PAPER

Salinity balance and historical flushing quantified in a high-rainfall catchment (Mount Lofty Ranges, South Australia)

Thomas A. Anderson[1] · Erick A. Bestland[1] · Ilka Wallis[1,2,3] · Huade D. Guan[1,2]

Abstract

Human-induced landscape salinization, including the effects of dryland salinity, is negatively impacting many catchments in southern Australia. Salinization occurs due to increased recharge and water-table rise following land clearing of deep-rooted native vegetation. In low-lying areas with poor drainage, groundwater-level rise can lead to increased evapotranspiration, mobilization of vadose zone salt, and salt scalding. Alternatively, these same processes of increased recharge and groundwater rise can lead to decreased salinization as accumulated salts are flushed into surface waters. This study in a high-rainfall area of the Mount Lofty Ranges of South Australia documents catchment desalinization. A 28-year record (1989–2016) of flow and salinity in Scott Creek was analysed based on monthly data. Analysis of catchment-scale chloride deposition and export determined that approximately three times more chloride is exported than is input to the catchment from atmospheric sources. Over the time period investigated, salt load exported to surface water decreased by, on average, 6.4 t annually due to catchment freshening. Analysis of monthly salinity balance of a sub-catchment drained by an intermittent stream demonstrates that accumulation of chloride, rather than export, occurs during drought years. In the catchment, as a whole, salts are being flushed via groundwater flow into the permanent stream in all years of the record. Deep groundwater is input to the permanent stream, with mixing of deeper more saline and fresher shallow groundwater. Thus, a complex interaction of landscape hydrologic parameters such as relief, precipitation, chloride deposition and land-use history, determine whether a catchment undergoes salinization or desalinization.

Keywords Dryland salinity · Salinization · Groundwater/surface-water relations · Australia

Introduction

Quantifying salinity balance of catchments over time is critical for evaluating overall river and catchment health (Peck and Hurle 1973; Williamson et al. 1987; Williamson and van der Well 1991; Jolly et al. 2001; Guan et al. 2010a; Biggs et al. 2013). Human-induced landscape salinization and catchment salt balances have been the focus of much hydrologic work in southern Australia (Ruprecht and Schofield 1989, 1991; Cox

et al. 1996), in the US (Brown et al. 1983; Scanlon et al. 2005) and in South America (Jayawickreme et al. 2011; Marchesini et al. 2017). It is well accepted that in many areas of Australia, increases in soil and stream salinization have resulted from wide-spread land clearing of deep-rooted native vegetation (eucalypt trees) combined with the planting of short-rooted crops and grasses (Schofield 1992; Greeff 1994; George et al. 1997; Walker et al. 1999; Jolly et al. 2000, 2001; Pannell 2001; Hatton et al. 2003; Poulsen et al. 2006); e.g. in agricultural regions where the native vegetation has been largely cleared and replaced with annual crop and pasture vegetation. In Australia, the eucalypt woodland absorbs substantially more water through root-uptake than the short-rooted pasture/crops and, as a consequence, salinity tends to accumulate in the unsaturated zone of uncleared areas. Following land clearing, the decrease in soil water uptake by vegetation increases the groundwater recharge rate, which can mobilize salinity present in the unsaturated zone during water-table rise (Fitzpatrick et al. 1994; Cox et al. 1996). Increases in

✉ Thomas A. Anderson
  tanderson@flinders.edu.au

1 Flinders University, GPO Box 2100, Adelaide 5011, Australia

2 National Centre for Groundwater Research and Training, Bedford Park 5042, Australia

3 University of Manitoba, 15 Gillson St, Winnipeg, MB R3T 5V6, Canada

near-surface evaporation can lead to landscape salinization. These same processes, however, may result in *decreases* in salinization in landscapes that are high in rainfall and well-drained (Norman 1995; Tyagi 2003; Guan et al. 2010a). In such settings, the increase in recharge and rise in water table are thought to have led to increases in stream flow and flushing of stored or historic salinity, i.e. 'dryland salinity flushing' (Jolly et al. 2001; Guan et al. 2010a), causing a change in the catchment salt balance over time.

