Mapping groundwater potential zones using remote sensing and geographical information systems in a fractured rock setting, Southern Flinders Ranges, South Australia

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In Australia, water resource management is a major socio-economic and environmental issue and an essential component of progress. This is more acute in arid and semi-arid regions of Australia. The Southern Flinders Ranges townships of Quorn and Hawker in common with much of the Flinders Ranges suffers from a lack of reliable data to help water resource managers. This paper discusses the delineation and assessment of groundwater potential zones using remote sensing and geospatial techniques in the region, using multi-criteria analyses. The study integrates many thematic layers (rainfall, lithology, lineament density, topographic wetness, slope and aspect) in a GIS environment in order to identify groundwater potential zones. Weights are assigned to class attributes within and between each thematic data layer using an Analytical Hierarchy Process based on the relative importance of each layer. The weighted thematic data layers are then combined to produce a probability of groundwater potential zone map of each study area. The groundwater potential zones were verified with available water data, and showed consistency with the interpretations.

Keywords. Geographical information systems; groundwater exploration; fractured rocks; lineaments.

1. Introduction

In areas of scarce water supplies, a more active approach to management of both potable and non-potable water resources is required. In its Water for Good plan, the Government of South Australia identified the need to manage non-prescribed water resources to avoid over-exploitation and enhance sustainability. South Australia is the driest state in the driest inhabited continent on Earth. More than one-third of its land area is underlain by fractured rock with low primary porosity (Lau et al. 1987). Groundwater in traditional sedimentary aquifers is generally well managed but is either over- or close to fully-allocated. However, limited knowledge of the occurrence, storage and quality of groundwater resources in fractured rock areas creates significant difficulties in the management and future development of groundwater systems in South Australia. Addressing this gap is essential because of increase in water demand, land use change and potential impacts of climate change.

Captured rain water and surface water provide reticulated water to the main population centres
and key surrounding agricultural regions. However, for more remote townships across regional South Australia, groundwater is the main source. The Flinders Ranges region in South Australia is almost completely dependent on natural springs, wells and bores fed by groundwater stored in fractured rocks to support the pastoral industry, tourism, mining and domestic users (Clark and Brake 2008, 2009; Alcoe and Berens 2011). Concurrent with an increase in tourism and mining activities in the Flinders Ranges, the dependence on groundwater in this region has also increased resulting in deterioration of water quality (Alcoe and Berens 2011). Except for minor supplies in recent alluvial deposits, most groundwater is sourced from fractured Neoproterozoic–Cambrian metasediments. The hydrogeology of the Flinders Ranges region has not been extensively studied and little is known about the size or quality of the resource to support future demands. Therefore, it is important to understand the groundwater resources of this region for its sustainable development.

Groundwater potential zone (GPZ) mapping is a classic multi-criteria decision problem (Eastman 1999; Steele et al. 2009) where the groundwater potential at any given location is determined by the relative importance of site-specific contributing factors. While the choice of factors for inclusion in the modelling process will vary depending on the scale of work being conducted and local variables (Díaz-Alcaide and Martínez-Santos 2019), the relevant factors chosen for this study were, rainfall, lithology, lineament density, topographic wetness, slope and aspect. A range of multi-criteria evaluation (MCE) techniques have been adopted by researchers to combine factors into an index of evaluation, which are broadly defined by their weighting procedure (Machiwal et al. 2014). Most widely used GPZ mapping procedures are knowledge-driven, where GPZ maps are generated by employing a weighted linear combination (WLC) of factors (Malczewski 2000) where weights are either directly assigned to factors based on subjective expert knowledge (Deepika et al. 2013; Nag and Ghosh 2013; Kumar and Karuppannan 2014; Elbeih 2015; Senanayake et al. 2016; Yeh et al. 2016; Kumar et al. 2017) or by using a more objective assessment such as the multi-influencing factor (MIF) approach (Magesh et al. 2012; Manikandan et al. 2014; Al-Ru zouq et al. 2015; Das and Pardeshi 2018; Mishra et al. 2019) or the analytical hierarchy process (AHP) developed by Saaty (1977) such as Jha et al. (2010), Agarwal et al. (2013), Ramu and Vinay (2014), Razandi et al. (2015), Zeinolabedini and Esmaeily (2015), Maheswaran et al. (2016), Yin et al. (2018) and Arulbalaji et al. (2019).

Less frequently used GPZ mapping procedures are data-driven where weights are developed by establishing a relationship between dependent (groundwater data) and independent variables (factors). Examples include probabilistic frequency ratio (Razandi et al. 2015; Balamurugan et al. 2017; Abrams et al. 2018), logistic regression (Ozdemir 2011; Chen et al. 2018), weights-of-evidence (Ozdemir 2011; Lee et al. 2012; Madani and Niyazi 2015) and more recently, machine learning using large groundwater datasets (Martinez-Santos and Renard 2019).

Data-driven methods require statistically robust borehole information to drive the modelling and validation process. In this study, high-quality borehole information was limited and considered only for general interpretations of results. This was largely due to the uneven distribution of well locations within the two study areas under investigation and where most wells were drilled only to shallow depths that reflect economic limitations and meeting minimal yield requirements for small-scale domestic stock grazing. Thus, yield measurements were considered an unreliable measure to compare with the spatial distribution of GPZ results and true groundwater potential, particularly for town water supply requirements. Consequently, a knowledge-driven AHP MCE approach was used in this study. The AHP is a well-established approach that has been widely used in quantifying weights for multi-criteria decision making (Ho 2008; Dos Santos et al. 2019) and an efficient and reliable method in GPZ factor evaluation and modelling (Jenifer and Jha 2017). It is transparent, repeatable, evaluates the consistency of comparisons between factors and is easily implemented within a GIS framework. It was used here to evaluate and combine spatial representations of significant factors, in a fractured rock setting, to map groundwater potential zones in pursuit of supplementing scarce water resources in the Southern Flinders Ranges of South Australia.

2. Study area

2.1 Location

The study focuses on the remote townships of Quorn and Hawker located in the Southern
Flinders Ranges, approx. 335 and 400 km north of Adelaide, respectively (Figure 1). Together these townships are the tourist gateway to this region. The study was the first stage of a four-stage pilot study for the South Australian Water Corporation (SA Water), a South Australian Government enterprise, in pursuit of supplementary groundwater supply for both townships as a key water security initiative. The study aimed to implement a timely, cost effective method to help better target areas for further field investigations in order to reduce exploratory drilling costs. To reduce pumping costs, each study site was restricted to a 10 km zone around each township (with an additional 5 km buffer to account for possible edge-effects of modelled input parameters) as a requirement by SA Water.

2.2 Climate

The Flinders Ranges is located in an arid to semi-arid environment experiencing hot, dry summers, cool to mild winters, and a low annual rainfall. Rainfall is highly variable, with the greatest variability in the lower rainfall areas. Average annual rainfall ranges from more than 500 mm along the higher elevations in the south, to below 200 mm at lower elevations in the north. Summer temperatures range from 28°C to 40°C and winter temperatures range from 6°C to 22°C. The wettest period occurs between May and October and the dry period extends from November to April. Occasional thunderstorms associated with tropical lows in northern Australia produce localised heavy falls in summer.

2.3 Geology

The study areas lie entirely within the Adelaide Fold Belt, consisting of a Paleoproterozoic to Mesoproterozoic cratonic basement overlain by a thick sequence of Neoproterozoic to Cambrian rift sediments (Preiss 1987; Paul et al. 1999). These sedimentary rocks and the underlying crystalline basement sequences were uplifted and deformed during the Late Cambrian–Early Ordovician Delamerian Orogeny. The distinctive strike-ridge dominated topography of the Flinders Ranges resulted. Within the study areas, the surface geology comprises predominantly low-grade metasediments (quartzite, limestone, siltstone and shale) of the Wilpena, Umbaratta and Hawker groups, overlain by undifferentiated Pleistocene–Holocene alluvial and fluval sequences that infill the broad valleys (figure 2). These sequences comprise gravel, silt and clayey sands, often interlayered with off-white to grey silty clays and range in thickness from a few metres to more than a hundred metres.

2.4 Hydrology

The hydrogeology of the region has not been extensively studied. Local studies of the Quorn and Hawker town water supplies are summarized in drilling reports (Osei-Bonsu and Evans 2002; Costar et al. 2010). Most other drillings in the Flinders Ranges have been used for mineral or hydrocarbon exploration. Some of these wells have subsequently been used for groundwater extraction, but most of them are no longer accessible. The topography is controlled by a series of anticline–syncline fold pairs trending between NNW and NW. The axial traces are doubly-plunging and show parallelism between these series. This creates a series of parallel ridges separated by wide relatively flat valleys. In both the Quorn and Hawker regions, ridges are composed of resistant Cambrian...
and Neoproterozoic quartzites, limestones and calcareous meta-siltstones (Figure 2). In the valleys these rocks are overlain by scree, alluvial and flood plain deposits. The ridges create groundwater divides and form the recharge zones for the more distal parts of the aquifer down-dip in the basin.

