the southern flank of the syncline might be explained to be caused by the aforementioned compartmentalisation and changes in the local geology.

The base of the unconfined Erskine Sandstone south of the Great Northern Highway, constitutes another zone of reasonable groundwater potential. The aquifer outcrops in a topographically high plateau and as such, it would receive its water directly from rainfall. Fresh groundwater, a relatively shallow water table (< 30 m bgl), and high hydraulic conductivity values (up to 23 m/day) make the groundwater resource acceptable for stock or domestic purposes. Nevertheless, the aquifer capacity for irrigated agriculture is dubious due to the limited saturated thickness of the formation (~ 25 m).

At a regional scale, the water budget of the aquifers in consideration has only a few significant components: rainfall recharge, lateral subsurface flow, outflows to the ocean, and evapotranspiration losses. Riverbank and streambed infiltration would take place near the May River. Stock and domestic water use, irrigation recharge, and return flows would represent only a small percentage of the hydrologic balance outside the Derby Peninsula. The prevalence of sandy Pindan soils throughout, and the absence of a defined stream network suggests that infiltration of precipitation in outcrop and subcrop areas accounts for the vast majority of the recharge into the system. Based on a comparison of the relative concentration of chloride in rainfall and groundwater, the present-day effective recharge to the Wallal Sandstone would approximate 3 % of the average precipitation, while the Erskine aquifer would receive approximately 1 % of that rainfall. Although somewhat lower, the results are close to calculations by Laws and Smith (1988), who estimated rainfall infiltration to be in the order of 3 % and 2 % for the Wallal and Erskine aquifers respectively. Knowing the approximate areal extent of the aquifers and the mean precipitation over the last decade, the total recharge was estimated as:

Total aquifer recharge = aquifer surface area x 10-year mean rainfall x effective recharge (1)

Coastal areas west of the Derby Highway were neglected, as the risk of saltwater intrusion would preclude any major use of groundwater. As the aquifers deepen, inflows into the confined sections would occur at a large time-scale and would be less immediate than direct recharge from precipitation (Petre et al. 2016). For simplicity's sake however, it was assumed that rainfall is transmitted uniformly downwards into the aquifer. Based on equation (1), present-day groundwater recharge would approximate 11.5 GL/year for the Wallal Sandstone, and about 22 GL/year for the Erskine Sandstone. These estimates quantify the amount of renewable water, but do not address what the sustainable extraction would be. In this regard, the concept of safe yield has been used by several hydrogeologists to establish the limits of pumpage from an aquifer (Sakiyan and Yazicigil, 2004). Safe yield is the rate at which groundwater can be withdrawn from an aquifer without causing an undesirable adverse effect (Todd, 1959; Dottridge and Jaber, 1999; Voudouris 2006)). Traditionally, it is expressed as a fraction of recharge. Limited experience suggests that average percentages may be around 40 %, which reflect the need to consider other factors besides conservation (Ponce, 2007). Following this approach, acceptable safe yields for the Wallal and Erskine Sandstone aquifers were calculated to total 4.5 GL/year and 8.7 GL/year respectively (Table 4). It can be concluded thus, that exploitation of the groundwater resource up to those volumes should remain within sustainable levels. Needless to say, any prospect of commercial groundwater abstraction will need yet to assess the interdependency with other factors and potential impacts on the surrounding ecosystem.

6. Uncertainties and limitations

The study provides an overall picture of the distribution and functioning of some of the aquifers with potential for irrigation supply in the West Kimberley region. Nevertheless, interpretation of the geological sequence and delineation of aquifer boundaries is an ongoing process that will improve along with additional drilling and a denser monitoring network. Similarly, hydraulic conductivity and transmissivity estimates are functions of test scale (Dagan, 1986). The larger the test area, the more the aquifer heterogeneity and properties' variability. Thus, the estimates of hydraulic parameters presented herein represent at best some average value, but might not be representative for the entire formation. The mapping of linear features is one of the keys to understanding groundwater occurrence (Sander, 2007). Fractures zones appear somewhat concealed and could not be clearly identified with the current data available. Thus, the distribution and significance of the lineaments remain inconclusive and open to further work. Finally, additional recharge data is needed to better quantify safe yields. A uniform recharge has been applied to estimate replenishment rates in the Erskine Sandstone. Vertical leakage was probably overestimated in the confined sections of the aquifer therefore, total inflows into those areas should be considered as a maximum. The simplifications and uncertainties discussed certainly complicate the hydrogeological interpretation but overall, the study still provides sufficient quantitative data to expand our understanding of the system and to contribute to a better management of the aquifers in the region.

7. Summary and conclusions

A hydrogeological investigation was carried out in areas of the West Kimberley region of WA for the identification of groundwater prospective zones suitable for agricultural irrigation. The majority of the groundwater is hosted by sediments historically attributed to the Wallal Sandstone, and to a minor extent by the lower member of the Erskine Sandstone underneath. Palynology results suggest that sediments from the Wallal Sandstone could be younger than previously thought. From a groundwater-resource perspective, the western outcrops of the Wallal Sandstone would be the most favourable for abstraction. This is confirmed by the high water-quality and bore yields in excess of 60 L/s. In contrast, there is an increase of fine-grained materials throughout much of the eastern part of the aquifer rendering the area less attractive for water supply.

The Erskine Sandstone has been interpreted to be part of an asymmetrical syncline trending towards the Derby Peninsula. The aquifer is typically confined around the syncline hinge whilst, unconfined conditions are prevalent along the structure flanks and nose. The chief source of water is located within the lower member of the sequence. Nonetheless, the heterogeneity of the sediments makes the aquifer poor to moderately productive in most places. Hydrochemistry results indicate that as a whole, groundwater is adequate for irrigation.