Catchment-scale stream salinity data have been analysed for the Murray–Darling Basin (Australia) with the aim to develop concepts and methods of evaluating ratios of salinity output to salinity input (O/I ratios; Jolly et al. 2001). These statistical methods were used to evaluate salinity trends in catchments where limited data were available. Peck and Hurle (1973) established that the O/I ratio could be used as a key indicator of catchments undergoing salinization, assuming steady state or salinity equilibrium prior to clearing. Guan et al. (2010a) further conceptualized catchment types and suggested how the O/I ratio could be applied. Allison et al. (1990) determined the influence that increased recharge due to land clearance had on the Murray River, South Australia, using groundwater modelling. Additionally, it has been conceptualized that following a disturbance such as land clearing, the catchment salinity balance would be changed and a new equilibrium or salinity balance would occur with time (Jolly et al. 2001; Guan et al. 2010a). Notably, the study presented here assumes steady-state conditions, despite various other factors influencing recharge and salinity balance, including environmental history (Dahlhaus et al. 2008; Cartwright et al. 2013), climate change (Currell et al. 2016) and flow paths through the regolith and aquifers (Ruprecht and Schofield 1989; Cox et al. 1996). However, many studies have shown that vegetation clearance has been a pivotal driver for hydrological change—for example, Ruprecht and Schofield (1989) determined the extent that land clearance had in raising groundwater levels and increasing streamflow in south-western Australia. Similarly (Ruprecht and Schofield 1991) found that land clearance transitioned catchments from salinity accumulating to salinity exporting. Additionally, Williamson et al. (1987) concluded that in higher rainfall catchments, more salinity had been exported than in drier catchments 8 years after clearance. These catchments are expected to attain a new salinity equilibrium sometime in the future. Having an established salinity equilibrium is required in order to utilize the chloride mass balance (CMB) method for estimating groundwater recharge (Wood 1999); thus, if catchment salinity input/export is significantly out of equilibrium, increased error for groundwater recharge estimates will result. For the Mount Lofty Ranges of South Australia, Guan et al. (2010a) established that the catchment salinity O/I ratio provides useful information to determine whether a catchment has reached a new salinity equilibrium and therefore whether the application of CMB methods is valid. Other studies have modelled the timespan required for reaching a new salinity equilibrium (Sivapalan et al. 1996; Smitt et al. 2003; Dawes et al. 2004; Gilfedder et al. 2009); however, these studies did not have continuous monitoring history of the physical parameters to verify the theory that there is a decreasing export of stored salinity from the system.

In addition to the estimation of salinity exported from catchments, much research has been undertaken to quantify atmospheric deposition of salinity (Eriksson 1959, 1960; Blackburn and McLeod 1983; Keywood et al. 1997; Biggs 2006; Guan et al. 2010b). Keywood et al. (1997) documented that there was a decrease in chloride deposition with the distance inland from the coast of Australia. Most chloride is deposited within approximately 100 km from the coast (Eriksson 1959, 1960). Biggs (2006) derived equations to estimate annual average rainfall chloride mass deposition as well as total salinity deposition in southern Queensland, Australia; furthermore, Guan et al. (2010b) created a quantitative map of the bulk chloride deposition in the Mount Lofty Ranges in which distance to the coastline, elevation, and slope orientation were reported as the most significant factors influencing chloride deposition. It is evident from Guan et al. (2010b) that the high-resolution data employed were important in influencing these findings, which has been a limiting factor of the aforementioned studies.

Many catchment salinity balance studies have claimed that insufficient data was a major cause that limited the key findings (Williamson et al. 1987; Ruprecht and Schofield 1989); thus, considering the available literature on salinity balance, it is evident that high-resolution data are required to thoroughly evaluate salinity input and export at the catchment scale. Necessary data include the duration of salinization or desalinization, saturated vs. unsaturated salinity storage, and influence of chloride content of wet-fall and dry-fall. The study presented here evaluates these factors; furthermore, the findings of this study should be considered when evaluating reforestation during the process of land management planning—for example, plans made in the Mount Lofty region (AMLRNRM 2013). The study presented here indicates that reforestation can increase salinity and decrease surface water flows. These conclusions are based on high-quality long-term stream and salinity time series data from the Scott Creek catchment (SCC) within the Mount Lofty Ranges. These data quantify the catchment salinity balance, resulting in monthly totals of chloride input and export for a permanent and an intermittent stream. Similar databases, containing river discharge and salinity exist elsewhere—e.g. the United States Geological Survey 'Water Data for the Nation' program (USGS 2018). Therefore, following the methods outlined in this study, these data can be used to quantify salinity loads in catchments across the globe. This study employs a multiple regression analysis that reveals a decrease in salinity load as a

