Quantifying near-surface, diffuse groundwater discharge along the south-west margin of the Great Artesian Basin

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Abstract

Few field measurements are available to constrain the diffuse discharge (or vertical leakage) component of the water balance of the Great Artesian Basin (GAB), even though numerical modelling indicates that it accounts for over half of the outflow of the GAB in South Australia. High leakage rates are observed along the southwestern margin of the GAB where the aquifer is close to the surface with the groundwater under artesian pressure. These zones contain both sporadic springs and distinct areas of leakage into the surface environment as shown by salt deposition at surface and very shallow water tables. These leakage zones typically occur along stratigraphic and structural features. Quantifying the component of vertical leakage occurring along the margin of the GAB will better constrain the water balance of the GAB and increase confidence in sustainable yields from this vital water resource. This project uses evapotranspiration monitoring (eddy correlation, microlysimeters) and soil water chloride profiles to estimate groundwater discharge rates. Preliminary data have been collected from the western side of the Peake-Denison Ranges and the northern edge of the Gammon and Willouran Ranges of South Australia. In these areas, diffuse discharge commonly occurs along or near the outcropping aquifer-aquitard. The discharge rates were consistently higher for the areas showing substantial salt crusting at the surface, with flux rates in the order of 10's mmyr^{-1}. In contrast, modelled annual flux rates from soil profiles drilled in areas lacking widespread surface salt precipitation were <10 mmyr^{-1} and similar to previously published rates in the Lake Eyre South region.

1. INTRODUCTION

The Great Artesian Basin (GAB) is the largest groundwater resource in Australia and one of the largest artesian basins in the world (Habermehl, 1980). It underlies 22% of the Australian continent and is the only practical water resource available to mining and pastoral operations through much of the arid and semi-arid zone of central and eastern Australia. Water is discharged from the GAB by bores, natural springs ("mound springs") and vertical leakage. Numerical modelling indicates that vertical leakage accounts for 58% of the outflow from the South Australian portion of the GAB (Bureau of Rural Sciences numerical modelling reported in AACWMB, 2004). Due to the large spatial scale of the GAB, only modelling methods have been used to estimate the vertical leakage at a sub-basin scale. Few field measurements are available to constrain the rate or regional distribution of this vertical leakage, despite it comprising such a large proportion of the GAB water balance in South Australia. Yet careful harvesting of the vertical leakage is considered to be the key to the sustainable use of the GAB resource in South Australia. The only study to have measured discharge rates in South Australia through the soil profile was by Woods *et al*., (1990) near Lake Eyre South. Increased water resource demand, particularly from mining operations, requires improved understanding of natural discharge processes in the GAB. This will lead to improved protection of unique ecosystems (mound springs) dependent on flow from the GAB and greater security of supply for all users of the GAB resource.

Vertical leakage is comprised of two components. A near surface component occurs as diffuse leakage to the shallow unconfined water table where the main GAB aquifers outcrop while under artesian pressure, or along fault structures where the aquifers are close to the surface. Under steady state conditions, when the shallow unconfined water table is within a few metres of the ground surface, evapotranspiration-driven fluxes through the soil profile are equal to the vertical leakage fluxes. The near surface component is particularly obvious in the southwest of the Basin where it often coincides with mound spring complexes and results in visible accumulations of salt at the surface. There is another component of indirect diffuse vertical leakage that forms a continuum with the near surface discharge but that is not further discussed in this paper. That is the vertical leakage from the confined GAB aquifer at depth that permits some discharge into overlying sediments and associated aquifers. A three year project commenced in 2007 that aims to quantify the diffuse near-surface discharge along the southwestern margin of the GAB. This paper describes the field based methods for measuring the discharge fluxes and presents some preliminary results of discharge rates.