3. Methods

3.1 Overview

The occurrence of groundwater is influenced by many contributing factors, such as rainfall, drainage, elevation, land use, slope, lithology, lineaments and soils, which can all be spatially represented. Geographical Information Systems (GIS) allow the integration of these factors, represented as thematic spatial data layers, through different spatial analysis techniques to reveal key areas for exploration. Groundwater potential assesses the possibility of groundwater occurrence in an area. The study follows similar approaches by Agarwal et al. (2013); Razandi et al. (2015); and Arulbalaji et al. (2019) integrating both GIS and remote sensing derived data in a multi-criterion weighted, spatial analysis process to help identify groundwater potential zones (GPZ). The approach uses key criterion (contributing factors) relevant to locating GPZs represented as thematic spatial data layers in a GIS. Weights are assigned to class attributes within and between each thematic data layer using an analytical hierarchy process (AHP) based on the relative importance of each layer (Saaty 2012; Brunelli 2015). The weighted thematic data layers are then combined to reveal groundwater potential zones.

3.2 Explanatory factors in groundwater potential zone mapping

Many groundwater resource studies demonstrate the use of GIS to integrate information derived from remote sensing and other spatial datasets to identify groundwater recharge potential zones (Tweed et al. 2007; Deepika et al. 2013; Nag and Ghosh 2013; Agarwal and Garg 2016). Locating potential sites for recharge is complex and greatly depends on a variety of interdependent and competing explanatory factors such as climate, slope, drainage and moisture related variables, land use, lithology, lineaments and soils, among others (Díaz-Alcaide and Martínez-Santos 2019). The
level of influence for each contributing factor has on groundwater recharge/infiltration can vary depending on the intensity of land use and the natural landscape setting of the area under investigation. Thus, the inclusion of specific factors may vary for different GPZ projects. Some studies are driven by data availability (Razandi et al. 2015) particularly where fine- or local-scale analysis may exclude datasets. For example, while recharge from rainfall is one of the most important factors in groundwater availability (Mohan et al. 2018), in sparsely populated areas the lack of rainfall measurements and minimal spatial variation in rainfall (and recharge) over areas that span only several tens of kilometres make the inclusion of this factor potentially meaningless (Díaz-Alcaide and Martínez-Santos 2019). At a local-scale, the assumption of rainfall uniformity might need to be applied. Notably, more than 50% of the 56 groundwater potential mapping studies presented for review by Díaz-Alcaide and Martínez-Santos (2019) excluded rainfall.

Factors may also be included or omitted depending on their relative importance within a specific landscape setting, such as land use where differences in water infiltration between land use types are considered minimal (Saraf and Choudhury 1998). The primary land use within 10 km of Quorn is recorded as grazing at 50%, cropping at 24%, residual native cover at 14%, and nature conservation at 6%, while the remaining 6% is largely ‘infrastructure’ land uses. Notably, little cropping is actually conducted around Quorn where these areas are often subjected to non-intensive sheep grazing. Land use within 10 km of Hawker is almost entirely grazing at 94%, with the remaining 6% distributed across cropping and ‘infrastructure’ land uses. In context of the influence land use has on water infiltration potential, the remote rural setting of both Quorn and Hawker show that there are insignificant impervious differences in land use types and only minimal uptake of water from non-intensive opportunistic cropping (almost non-existent around Hawker). Residual native vegetation is sparse at both locations. Consequently, land use was not included in the multi-criteria analysis as variation in water infiltration according to land use categories was judged to be a minor contributing factor that would not significantly affect the AHP weighted outcome on mapped results. The final factors used to construct the GIS models for Quorn and Hawker are shown in figure 9, which also details the final factor AHP weightings.

3.3 Key contributing factors for Quorn and Hawker

The key factors affecting groundwater accumulation are divided into three groups:

1) Supply – source and availability of water to contribute to groundwater;
   a. Rainfall
   b. Aspect

2) Infiltration – possible pathways for infiltration;
   a. Lithology
   b. Lineaments

3) Opportunity – relates to potential duration of available supply to infiltrate.
   a. Topographic Wetness
   b. Slope

All spatial representations of these factors and their potential derivatives were gridded to a 30 m spatial resolution and transformed to the same coordinate system for input to a GIS for MCE.

3.3.1 Supply factors

3.3.1.1 Rainfall: Rainfall duration and frequency largely determine the amount of water available for groundwater recharge (Agarwal and Garg 2016; Yeh et al. 2016; Mogaji and Lim 2017). In arid environments of sedimentary composition, episodic recharge will occur during infrequent, high intensity precipitation events (Crosbie et al. 2012), while in fractured rock environments, such as in the Flinders Ranges, it is prolonged, low intensity rainfall events that lead to recharge as most of the water from high intensity events runs off quickly and drains from the region (Ahmed and Clark 2016). Notably, this study was conducted at a local scale where there is only one weather station located within 10 km (the prescribed search area) of Quorn and Hawker. Consequently, spatial variation in localised rainfall parameters could not be modelled with any reasonable certainty. Nevertheless, variations in mean annual rainfall for both Quorn and Hawker were interpolated from 5 km national gridded centroids to produce 10 mm rainfall isoline intervals based on a standard 30-yr (1986–2015) period (Jones et al. 2009). Notably, spatial variations in rainfall across both locations showed good alignment with local topography where elevated areas exhibit higher rainfall than
lower areas (figure 3). However, the relatively small area of the region being modelled shows only a small variation in rainfall, hence it may be of little influence on the final outcome.

3.3.1.2 Aspect: Complementary to the rainfall gridded dataset, aspect was derived from the 1 arc-second Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) (Geoscience Australia 2011). Aspect provides some control on the supply of rainfall where it can delineate areas exposed to prevailing winds and annual precipitation, solar illumination, erosion potential and runoff (Agassi and Ben-Hur 1991; Marques and Mora 1992; Beullens et al. 2014). It has been considered as an important controlling factor in GPZ mapping (Naghibi et al. 2017; Ahmed and Sajjad 2018; Chen et al. 2018) and was included here as a surrogate for mapping variations in exposure to rainfall where windward facing areas are likely to receive more rainfall than local scale leeward ‘rain shadowed’ areas. The aspect grid of values between 0 and 360 degrees was reclassified into 45-degree segment directions of N, NE, E, SE, S, SW, W, and NW.

Monthly climate statistics and wind rose diagrams for Hawker were used to rank the aspect directions (1–5) for both Quorn and Hawker in order of wind direction duration and speed (where a score of 1 is the prevailing wind and highest speed direction) (figure 3). Wind rose diagrams were chosen based on the highest annual rainfall months from May through to October, determined from mean annual rainfall statistics between 1882 and 2020 (Bureau of Meteorology 2020).

3.3.2 Infiltration factors

3.3.2.1 Lithology: Lithology plays an important role in the occurrence and distribution of groundwater, particularly in a fractured rock environment. Lithology was incorporated into almost all groundwater potential studies reviewed by Díaz-Alcaide and Martínez-Santos (2019). The type of rocks exposed at the surface significantly affects groundwater recharge by controlling the percolation of water flow. The two study areas are underlain by deformed low-grade metasediments, which are overlain by valley fill sediments and minor alluvium along the drainage courses. The

Figure 3. Annual rainfall distribution map overlaid on aspect direction for the study areas of (a) Quorn and (b) Hawker. Spatial data source: Rainfall (Bureau of Meteorology 2019) and aspect derived from SRTM 1 arc-sec digital elevation model (Geoscience Australia 2011).
metasediments have low primary porosity but varying secondary porosity and permeability dependent upon the presence or absence of bedding and/or fractures. Undifferentiated shallow cover overlies these fractured rocks in places. Fracture density was measured in the field and enabled the establishment of five fracture-determined permeability classes, which were incorporated into the AHP calculation to determine the overall weighting (table 3). The digital geological map was downloaded from SARIG (South Australian Resources Information Gateway) Geoscientific database and used to map the distribution of the various lithological units (figure 2) (Department for Energy and Mining 2012).

3.3.2.2 Geo-lineaments: Geological lineaments are measurable linear features such as faults, bedding planes, rock cleavage or joints. In areas of crystalline rocks, they may be the only zones of permeable rock capable of groundwater flow and accumulation. They can be identified from geological maps or remotely sensed from satellite and airborne platforms. They range in length from metres to kilometres and their spatial orientation can be expressed as a dip and strike (if measured in the field) or as a trend direction (if measured from images).

Lineaments represent the zones of faulting and fracturing which results in increased secondary porosity and permeability. These factors are hydrogeologically very important as they provide the pathways for groundwater movement in otherwise impermeable rocks. Lineament density of an area can indirectly reveal the groundwater potential since the presence of lineaments usually denotes a permeable zone (Park et al. 2000). Long geological lineaments have a higher potential to be hydrogeological faults because their length and depth means that they are able to penetrate more potential recharge zones. The zone of fractured rock associated with longer lineaments is generally wider (Sander 2007) and therefore has a higher hydrogeological significance. The width of fractured rock measured along a quartzite bed perpendicular to the strike of the major E–W lineament at Hawker is more than 30 m. A comprehensive structural geology study of lineaments by Zulfic et al. (2010) associated with more than 300 bores at 84 sites in the same suite of rocks south of this study identified a fracture model broadly divided into a densely fractured upper zone (0–100 m), a less fractured transitional zone (100–200 m) and a broadly fractured lower zone (>200 m). Bore yield results showed that the highest flows were from bores in the upper 100 m. The possible variation of yield with bore depth was not factored into the lineament weighting process in the current study because bores deeper than 100 m would not be considered.

