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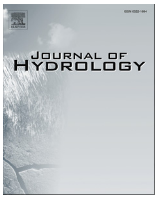

Field comparison of methods for estimating groundwater discharge by evaporation and evapotranspiration in an arid-zone playa

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SUMMARY

Evaporative losses typically play a substantial role in the water balances of arid regions. However, they are often poorly understood due to low flux rates and difficulty in direct measurement. We compared six field methods to quantify groundwater discharge due to evaporative and evapotranspirative fluxes from Stirling Swamp, a playa in central Australia; Bowen ratio–energy balance (BREB), maximum entropy production (MEP), chloride and stable isotope profiling, change in groundwater level, and ^{14}C profiles within the aquifer. The latter method has not been previously used to determine groundwater discharge. Evaporative groundwater discharge estimates varied between 0 and 300 mm/y, partly due to variability in spatial and temporal scales captured by the individual methods. Within playa systems where evapotranspiration within the soil is negligible but the depth to groundwater is small, land surface energy balances were found to have the advantage of integrating over hundreds of metres, and when upscaled to annual estimates they agreed well with expected evaporative flux values. Soil profile methods yielded a wide range of results depending on the values of several constants that must be assumed, and the assumption of steady state was found to be a disadvantage. Groundwater methods also had the advantage of integrating over some distance within the aquifer; however, advective transport in the subsurface may have led to under-estimation of evaporative flux with these methods.

1. Introduction

Use of groundwater in arid regions is increasing worldwide, in response to a growing global population (Seely et al., 2003). To determine the impacts of this groundwater use on the long-term viability of the resource, as well as on the flora and fauna in these fragile arid ecosystems, accurate water budgets must be developed. Many arid environments are found in closed basins, where water lost to the combined processes of transpiration by plants and evaporation from bare surfaces can account for up to 95% of the total annual rainfall (Wilcox and Thurow, 2006). In playas or salt pans where water tables are shallow, diffuse discharge of groundwater is typically considered to be a large component of the water balance (Thorburn et al., 1992; Holland, 2002). However, evaporative loss through these features can be difficult to quantify due to harsh conditions and low evaporative fluxes (Tyler et al., 1997).

Due to these difficulties, relatively few field studies have been conducted in natural playa ecosystems to determine evaporative fluxes. Tyler et al. (1997) estimated mean groundwater evaporation from the playa surface at Owens Lake, California to be in the range of 88–104 mm/y using lysimeters and eddy correlation, but only 17–22 mm/y using chloride profiles. Malek et al. (1990) reported groundwater evaporation of 229 mm/y from a playa surface in eastern Utah. At the dry, saline bed of Lake Frome in South Australia, an early study using isotope and chloride profiles estimated an annual evaporation rate of 50–240 mm/y (Allison and Barnes, 1985). At the nearby dry, saline Lake Eyre, Ullman (1985) estimated a lower annual evaporation rate of only 9–28 mm/y using chloride and bromide soil profiles. Ullman (1985) attributed the low evaporative flux at Lake Eyre to the mulching effect and higher albedo associated with the salt crust at the soil surface. Also in this general region, Costelloe et al. (2014) estimated evaporation rates of approximately 7–79 mm/y using soil profiles. In a

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study of the soil water in the Sahara, Fontes et al. (1986) estimated even lower evaporation rates of 1–2 mm/y of evaporative flux from the groundwater.

Australia represents the driest inhabited continent on earth, with more than 70% of the land area considered arid or semi-arid (James et al., 1999). The scarcity of water across vast areas of the Australian continent is a limiting factor for the development of human and economic activities and a permanent challenge to the equilibrium of fragile desert ecosystems. It has also provided the ideal setting for some seminal studies on dry lake or playa evaporation (Allison and Barnes, 1983, 1985; Ullman, 1985; Woods, 1991). As in other parts of the world, many of the dryland basins of inland Australia are being considered for further development. One example is the Ti Tree Basin north of Alice Springs in the Northern Territory of Australia. The basin is largely undeveloped pasture land; however, increased horticultural development is being encouraged. Previously developed water budgets for the basin suggest that groundwater is largely recharged in the southern and western margins of the basin, and that the water balance is regulated by evaporative fluxes through the Stirling Swamp, a sparsely vegetated playa at the northern extent of the basin (Harrington et al., 2002; DIPE, 2002). However, the magnitude of these fluxes has not been measured.

In this study, we examine evaporative fluxes through Stirling Swamp using six different methods. The objective of the study is to compare well established techniques of measuring evaporation with novel techniques that have not previously been compared and to evaluate the usefulness of these methods for estimating groundwater discharge through evaporation at the Swamp. This analysis includes methods from three standpoints: land surface energy balances (Bowen ratio–energy balance and maximum entropy production methods), unsaturated soil profiles (chloride and stable isotope profile methods), and groundwater measurements (^{14}C profiles within the aquifer and temporal groundwater level variation). The selection of methods offers a comparison of estimates covering a wide range of spatial and temporal scales, and highlights the advantages and disadvantages of each method for use in arid, playa environments.