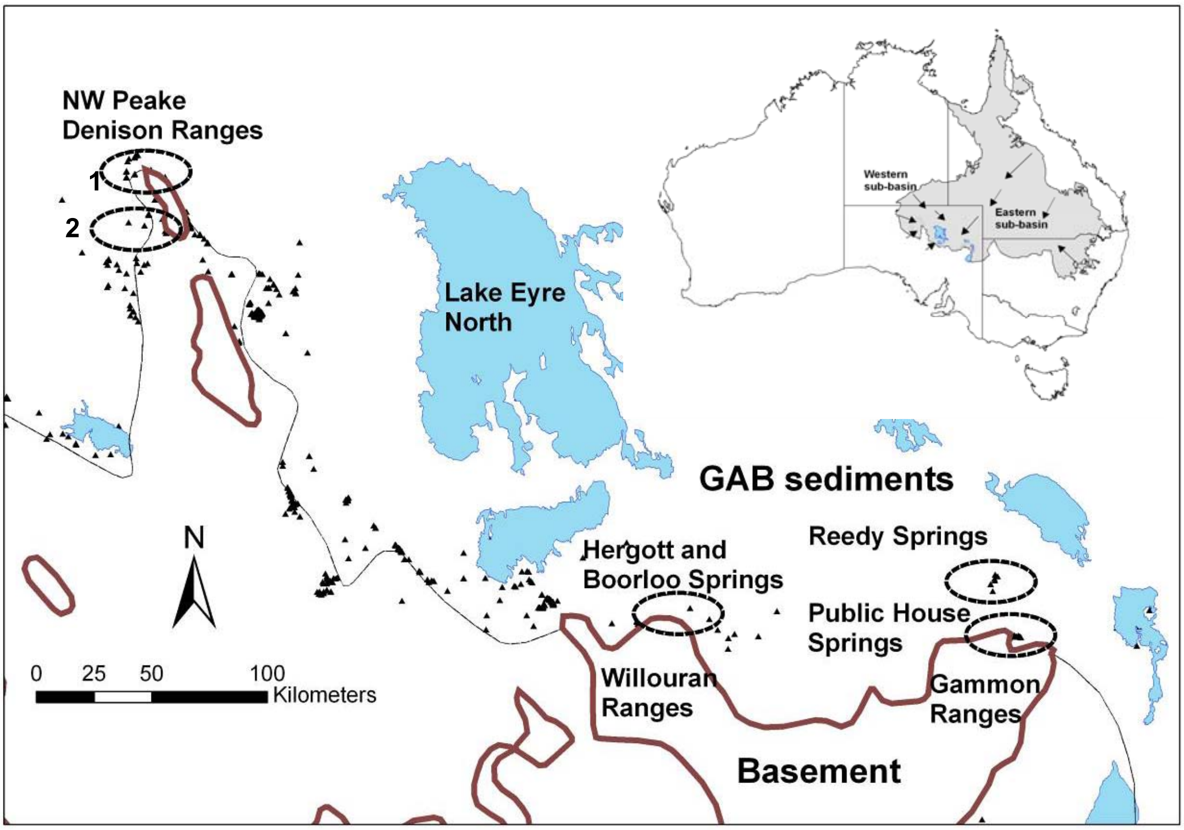

Figure 1 Location of field area covering the southwestern margin of the GAB. Dashed ovals show the specific field sites described in the text; Peake-Denison (areas 1 and 2 described in the text and Figure 2), Hergott and Boorloo Springs, Public House Springs and Reedy Springs. Areas of crystalline basement rock outcrop are enclosed by the thick line, the position of GAB mound springs by small triangles and the approximate south-west limit of artesian flow by the thin black line. Arrows on inset map of Australia show general groundwater flow direction.

1.1. Study area

The study area encompasses the southwestern portion of the GAB from the Peake-Denison Ranges (southeast of Oodnadatta), through the Marree area to the northern edge of the Gammon Ranges (Figure 1). Near surface, diffuse leakage occurs sporadically over significant sections of this area and can be divided into: (1) basin margin areas with outcropping GAB aquifers, (2) off-margin areas where folding and/or faulting has the GAB aquifer close to the surface (but not outcropping). The pattern of natural mound springs (Figure 1) illustrates the two location types of discharge areas. The basin margin areas under study (see Figure 1) are the northwestern side of the Peake-Denison Ranges, the northern margin of the Willouran Ranges (Boorloo site) and the northern margin of the Gammon Ranges (Public House Springs site). In these areas the springs and diffuse discharge occur in the basal units of the GAB where they onlap the Proterozoic basement rocks of the Peake-Denison, Willouran and Gammon Ranges. The mound springs and obvious saline discharge areas are often concentrated along stratigraphic boundaries (Figure 2) but can also disappear along strike where the GAB aquifers become sub-artesian and the depth of the local water table increases. The basin margin sites also differ in their hydrogeologic position within the GAB. The western Peake-Denison site occurs in the western sub-basin of the GAB where the recharge areas and flow patterns are from the west. The Boorloo and Public House Springs sites occur in the much larger eastern sub-basin of the GAB and the groundwater flow is from the east, originating from recharge areas on the western slopes of the Great Dividing Range in Queensland and New South Wales. The Peake-Denison and Public House areas are characterised by occasionally flowing mound springs and large areas of salt deposition at surface (Figure 2). In contrast, the Boorloo site had only one mound spring and that spring had ceased to flow early in the 20th Century and the area had no observable salt deposition at surface.