Shorter lineaments and minor faults are also of interest because they may connect major faults. Because of their potential to capture and store groundwater, areas of high lineament density will have a higher groundwater potential. Similarly, an area with a higher number of intersections or cross-points will have a higher groundwater potential because they facilitate flow and recharge (Sener et al. 2005). Proximity of existing wells to lineaments is also used to evaluate the groundwater occurrences in an area. To distinguish potential hydrogeological lineaments, the distribution of wells vs. their distance from a lineament is categorized according to yield and salinity. Higher potential lineaments are those in close proximity to wells with high yield and low salinity.

Studies by Sander (2007), Corgne et al. (2010), and Adiri et al. (2017) demonstrate the use of edge detection filters to automate geo-lineament identification and mapping using satellite and airborne images. However, these studies were largely conducted in remote homogenous areas largely void of anthropogenic-derived linear features, where both visually apparent and semi-concealed discontinuous surface geo-lineaments dominate. While Quorn and Hawker are located in remote regional settings, there are extensive nongeo-lineament features present, such as fence lines, animal tracks, grazing lines, and roads that were considered too complex to remove through post-processing of automated geo-lineament mapping. Consequently, the geological lineaments used in this study were derived from several sources and at different scales. They include the 1:100 k and 1:2 M lineament datasets, and the Neoproterozoic–Ordovician Faults at 1:2 M produced by the Geological Survey of SA and accessed via SARIG. Photo-interpreted lineaments were also manually digitized using both enhanced Sentinel satellite imagery (20 m spatial resolution mineral-enhanced imagery) and high-resolution imagery from Google Earth using 3D surface visualization. All datasets were combined with appropriate attribution to identify source lineage and accuracy level. Only those lineament features
from the SARIG datasets attributed as fault position ‘accurate’ and ‘approximate’ were included in the combined dataset, while all Google Earth and Sentinel derived lineaments were labelled as ‘interpreted’. It was considered reasonable to combine these datasets captured at different scales because lineament density would be calculated at a relatively broad scale.

In some studies, bedding is used as a lineament and adds to the lineament density of an area of well-bedded sedimentary or metasedimentary rocks such as the Flinders Ranges. Infiltration along bedding planes can be significant and justifies their incorporation. In this study, the impact of infiltration along bedding planes based on field observations was taken into account in the weighting of different lithologies rather than in the lineament density layer.

In this study, a weighted density approach was used to characterise the relative importance of each geo-lineament. A multiplication factor (how many times a geo-lineament would be counted in the density function) was assigned to each lineament based on a sum of scores given to lineament length as an indicator of its ability to intersect unmapped lineaments (5-class lengths of $<1, 1–3, 3–6, 6–10, >10$ km to yield scores of 0.2, 0.4, 0.6, 0.8, and 1.0, respectively) and lineament type as an indicator of the width/size of the fracture zone (where 1:2 M Neoproterozoic–Ordovician faults obtained a score of 2 and all other lineaments a score of 1). Thus, multiplication factors for the geo-lineament density function ranged from 1 to 3. Geo-lineament density results are expressed in km/km$^2$. The search radius used in this study was 1200 m from each grid cell of 30 m. This was determined by expert judgment after assessment of yield and electrical conductivity (EC) measurements as a function of distance from geo-lineaments and the behaviour of density patterns relative to distance from geo-lineaments (figure 6). Geo-lineament density results were subsequently reclassified into five linear classes for incorporation into the AHP weighting process.

3.3.3 Opportunity factors

3.3.3.1 Topographic wetness index (TWI): The TWI estimates the relative wetness within a catchment where higher index values indicate areas of infiltration potential where moisture is more likely to accumulate and drain by saturation excess. It is also known as the compound topographic index (CTI) and has been used to quantify runoff processes (Sørensen et al. 2006). It is a unitless steady state wetness index and is calculated as:

$$CTI = \ln \frac{a}{\tan b},$$

where $a$ is the local upslope contributing area per unit contour length and $\tan b$ is the local slope in radians.

The TWI used in this study was derived from the 1 arc-sec Shuttle Radar Topography Mission (SRTM) DEM-H (hydrologically enforced) product ($\sim 30$ m spatial resolution) and accessed from the Commonwealth Scientific and Industrial Research Organization’s (CSIRO) Data Collection (Gallant and Austin 2012). CSIRO’s version of the TWI model is derived using their contributing area – multiple flow direction (Partial) algorithm where contributing areas were computed on 1-degree tiles with 200 cell overlaps ($\sim 5$ km). Thus, the contribution to ‘channels’ beyond this size is not accounted for (hence the ‘Partial’ in the title). Consequently, CSIRO’s TWI model is a conservative one and not likely to overestimate ‘wetness’.

The range of TWI values is often normalised (standardised) by rescaling values between 0 and 1 to obtain the probability of areas more likely to drain by saturation excess flow. However, to avoid the influence of outlier index values on the results of the normalised linear transformation, TWI values were visually assessed and reclassified against positions on the landscape (e.g., ridgetop, upper-slope, mid-slope, lower-slope and valley bottoms/channels or swale/flat areas). Correspondingly, a 5-class system was used where a score of 1 was assigned to TWI values $>12$ indicating very high flow accumulation in areas largely corresponding to channels or swale areas (figure 4). Conversely, a score of 5 was assigned to TWI values $<6$ indicating very low flow accumulation in largely ridgetop areas. The resulting TWI class intervals (table 3) are similar to the three broader landscape position classes described by Gallant and Austin (2012).

3.3.3.2 Slope: While the TWI incorporates slope in its calculation, it was considered here separately as a function of runoff potential as opposed to accumulation potential (i.e., a function of...
contributing area and slope). Slope is widely used in this context (Díaz-Alcaide and Martínez-Santos 2019) and while other factors will affect infiltration (Liu et al. 2001) in general, steeper slopes imply greater runoff and thus less time/opportunity for infiltration, while gentle slopes imply less runoff and thus more time/opportunity for infiltration (Mu et al. 2015). Slope-angle in degrees was calculated using the 1 arc-sec Shuttle Radar Topography Mission (SRTM) DEM (~30 m spatial resolution) (figure 5). Slope values were reclassified into five progressively larger slope-class ranges to better reflect the non-linear effect slope has on runoff (Liu et al. 2001) (table 3).

3.3.3.3 Drainage density: Drainage density is a frequently used water related infiltration factor in GIS-based GPZ mapping (Díaz-Alcaide and Martínez-Santos 2019). In general, higher drainage density is more likely to occur in high relief, steeper sloped areas where water runoff is greater, while lower drainage density is more likely to occur in low relief, flatter areas where water accumulates (Nag and Ghosh 2013). Therefore, high drainage density areas indicate lower water infiltration potential, while low drainage density areas indicate higher water infiltration potential (Bagyaraj et al. 2013). However, there are exceptions to this rule. In both Hawker and Quorn study areas, there are lower areas of alluvial deposits where higher groundwater potential can be expected, though higher drainage density was observed in these areas due to the presence of many rills, erosional gullies and braided streams. The typical relationship between drainage density and surface water runoff potential was assessed as being highly variable over both locations and thus, it was judged to be an unreliable factor. Moreover, surface runoff potential is largely accounted for using slope and TWI, thus in the interest of model redundancy (Malczewski 2000) and inconsistent influence, drainage density was not used in this study.

3.4 Incorporation of analytical hierarchy process (AHP)

Multi-criteria evaluation (MCE) typically requires weights to be assigned to each criterion/factor that reflect their relative importance. Higher importance given to one factor typically trades-off against others (Eastman 1999), thus relative weights between factors must be chosen carefully. In this study, the Analytical Hierarchy Process (AHP) was used. The AHP technique for decision making was developed by Saaty (1977, 1980) to minimise the challenges of ranking the relative
importance of multiple factors simultaneously. It is frequently used in the groundwater potential literature (Machiwal et al. 2014; Razandi et al. 2015; Agarwal and Garg 2016; Abrams et al. 2018; Dos Santos et al. 2019, among others). Pairwise comparisons are used to rank the relative importance each factor has on groundwater occurrence from the most influential to the least influential on a scale of 1–9, where 1 indicates equality between factors and 9 indicates extreme importance of one factor over another (table 1). While expert judgment is sought, the choice of relative importance is qualitative and will vary from one judge to another and from one region to another.

