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Framework for incorporating spectral observations into steady state analysis of groundwater discharge around the margins of the Great Artesian Basin

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Abstract: Diffuse groundwater discharge (also known as vertical leakage) forms an important and poorly constrained component of the water balance of the Great Artesian Basin (GAB), Australia's largest groundwater resource. Around the south-western margin of the GAB, the diffuse leakage from the artesian aquifer discharges into the unconfined water table and subsequently into the atmosphere via evapotranspiration (ET). Under steady state conditions (i.e. prior to the development of the GAB), the evaporative flux, in addition to natural artesian discharge from springs, are considered to equal the potentiometric head driven flow to the Basin margin. Since 2007, a project has been collecting field data on the evaporative discharge rates using a number of essentially point-based techniques. These techniques involved bare soil evaporation measured by microlysimeters, evapotranspiration measured by an eddy covariance flux station, and long-term evaporative discharge rates through the soil column estimated from soil solute profiles using an advection-diffusion model. Spatial heterogeneity provides a major challenge in utilizing these data for estimating the diffuse groundwater discharge over a large area. In this study we use spectral data from the ASTER, Landsat and Quickbird satellites, in addition to geomorphic mapping and digital elevation data, to characterize discharge zones according to a conceptual framework based on the physical attributes of varying evaporative discharge, in particular the salt content at the surface, soil moisture and thermal properties. The conceptual framework aims to relate subsurface processes, and ultimately rates of diffuse discharge, with their expected surface expressions. The framework classifies discharge areas into zones which represent approximately order of magnitude variations in discharge rates, as defined by their subsurface processes. The field-based estimates of discharge ranges are assigned to the land surface classes according to spatial location and spectral similarities. This method was applied to a study area (Public House Springs) located on the margin of the GAB with the Gammon Ranges in South Australia. An analysis of groundwater flux rates over the study area was conducted to determine if the estimated evaporative discharge and artesian spring discharge rates complied with steady state conditions. Inflow to the model domain was estimated with Darcy's Equation, using measured differences between the artesian head and the artesian spring mean elevation and best estimates of aquifer parameters from other studies of the GAB. This approach provides a framework for both estimating diffuse discharge at large spatial scales and further investigating the effects of uncertainties in the major input data sources.

Keywords: *evaporative discharge, satellite data, artesian springs, eddy covariance*

1. INTRODUCTION

Diffuse groundwater discharge (also known as vertical leakage) forms an important and poorly constrained component of the water balance of the Great Artesian Basin (GAB), Australia's largest groundwater resource (Habermehl, 1980). Around the south-western margin of the GAB in South Australia, the principal aquifers outcrop, or occur in near-surface positions whilst under artesian pressure. As a result, much of the diffuse leakage from the artesian aquifer discharges into the unconfined water table and subsequently into the atmosphere via evapotranspiration (ET). Under steady state conditions (i.e. prior to the development of the GAB), the evaporative flux, in addition to natural artesian discharge from springs, are considered to equal the potentiometric head driven flow to the Basin margin. An important assumption of this hypothesis is that any pluvial or fluvial contribution to the water table in the discharge areas is minimal.

The areas of highest discharge are characterised by groups of artesian springs and areas of salt accumulation at the surface. These areas are controlled on the macro scale by stratigraphic (e.g. outcrop areas of aquifer units along the GAB margin) and structural (e.g. fault lines) features. However, the areas of highest discharge are scattered and form a relatively small proportion of the landscape, but potentially experience discharge rates orders of magnitude different from surrounding areas. Given the large area and variable characteristics of zones of potential discharge, the use of remotely sensed data is critical in defining zones of differing discharge rates and incorporating this information into the analysis of groundwater fluxes at the GAB margins.

Compared to areas with negligible evaporative flux, areas of enhanced leakage are expected to be characterised by higher soil moisture, higher evaporation rates and possibly by salt deposition at the surface. In terms of spectral characteristics, these conditions can result in contrasts in the infrared (e.g. lower reflectance in discharge zones because of higher soil moisture and salt absorption features in the shortwave infrared (SWIR)) and visible bandwidths (e.g. high reflectance because of salt deposition at the surface following the evaporation of the saline groundwater).