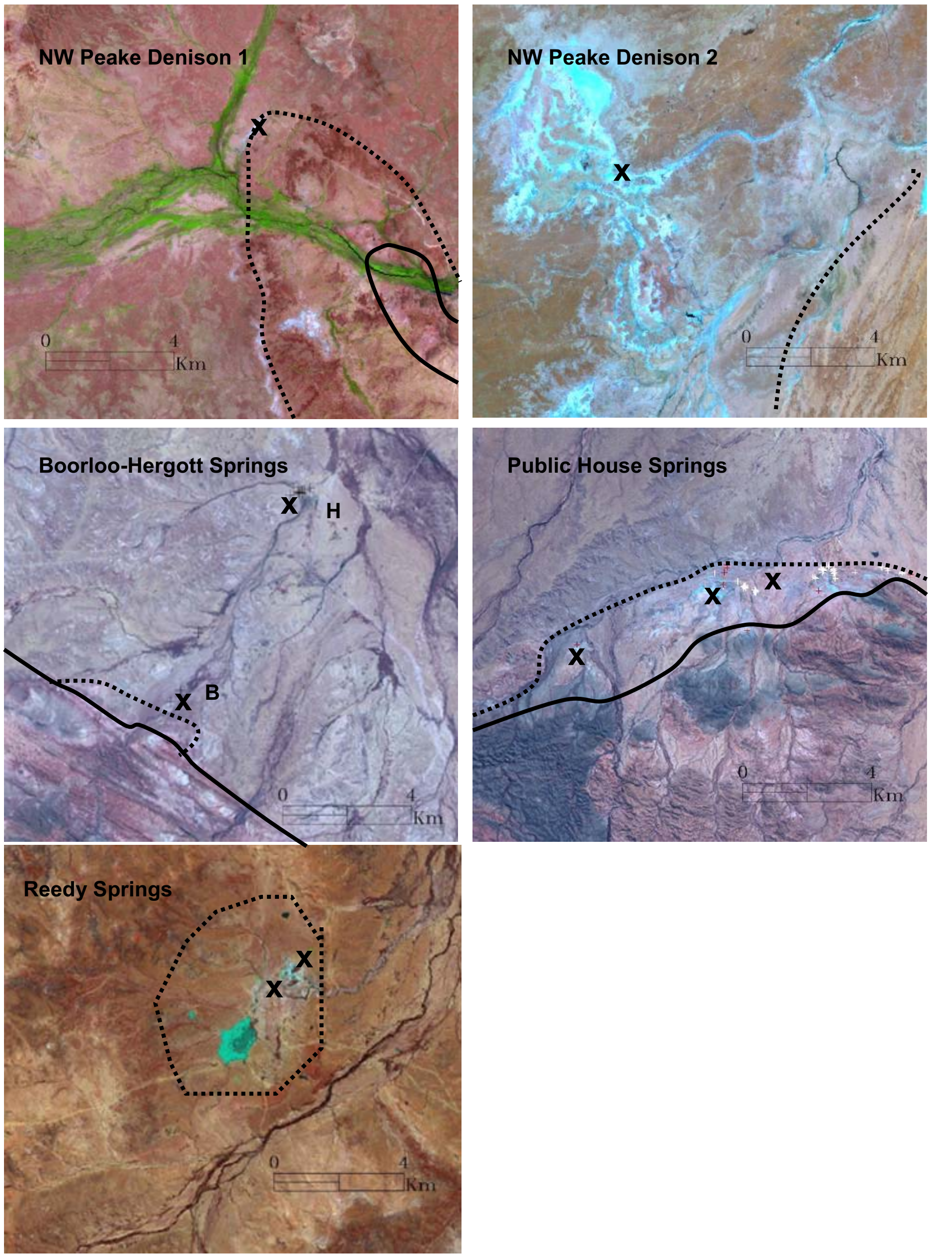

Figure 2 Landsat images showing field areas (see Figure 1 for general locations). All images are to the same scale but are not spectrally standardised. The solid lines mark the boundary between basement rocks and GAB sediments. The dotted line marks the boundary between the GAB aquifer unit and the GAB aquitard (Bulldog Shale), except for Reedy Springs where the dotted line encloses the area of Bulldog Shale within younger sediments. The crosses show the positions of representative borehole locations. Areas of significant salt precipitation on the soil surface show as the white-blue colour. Note the large amount of surface salt at the Peake-Denison 2 site (see Figure 1 for location) compared to no areas of visible salt in the Boorloo-Hergott Springs area.

The off-margin areas under study are the Hergott Spring area north of the Willouran Ranges and the Reedy Spring group north of the Gammon Ranges. Both sites occur within the eastern sub-basin of the GAB and provide examples of off-margin discharge areas associated with folding/faulting and complement the analysis of the basin margin processes. Hergott Spring occurs as a single spring outlet located 8 km northwest of the GAB margin with the Willouran Ranges at the Boorloo Spring site. The Reedy Spring area occurs approximately 30-40 km north of the Public House Springs and from the GAB margin. The springs occur on the eastern side of a domal structure with a diameter of 8 km defined by outcropping Bulldog Shale (a marine mudstone that forms the main aquitard unit to the GAB aquifers) but no outcropping GAB aquifer rocks. There is less evidence for widespread salt deposition at surface compared to the Public House springs area.