Sequential pairwise comparisons between factors result in a ratio of importance for each factor pair, \( a_{ij} \), and is used to build a pairwise comparison matrix, \( A \) of \( n \) factors, as defined by equation (2).

\[
A = [a_{ij}], \quad i, j = 1, 2, 3, \ldots, n. \tag{2}
\]

The matrix has reciprocal properties where comparing factor \( A \) to factor \( B \) is the reciprocal value of comparing factor \( B \) to factor \( A \), which is expressed as:

\[
a_{ij} = 1/a_{ji}. \tag{3}
\]

In AHP, priorities (weights) are derived from a positive reciprocal consistent or near consistent matrix (Saaty 2001; Goepel 2013). Thus, final weightings \((w)\) for factors are the normalised values of the priority vector (eigenvector) determined from the row means of the normalised comparison matrix of \( A \), or from \( \ln(A) \) using the row geometric mean method (RGMM), which maintains the reciprocal properties of the comparison matrix with respect to the priority vector (Dijkstra 2011). In this study, the latter was used taking advantage of the AHP Excel template developed by Goepel (2013) where the steps are (1) calculating \( \ln \) function for the values in the comparison matrix \( A \), (2) calculating the mathematical constant \( e \), raised to the power of the average for each row in \( \ln(A) \), and (3) calculating the geometric mean (final normalised weights, \( w \)) by dividing the exponent result for each row by the sum of all row exponents. Table 2

![Figure 5. Slope angle maps for study areas of (a) Quorn and (b) Hawker. Spatial data source: derived from SRTM 1 arc-sec digital elevation model (Geoscience Australia 2011).](image)

| Intensity of importance | Description                        |
|-------------------------|------------------------------------|
| 1                       | Equal importance                  |
| 3                       | Moderate importance               |
| 5                       | Strong or essential importance    |
| 7                       | Very strong or demonstrated        |
| 9                       | Extreme importance                |
| 2, 4, 6, 8              | Intermediate values               |

Table 1. Scales for pairwise comparisons (Saaty 1977).
Table 2. Four pairwise comparison matrices, corresponding factor weights and consistency ratio as judged by four individual experts (participants), includes a consolidated pairwise matrix (bottom of table), which aggregates all judgments.

| Factors                  | 1   | 2   | 3   | 4   | 5   | 6   | Normalised Eigen values ($w$) |
|--------------------------|-----|-----|-----|-----|-----|-----|-------------------------------|
| Participant 1 ($P_1$)    |     |     |     |     |     |     |                               |
| (1) Rainfall             | 1   |     |     |     |     |     | 0.144                         |
| (2) Lithology            |     | 3   | 1   |     |     |     | 0.314                         |
| (3) Lineament density    |     |     | 3   | 1   | 1   |     | 0.341                         |
| (4) TWI                  |     | 1   | 1/4 | 1/4 | 1   |     | 0.127                         |
| (5) Slope                |     | 1/5 | 1/4 | 1/7 | 1/5 | 1   | 0.048                         |
| (6) Aspect               |     | 1/7 | 1/8 | 1/9 | 1/5 | 1/3 | 1                           | 0.026 |
| Consistency ratio:       |     |     |     |     |     |     | 0.057                         |
| Participant 2 ($P_2$)    |     |     |     |     |     |     |                               |
| (1) Rainfall             | 1   |     |     |     |     |     | 0.344                         |
| (2) Lithology            |     | 1   | 1   |     |     |     | 0.236                         |
| (3) Lineament density    |     | 1/3 | 1/3 | 1   |     |     | 0.103                         |
| (4) TWI                  |     | 1/3 | 1   | 5   | 1   |     | 0.252                         |
| (5) Slope                |     | 1/9 | 1/6 | 1/3 | 1/8 | 1   | 0.040                         |
| (6) Aspect               |     | 1/9 | 1/6 | 1/8 | 1/8 | 1/3 | 1                           | 0.025 |
| Consistency ratio:       |     |     |     |     |     |     | 0.075                         |
| Participant 3 ($P_3$)    |     |     |     |     |     |     |                               |
| (1) Rainfall             | 1   |     |     |     |     |     | 0.043                         |
| (2) Lithology            |     | 5   | 1   |     |     |     | 0.336                         |
| (3) Lineament density    |     | 5   | 1   | 1   |     |     | 0.336                         |
| (4) TWI                  |     | 4   | 1/4 | 1/4 | 1   |     | 0.138                         |
| (5) Slope                |     | 4   | 1/4 | 1/4 | 1/2 | 1   | 0.110                         |
| (6) Aspect               |     | 1   | 1/7 | 1/7 | 1/5 | 1/5 | 1                           | 0.035 |
| Consistency ratio:       |     |     |     |     |     |     | 0.054                         |
| Participant 4 ($P_4$)    |     |     |     |     |     |     |                               |
| (1) Rainfall             | 1   |     |     |     |     |     | 0.026                         |
| (2) Lithology            |     | 7   | 1   |     |     |     | 0.161                         |
| (3) Lineament density    |     | 9   | 3   | 1   |     |     | 0.422                         |
| (4) TWI                  |     | 7   | 2   | 1/3 | 1   |     | 0.261                         |
| (5) Slope                |     | 5   | 1/2 | 1/5 | 1/5 | 1   | 0.083                         |
| (6) Aspect               |     | 3   | 1/5 | 1/7 | 1/7 | 1/2 | 1                           | 0.047 |
| Consistency ratio:       |     |     |     |     |     |     | 0.051                         |
| Consolidated ($C_k$)     |     |     |     |     |     |     |                               |
| (1) Rainfall             | 1   |     |     |     |     |     | 0.096                         |
| (2) Lithology            |     | 3/15| 1   |     |     |     | 0.287                         |
| (3) Lineament density    |     | 2/3 | 5   | 1   | 1   |     | 0.298                         |
| (4) TWI                  |     | 1/3 | 3/5 | 4/7 | 1   |     | 0.208                         |
| (5) Slope                |     | 4/5 | 1/4 | 2/9 | 2/9 | 1   | 0.074                         |
| (6) Aspect               |     | 1/2 | 1/6 | 1/8 | 1/6 | 1/3 | 1                           | 0.037 |
| Consistency ratio:       |     |     |     |     |     |     | 0.018                         |

Participant consensus: 76.2%

shows four pairwise comparison matrices and corresponding derived eigen value weights as judged by four individual experts (participants) (see section 3.4). Table 2 also includes a consolidated pairwise matrix, which aggregates all judgments and corresponding weights. Further pairwise companions were undertaken to determine the relative weights of the sub-criteria/classes of each factor (table 3). Factor class weights ($x$) were rescaled and normalised between 0 and 1 to standardise their range with other factors (Malczewski 2000).
Table 3. *Pairwise comparison matrix, corresponding weights and consistency ratio for factor sub-classes.*

| Factor sub-classes | 1   | 2   | 3   | 4   | 5   | Normalised class | Eigen values (x) | Standardised |
|--------------------|-----|-----|-----|-----|-----|----------------|-----------------|--------------|
| Rainfall Quorn (mm) |     |     |     |     |     |                |                 |              |
| (1) > 490          | 1   |     |     |     |     |                | 0.339           | 1.000        |
| (2) 430–490        | 2/3 | 1   |     |     |     |                | 0.250           | 0.739        |
| (3) 370–430        | 1/2 | 2/3 | 1   |     |     |                | 0.182           | 0.536        |
| (4) 310–370        | 2/5 | 1/2 | 2/3 | 1   |     |                | 0.132           | 0.388        |
| (5) < 310          | 1/3 | 2/5 | 1/2 | 2/3 | 1   |                | 0.098           | 0.288        |
| Consistency ratio: | 0.003 |     |     |     |     |                |                 |              |
| Rainfall Hawker (mm) |     |     |     |     |     |                |                 |              |
| (1) > 340          | 1   |     |     |     |     |                | 0.267           | 1.000        |
| (2) 320–490        | 5/6 | 1   |     |     |     |                | 0.229           | 0.857        |
| (3) 300–320        | 5/7 | 5/6 | 1   |     |     |                | 0.195           | 0.729        |
| (4) 280–300        | 5/8 | 5/7 | 5/6 | 1   |     |                | 0.166           | 0.621        |
| (5) < 280          | 5/9 | 5/8 | 5/7 | 5/6 | 1   |                | 0.142           | 0.532        |
| Consistency ratio: | 0.000 |     |     |     |     |                |                 |              |
| Aspect             |     |     |     |     |     |                |                 |              |
| (1) NW (windward)  | 1   |     |     |     |     |                | 0.447           | 1.000        |
| (2) W              | 1/2 | 1   |     |     |     |                | 0.285           | 0.636        |
| (3) N,S            | 1/4 | 1/2 | 1   |     |     |                | 0.142           | 0.318        |
| (4) SW             | 1/5 | 1/5 | 1/2 | 1   |     |                | 0.083           | 0.186        |
| (5) NE, E, SE (leeward) | 1/7 | 1/6 | 1/4 | 1/3 | 1   |                | 0.042           | 0.094        |
| Consistency ratio: | 0.031 |     |     |     |     |                |                 |              |
| Lithology          |     |     |     |     |     |                |                 |              |
| (1) Recent alluvium| 1   |     |     |     |     |                | 0.474           | 1.000        |
| (2) Sandstone      | 1/3 | 1   |     |     |     |                | 0.275           | 0.580        |
| (3) Siltstone & Shale | 1/4 | 1/4 | 1   |     |     |                | 0.169           | 0.357        |
| (4) Limestone & Dolomite | 1/7 | 1/6 | 1/6 | 1   |     |                | 0.051           | 0.108        |
| (5) Quartzite      | 1/9 | 1/9 | 1/8 | 1/2 | 1   |                | 0.032           | 0.068        |
| Consistency ratio: | 0.099 |     |     |     |     |                |                 |              |
| Lineament density (km/km²) |     |     |     |     |     |                |                 |              |
| (1) > 3.5          | 1   |     |     |     |     |                | 0.339           | 1.000        |
| (2) 2.2–3.5        | 2/3 | 1   |     |     |     |                | 0.250           | 0.739        |
| (3) 1.2–2.2        | 1/2 | 2/3 | 1   |     |     |                | 0.182           | 0.536        |
| (4) 0.5–1.2        | 2/5 | 1/2 | 2/3 | 1   |     |                | 0.132           | 0.388        |
| (5) 0–0.5          | 1/3 | 2/5 | 1/2 | 2/3 | 1   |                | 0.098           | 0.288        |
| Consistency ratio: | 0.003 |     |     |     |     |                |                 |              |
| TWI                |     |     |     |     |     |                |                 |              |
| (1) > 12 valley bottom | 1   |     |     |     |     |                | 0.432           | 1.000        |
| (2) 10–12 lower-slope | 1/2 | 1   |     |     |     |                | 0.262           | 0.607        |
| (3) 8–10 mid-slope | 1/3 | 1/2 | 1   |     |     |                | 0.179           | 0.415        |
| (4) 6–8 upper-slope | 1/5 | 1/3 | 1/3 | 1   |     |                | 0.086           | 0.200        |
| (5) < 6 ridgetop   | 1/7 | 1/6 | 1/5 | 1/3 | 1   |                | 0.041           | 0.095        |
| Consistency ratio: | 0.028 |     |     |     |     |                |                 |              |
| Slope (deg)        |     |     |     |     |     |                |                 |              |
| (1) < 2            | 1   |     |     |     |     |                | 0.453           | 1.000        |
| (2) 2–5            | 1/2 | 1   |     |     |     |                | 0.365           | 0.673        |
| (3) 5–10           | 1/4 | 1/3 | 1   |     |     |                | 0.152           | 0.335        |
| (4) 10–20          | 1/7 | 1/6 | 1/4 | 1   |     |                | 0.059           | 0.130        |
| (5) >20            | 1/9 | 1/8 | 1/6 | 1/3 | 1   |                | 0.032           | 0.070        |
| Consistency ratio: | 0.049 |     |     |     |     |                |                 |              |
It is important that weights derived from the pairwise comparison matrix be consistent. One of the strengths of the AHP is that, it provides a consistency ratio (CR) as an indicator of the degree of consistent or inconsistent user(s)-defined factor relationships (Feizizadeh et al. 2014). Note that improving CR will not necessarily improve GPZ mapping results, rather it is used to assess the ratio estimates in the matrix as closer to being logically related than being randomly chosen (Saaty 1977, p. 237). The CR is defined as:

$$CR = \frac{CI}{RI},$$

where the random consistency index (RI) is derived from a sample of size 500 matrix of a randomly generated pairwise comparison matrix using the scale 1/9, 1/8, ..., 1, ..., 8, 9, according to the number of factor pairs (Saaty 1987, p. 171) and where CI is the consistency index expressed as:

$$CI = \frac{(\lambda_{\text{max}} - n)}{n - 1},$$

in which $\lambda_{\text{max}}$ is the largest or principal eigen value of the matrix and $n$ is the number of factors. According to Saaty (1980), a CR of 0.10 (10%) or less indicates an acceptable level of consistency. If the CR is $>0.10$, the decision maker(s) need to revise their judgement of the pairwise comparisons. Notably, as indicated by Goepel (2013), the CI calculation in this study adapts a different estimation method for RI developed by Alonso and Lamata (2006), which uses a least-square line to estimate the values of $\lambda_{\text{max}}$ as $n$ increases. Thus, it is less restrictive when the size of the matrix increases. It is defined by equation (6).

$$CI = \frac{(\lambda_{\text{max}} - n)}{2.7699n - 4.35513 - n}.$$

In this study, all CR values were consistently $<0.10$ for both factors and their sub-criteria/class pairwise comparisons (tables 2 and 3, respectively). Thus, they provide confidence in the use of the corresponding weights in the MCE process.

Once the consistency of pairwise comparisons is satisfied, the standardised class weights ($z$) are assigned to corresponding classes, per $(x_i, y_i)$ grid cell, of the thematic spatial layer (factor classes) using recode or reclassify functions in a GIS. Implementation of the AHP factor weights to map groundwater potential, $GP$, for any location, $x_i, y_i$, is given by:

$$GP_i = \sum_{j=1}^{n} w_j \times x_{ij},$$

where $w_j$ is the normalised weight of the $j$th thematic layer (factor), $x_{ij}$ is the standardised weight (table 3) of the $j$th factor class (with respect to the $x_i, y_i$ coordinate location) of the corresponding $j$th thematic layer (factor), and $n$ is the number of factors. Thus, the standardised AHP weights (0–1) for each factor class is multiplied against the determined AHP weighting for that factor. Each influencing factor is then spatially overlaid and summed together in a GIS environment to yield a final normalised range of values between 0 and 1 representing the probability of groundwater potential per grid cell. This range can be further classified into qualitative classes of low to high GPZs.

### 3.5 Uncertainty in AHP weights

As discussed in section 3.4, the AHP is a knowledge-based decision approach, and thus the uncertainty of weights derived from pairwise comparisons lies in the subjective judgment of experts on the relative importance of factors. While we can be assured of judgment consistency in the AHP comparison matrix, there may be different perceptions by experts on the influence each factor has on surface water infiltration and groundwater occurrence. These perceptions are typically conveyed from the expert’s opinion into the weight assignment (Feizizadeh et al. 2014).

In this study, expert opinion on the relative importance of one factor over another, using Saaty’s scale range 0–9, was sought from three hydrogeologists and one geospatial specialist, all with personal experience and knowledge of the study areas. Notably, consensus between all experts or participants to derive a single priority vector (factor weights) was not sought, rather aggregation of individual judgments to a consolidated decision matrix $C$, was achieved using the weighted geometric mean of all $k$ participants’ judgments (Aull-Hyde et al. 2006; Goepel 2013) (table 2). As detailed by Goepel (2013), an AHP consensus indicator $S^*$ between all $k$ participants is calculated based on the RGMM results of each participant using Shannon alpha and beta entropy. The consensus indicator ranges from 0 (no consensus between participants) to 100% (full consensus between participants) (table 4).
In this study, the consolidated matrix \(C_k\) derived AHP factor weights (where \(S^* = 76.2\%\)) were used as the primary determinants of final GPZ mapping results for both study areas, while individual participant derived AHP factor weights were used as a sample spread of uncertainty in the final GPZ mapping. This uncertainty is highlighted using a simple standard deviation (SD) raster showing the spatial variation in the degree of difference between individual participant GPZ mapping results on a cell-by-cell basis. Thus, the SD raster image may be used to determine the risk at any one location based on the degree of ‘agreement’ between the individual participant GPZ mapping results.

### 4. Results

#### 4.1 Field observations

Field mapping was undertaken at both locations to confirm information gained from published sources in areas of interest around Quorn and Hawker. Identification of major lithologies and their outcrop characteristics were observed (dip, bedding plane roughness, bedding and layering thickness, fracture density and orientation). These observations were used to help identify lithology classes (figure 2), their associated porosity and AHP weightings (table 3).

#### 4.2 Groundwater potential model

In order to identify groundwater potential zones surrounding Quorn and Hawker, six thematic spatial data layers of annual rainfall, aspect, lithology, lineament density, topographic wetness and slope were prepared for each area. Existing well-yield and salinity data were also used to aid interpretation. Analysis of the lithology and geolineament thematic maps generated from airborne, satellite and field data, together with groundwater potentials are discussed below.

### 4.2.1 Lineament analysis

Two dominant lineament directions were identified for Hawker NE–SW and NW–SE as well as a minor set E–W (figure 6b). In the Quorn area, the dominant lineament orientation is N–S swinging to NE with two minor sets E–W and NW–SE (figure 6a). Fracture/lineament patterns measured in the field confirmed these results. Analysis of lineament orientation is valuable for the study of groundwater flow as the orientation of fractures is most likely to be identical to the preferential flow path.

Figure 6(a and b) shows the lineament density for Quorn and Hawker, respectively. The size of the grid cell used to compute the densities is 30 m with a search radius of 1200 m. In the Hawker region, the overall lineament density is not high. The area is characterised by a series of relatively long widely-separated faults with few intersection points. The highest densities in the area are north and north-east of the township and north-west, where there is a relatively high concentration of closely-spaced short faults, which intersect with longer northeast trending faults. In the north-east, the array is associated with disrupted rocks in a sedimentary diapiric structure. The discontinuous nature of rocks in diapirs makes sub-surface interpretation difficult and prediction of groundwater supplies difficult. The higher lineament density in the north-western part of the region is associated with an area of highly contorted relatively brittle Neoproterozoic rocks in the hinge of a tightly-folded south-plunging syncline. The high density of faults in this area and the proximity to the long E–W fault north of the township suggests higher permeability and infiltration. This conclusion is supported by the occurrence of the large spring fed permanent waterhole (Yappala Waters) in this area (figure 6b). Groundwater salinity in this area is relatively low: TDS 840 mg/L for well 2 and 2000 mg/L TDS for well 32. Yield data is not available for these wells.

Over the entire area, wells with low salinity and higher yields tend to be close to faults while the higher salinities are found in wells further away from faults, but there are exceptions and as the wells are not evenly spread across the region such a conclusion is fairly weak (figure 7).

The Quorn study area is dominated by relatively long N–S trending curvilinear faults concentrated in the western half (figure 6a). Shorter NW–SE trending faults intersect with the longer faults producing many cross-points. The concentration in

| \(S^*\) | Consensus |
|------|--------|
| \(\leq 50\%\) | Very low |
| 50–65% | Low |
| 65–75% | Moderate |
| 75–85% | High |
| \(\geq 85\%\) | Very high |
the west may be partly due to the uneven distribution of older Neoproterozoic bedrock in the west and young recent alluvium in the eastern part of the region. Faults in the Neoproterozoic rocks are more readily observed than under the cover of the alluvium. The concentration of faults in the west coincides with higher altitude outcrops. This part of the area is more likely to experience higher rainfall so together with the presence of a system of long intersecting faults implies higher infiltration and groundwater flow.