2. METHODS

2.1. Field area

Since 2007, a project has been collecting field data on the evaporative discharge rates at field sites along the southwest margin of the GAB. This paper describes a framework for a discharge site located on the southern boundary of the GAB with the Gammon Ranges (North Flinders Ranges). At this location, the local equivalent of the main Jurassic – early Cretaceous basal aquifer of the GAB (Parabarana Sandstone) outcrops unconformably against the Proterozoic crystalline basement rocks of the Gammon Ranges. A number of artesian spring vents, termed the Public House Springs (Figure 1), occur within the discharge zone in conjunction with areas of thin salt crusting at the surface, coinciding largely with the interpreted outcrop area of the Parabarana Sandstone. The aquifer unit dips to the north and is overlain by the Bulldog Shale, a marine mudstone that forms the main aquitard to the GAB principal aquifers. The only two artesian bores located close to the study area are shown in Figure 1, along with the potentiometric heads measured at these two locations. While the dominant dip direction of the GAB strata is to the north, the head data indicate that the potentiometric surface has a higher head to the west of the Public House Springs and decreases to the east as it approaches an area of low head around Lake Frome (Habermehl, 1980).

2.2. Field measurements and remote sensing

Field estimates of evaporative discharge from the unconfined water table used a number of essentially point-based techniques. These techniques involved bare soil evaporation measured by microlysimeters (Tyler et al., 1997), evapotranspiration measured by an eddy covariance flux station, and long-term evaporative discharge rates through the soil column estimated from soil solute profiles using an advection-diffusion model (Allison and Barnes, 1985). Spatial heterogeneity provides a major challenge in utilising these data for estimating the diffuse groundwater discharge over a large area. In this study we use spectral data from the ASTER, Landsat and Quickbird satellites, in addition to geomorphic mapping and digital elevation model (DEM) data, to characterise discharge zones according to a conceptual framework based on the physical attributes of varying evaporative discharge, in particular the salt content at the surface, soil moisture and thermal properties. The conceptual framework aims to relate subsurface processes, and ultimately rates of diffuse discharge, with their expected surface expressions. The framework classifies discharge areas into zones which represent approximately order of magnitude variations in discharge rates, as defined by their subsurface processes. The field-based estimates of discharge ranges are assigned to the land surface classes according to spatial location and spectral similarities.

2.3. Groundwater flow analysis

A study area over the Public House springs was defined with a 250 m x 250 m grid cell size (model domain 13.5 km x 9 km, see Figure 1). The ground surface topography was derived from the Shuttle Radar Topographic Mission (SRTM) DEM with a 90 m cell resolution. The dip and thickness of the artesian layer was determined from two bores 8 - 12.5 km from the model domain. The measured piezometric head from these bores was also used to determine the constant head boundary conditions for the artesian layer (Figure 1). There were no aquifer parameter data available for the study area so a range of hydraulic conductivity and specific storage values were used based on studies of the GAB aquifer 250 km west of the model domain (Berry and Armstrong, 1995).