It was estimated that groundwater would replenish at a rate close to 11.5 GL/year in the Wallal Sandstone, and 22 GL/year in the Erskine Sandstone. Adopting a safe yield of 40 %, it was concluded that groundwater abstraction from the Wallal Sandstone should limit to 4.5 GL/year. In turn, optimal safe groundwater yields from the Erskine Sandstone would be in the order of 8.7 GL/year. Additional water reserves could be found in vicinities of Derby and near the coast however, their exploitation would be restricted by the town-water supply and potential saltwater intrusion.

The present investigation provides authorities and planners with critical information about the availability and quality of the groundwater resource in the West Kimberley. Results can be used as a tool to guide management strategies and to formulate the corresponding water conservation and regulation policies. Additionally, the present work constitutes the basis to address more specific questions about sustainable development in the region. In this regard, future investigations are expected to test the robustness of the concepts here presented, and will aid in the understanding of the groundwater dynamics.

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the ways of overcoming this disadvantage is through participation

References

Aksever, F., Davraz, A., Bal, Y. 2016. Assessment of water quality for drinking and irrigation purposes: a case study of Başköy springs (Ağlasun/Burdur/Turkey). Arab J Geosci. 9, 748. DOI 10.1007/s12517-016-2778-y.

Allen, AD., Laws, AT., Commander, DP. 1992. A review of the major groundwater resources in Western Australia. Report to Kimberley Water Resources Development Office.

ANZECC, 2000. Paper No. 4 Australian and New Zealand guidelines for fresh and marine water quality. Volume 1 – The Guidelines. Available at http://www.environment.gov.au/water/quality/publications/australian-and-new-zealand-guidelines-fresh-marine-water-quality-volume-1. (accessed 15 October, 2018).

Australian Bureau of Statistics, 2016. National aboriginal and Torres Strait islander social survey, 2014-2015. Canberra, 10p.

Backhouse, J. 2015. Palynology results for 3 boreholes, Mowanjum irrigation trial, near Derby. Report prepared for the Department of Water, May 2015. 5p.

Botvinkina, L.N., Yablokov, V.S. 1963. Specific features of deltaic deposits in coal-bearing and cupriferous formations. In: van Straaten, L.M.J.U (Ed.), Developments in Sedimentology Volume I - deltaic and shallow marine deposits. Proceedings of the sixth international and sedimentological congress. The Netherlands and Belgium – 1963. Elsevier Publishing Company.

Butler, J.J., Jr. 1998. The design, performance, and analysis of slug tests. Lewis Publishers, New York, 252p.

Centre of Excellence in Natural Resource Management, 2010. Fitzroy Catchment Management Plan. Centre of Excellence in Natural Resource Management, the University of Western Australia. March 2010. 85p. Available at http://www.environskimberley.org.au/wp-content/uploads/2014/11/Fitzroy-Catchment-Action-Management-Plan.pdf. (accessed 30 July 2018).

CSIRO, 2009. Water in the Timor Sea Drainage Division. A report to the Australian Government from the CSIRO Northern Australia Sustainable Yields Project. CSIRO Water for Healthy Country Flagship, Australia.

City of Darwin, 2011. Climate change action plan 2011 – 2020. 52 p. "Living report" available at https://www.darwin.nt.gov.au/sites/default/files/DCC_ClimateChangeActionPlan_web.pdf (accessed 20 July 2018).

Department of Water, 2008. Derby water reserves drinking water source protection plan – Derby town supply. Water protection series: report No. 98, 43p.

Kimberley Development Commission, 2018. Kimberley demographics. Available at http://kdc.wa.gov.au/economic-activity/demographics/(accessed 19 June 2018).

Fitzpatrick, A., Munday, T.J., Cahill, K., Stelfox, L. 2011. An interpretation of SkyTEM airborne EM data for the Fitzroy River, Western Australia: Final Report. CSIRO Water for a Healthy Country Flagship. Technical Report No. CESRE P2010/1235.

Dagan, G. 1986. Statistical theory of groundwater flow and transport: pore to laboratory, laboratory to formation, and formation to regional scale, Water Resour Res., 22 (9), 120S – 134S.

Dottridge, J., Jaber, N.A. 1999. Groundwater resources and quality in northeastern Jordan: Safe yield and sustainability. Applied Geography 19, 313 – 323.

Freeze R.A, Cherry J.A. 1979. Groundwater. Englewood Cliffs, Prentice- Hall.

GCS (Groundwater Consulting Services Pty Ltd). 2008. Study for Derby groundwater management plan review. Report prepared for the Department of Water, Perth, 58p.

Geoscience Australia, 2018. Australian Stratigraphic Units Database. Available at http://dbforms.ga.gov.au/pls/www/geodx.strat_units.sch_full?wher=stratno=27250 (accessed 10 October 2018).

Gibson, D.L., Crowe, R.W.A. 1982. 1:250 000 Geological Series – Explanatory notes Mount Anderson Sheet SE/51-11 International Index, Australian Government Publishing Service, Canberra.

Global Groundwater, 2014. Derby – Mowanjum Station Bore Appraisal for Department of Water. Global Groundwater Hydrogeologists, 93p

Global Groundwater, 2015. Mowanjum station test pumping and bore capacity production bore MW15PB001. Report prepared for Department of Water, 46p.

Guppy, D.J., Lindner, A.W., Rattiggan, J.H., Casey, J.N. 1958. The geology of the Fitzroy Basin, Western Australia. Bur. Min. Resour. Aust., Bull. 36.