There is no clear relationship between proximity to faults and well salinity or yield (figure 8). The wells are concentrated along the eastern part of the upland area and further east. Overall salinity is relatively low when compared with other parts of the Flinders Ranges and well yields vary inconsistently across the area. Again, such interpretations are uncertain because of the unreliability of the data, which was recorded at the time each individual well was drilled which spans several decades.

4.2.2 Lithology analysis

In both the Hawker and Quorn areas, the surface geology has been interpreted from published geological maps and field observations. Lithological log data for the majority of the wells is not available and those logs that are available only broadly classify the rock type and not the stratigraphic information. Further work is required to develop a good subsurface interpretation of the eastern part of both areas, which are largely overlain by young alluvial and surficial deposits. In both areas, the higher elevation areas are underlain by Neoproterozoic metasediments (quartzite, sandstone, limestone, shale and siltstone) and the lower elevation regions are covered by recent alluvial sediments over the older metasediments (figure 2). In many cases, it is not possible to determine whether the wells in the alluvial material have penetrated into the underlying fractured rock, so the well data was not interpreted.

4.2.3 Groundwater potential zones

After the weights of the six thematic layers (and sub-classes) prepared for each area were normalised using the AHP process, they were integrated using a weighted sum overlay (equation 7) in a GIS environment to generate groundwater potential maps. These maps include those generated as a result of
individual participant judgment (figures 12 and 13) and those generated as a result of aggregating all participants’ judgments. Aggregation was derived from the consolidated pairwise matrix $C_k$ (table 2) where the resulting GPZ maps will be the focus of discussion (figures 10 and 11). The final process model is presented in figure 9.

As would be expected, the spatial distributions of the various groundwater potential zones obtained from the consolidated AHP model generally show that the high potential zones are where the higher weighted layers (lineament density, lithology and TWI) coincide. This is moderated by the remaining rainfall, slope and aspect layers. The benefit of this process is the ability to superimpose the six appropriately weighted themes to produce a single potential map. Although the AHP weighting is subjective, it is based on information in the literature and moderated by field observations.

5. Discussion

5.1 Hawker groundwater potential

The groundwater potential model for Hawker shows several higher potential areas and two elongated areas of moderate potential (figure 10a). It is important to note that the range of GPZ values is relatively small so the difference between the upper level regions (high to very high classes) is probably not significant. The high potential areas as earlier discussed are associated with the regions where there are clusters of short faults related to highly fractured diapiric rocks or tightly folded brittle rocks. However, the cluster of faults located just outside of the 10 km zone in the N–W are moderated by other competing factors such as high slope and low TWI values.

The two elongated regions of high to very high potential are influenced by the presence of long...
faults and lithology. The more northerly E–W zone also follows the Wonoka Creek, so its higher potential value is influenced by the higher TWI value. The western end of the fault is close to the highly faulted area in the western part of the region and its higher elevations. It is possible that the long fault will provide a pathway from west to east from the higher potential intake area.

The V-shaped higher potential region east of the township is similarly influenced by lineaments and lithology. The intersection of two larger lineaments in the alluvial area to the south and west of the higher ridges also enhance the potential of this region, with the town water supply (TWS) bore field situated between and in close proximity to this high potential fault zone and the high potential zone following the Wonoka Creek.

The areas in the central part of the region are strongly influenced by lithology. There are few significant lineaments, so the potential zones mimic the shape of the underlying geology with the lowest values coinciding with quartzite ridges and the moderate values over the alluvial plains. There is no pattern in the salinity or yield data with both high and low values for each distributed evenly across the area (figure 10b).

5.2 Quorn groundwater potential

There are three distinct areas that are in the highest value range (figure 11a) centrally located with the township of Quorn on their eastern edge. They are merged in a N–W direction and largely encompassed by the next highest range. The controlling factor is lineaments with lithology having a lesser influence. The central and northern high GPZ areas are where there are intersections of relatively long lineaments and the southern area is between two long N–S trending lineaments and bisected by a third. All three are in alluvial areas and adjacent to higher elevation regions and each is within 10 km of the township.
The lowest values coincide with higher elevation quartzite ridges and the moderate values to the eastern side of the area are underlain by recent alluvium and are areas of low lineament density. The well data for the eastern part of the area show relatively higher salinity values and lower yields suggesting that the main intake areas are the higher elevation areas to the west (figure 11b).

The wells in the northern and central high GPZ areas have higher yields and lower salinity, which can probably be attributed to their connection by lineaments to and proximity to the higher elevation areas, which experience higher rainfall. There are not enough wells in the southern area to draw any conclusions.

5.3 Risk and uncertainty in GPZ mapping results

As detailed in section 3.5, much of the uncertainty in mapping GPZs using the knowledge-based AHP method, lies largely in the subjective judgment of experts on the relative importance of factors. Different perceptions by experts on the influence of factors on groundwater occurrence will propagate through to different GPZ mapping results. In this study, final factor weights were derived from the aggregation of all separate expert judgments through a consolidated matrix approach. Based on the geometric mean method, larger pairwise differences between experts are minimized in the aggregation process while maintaining that each judgment has an influence on the final consolidated AHP weights. The consolidated matrix factor weights were then used to generate a final aggregated GPZ model for both study areas (figures 10 and 11). Individual participant derived AHP factor weights were used as a sample spread of model uncertainty. GPZ maps based on individual AHP judgments are presented in figures 12 and 13 for Hawker and Quorn, respectively. These figures show the effect of different participant judgments have on the modelled spatial distribution of groundwater potential. A standard deviation (SD) raster is included in each figure that
shows the spatial variation in the degree of difference in GPZ index values between each participant. The SD raster may be used to determine the uncertainty or risk at any one location based on the degree of ‘agreement’ between the individual participant GPZ mapping results. They are not to be confused with high or low groundwater potential areas and should be interpreted with care.

For Hawker, the GPZ mapping results for participants 1, 3 and 4 are similar and reflect greater importance given to lithology and lineaments, typical in a fractured rock environment. However, participant 2 has given much greater importance to rainfall. This can be seen by the higher GPZ index values in the S–W near the 10 km line where there is higher rainfall (also noticeable in the SD raster as rainfall ‘isolines’) relative to the other participant maps. Lineament density has also much less influence in participant 3’s map, where the boundary of the large E–W elongated lineament zone is less noticeable compared with all other maps. However, while this area has no distinct lineament boundary shown in participant 3’s map, it does share higher GPZ values with other participants’ results, including the V-shape lineament zone in the S–E. The SD raster also shows relatively good agreement between all participant maps in these higher potential areas with low SD values indicating lower risk or uncertainty in groundwater potential based on these comparisons.

For Quorn, there is a similar relationship between participants’ relative weights (and thus GPZ results) as that described for Hawker. While the SD raster highlights differences to the west and south due to the higher influence given to rainfall by participant 3, the central zone of higher GPZ values is obvious in all four GPZ maps and is highly influenced by the presence of lineaments. The SD values for this central area range from moderate to high agreement (low SD values), with higher agreement on the western edge of this central zone indicating lower risk and uncertainty in this higher groundwater potential area based on these comparisons.

Figure 10. The Hawker study area showing: (a) groundwater potential zones; and (b) groundwater potential zones with well data and the location of the town water supply (TWS) well field. Spatial data source: Lineaments constructed from 100 k linear structures (Department for Energy and Mining 2018) and author image-interpretations; well yield and EC data (Department of Environment and Water 2014); sealed roads (Department of Planning Transport and Infrastructure 2015).
6. Study limitations

In addition to the subjective judgment of experts and thus the uncertainty in GPZ mapping results detailed in section 5.3, other potential limitations in this multi-criteria GIS approach are largely associated with the choice of factors and suitability of their spatial representation. The latter in turn is largely associated with spatial scale and spatial form. This study was conducted at a local scale where the relevance of some factors may be compromised, such as the spatial variation in rainfall interpolated from measurements at much broader scales. This may also extend to the Neoproterozoic–Ordovician faults mapped at 1:2 M scale where their positional accuracy is compromised at a much larger local cartographic scale. However, for most faults mapped at the 1:2 M scale, there were also 1:100 k scale faults mapped with coincidental boundaries. Consequently, wherever possible 1:100 k faults were used as a substitute to improve positional accuracy. Moreover, a comprehensive visual assessment and mapping of surface lineaments were conducted using band-ratio enhanced Sentinel-2A (10–20 m resolution) imagery as well as higher resolution Google Earth imagery. This enabled confirmation of the positional accuracy of mapped and unmapped lineaments over both study areas and thus improved confidence in the mapping accuracy of this factor.

Similarly, the authors have more confidence in the spatial representation of lithology, despite its spatial form derived from a broad scale polygon dataset, where the assumption of uniformity in each polygon applies. Extensive field work was conducted over both study areas to better understand the primary and secondary porosity and permeability characteristic of lithology. For this reason, the authors have greater confidence in the AHP weightings applied to this factor and its sub-categories.