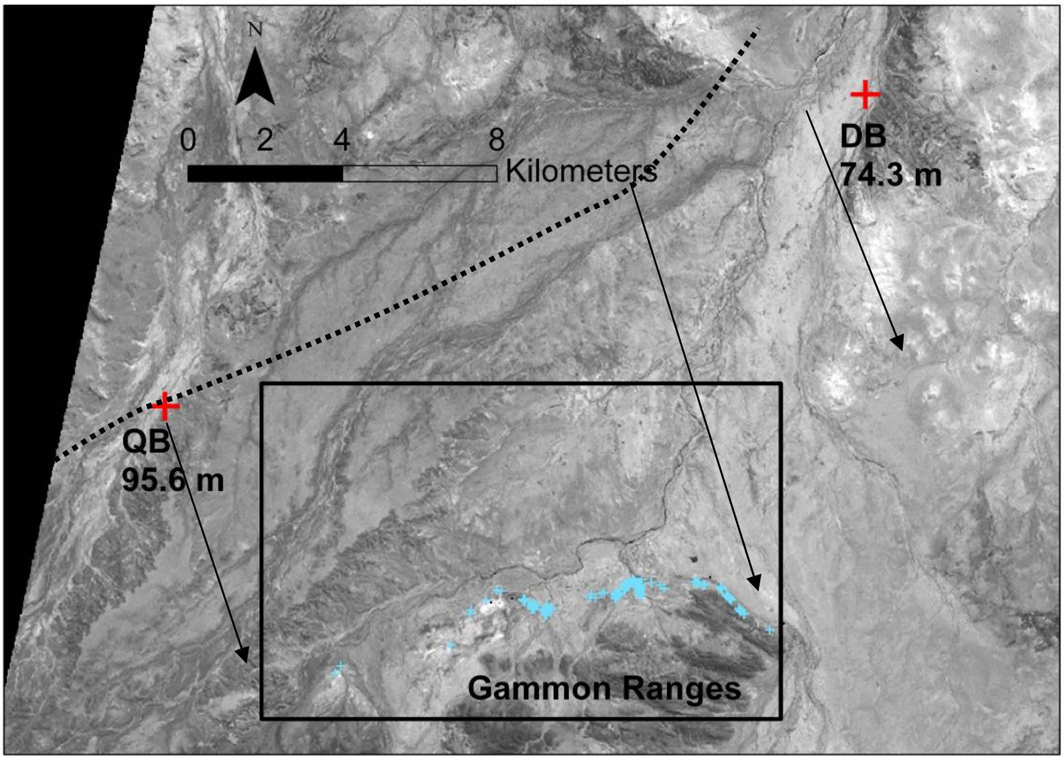

Figure 1. Public House Springs study area showing 13.5 km x 9 km box covering the model domain. Locations of artesian springs are shown as blue crosses and the locations of the two closest artesian bores (Quartpot Bore – QB, Dean's Lookout Bore – DB) are shown as large red crosses. The piezometric heads of the two bores are also shown. The dashed line is a potentiometric contour and the arrows show the interpreted dominant flow direction. Background to figure is a Landsat grey colour image (Band 4).

The inflow of artesian groundwater to the model domain was determined by the potentiometric surface and the hydraulic conductivity of the artesian aquifer. Outflow from the model domain was by evaporative flux from the unconfined groundwater table and flow from artesian springs. No information was available on flow rates from the artesian springs but spring location data were available (unpubl. data, Travis Gotch, South Australian Arid Lands Natural Resource Management Board). This dataset identified 199 locations with evident discharge that ranged from damp seeps to small pools maintained by spring discharge. No strongly flowing springs were observed in the study area. The springs occurred in DEM cells with elevations ranging between 60 – 90 m AHD and had a mean elevation of 70.1 m AHD. The evaporative discharge from the unconfined groundwater table was set by assigning field ET measurement ranges to geomorphic units identified by remote sensing.

In order to calculate the steady-state inflow to the model domain from the artesian aquifer, Darcy's Equation was employed, using the difference between the artesian head and the mean elevation of the artesian springs, in addition to estimates of the aquifer hydraulic conductivity from other studies. The potentiometric surface of the GAB artesian aquifer was poorly constrained by only two bores in the vicinity of the study area but the available data for the study area indicate that the potentiometric contours are from the southwest to the northeast and that the artesian groundwater dominant flow direction is to the southeast. The estimated potentiometric contour through Quartpot Bore (95.6 m AHD, see Figure 1) was used as a baseline for determining flow lines into the model domain. Darcy's Equation was used to estimate flux rates from this contour to the high discharge area marked by the line of artesian springs, along 3 km wide sectors with approximately perpendicular flow lines from the potentiometric contour to the artesian springs (see arrows in Figure 1 that define the start and end points of these 3 km sectors). This approach provides a framework for both estimating diffuse discharge at large spatial scales and further investigating the effects of uncertainties in the major input data sources.

3. RESULTS

3.1. Remote Sensing

Landforms in the model domain were classified into a number of various geomorphic units, relating to variation in probable evaporative discharge rates, using remotely sensed data. Information from field mapping and soil profiling was used to refine and ground-truth the classification from the remotely sensed data and the different units are described below, moving from south to north (Figure 2).

The crystalline ***basement rocks*** of Proterozoic age comprise the hills that form along the southern part of the model domain. These rocks are considered to form the impervious underlying layer to the GAB aquifer sediments and so are excluded from the water balance analysis. This unit was mapped using the DEM, available geological data and satellite data.