Hanich, L., Zouhri, L., Dinger, J. 2011. Characterization of the Cretaceous aquifer structure of the Meskala region of the Essaouira Basin, Morocco. J. African Earth Sciences 59, 313 – 322.

Harrington, G.A., Stelfox, L., Gardner, W.P., Davies, P., Doble, R., Cook., P.G. 2011. Surface water-groundwater interactions in the Lower Fitzroy River, Western Australia. Technical Report, August 2011, CSIRO Water for a Healthy Country, 54pp.

Harrington, G.A., Harrington, N.M. 2015. Lower Fitzroy River groundwater review. A report prepared by Innovative Groundwater Solution for Department of Water. 111p.

Hvorslev, M.J. 1951. Time Lag and Soil Permeability in Ground-Water Observations, Bull. No. 36, Waterways Exper. Sta. Corps of Engs, U.S. Army, Vicksburg, Mississippi, pp. 1 – 50.

Jacob, C.E., 1944. Notes on determining permeability by pumping tests under water-table conditions. U.S. Geological Survey Mimeo Report, US Geological Survey, Reston, VA.

Inverarity, K., Heinson, G., Pedler-Jones, D., Wurst, S., Mclean G., Simmons, C. 2011. Locating groundwater resources for Aboriginal communities in remote and arid parts of South Australia. The Leading Edge April 2011, 402 – 408. Groundwater for Sustainable Development 7, 212 – 219.

Iqbal, J., Nazzal, Y., Howari, F., Xavier, C., Yousef, A. 2018. Hydrochemical processes determining the groundwater quality for irrigation use in an arid environment: The case of Liwa Aquifer, Abu Dhabi, United Arab Emirates.

Laws, A.T., Smith, R.A. 1988. Derby regional groundwater investigation 1987. Hydrogeology report 1988/18. Geological survey of Western Australia, pp38.

Leech, R.E.J., 1972. Derby town water supply. Geological Survey of Western Australia, Record No. 1972/15. 8p.

Leech, R.E.J., 1979. Geology and groundwater resources of the Southwestern Canning Basin, Western Australia. Geological Survey of Western Australia. Record 1979/9. Perth 1979. ISBN No. 072448034X.

Li P., Qian H., Wu J. 2018. Conjunctive use of groundwater and surface water to reduce soil salinization in the Yinchuan Plain, North-West China. International Journal of Water Resources Development, 34 (3): 337–353. doi:10.1080/07900627.2018.1443059

Lindsay R., Commander D. 2006, Hydrogeological Assessment of the Fitzroy Alluvium. Department of Water Hydrogeological Record Series Report HG16. 41p.

Mory, A.J. 2010. A review of mid-Carboniferous to Triassic stratigraphy, Canning Basin, Western Australia. Geological Survey of Western Australia, Report 107, 130p.

Mory, A.J., Hocking, R.M. 2011. Permian, Carboniferous and Upper Devonian geology the northern Canning Basin, Western Australia — a field guide: Geological Survey of Western Australia, Record 2011/16, 36p.

Moussa, A.B., Salem, S.B.H., Zouari, K., Jelassi, F. 2017. Hydrochemical and stable isotopic investigation of groundwater quality and its sustainability for irrigation in the Hammamet-Nabeul basin, northeastern Tunisia. Arabian J. Geos. 10, 446. https://doi.org/10.1007/s12517-017-3233-4

Neuman, S.P., 1974. Effect of partial penetration on flow in unconfined aquifers considering delayed gravity response. Water Resour Res. 10 (2), 303 - 312.

Petre, M-A., Rivera, A., Lefebvre, R., Jim Hendry, M., Attila, J., Folnagy, B. 2016. A unified hydrogeological conceptual model of the Milk River transboundary aquifer, traversing Alberta (Canada) and Montana (USA). Hydrogeol. J. 24, 1847–1871.

Ponce, M.V. 2007. Sustainable yield of groundwater. Groundwater resources Association, 17th Annual Conference and Meeting, San Diego, California.

Ramesh, H., Mahesha, A. 2006. An overview of planning and management of rural water supply – a case study. ISH Journal of Hydraulic Engineering, 12 (1), 61–72.

Rockwater, 1987. ACP No.1 artesian bore completion report Broome, WA. Report for Australian City Properties Pty Ltd.

Resource Water Group, 2016. Test pumping report. Erskine production bore ER16PB001 Knowsley area. Report prepared for Department of Water – Water for Food, 30p.

Ross, J.B. 2014. Groundwater resource potential of the Triassic Sandstones of the Southern Sydney Basin: an improved understanding, Australian Journal of Earth Sciences, 61:3, 463 – 474, Doi:10.1080/08120099.2014.910548.

Saha, R., Dey, N.C., Rahman, S., Galagedara, L., Bhattacharya, P. 2018. Exploring suitable sites for installing safe drinking water wells in coastal Bangladesh. Groundwater for Sustainable Development 7, 91 – 100.

Sander, P. 2007. Lineaments in groundwater exploration: a review of applications and limitations. Hydrogeology Journal 15, 71–74.

Smith, R.A. 1988. Slug testing of Derby regional groundwater investigation bores. Geological Survey of Western Australia, Hydrogeological Report 1988/21.

Theis, C.V. 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage, Am. Geophys. Union Trans., 16, 519 –524.

Thomas, M.C. 2012. Erskine Sandstone Formation; a provenance and geochronological study within the Fitzroy Through, Western Australia. Bcs Thesis, University of Adelaide. 76p.

Todd, D.K. 1959. Ground Water Hydrology. John Willer & Sons, USA.