2. METHODS

Estimates of diffuse discharge in the study areas have been made using three differing methods; microlysimeters, evapotranspiration (ET) measurements using Eddy Correlation (EC) and Bowen Ratio (BR) instruments and inverse modelling of soil chloride concentration profiles. The microlysimeters and EC-BR instruments measured short-term (i.e. over a few days) ET losses, assuming that the soil moisture was due to upward fluxes (i.e. diffuse discharge of groundwater) rather than rainfall infiltration. This assumption is reasonable in the arid climate of the study area but can overestimate evaporation/discharge rates when recent rainfall contributes significant water to the soil layer. The microlysimeters measured soil evaporation fluxes at the approximate spatial scale of 1 m^2 while the EC/BR instruments measured combined ET fluxes above the ground surface at the spatial scale of 1000's m^2. The chloride profile method complements the other techniques in providing a long-term, steady state point measure of evaporative discharge through the soil profile.

2.1. Microlysimeters

Microlysimeters were used to estimate evaporative losses from soil cores installed in areas with evidence of relatively high evaporative discharge from the ground surface shown by the presence of salt deposition. This simple technique has been used to estimate evaporative loss acting as a proxy for groundwater discharge in salt lakes in the U.S.A and Chile (Tyler *et al*., 1997). Each microlysimeter consisted of a 0.3 m length of 0.09m diameter PVC pipe hammered into the surface to obtain a soil core (Figure 2). The soil core was excavated and the bottom of the pipe was capped and then installed into another PVC pipe of slightly larger diameter that had been inserted into the soil and cleared. Both PVC pipes were installed flush with the ground surface and the disturbance of the salt/surface crust of the soil core and surrounding ground surface was minimised. The microlysimeters were weighed daily at approximately the same time of day over a 4-7 day period. The daily weight loss is converted to a volumetric water loss and expressed as an evaporative loss in mmd^{-1} using the cross-sectional area of the microlysimeter.

Figure 3 Microlysimeter installed in a salt scald coinciding with the CadnaOwie Formation and Bulldog Shale boundary, Neales catchment.

Three microlysimeters were installed on the northwestern flank of the Peake-Denison Ranges in April and November 2005. Five microlysimeters were installed around Hergott Springs in June 2007, seven were installed in areas of salt flats around the Public House Springs and six were installed around the Reedy Springs in July 2007.

2.2. Evapotranspiration measurements

Short term ET fluxes above the ground surface were measured using EC and BR instruments during June-July 2007. The EC instruments measured the covariance of vertical wind speed and vapour flux to estimate the latent heat flux. The instruments used a three-dimensional sonic anemometer (CSAT3, Campbell Scientific) and a gas analyser (LICOR 7500). These were installed approximately 2.5 m above the ground surface and were operated at 10 Hz while averaging fluxes over 30 minute intervals. The BR instrument measured temperature and vapour density gradients at heights 1.5 m and 2.5 m above the ground surface. These data were used with net radiometer and soil heat flux data to provide 30 minute averages of the Bowen Ratio and latent heat flux.

The upwind fetch of the instruments was in the region of 250-300 m and the instruments were installed in areas with relatively uniform upwind areas over a distance of a few hundred metres. A net radiometer and soil heat flux plates were also installed at the EC and BR locations to measure the available energy. EC instruments have been used in studies of evaporative discharge from salt lakes in the arid zone of California (USA) and Chile (Tyler *et al*., 1997; Kampf *et al*., 2005). The BR instrument was also used in the California study (Tyler *et al*., 1997) but was found to be unable to resolve the low ET fluxes occurring in that study.

2.3. Soil profiles

Shallow cored auger holes (<6 m depth) were drilled at all locations and the chloride concentration of soil water samples was used to estimate long term flux rates through the unsaturated sections of the soil profile, using a steady state convection-diffusion model. Steady state discharge profiles are typified by high tracer concentrations at the evaporating front that decrease exponentially to the value of groundwater below. Soil samples were also submitted for determination of oxygen isotope ($\delta^{18}O$) concentration and results are pending. The model described in Barnes & Allison (1983) allows for soil sediment heterogeneity by including a modified depth function that accounts for water content changing with depth. The modified depth function has been further developed to account for the effects of soil textural changes through the profile. The original model has been applied by Woods *et al*. (1990) to estimate vertical leakage from the GAB in the region around Lake Eyre South and has also been used to estimate groundwater discharge at terminal salt lakes (Allison & Barnes, 1985; Ullman, 1985).