North of the basement rocks and south of a high discharge area (described in following paragraph) was a ***carbonate cap rock*** area. The carbonate cap rock typically had a sharp boundary with the high discharge area, forming a low plateau 1-2 m higher than the discharge area and which extended back to the Proterozoic basement rocks (often under a thin sand cover). The carbonate cap rock showed a clear spectral response in the visible and near infrared bandwidths but did not exhibit an SWIR absorption feature, as is expected from carbonate minerals, and this may be a function of thin sediment cover. This unit was too subtle a topographic feature to be apparent in the DEM data. The carbonate layer had an apparent thickness of 1-2 m and typically did not show any evidence of surface salts or high soil moisture contents close to the surface.

The ***high discharge area*** was characterised by thin, sporadic salt crusting at the surface and variably high soil moisture. This unit also contained a significant rock lag component that partly obscured the spectral response from the salt crusting and so field mapping and the DEM were also used in defining this unit. The patches with the most salt crusting showed strong absorption features in SWIR reflectance, centered on 1900 nm and this is characteristic of evaporate minerals (e.g. halite, gypsum and carbonates). This zone coincided with the subcrop position of the GAB aquifer unit (Parabarana Sandstone) and also contained most of the flowing artesian springs in the area.

The ***transition zone*** occurred between the high discharge area and the areas of outcropping Bulldog Shale to the north. This zone showed a mixed spectral response and generally occurred in topographically low areas. Geomorphic mapping and limited soil coring indicated that this area coincided with some cover over the subcropping Parabarana Sandstone (including low sand dunes and thin Bulldog Shale cover) or drainage lines emanating from the Gammon Ranges.

To the north of the high discharge zone, and mostly separated by a creek system, was the rolling plateau composed of ***gibber covered Bulldog Shale***. This unit is a marine mudstone that directly overlies and forms the main aquitard to the GAB aquifer units. This unit showed as a distinctive rise in the DEM data and did not show any of the low infrared reflectivity and high visible reflectivity characteristics of the high discharge zone.

3.2. Field estimates of discharge

Estimates of evaporative discharge from using the eddy covariance equipment and microlysimeters were mostly confined to the high discharge zone. Fieldwork in July 2007 found that annualized rate of mean daily discharge from the eddy covariance equipment was 56 mm y^{-1} and that of the microlysimeters was 157 – 176 mm y^{-1}. An annualised rate of 390 mm y^{-1} was measured by eddy covariance equipment in November 2008 but this was immediately after local rainfall and probably overestimates the evaporative discharge rate. The depth to groundwater in the high discharge zone was 1.3 – 1.6 m below ground surface as measured in two piezometers. Soil profile modelling results for two cored profiles in the transition zone indicated that the evaporative discharge rate was 2 - 35 mm y^{-1}. Due to the relatively shallow water table and sporadic salt crusting in the transition zone, it was assigned relatively high evaporation rates of between 10-50 mm y^{-1} in the analysis.