Tularam, G.A., Krishna, M. 2009. Long term consequences of groundwater pumping in Australia; a review of impacts around the globe. J. Applied Sci. Env. Sanitation 4 (2), 151–166.

Voudouris, K.S. 2006. Groundwater balance and safe yield of the coastal aquifer system in NEastern Korinthia, Greece. Applied Geography 26, 291 – 311.

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Table 1. Summarised stratigraphy of the study area.

Formation	**Accepted Age**	**Postulated age**	**Palynology results**	**Lithology**	**Maximum thickness in study area**
ALLUVIUM	Quaternary	-	-	Silts, sands, minor gravels	40 m
WALLAL SANDSTONE	Early to Late Jurassic	Post-Cretaceous	-	Sandstones, minor silts	90 m
MUNKAYARRA SHALE	Middle to Late Triassic	Middle Jurassic – Late Cretaceous	Callovian to Kimmeridgian Late Aptian to Cenomanian	Shales, siltstones	100 m
ERSKINE SANDSTONE	Late Early – Middle Triassic	-	Scythian to Anisian	Fine sands and silts	265 m
BLINA	Early Triassic	-	-	Shales, minor sands	~ 400 m

Table 2. Estimated hydraulic parameters of the aquifer system.

Formation	Aquifer character	Maximum bore yields (L/s)	Average Transmissivity (m^2/day)	Hydraulic Conductivity (m/day)	Storativity	Specific yield (Sy)
WALLAL SANDSTONE	Unconfined	66	273	4.8	–	0.28
ERSKINE SANDSTONE	Confined – unconfined aquifer	4.5	260	3.6	2.6 x 10^{-4}	0.2

Table 3. Results of chemical analysis for major ions in the study area.

	Statistics	K^+ *mg/L*	Na^+ *mg/L*	Ca^{2+} *mg/L*	Mg^{2+} *mg/L*	Cl^- *mg/L*	SO_4^{2-} *mg/L*	HCO_3^- *mg/L*	N *mg/L*	pH	TDS *mg/L*
Wallal Sandstone	No. samples	11	11	10	10	11	11	11	11	11	11
	Minimum	36	1.4	2.1	5	50	5	19	3.1	6.3	174
	Maximum	68	6.4	5.3	9.2	89	5	35	7.1	7.3	270
	Mean	44.6	4.5	4.3	7.1	72.4	5.0	24.1	5.7	7.0	244
	Median	40	4.4	4.4	7	70	5	22	5.4	7.0	250
Erskine Sandstone	No. samples	9	9	9	9	9	9	9	9	9	9
	Minimum	40	6.3	2.5	3.3	60	9	34	0.02	6.6	149
	Maximum	150	32	71	18	280	82	110	0.6	8.2	570
	Mean	84.0	12.9	13.9	9.0	122.8	20.8	59.2	0.2	7.4	305
	Median	82	9.9	4.8	6.8	90	12	43	0.12	7.2	300
Irrigation guidelines (ANZECC 2000)			<115			<175			5-25	6-8.5	<520

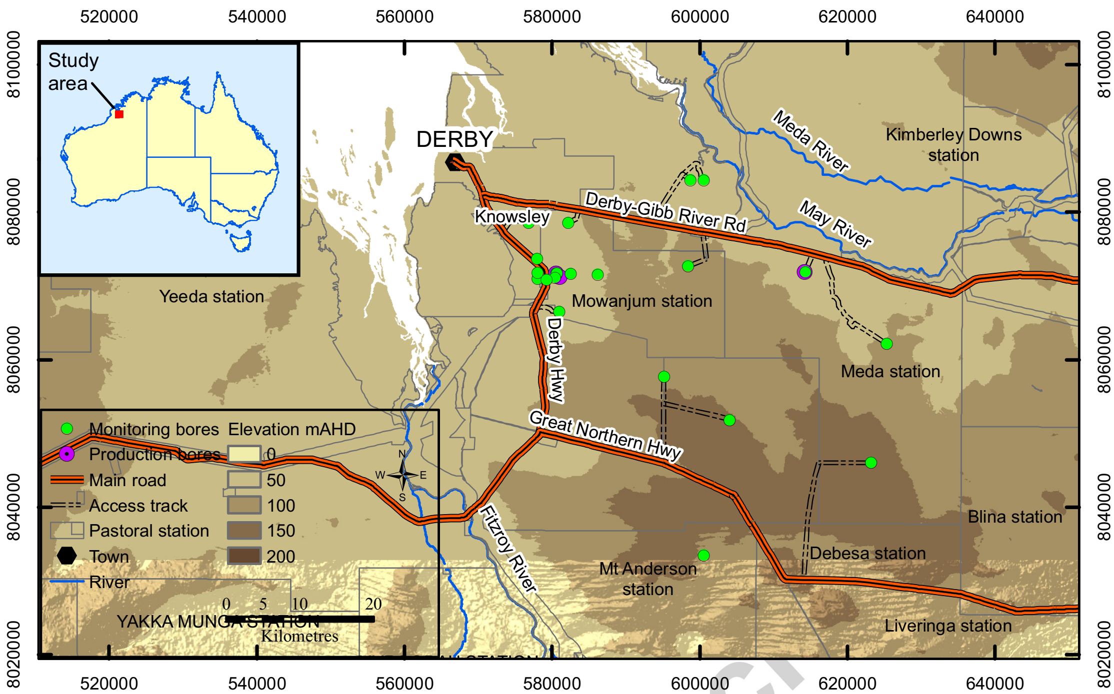
Table 4. Groundwater availability and safe yield.