function of both time and flow. These data and quantifications conclusively show that a decrease in catchment-scale salinity is occurring; furthermore, this study evaluates the atmospheric chloride deposition and the stored chloride export (or accumulation) at monthly time intervals. Moreover, the methods presented here have the potential to quantify the flushing of stored salinity for other catchments with significant monitoring data and allow the timespan in which the catchment will reach a new salinity equilibrium post land clearance to be determined. This paper presents a definition of terms (Table 1) to assist the reader in understanding frequently used terms and concepts.

Site background

Hydrology and climate

Numerous hydrogeological studies have been completed at the SCC (Fig. 1), which includes both the Scott Bottom and Mackreath Creek sites (Chittleborough et al. 1992; Stevens et al. 1999; James-Smith and Harrington 2002; Harrington 2004a, b; Ranville et al. 2005; Banks et al. 2009; Bestland et al. 2016; Anderson et al. 2017). These studies have outlined the hydrogeological heterogeneity and geological complexity of the site as well as the soil hydrology of the dominant Red

Brown Earth soils (Xeralfs). Banks et al. (2009) and Bestland and Stainer (2013) documented the importance of the fractured rock and deep clayey regolith for the groundwater/ surface-water interactions at the site. In addition, several soil-water studies have recognized the through-flow hydrochemical characteristics on site (Chittleborough et al. 1992; Stevens et al. 1999; Bestland et al. 2009). These studies expanded the investigations of James-Smith and Harrington (2002) and Harrington (2004a, b) that described the basic hydrology and hydrogeology of the SCC.

The SCC has an area of 28 km^2 and is located about 30 km southeast of Adelaide. Scott Creek flows into the Onkaparinga River; upstream of Clarendon Weir and downstream of Mount Bold Reservoir. Land-use patterns have changed over the years in the SCC. Following European settlement of the SCC beginning in 1838, farming and logging began in nearby Scott Creek. The building industry in Adelaide made use of the original red, blue and manna gum, as well as stringy bark. In 1850 the site was mined for copper followed by silver (DEHAA 1999); however, since the declaration of the Scott Creek Conservation Reserve in 1985 (as described in Nicholson and Clark 1992), agricultural use has decreased and the native vegetation of the area has been restored to some extent. At that time, the vegetation was reported to be 47% native vegetation, 29% residential living and 16% grazing modified pastures (EPA 2013).

Table 1 Definition of terms		
	Annual cumulative mean export	The summation of the mean mass of salinity (or chloride) exported each year, which updates by adding the annual mean export from the previous running total
	Atmospheric deposition	Mass of salinity or chloride deposited from wet-fall and dry-fall processes
	Bulk chloride deposition	As above
	Chloride accumulation	The process by which the mass of chloride deposited to the catchment via bulk chloride deposition is greater than the mass discharged via surface water over a given period
	Chloride export	The process by which the mass of chloride deposited to the catchment via bulk chloride deposition is less than the mass discharged via surface water over a given period
	Dryland salinity	Increases in salinization [as] a result of significant clearing of perennial native vegetation and… replacement with annual crops and pastures… reducing the amount of evapo-transpiration and resulting in increased groundwater recharge, sensu stricto (Jolly et al. 2001)
	Historic salinity	Salinity accumulation in the groundwater and unsaturated zone prior to clearance of native vegetation and subsequent dryland salinity occurring
	Intermittent stream	[A stream] that flows only at certain times when it receives water from springs [or surface water], sensu stricto (Meinzer 1923)
	Output/input ratio	The proportion of salinity (or chloride) deposited into the catchment via precipitation in relation to that exported out via stream flow
	Salt balance	The output of salinity in stream flow equals the current input of salinity in precipitation [and therefore] a salinity output to input ratio equal to one, sensu stricto (Williams et al. 1998)
	Salinity load	The mass of salinity exported from a catchment via streamflow
	Weighted salinity concentration	The mass of salinity (salinity load) per volume of water discharged from the catchment (flow)