2. Study area and field methods

The Stirling Swamp is located north of the Tropic of Capricorn, at a latitude of 22.8°S and a longitude of 133.7°E. It forms the northern extent of the Ti Tree Basin, approximately 35 km north of the town of Ti Tree, in the Northern Territory, Australia (Fig. 1). Although labelled a "swamp", this feature would more typically be considered a salt pan or playa. Most of the area is covered with bare soil, with patches of low-lying vegetation appearing seasonally, including salt tolerant *Frankenia* species and *Marsilea hirsute*, a freshwater fern. Depth to groundwater is typically between 1 and 3 m, with soil and groundwater exhibiting very high salinity levels (average groundwater chloride concentration is 48 g/L). During the summer months the entire Swamp is typically inundated with water for some period of time, including all sites included in this study. There is no development on the Swamp and little or no regular groundwater pumping, although the land is used for cattle grazing. Basement rock (sandstone or conglomerate, often fractured in the top few metres) was observed in all bores drilled below 8–10 m, suggesting a total aquifer depth of approximately 10 m. About 1–1.5 m of compacted silt, very fine silty sand, and clay overlies sandstones and siltstones throughout the Swamp.

There are no long-term precipitation records near the Swamp; however, depending on the station chosen and the period available for that station, long-term average precipitation estimates for areas within the Ti Tree Basin range between 270 and 318 mm/y, (Harrington, 1999; DIPE, 2002; Fritz, 2007). Historical data at Territory Grape Farm, located approximately 75 km from Stirling Swamp, shows an average of 56 rain days per year over 124 years of record (1889–2013; Station 015643; BOM, 2014). Groundwater recharge has been estimated at between 0.1 and 500 mm/y, with a median of 0.9 mm/y (Harrington et al., 2002). Like many arid regions, precipitation is extremely variable spatially and temporally (Gutzler and Preston, 1997; Mudd, 2006). The basin falls within the low-latitude, desert climate classification, with the majority of precipitation (72–86%) typically occurring during storm events coming from the northeast in the hot summer months (Cleverly et al., 2013a,b).

The area of the Swamp is approximately 10 km^2, extending as a long, narrow tongue from the southeast to the northwest. It is bounded by sand dunes on the southwest side and low rises on the northeast side, both of which contribute local runoff during large rain events. The ephemeral Hanson River is located to the west, and a paleochannel of this distributary system may flow into the Swamp during very large rain events.

To study the Swamp, a transect of 5 sites (labelled A–E in Fig. 1) was installed at approximately 1.5 km intervals. A Bowen ratio–energy balance (BREB) system was installed at site E on 10 April 2013. The setup consisted of differential temperature and relative humidity (Model HMP4C, Campbell Scientific, Logan, Utah), and water vapour measurements (Model Dew-10, General Eastern Corp, Watertown, MA) from sensors mounted 1 m and 2 m above ground surface. Mean soil heat flux at the soil surface was computed by adding the measured soil heat flux at a depth of 0.08 m with the energy stored in the layer above this measurement. This was achieved using two sets of thermocouples installed at depths of 0.02 and 0.06 m, and heat flux plates installed at 0.08 m (TCAV and HFP01 sensors, Campbell Scientific, Logan, Utah), as well as soil moisture probes installed at depths of 0.05 and 0.10 m (Theta probes, Campbell Scientific, Logan, Utah). Solar radiation was measured using a net radiometer (NR-LITE2, Campbell Scientific, Logan, Utah) mounted at a height of 1 m, and corrected for windspeed. All instruments were connected to a CR3000 data logger (Campbell Scientific, Logan, Utah) and set to record averages at 20 min intervals. After 4 September 2013, rainfall was recorded daily using a tipping bucket also connected to the datalogger. Vegetation near site E is sparse (short plants and grasses typically less than 30 cm tall and typically only active between December and April) or non-existent for at least 100 m in every direction (Fig. 2), creating uniform, almost bare soil conditions within a large fetch. These cover conditions are also typical of sites A–D. Cracking at the surface can be observed, especially at sites D and E, suggesting the prevalence of surface clays at these sites. This was also confirmed in drill core observations at the sites. A salt crust can appear seasonally on some parts of the Swamp.

For the soil profiles, three soil cores were dug by hand using a hand-held auger on 13 June 2013 (sites A, C, and E; see Fig. 1), and one additional core was collected on 4 September 2013 (site D). Samples were sealed in air-tight containers and returned to the laboratory for analysis.

Finally, five groups of four nested piezometers were installed in Stirling Swamp at sites A–E for the groundwater measurements. The piezometers were installed in 2012 (Fig. 1), with rotary air drilling, to depths of 3–12 m. The screen length of each piezometer was between 0.4 and 1.0 m, and depth below water at time of sampling ranged from 1.7 to 9.9 m (Table 1). Samples for both δ^{13}C and ^{14}C were collected using a submersible 12 V Whale pump (Whale; Bangor, Ireland) 26 June–1 July 2012. At this time the groundwater level was observed to decrease at a consistent slope from an elevation of 473.9 m above sea level at site E to 472.6 m above sea level at site A; a slope of 0.00036 across a direct line of 3.6 km between