Aquifer	Aquifer character	Area (km^2)	Groundwater recharge (GL/year)	Safe yield (GL/year)
Wallal Sandstone	Unconfined	490	11.4	4.5

Erskine Sandstone	Unconfined	2,100	16.8	6.7
Erskine Sandstone	Confined	630	5.05	2.0

Highlights

- Potential groundwater resources were explored in the West Kimberley, Australia
- The bulk of groundwater was found in the Wallal and Erskine Sandstone formations
- Aquifers' recharge would range between 1 % and 3 % of the average annual rainfall
- The safe yield of the entire aquifer system was estimated to approximate 13 GL/year
- Groundwater in the study area is typically suitable for agricultural irrigation



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May River
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Yeeda station
Mowanjum station
Derby Hwy
Meda station
Great Northern Hwy
Fitzroy River
Blina station
Debesa station
Mt Anderson station
Liveringa station
YAKKA MUNGA STATION
Monitoring bores
Production bores
Main road
Access track
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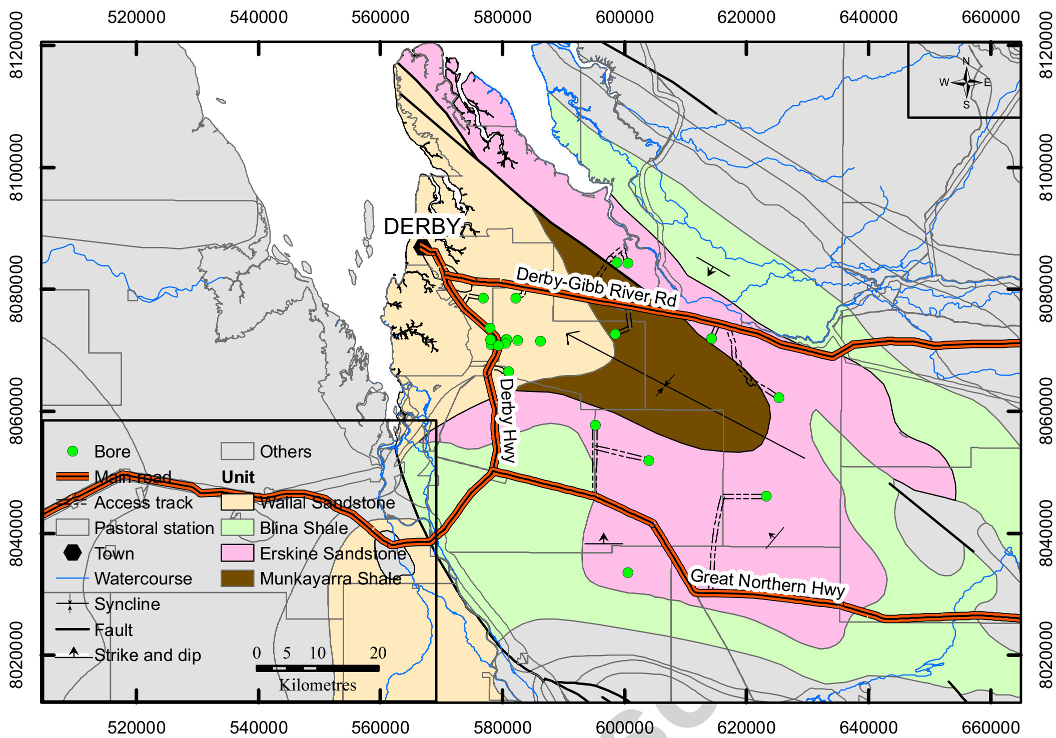
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Derby Hwy
Great Northern Hwy
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Bore
Main road
Access track
Pastoral station
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Watercourse
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Erskine Sandstone
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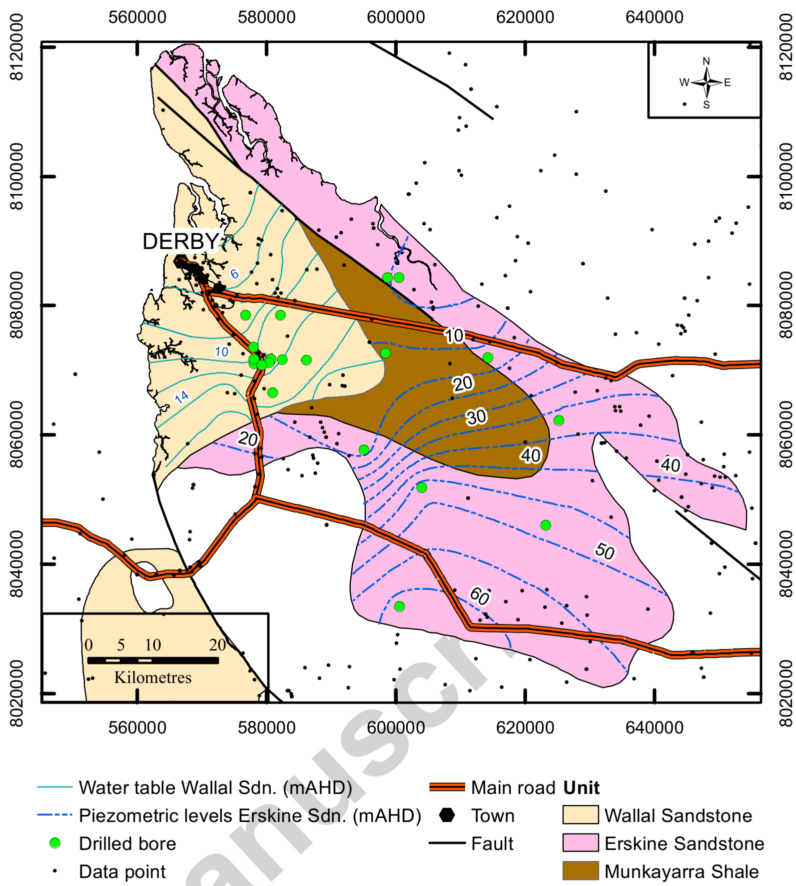
Kilometres