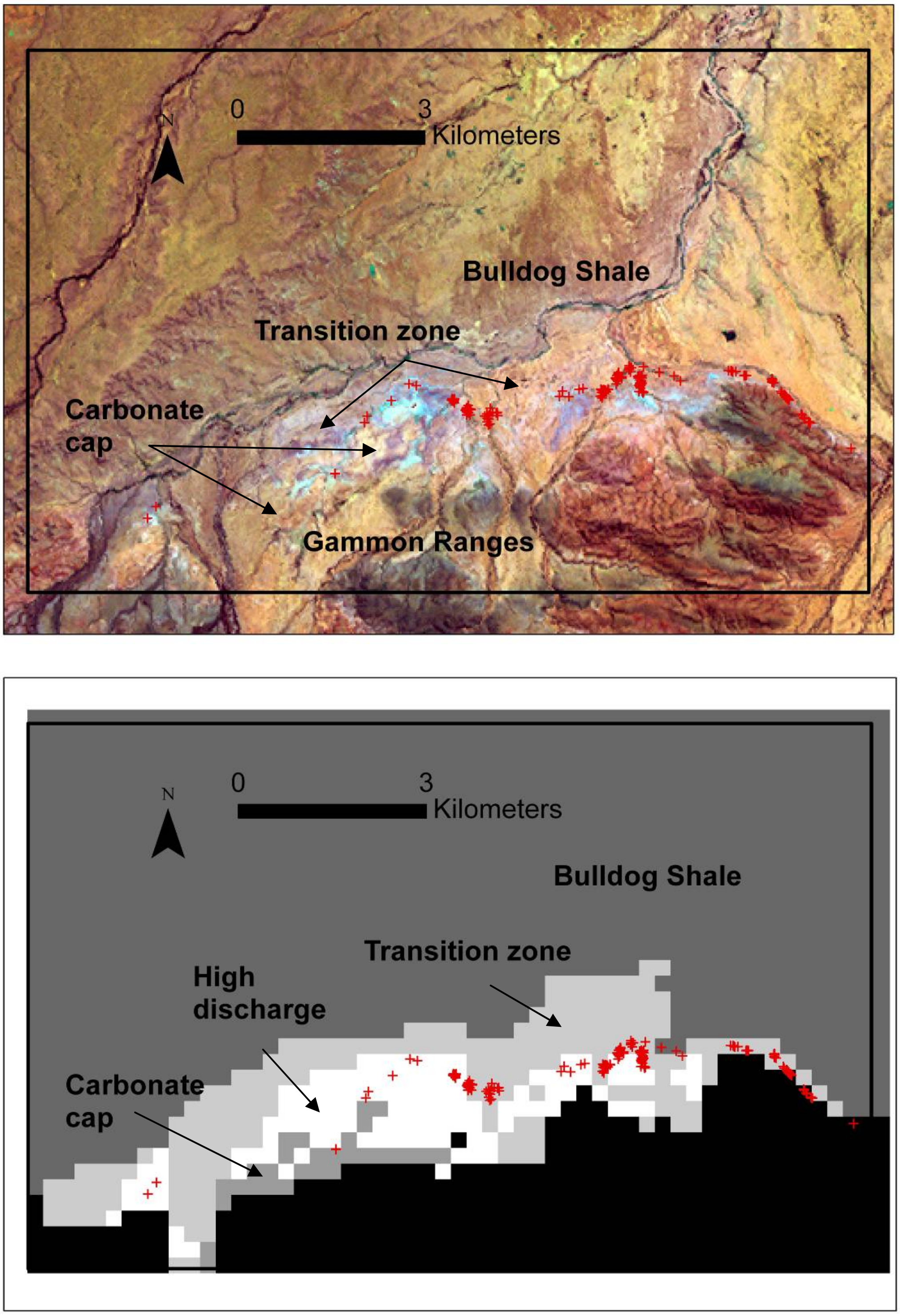

Figure 2. Public House Springs study area using Landsat false colour image (upper panel) with Bands 7 (red), 3 (green) and 1 (blue) to illustrate differences between evaporative discharge units. The lower panel shows the distribution of five classes of evaporative discharge using a 250x250 m cell size. The position of spring vents are shown as small red crosses and areas of blue-white in the upper panel are due to salt deposition in the high discharge zone.

No field estimates are yet available in the carbonate cap zone (results from one soil profile are pending). The increase in the depth of the water table and the less pervious nature of the carbonate suggest that the evaporative discharge rate would be significantly lower than the high discharge zone and lower than that of the transition zone. The evaporative discharge rate for the crystalline basement rocks was assumed to be zero.

Soil profile modelling with the advection-diffusion model (Allison and Barnes, 1985) was used to estimate steady state evaporative discharge rates from the Bulldog Shale area. The results varied considerably when using the chloride compared to the ^{18}O isotope profiles, with the chloride data indicating discharge rates between 0.2 - 0.6 mm y^{-1}, while the ^{18}O isotope data indicated discharge rates between 2 – 14 mm y^{-1}. The unconfined water table was not intersected during drilling in this unit but field relationships between the topography and known water table depths indicate that depths are likely to be >3 m and probably >10 m in the higher elevation areas of Bulldog Shale in the northwestern part of the model domain. Based on the available field data, the estimates of evaporative discharge for each of the discharge units identified in the remote sensing analysis are shown in Table 1.

Table **1**. Evaporative discharge rates estimated for geomorphic units at Public House Springs

Unit	Lower discharge rate (mm y^{-1})	Higher discharge rate (mm y^{-1})	Field measurement
Basement	0	0	Estimated
Carbonate cap	5	20	Estimated
High discharge	50	200	Microlysimeters and eddy covariance
Transition	10	50	Soil profile modelling and eddy covariance
Bulldog Shale	0.2	10	Soil profile modelling

3.3. Groundwater flux analysis

Using the low and high evaporative discharge estimates from Table 1 and assigning these to the appropriate 250 x 250 m grid cells of the model domain, the total annual evaporative discharge is estimated to range between 500,250 – 2,808,125 m^3. The total spring discharge was estimated using a range of individual spring discharge rates between 1 – 10 m^3 d^{-1}, resulting in an annual discharge range of 72,635 – 726,350 m^3. These figures imply a maximum annual steady state outflow rate from the model domain of 3,534,475 m^3 and a minimum outflow rate of 572,885 m^3.