3. RESULTS

The results for the microlysimeters are shown in Table 1, for the EC measurements in Table 2 and for the soil profile modeling in Table 3. The results are then presented and discussed for each of the field sites.

Table 1. Evaporation flux rates from microlysimeters. The mean daily loss is calculated by dividing the cumulative loss by the number of days of measurement. The best fit daily loss is calculated using a line of best fit through the cumulative loss

Location	Mean daily loss		Best fit daily loss		Mean daily range	Best fit daily range
	mmd^{-1}	$mmyr^{-1}$	mmd^{-1}	$mmyr^{-1}$	mmd^{-1}	mmd^{-1}
Peake Apr05	0.35	127.8	0.31	113.2	0.11 - 0.65	0.07 - 0.61
Peake Nov05	0.90	328.5	0.91	332.2	0.77 - 1.15	0.75 - 1.21
Hergott Jun07	0.28	102.2	0.26	94.9	0.18 - 0.37	0.19 - 0.33
Public House Jul07	0.48	175.2	0.43	157.0	0.14 - 0.70	0.14 - 0.66
Reedy Jul07	0.24	87.6	0.25	91.2	0.20 - 0.29	0.22 - 0.30

Table 2. Evapotranspiration flux rates from Eddy Correlation instruments

Location	Mean daily ET flux (mm)	Daily range (mm)	Days	Annual flux rate (mm)
Hergott Jun07	0.22	0.10 - 0.40	6	80.3
Public House Jul07	0.15	0.10 - 0.20	4	54.8
Reedy Jul07	0.24	0.16 - 0.43	5	87.6

Table 3. Annual discharge flux rates from modeled soil chloride profiles

Borehole	Lower limit ET ($mmyr^{-1}$)	Upper limit ET ($mmyr^{-1}$)	Position
PEAK01	50	80	Basin margin, near active spring
PEAK02	35	45	Basin margin, no active springs
BOOR01	1.6	3.3	Basin margin, no active springs
HERG01	2.7	2.9	Off-margin, near active spring
PUBL01	0	47	Basin margin, near active springs
PUBL02	2.9	9	Basin margin, edge of active spring area
PUBL03	2.1	2.1	Basin margin, underlain by basement
PUBL04	13	35	Basin margin, near active springs
PUBL05	3.3	3.3	Basin margin, overlying Bulldog Shale
PUBL08	0.1	0.1	Basin margin, overlying Bulldog Shale
REED01	5	17	Off-margin, near active springs
REED03	0.5	0.5	Off-margin, distant from active springs

3.1. Peake Denison Ranges

The microlysimeter measurements in April and November 2005 were collected along a saline discharge zone coinciding with the boundary between the GAB aquifer and aquitard units on the flank of the Peake-Denison Ranges. The results vary considerably within and between field trips but indicate that the evaporative loss rates from this zone of diffuse leakage are relatively high (Table 1). The November 2005 results were higher than the April 2005 results reflecting increased soil moisture supply because of rainfall three weeks prior to the installation of the microlysimeters. The April 2005 mean loss rates were between 11-12% of the April daily areal potential evapotranspiration rate for the area (Australian Bureau of Meteorology) and equated to an annual discharge rate of 114 -126 $mmyr^{-1}$. No ET measurements were collected from this site using EC or BR instruments.

Borehole PEAK01 was drilled at the northern end of the Peake-Denison Ranges (Area 1 in Figures 1 and 2) near the microlysimeter locations. The potentiometric head of the water table underlying the saline discharge zone was up to 0.3 m above the ground surface and the modelled steady-state discharge rate was 50-80 $mmyr^{-1}$. Borehole PEAK02 was drilled to the west of the Peake-Denison Ranges, near the contact between the GAB aquifer and aquitard units (Area 2 in Figures 1 and 2) on the western side of the Peake-Denison Ranges. The potentiometric head of the local water table was 0.8 – 1.0 m above the ground surface at this location, which was also characterised by extensive salt precipitation at the surface. The modelled steady-state discharge rate for PEAK02 was 35-45 $mmyr^{-1}$.