Arguably, the slope and TWI factors may be considered high quality datasets derived from the SRTM 1 arc-sec DEM product; however, sub-class ranges to which AHP weightings are assigned, particularly for slope as an indicator of surface
Figure 12. The Hawker study area showing: (a–d) groundwater potential zone maps based on individual participants’ judgments ($P_1$–$P_4$, respectively) of factor pairwise comparisons; and (e) the degree of ‘agreement’ between participants’ GPZ maps using standard deviation (SD) as a measure of groundwater potential uncertainty.

Figure 13. The Quorn study area showing: (a–d) groundwater potential zone maps derived from individual participants’ judgments ($P_1$–$P_4$, respectively) of factor pairwise comparisons; and (e) the degree of ‘agreement’ between participants’ GPZ maps using standard deviation (SD) as a measure of groundwater potential uncertainty.
runoff, are not well justified in the GPZ literature. Thus, sub-class ranges (factor classes) were delineated by subjective opinion, which may compromise the quality of its spatial representation as an indicator of surface runoff and infiltration potential. The TWI class ranges were also subjectively chosen, although they were guided by landscape position classes described by Gallant and Austin (2012).

Considering the above limitations, it is argued that the relative importance of factors by experts should not be judged independently, but also in the context of the quality of their spatial representation, including their spatial form, scale and accurate variation over the study area. The methods used to produce the GPZ maps in this study have been well considered and in line with current literature, but they should be interpreted in the context of these limitations.

7. Conclusion

The results for both the Hawker area and the Quorn area are the same. The zones identified are closely related to the relative weights determined by the six parameters chosen: rainfall, aspect, lithology, lineament density, topographic wetness and slope. Different weights or alternative parameters will clearly produce a different result as seen in section 5.3. The parameters chosen were carefully considered and justified as described in section 3.3. The major departure from previous studies described in the literature was the use of the topographic wetness index (TWI) and slope in place of drainage density. This was judged in the interest of model redundancy (Malczewski 2000) where drainage density is often included as an indicator of surface runoff potential (Díaz-Alcaide and Martínez-Santos 2019). This is largely accounted for using slope and TWI and where the behaviour of drainage density and its relationship with surface runoff and infiltration was inconsistent over both study areas.

The AHP process was used to calculate parameter weights. This method is one of several that are reported in the literature and is widely regarded for multi-criteria decision-making (Malczewski 2006; Agarwal et al. 2013). The calculated weight is dependent on the pairwise comparison of each of the parameters. Since comparisons between pairs are subjectively determined, where each pair can be between 1 (equal weight) and 9 (one of the pair is strongly favoured), there is considerable scope for variation between experts. To some extent, this is controlled by the consistency ratio incorporated into the AHP calculation, while a consolidated matrix method aggregates all expert judgments (Goepel 2013) as a pseudo consensus approach. The incorporation of a standard deviation raster calculated from all participant inputs also provides a measure of confidence in the spatial variation and uncertainty in groundwater potential mapping results.

The validity of the final result of the process can be assessed by comparison with independent parameters, in this case, well salinity and yield. These data have some limitations. The wells are not evenly distributed across the areas, the depth of the well/water source is not known, and the available data was mostly obtained when the well was drilled rather than at a single time, which would be necessary for a proper calculation. Considering these limitations, there is reasonable confirmation for the Quorn sites but no useful pattern of well data for the Hawker area.

The use of GIS and remote sensing in combination with field-collected data has enabled the delineation of groundwater potential zones across a wide area. It is concluded that, this spatial approach has the potential to be of high value. Subject to appropriate spatial representations, expert judgment of weightings and field observations, the GIS-based method is relatively quick, inexpensive and transferable across landscapes. The process provides first-stage evaluation of GPZs over large areas that enable a more strategic on-ground assessment of high potential areas.

Acknowledgements

The authors gratefully acknowledge the financial support provided by SA Water (Grant No. IN226613) to conduct this research. The authors also acknowledge an early contribution to the project by Dr Alaa Ahmed.

References

Abrams W, Ghoneim E, Shew R, LaMaskin T, Al-Bloushi K, Hussein S, AbuBakr M, Al-Mulla E, Al-Awar M and El-Baz F 2018 Delineation of groundwater potential (GWP) in the northern United Arab Emirates and Oman using geospatial technologies in conjunction with Simple Additive Weight (SAW), Analytical Hierarchy Process (AHP), and
Probabilistic Frequency Ratio (PFR) techniques; *J. Arid Environ.* 157 77–96, https://doi.org/10.1016/j.jaridenv.2018.05.005.

Adiri Z, El Harti A, Jellouli A, Lhissou R, Maacha L, Azmi M, Zouhair M and Bachaoui E M 2017 Comparison of Landsat-8, ASTER and Sentinel 1 satellite remote sensing data in automatic lineaments extraction: A case study of Sidi Flah-Bouskour inlier, Moroccan Anti Atlas; *Adv. Space Res.* 60 2355–2367, https://doi.org/10.1016/j.asr.2017.09.006.

Aagarwal E, Aagarwal R, Garg R D and Garg P K 2013 Delineation of groundwater potential zone: An AHP/ANP approach; *J. Earth Syst. Sci.* 122 887–898, https://doi.org/10.1007/s12040-013-0309-8.

Aagarwal R and Garg P K 2016 Remote sensing and GIS based groundwater potential and recharge zones mapping using multi-criteria decision making technique; *Water Resour. Manag.* 30 243–260, https://doi.org/10.1007/s11269-015-1159-8.

Ahmed M and Ben-Hur M 1991 Effect of slope length, aspect and phosphygoseum on run off and erosion from steep slopes; *Austr. J. Soil Res.* 29 129–207, https://doi.org/10.1071/SR9910197.

Ahmed A and Clark I 2016 Groundwater flow and geochemical evolution in the Central Finders Ranges, South Australia; *Sci. Total Environ.* 572 837–851, https://doi.org/10.1016/j.scitotenv.2016.07.123.

Ahmed R and Sajjad H 2018 Analyzing factors of groundwater potential and its relation with population in the Lower Barpani Watershed, Assam, India; *Nat. Resour. Res.* 27 503–515, https://doi.org/10.1007/s11269-015-9367-y.

Al-Ruzzouq R, Shanableh A and Merabtine T 2015 Geomatics for mapping of groundwater potential zones in northern part of the United Arab Emirates – Sharjah City; In: ISPRS – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XL-7/W3, 2015. 36th International Symposium on Remote Sensing of Environment XL-7/W3, pp. 581–586, https://doi.org/10.5194/isprsarchives-XL-7-W3-581-2015.

Alceo D and Berens V 2011 Non-prescribed groundwater resources assessment – Northern and Yorke Natural Resources Management Region. Phase 1: Literature and data review; Department for Water, DFW Technical Report 2011/17. Government of South Australia, Adelaide.

Alonso J A and Lamata M T 2006 Consistency in the analytic hierarchy process: A new approach; *Int. J. Uncertain. Fuzziness Knowl. Based Syst.* 14 445–459, https://doi.org/10.1142/S0218488506004114.

Arulbalaji P, Padmalal D and Sreelash K 2019 GIS and AHP techniques based delineation of groundwater potential zones: A case study from Southern Western Ghatls, India; *Sci. Rep.* 9 2082, https://doi.org/10.1038/s41598-019-38567-x.

Aull-Hyde R, Erdogan S and Duke J M 2006 An experiment on the consistency of aggregated comparison matrices in AHP; *Eur. J. Oper. Res.* 171 290–295, https://doi.org/10.1016/j.ejor.2004.06.037.

Bagyaraj M, Ramkumar T, Venkatramanan S and Gurug-nanam B 2013 Application of remote sensing and GIS analysis for identifying groundwater potential zone in parts of Kodaiakanal Taluk, South India; *Front. Earth Sci.* 7 65–75, https://doi.org/10.1007/s11707-012-0347-6.

Balamurugan G, Karthik S and Somnath B 2017 Frequency ratio model for groundwater potential mapping and its sustainable management in cold desert, India; *J. King Saud Univ. Sci.* 29 333–347, https://doi.org/10.1016/j.jksus.2016.08.003.

Beuillin J, Van de Velde D and Nyssen J 2014 Impact of slope aspect on hydrological rainfall and on the magnitude of rill erosion in Belgium and northern France; *Catena* 114 129–139, https://doi.org/10.1016/j.catena.2013.10.016.

Brunelli M 2015 Introduction to the Analytic Hierarchy Process; Springer Briefs in Operations Research, Springer International Publishing, https://doi.org/10.1007/978-3-319-12502-2.

Bureau of Meteorology 2019 Rainfall Map Information. Information on rainfall data products, http://www.bom.gov.au/climate/averages/tables/cw_019017.shtml.

Bureau of Meteorology 2020 Climate Data Online, Climate Statistics for Australian Locations. Summary statistics Hawker, http://www.bom.gov.au/climate/averages/tables/cw_019017.shtml.

Chen W, Li H, Hou E, Wang S, Wang G, Panahi M, Li T, Peng T, Guo C, Niu C, Xiao L, Wang J, Xie X and Ahmad B B 2018 GIS-based groundwater potential analysis using novel ensemble weights-of-evidence with logistic regression and functional tree models; *Sci. Total Environ.* 634 853–867, https://doi.org/10.1016/j.scitotenv.2018.04.055.