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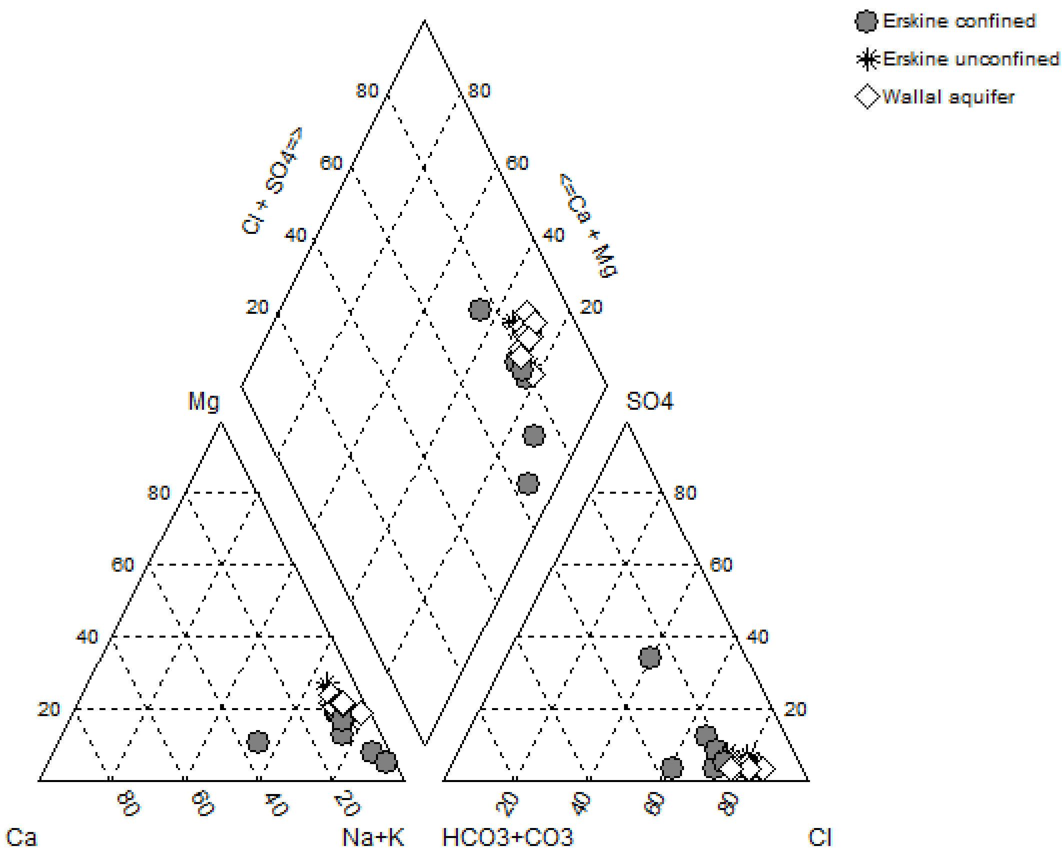
Water table Wallal Sdn. (mAHD)
Piezometric levels Erskine Sdn. (mAHD)
Drilled bore
Data point
Main road
Town
Fault
Unit
Wallal Sandstone
Erskine Sandstone
Munkayarra Shale