3.2. Willouran Ranges - Boorloo

The Boorloo site on the margin of the Willouran Ranges showed evidence of only small discharge fluxes. The Bowen Ratio (BR) equipment was installed 470 m from the extinct Boorloo Spring and measured very small vapour pressure differences which lead to small, generally negative latent energy fluxes. This indicated that evapotranspiration fluxes at this site were very small and beyond the capability of the BR instruments to measure. This is supported by the absence of any salt crusting at the surface and a water table depth >5.5 m, demonstrated by the drilling of a dry borehole. No microlysimeters were installed at this site due to the dry, coarse grained nature of the upper soil profile. The Boorloo borehole (BOOR01) was drilled 170 m from Boorloo Spring and intersected gravelly colluvial-alluvial sediments from surface to 0.6 m, gypsiferous clay (gypsum up to 80% of core at top of interval) from 0.6-1.5 m (probably altered Bulldog Shale), then Bulldog Shale from 1.5-5.5 m (weathered at top, mostly unoxidised at bottom of interval). The chloride profile showed a distinctive discharge profile with concentrations above the halite saturation level until 0.3 m indicating a deep evaporation front occurring in the coarse gravels in the uppermost layer. The depth of the evaporation front explains the lack of salt deposition at surface. The chloride profile modelling indicates a long-term evaporation rate of 1.6 – 3.3 $mmyr^{-1}$ and profile establishment times of 160-560 years. The heavy gypsum crystallization and matrix replacement at the top of the Bulldog Shale suggested that the capillary fringe of the groundwater or evaporation front was once around the 0.6-1.25 m depth range.

3.3. Hergott Springs

The Eddy Correlation (EC) and microlysimeter instruments for the Hergott Springs area were installed within an 800 m radius of Hergott Spring. The general area was characterized by salt tolerant vegetation (e.g. saltbush), large patches of bare soil and occasional areas of thin salt crusting at the surface. The mean ET rate measured by the EC equipment was 0.22 mmd^{-1} and was consistent with the average evaporation loss measured by four microlysimeters of 0.26-0.28 mmd^{-1} (Table 1). The higher reliability microlysimeter data (excluding data from microlysimeters that showed weight gains over the installation period, see Section 3.6) returned mean daily evaporation rates in the range of 0.26-0.33 mmd^{-1}. The similarity between the EC and microlysimeter data provided reasonable confidence in these flux estimates. The ET estimates were affected by 0.9 mm of rainfall that fell in the 24 hours prior to installation of the equipment. The ET fluxes measured by the EC equipment showed a generally decreasing pattern over the period of measurement (from 0.40 mmd^{-1} to 0.10-0.20 mmd^{-1}) that was consistent with the influence of light rain. Removing the contribution of the 0.9 mm rainfall from the cumulative losses measured by the EC equipment and microlysimeters indicated a mean daily rate of between 0.07 – 0.09 mmd^{-1} (26 -33 $mmyr^{-1}$).

The Hergott Springs borehole (HERG01) intersected 0.05 m of silt with a thin saline crust then Bulldog Shale to the final depth of 3.5 m. The top 0.7 m of the Bulldog Shale was a completely oxidized and sticky brown clay but became relatively unoxidised, lithified and dark grey in colour by 1.0 m depth. Occasional halite flecks were observed from 0-0.4 m and then some gypsum in fractures but no matrix replacement as seen at Boorloo Springs borehole. The standing water level was approximately 1.6 m below the ground surface and occurs as a fractured rock aquifer in the Bulldog Shale. The chloride profile modelling indicates a long-term evaporation rate of 2.4 $mmyr^{-1}$ and a profile establishment time of 730 years. This long term rate is an order of magnitude less than the rate indicated by the EC and microlysimeter measurements, even after removing the effect of the small rainfall event prior to the equipment installation. Given the dry conditions preceding the field trip (no other rainfall in June, only 2.4 mm in mid-May and 1.5 mm in April), the short term ET techniques are not considered to be unduly biased by soil moisture contributed by atmospheric sources – although condensation may be a factor in the winter months. Another possibility is that the fractured nature of the Bulldog Shale aquifer and unsaturated zone may need to be better taken into account with the bulk diffusivity and porosity values used in the profile modelling.

3.4. Public House Springs

At the Public House Springs site, the EC equipment was installed in the central zone of a large area of thin salt crusting at the surface that coincided with the mapped outcrop position of the GAB aquifer unit, the Parabarana Sandstone. The average ET rate from the EC equipment over the four full days of measurements (1-4 July) was 0.15 mmd^{-1} (54.8 $mmyr^{-1}$). Trace amounts of rain were recorded on the night of the 3-4 July but this did not lead to noticeably larger ET measured on the 4 July (0.20 mm compared to the range of 0.10-0.20 mm over the preceding 3 days). The mean microlysimeter evaporation loss rates range was 0.43-0.48 mmd^{-1} (157-175 $mmyr^{-1}$) with the higher reliability microlysimeter data (see Section 3.6) returned mean daily evaporation rates in the range of 0.14-0.66 mmd^{-1}.These are significantly higher (approximately 2x to 4x) than the EC measurements. The BR equipment was installed several hundred metres from the high discharge area and was located on colluvium overlying probable Bulldog Shale with no sign of salt crusting at surface, although a nearby borehole (PUBL08) did show a discharge profile with a deep (0.2-0.3 m) evaporation front. The BR site at Public House Springs showed quite noisy data, particularly for the vapour pressure but there were significantly larger variations with recognizable diurnal patterns than measured at the Boorloo BR site. The daily ET rates varied between 0.23 - 2.03 mmd^{-1} with an average rate of 0.85 mmd^{-1}. There is less confidence in these results than for the EC results because of the uncertainty in the capability of the BR method in measuring small flux rates.