Table **2**. Head driven flux rates into model domain

Hydraulic conductivity (m d^{-1})	Aquifer thickness (m)	Flow length	Daily flux (m^3 d^{-1})	Annual flux (m^3)
1.6	60	standard	3831.5	1,398,494
1.6	30	standard	1915.7	699,247
1.6	60	+1000 m	3442.0	1,256,343
8.5	60	standard	20,354.8	7,429,500
8.5	30	standard	10,177.4	3,714,750

The possible range of inflow values were investigated using likely aquifer parameter values and Darcy's Equation (Table 2). Berry and Armstrong (1995) reviewed estimates of aquifer values in the GAB from aquifer tests conducted 250-300 km to the west of the study area. The reported range of hydraulic conductivity values was 1.6 – 17 m d^{-1} (mean 8.5 m d^{-1}, n=24) and transmissivity values were 5 – 380 m^2 d^{-1} (mean 182.6 m^2 d^{-1}, n=24). Based on data from the two local artesian bores, the estimated thickness of the GAB aquifer around the boundary of the model domain was 60 m. The head gradient was taken as the difference between the Quartpot Bore head and the mean elevation of the artesian springs. The length of each 3 km sector varied based on the interpreted trend of the 95.6 m potentiometric contour. The range of flux values for the head driven inflow to the model domain is shown in Table 2 using a range of appropriate hydraulic conductivity and aquifer thickness. In one case, the flow length of each of the 3 km sectors was increased by 1000 m to test for the sensitivity of the interpreted position of the 95.6 m potentiometric contour. However, the results indicate that steady state analysis was more sensitive to the hydraulic conductivity and aquifer thickness values used than moderate changes in the length of the flow path. The steady state analysis of possible head driven inflow rates to the model domain (Table 2) shows that the estimated range of annual outflow calculated for the artesian springs and evaporative discharge (572,885 - 3,534,475 m^3) is consistent with head driven inflow rates using low to mean values of hydraulic conductivity and aquifer thickness.

4. DISCUSSION AND CONCLUSIONS

The groundwater flux analysis and framework constructed for the study area assist in the understanding of the movement of groundwater from the artesian aquifer to the unconfined groundwater table. Observed water table depths from three shallow bores had highest levels in the southwestern quadrant of the model domain (coinciding with the high discharge zone) and decreased to the north and east moving away from the GAB margin (similar to the pattern shown by the two GAB bores). The highest elevation unconfined groundwater in the southwestern part of the model domain had a low salinity, depleted isotopic signature consistent with the GAB artesian groundwater, and the unconfined groundwater intersected at lower elevations moving to the north had a progressively higher salinity and more enriched isotopic signature. These observations indicate that upwelling artesian groundwater is discharging into the unconfined groundwater table in the discharge zone, and while most is transferred to the atmosphere as evaporation, a component apparently drains downslope to the north. As a result, the unconfined groundwater table moving away from the GAB margin is likely to receive lateral, down gradient flow in addition to upward leakage from the artesian aquifer.

The assignment of field estimates of evaporative discharge to geomorphic units, identified by analysis of remotely sensed data, has allowed an analysis of major components of the steady-state groundwater balance. In particular, the identification of the land units with different discharge characteristics provides a robust means of scaling scarce point based estimates of discharge to the landscape scale and also in investigating the effects of uncertainties in discharge estimates on the modelled water balance. The use of the satellite data to classify land units in terms of spectral characteristics related to evaporative discharge (e.g. reflectance and absorption features of evaporative minerals, soil moisture effects) provides a direct link between the remote sensing classification and the process of interest. However, additional datasets, such as elevation data and field mapping, were required to refine the classification of the remote sensing data. No spectral signature was able to be used to provide estimates of evaporative discharge as a continuous field but further work is planned to investigate this possibility. Future work will also model the conceptual framework for the system using MODFLOW to allow further analysis and exploration of the sensitivity of the system to the assumptions and uncertainties used in this analysis.

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