Clark I and Brake L 2008 Sustainable management of groundwater resources in parts of arid South Australia. In: *IAHR International Groundwater Symposium. Flow and Transport in Heterogeneous Subsurface Formations; Theory, Modelling and Applications* (eds) Copty N and Findikakis A, June 18–20, 2008, Istanbul, Turkey.

Clark I and Brake L 2009 Using local knowledge to improve understanding of groundwater supplies in parts of arid South Australia; *GeoJ.* 74 441–450, https://doi.org/10.1007/s10708-008-9236-7.

Cogne S, Magagi R, Yergeau M and Sylla D 2010 An integrated approach to hydrogeological lineament mapping of a semi-arid region of West Africa using Radarsat-1 and GIS; *Remote Sens. Environ.* 114 1863–1875, https://doi.org/10.1016/j.rse.2010.03.004.

Costar A, Kruger N and Howles S 2010 Far North Town Water Supplies – Quorn and Wilmington, South Australia; Department of Water, Land and Biodiversity Conservation. Technical Report Number 2010/04. Government of South Australia, Adelaide.

Crosbie R S, McCallum J L, Walker G R and Chiew F H S 2012 Episodic recharge and climate change in the Murray-Darling Basin, Australia; *Hydrol. J.* 20 45–261, https://doi.org/10.1007/s10040-011-0804-4.

Das S and Pardeshi S D 2018 Integration of different influencing factors in GIS to delineate groundwater potential areas using IF and FR techniques: A study of Pravara basin, Maharashtra, India; *Appl. Water Sci.*, https://doi.org/10.1007/s13201-018-0484-x.

Deepika B, Avinash K and Jayappa K S 2013 Integration of hydrological factors and demarcation of groundwater prospect zones: Insights from remote sensing and GIS techniques; *Environ. Earth Sci.* 70 1319–1338, https://doi.org/10.1007/s12665-013-2218-1.

Department for Energy and Mining 2012 100 k Geology (Surface Geology); Government of South Australia. Data accessed via South Australian Resources Information Gateway (SARIG), https://map.sarig.sa.gov.au/.
potential zones using a multi-criteria data mining methodology; *Environ. Monit. Assess.* 189:321. https://doi.org/10.1007/s10661-017-5990-7.

Mohan C, Western A W, Wei Y and Saft M 2018 Predicting groundwater recharge for varying land cover and climate conditions – a global meta-study; *Hydrol. Earth Syst. Sci.* 22 2689–2703. https://doi.org/10.5194/hess-22-2689-2018.

Mu W, Yu F, Li C, Xie Y, Tian J, Liu J and Zhao N 2015 Effects of rainfall intensity and slope gradient on runoff and soil moisture content on different growing stages of spring maize; *Water* 7 2990–3008. https://doi.org/10.3390/w7062990.

Nag S K and Ghosh P 2013 Delineation of groundwater potential zone in Chhatna Block, Bankura District, West Bengal, India, using remote sensing and GIS techniques; *Environ. Earth Sci.* 70 2115–2127. https://doi.org/10.1007/s12665-012-1713-0.

Naghibi S A, Moghadam D D, Kalantari B, Pradhan B and Kisi O 2017 A comparative assessment of GIS-based data mining models and a novel ensemble model in groundwater well potential mapping; *J. Hydrol.* 548 471–483. https://doi.org/10.1016/j.jhydrol.2017.03.020.

Osei-Bonsu K and Evans S 2002 Groundwater exploration – *Quorn Township Water Supply Wellfield, South Australia*; Department of Water, Land and Biodiversity Conservation. Report DWLBC 2002/28. Government of South Australia.

Ozdemir A 2011 GIS-based groundwater spring potential mapping in the Sultan Mountains (Konya, Turkey) using frequency ratio, weights of evidence and logistic regression methods and their comparison; *J. Hydrol.* 411 290–308. https://doi.org/10.1016/j.jhydrol.2011.10.010.

Park Y-J, Lee K-K and Kim J-M 2000 Effects of highly permeable geological discontinuities upon groundwater productivity and well yield; *Math. Geol.* 52 605–618. https://doi.org/10.1023/A:1007514405501.

Paul E, Flöttmann T and Sandiford M 1999 Structural geometry and controls on basement-involved deformation in the northern Flinders Ranges, Adelaide Fold Belt, South Australia; *Austr. J. Earth Sci.* 46 343–354. https://doi.org/10.1046/j.1440-0952.1999.00711.x.

Preiss W V 1987 *The Adelaide Geosyncline – late Proterozoic stratigraphy, sedimentation, palaeontology and tectonics*, South Australian Geol. Survey Bull., 53 edn. Government Printer, South Australia, Adelaide, 438p.

Ramu M B and Vinay M 2014 Identification of ground water potential zones using GIS and remote sensing techniques: A case study of Mysore taluk, Karnataka; *Int. J. Geomat. Geosci.* 5 393–403.

Razandi Y, Pourghasemi H R, Neisani N S and Rahmati O 2015 Application of analytical hierarchy process, frequency ratio, and certainty factor models for groundwater potential mapping using GIS; *Earth Sci. Infor.* 8 867–883. https://doi.org/10.1007/s12145-015-0220-8.

Saaty R W 1987 The analytic hierarchy process – what it is and how it is used; *Math. Model.* 9 161–176. https://doi.org/10.1016/0270-0255(87)90473-8.

Saaty T L 1977 A scaling method for priorities in hierarchical structures; *J. Math. Psychol.* 15 234–281. https://doi.org/10.1016/0022-2496(77)90033-5.

Saaty T L 1980 *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*, McGraw-Hill, New York.

Saaty T L 2001 Decision-making with the AHP: Why is the principal eigenvector necessary; In *Proceedings of the international symposium on the analytic hierarchy process*, Berne, Switzerland, pp. 1–19.

Saaty T L 2012 *Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World*; 3rd Rev. edn, RWS Publications, Pittsburgh.

Sander P 2007 Lineaments in groundwater exploration: A review of applications and limitations; *Hydrol. J.* 15 71–74. https://doi.org/10.1007/s10040-006-0138-9.

Saraf A K and Choudhury P R 1998 Integrated remote sensing and GIS for groundwater exploration and identification of artificial recharge sites; *Int. J. Remote Sens.* 19 1825–1841. https://doi.org/10.1080/014316498215018.

Senanayake I P, Dissanayake D M D O K, Mayadunna B B and Weerasekera W L 2016 An approach to delineate groundwater recharge potential sites in Ambalantota, Sri Lanka using GIS techniques; *Geosci. Front.* 7 115–124. https://doi.org/10.1016/j.gsf.2015.03.002.

Sener E, Davraz A and Ozcelik M 2005 An integration of GIS and remote sensing in groundwater investigations: A case study in Burdur, Turkey; *Hydrol. J.* 13 826–834. https://doi.org/10.1007/s10040-004-0378-5.

Sørensen R, Zinko U and Seibert J 2006 On the calculation of aridity of rainfall intensity and slope gradient on runo.

Saraf A K and Choudhury P R 1998 Integrated remote sensing and GIS for groundwater potential mapping in the Sultan Mountains (Konya, Turkey) using frequency ratio, weights of evidence and logistic regression methods and their comparison; *J. Hydrol.* 411 290–308. https://doi.org/10.1016/j.jhydrol.2011.10.010.

Saraf A K and Choudhury P R 1998 Integrated remote sensing and GIS for groundwater potential mapping in the Sultan Mountains (Konya, Turkey) using frequency ratio, weights of evidence and logistic regression methods and their comparison; *J. Hydrol.* 411 290–308. https://doi.org/10.1016/j.jhydrol.2011.10.010.

Steele K, Carmel Y, Cross J and Wilcox C 2009 Uses and misuses of multicriteria decision analysis (MCDA) in environmental decision making; *Risk Anal.* 29 26–33. https://doi.org/10.1111/j.1539-6924.2008.01130.x.

Tweed S O, Leblanc M, Webb J A and Lubczynski M W 2007 Remote sensing and GIS for mapping groundwater recharge and discharge areas in salinity prone catchments, south-eastern Australia; *Hydrol. J.* 15 75–96. https://doi.org/10.1007/s10040-006-0129-x.

Yeh H-F, Cheng Y-S, Lin H-I and Lee C-H 2016 Mapping groundwater recharge potential zone using a GIS approach in Hualien River, Taiwan; *Sustain. Environ. Res.* 26 33–43. https://doi.org/10.1016/j.serj.2015.09.005.

Yin H, Shi Y, Niu H, Xie D, Wei J, Lefticariu L and Xu S 2018 A GIS-based model of potential groundwater yield zonation for a sandstone aquifer in the Juye Coalfield, Shandong, China; *J. Hydrol.* 557 434–447. https://doi.org/10.1016/j.jhydrol.2017.12.043.

Zeinolabedini M and Esmaeily A 2015 Groundwater potential assessment using geographic information systems and AHP method (Case study: Baft City, Kerman, Iran); *ISPRS Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* XL-1-W5 769–774. https://doi.org/10.5194/isprsarchives-XL-1-W5-769-2015.

Zulfi D, Wilson T, Costar A and Mortimer L 2010 Predicting catchment scale processes, Mount Lofty Ranges, *South Australia*; DFW Technical Report 2010/17, Department for Water, Adelaide, Government of South Australia.

Corresponding editor: SUBIMAL GHOSH