Eight boreholes were drilled at Public House Springs but only six showed distinctive discharge profiles in the soil chloride concentration data. Only three boreholes intersected shallow groundwater ((PUBL01-02, PUBL07), often because of the difficulty in penetrating alluvial-colluvial gravels overlying the GAB sediments. Saline groundwater was intersected at depths of 1.3 – 2.0 m below ground surface and occurred as a low-yielding, unconfined aquifer in the Parabarana Sandstone (GAB aquifer unit) or fractured Bulldog Shale (GAB aquitard unit). Modelled discharge rates based on soil water chloride data are shown in Table 3. Three boreholes (PUBL01, PUBL02, PUBL04) were drilled into thin alluvial-colluvial sediments overlying the probable GAB aquifer and all coincided with areas of thin salt crusting at the surface. The profiles from these boreholes returned the highest modelled discharge rates (up to 46.7 mmyr^{-1}, Table 3) but with significant variability, depending whether the observed peak chloride concentration of the profile was used in the modelling or the chloride saturation concentration (see Section 3.6). The other boreholes were drilled into metasediments close to the contact with the GAB sediments (PUBL03) or into alluvial-colluvial sediments overlying Bulldog Shale (PUBL05-08). The modelled discharge rates for these profiles were low (0.1-3.3 mmyr^{-1}, Table 3), with the lowest modelled discharge occurring in the borehole drilled furthest from the salt crusted, high discharge zone (PUBL08). At this latter site, the evaporation front was between 0.2-0.3 m deep (towards base of gravels) and the top of the underlying, weathered Bulldog Shale was composed of up to 50% calcite. Similar to the Boorloo site, the abundant calcite may indicate that the capillary rise of the groundwater may once have been in the 0.4-1.0 m deep zone.

3.5. Reedy Springs

At the Reedy Springs area the EC equipment was located within 200m of the upwind side of two large spring complexes and in an area with very shallow groundwater (<0.5 m). The EC gear measured a net daily evaporation flux of 0.24 mmd^{-1}, which was noticeably higher than that recorded at Public House Springs but similar to that measured at Hergott Springs (the latter affected by rainfall). The microlysimeter data for Reedy Springs showed variable results. Two of the six microlysimeters showed highly variable results over the four day period and could not be used to calculate evaporation losses. Three of the microlysimeters showed increases in weight after the first day and then more regular weight losses in the following days. The initial data point was ignored for these microlysimeters and the evaporation rate was calculated on three days of data. Only one microlysimeters had four days of reasonably consistent data but even that had one day with a slight weight gain. The results from the four microlysimeters showed reasonable similarities, particularly considering the problems with the raw data. The mean evaporation loss rate was 0.25 mmd^{-1}and the overall range between microlysimeters was 0.20-0.30 mmd^{-1} (Table 1). These compare well with the EC measured ET rates. Given the shallow nature of the water table around the mound springs, discharge rates are expected to be higher here than at Public House Springs or Hergott Springs.

Of the three boreholes drilled at Reedy Springs, two showed evaporative discharge profiles while one (REED02) indicated infiltration redistribution of a saline profile. Borehole REED01 was drilled within 400 m of the largest mound spring complexes and intersected groundwater with a potentiometric head 0.15 m below ground level. The long-term discharge rate at REED01 was calculated as 5-17 mmyr^{-1}. REED01 did not have an obvious salt crust at surface and the first 0.25 cm was comprised of 1-2 cm of coarse sand and then fine sands, overlying weathered Bulldog Shale. Using the measured chloride concentration at the surface provides a better fit to the profile data but this concentration (16,900 mgL^{-1}) may be underestimated by the presence of wind-blown sand. Despite the presence of sands, there is no indication in the profile of infiltration events. Borehole REED03 was located approximately 800 m and slightly uphill from the mound springs and showed a distinctive evaporative profile with an evaporation front at around 0.3 m depth. There was a gypsum layer between 0.88-1.10 m and then Bulldog Shale that contained decreasing amounts of gypsum blotches and became increasingly unoxidised with depth. Chloride concentrations remained high through the Bulldog Shale and no groundwater was intersected to the maximum depth of 5.5 m. The evaporative discharge modelling for this profile estimated a discharge rate of only 0.5 mmyr^{-1}.