Erskine confined
Erskine unconfined
Wallal aquifer
Cl + SO4=>
<=Ca + Mg
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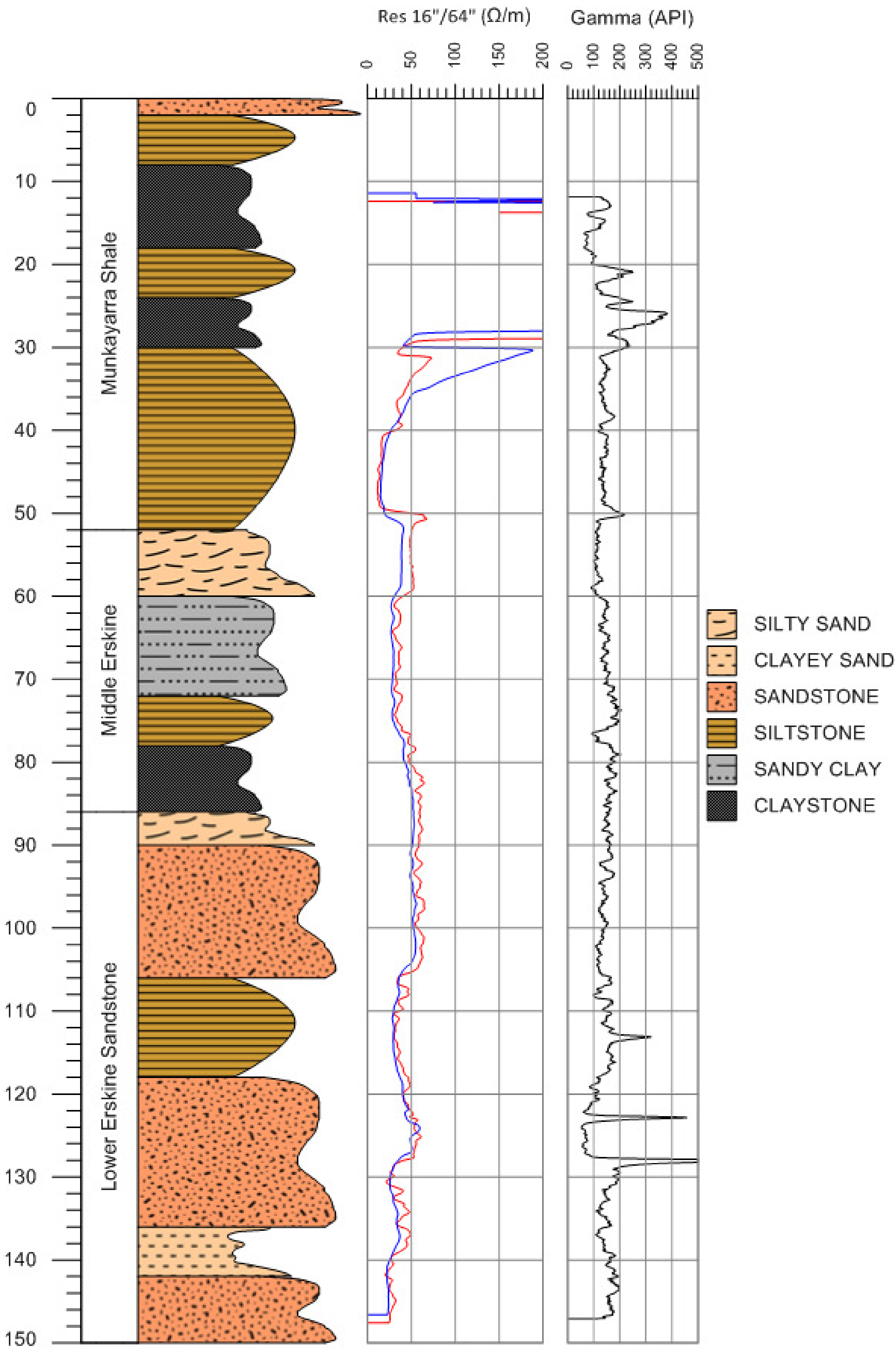
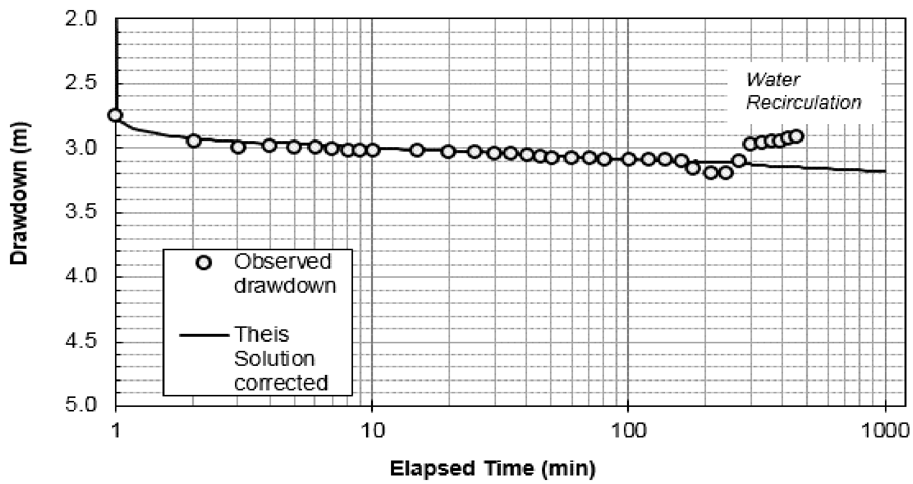
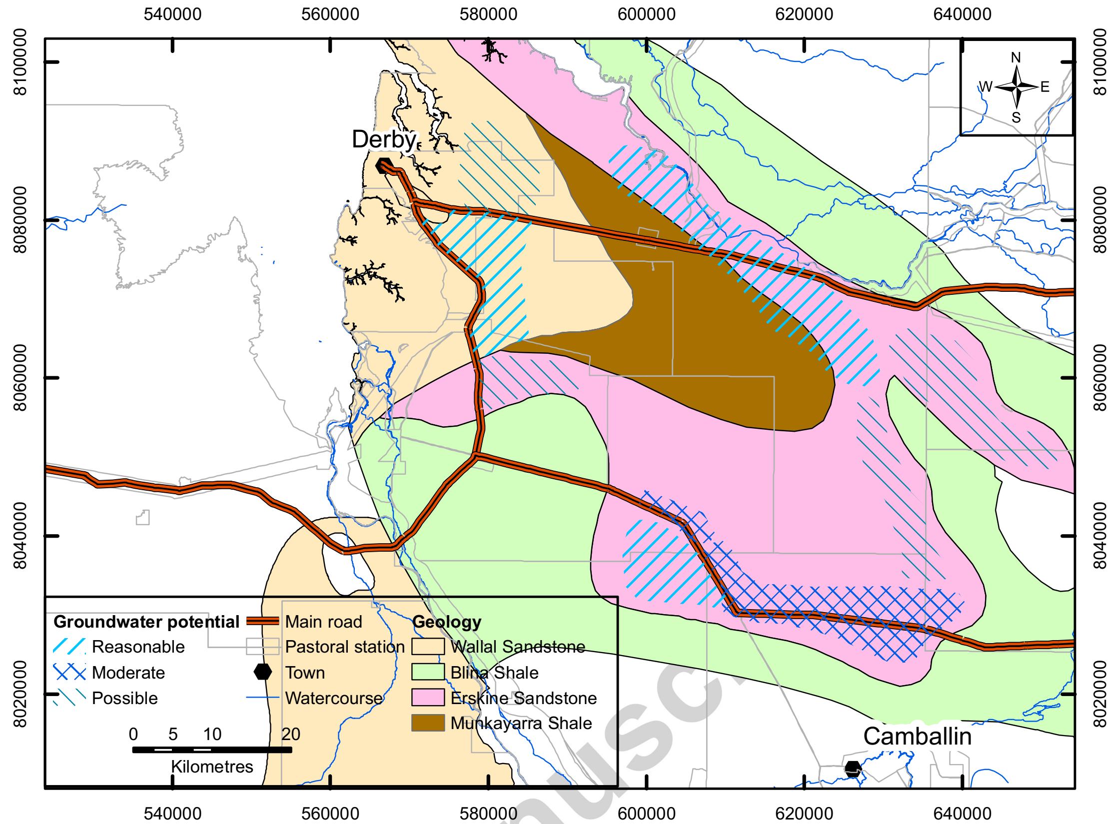
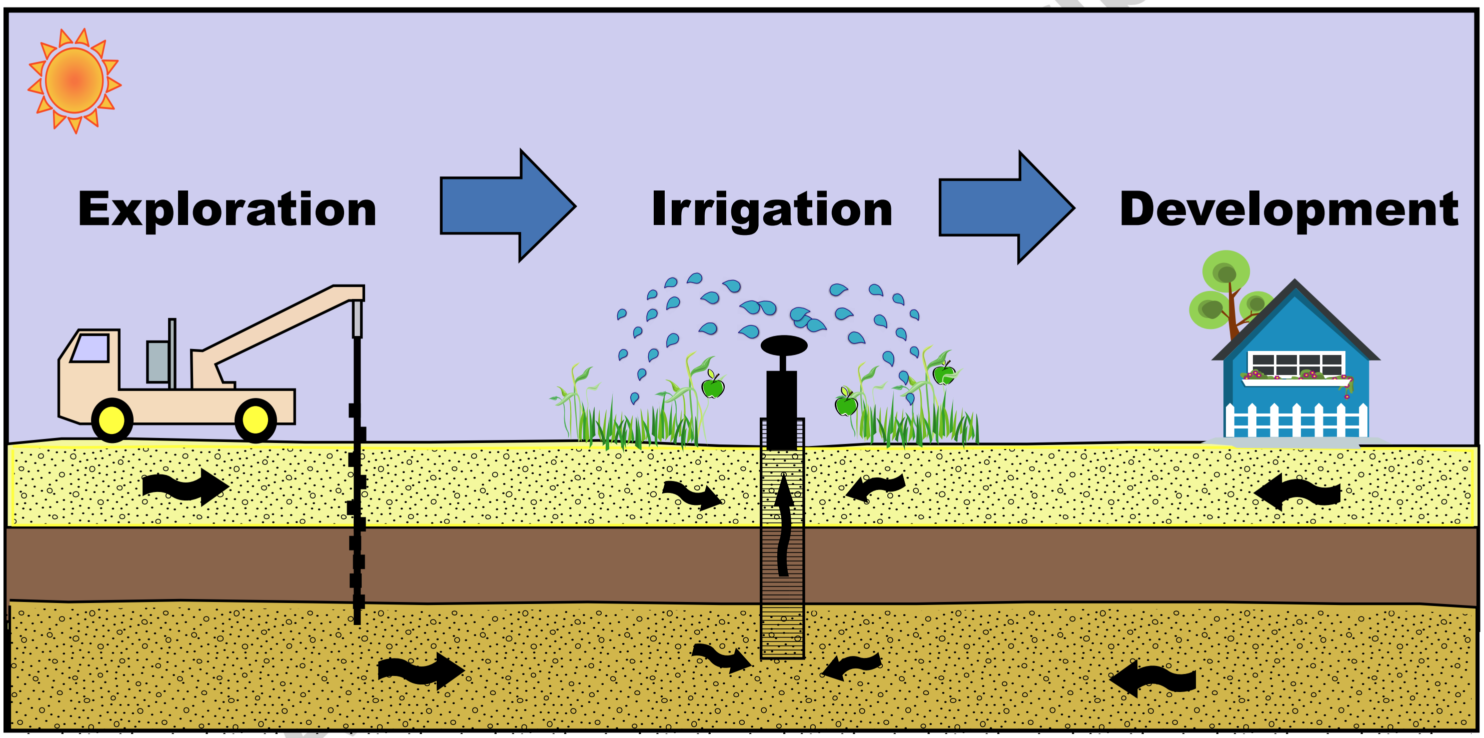


Res 16"/64" (Ω/m)
Gamma (API)
0
50
100
150
200
0
100
200
300
400
500
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Munkayarra Shale
Middle Erskine
Lower Erskine Sandstone
SILTY SAND
CLAYEY SAND
SANDSTONE
SILTSTONE
SANDY CLAY
CLAYSTONE


2.0
2.5
3.0
3.5
4.0
4.5
5.0
Drawdown (m)
Water Recirculation
Observed drawdown
Theis Solution corrected
1
10
100
1000
Elapsed Time (min)


540000
560000
580000
600000
620000
640000
8100000
8080000
8060000
8040000
8020000
N
W
E
S
Derby
Camballin
Groundwater potential
Reasonable
Moderate
Possible
Main road
Pastoral station
Town
Watercourse
Geology
Wallal Sandstone
Blina Shale
Erskine Sandstone
Munkayarra Shale
0 5 10 20
Kilometres


Exploration
Irrigation
Development