3.6. Measurement uncertainties

The accuracy of the ET rates measured by the EC equipment is generally assessed by determining if the energy balance is closed (Twine *et al*., 2000). The energy balance closure requires that the net radiation (Rn) less the soil heat flux (G) is equal to the sum of the latent (LE) and sensible heat (H). The Rn and G values are measured independently of the EC equipment but the LE and H values are derived from the EC data. Typically the LE+H term underestimates the Rn-G term by 10-30% and provides the uncertainty range of the ET measurements (Twine *et al*., 2000). The EC data from this study showed that despite good correlations between the Rn-G and LE+H terms (R^2 value of 0.80-0.85 without any cleaning of the data) but the LE+H terms underestimated the Rn-G terms by 58-67%. The reasons for this are unclear and require further investigation but suggest that one or both of the LE (ET) and H terms are significantly underestimated. The ET flux rates measured in this study by the EC equipment were similar to microlysimeter estimates of evaporation at the Hergott Springs and Reedy Springs sites but were underestimated in comparison to the Public House microlysimeter results.

The measurement uncertainty in weighing the microlysimeters was 0.1 g, which equates to an error margin of 0.016 mm of evaporation. However, a number of the microlysimeters showed occasional increases in daily measurement that decreased the reliability of those particular microlysimeters. Possible causes of these weight gains were damp material sticking to the outside of the PVC casing or sediment blown into the microlysimeters. In general, the microlysimeter data did not show large decreases in weight that could suggest sediments were blown out of the casing or dropped during transport of the microlysimeters to where they were weighed. The weight gains affected three of the five microlysimeters at Hergott Springs, three of the seven microlysimeters at Public House Springs and all six of the microlysimeters at Reedy Springs. In most cases, the increases in weight only affected a single measurement and mean evaporation losses could still be estimated. In the case of the Public House area, the less reliable microlysimeter estimates of ET loss (i.e. showing at least one day with a weight gain) fell within the range of the more reliable microlysimeter estimates (containing no days with a weight gain). Over the three study areas using microlysimeters, the less reliable data fell within the range of the more reliable microlysimeter data (uncorrected for rainfall contribution).

The long-term discharge rates modelled from the soil chloride profiles were dependant on the boundary conditions used in the model, in particular the depth and chloride concentration of the evaporation front and these assumptions contribute to the uncertainty. The upper limit of annual discharge shown in Table 3 was derived using the concentration of chloride at halite saturation at the depth of the evaporation front. Most boreholes had thin salt crusts on the surface indicating halite saturation had been reached. The lower limit was derived using the highest measured chloride concentration at the evaporation front and these concentrations below the halite saturation level may indicate that the profile had not reached steady state conditions. The upper discharge estimates from the modelled profiles were always less than the EC and microlysimeter measured short-term rates at each of the field sites.

4. DISCUSSION

The discharge rates were consistently higher for the areas showing substantial salt crusting at the surface (e.g. Peake-Denison Ranges, Public House Springs), having flux rates in the 10's mmyr^{-1}. In contrast, modelled annual flux rates from soil profiles drilled in areas lacking widespread surface salt precipitation (e.g. Hergott Springs, distal areas of Public House and Reedy Springs) were less than 10 mmyr^{-1}. These latter flux rates are consistent with those measured by Woods *et al*. (1990) in the Lake Eyre South area, which found discharge rates of 3.0 – 7.0 mm yr^{-1} in similar stratigraphic and structural positions (i.e. salinised areas around mound springs and underlain by the aquifer rocks). These high flux rates from the obvious salinised areas were similar to those measured from 'dry' salt lakes in groundwater discharge areas in Australia, U.S.A. and Chile. For instance, discharge rates from Lake Frome were estimated to vary between 90 – 230 mm yr^{-1} (Allison & Barnes, 1985), between 9 – 28 mm yr^{-1} in Lake Eyre (Ullman, 1985) and 88 – 104 mm yr^{-1} from a salt lake in California (Tyler *et al*., 1997).

5. CONCLUSIONS

The combination of methods for calculating ET losses provides the means of independently verifying the measured and modelled fluxes. The different methods provide complementary point (microlysimeters, modelled soil profiles) and areal (EC, BR) estimates, as well as short term (microlysimeters, EC, BR) and long term (modelled soil profiles) estimates of ET/discharge fluxes. In general, the measured short term flux rates exceed that of the modelled long term flux rates. The association of higher discharge zones with areas of soil salinisation will assist in scaling these flux rate estimates to provide regional estimates of discharge rates from the GAB over the southwestern margin of the Basin.

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