Fig. 1 a–d Location maps of the Scott Creek Catchment, South Australia, showing location of gauging stations (GS) and Mackreath Creek catchment
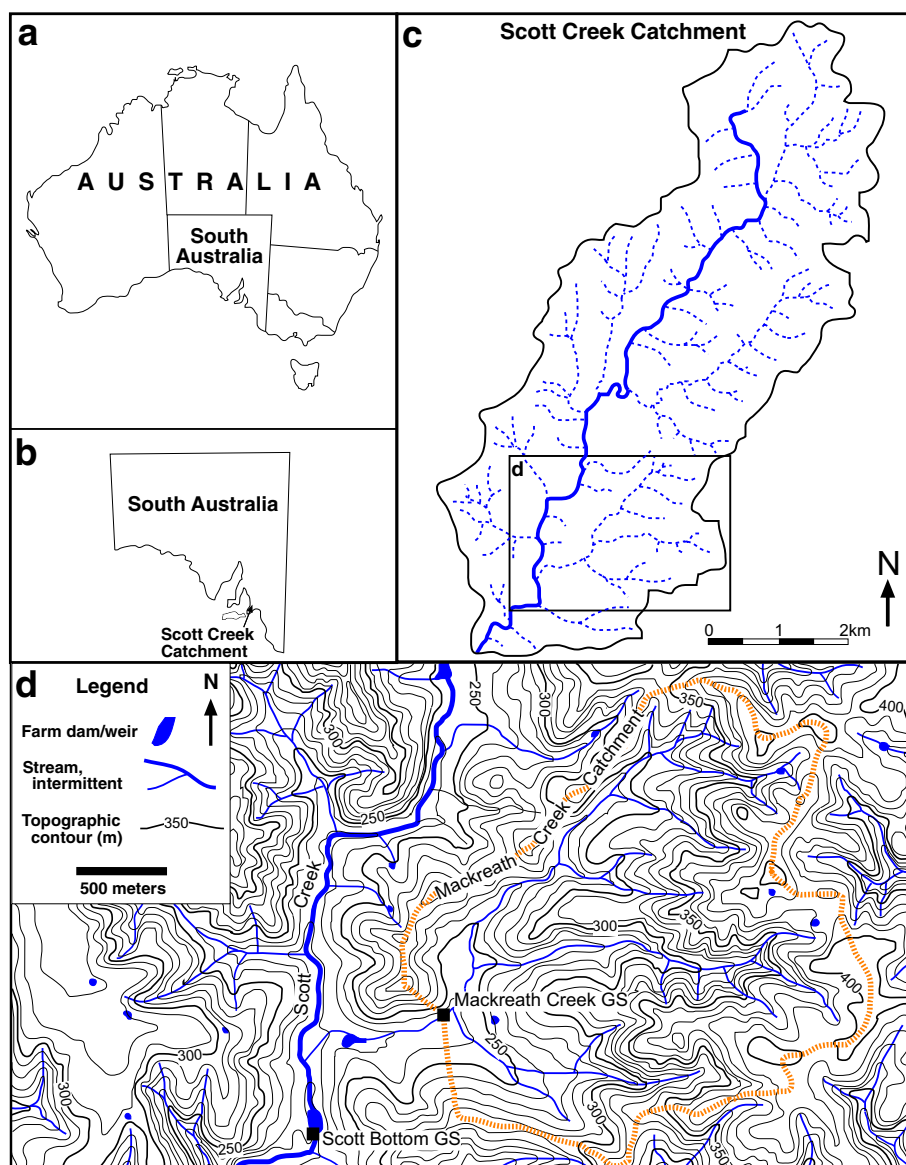
The SCC has a Mediterranean climate with cool, moist winters and warm, dry summers. Here the mean temperature ranges from 7 to 13 °C in winter, and 14 to 25 °C in summer. The Mount Lofty Ranges receives varying seasonal precipitation (almost all as rainfall) with yearly totals ranging from 400 to over 1,000 mm/yr and with 85% of the rainfall occurring between May and September (BOM 2016). The great annual variability in rainfall in this area impacts the groundwater/ surface-water systems as demonstrated by the aforementioned very low flow and disconnected flow during droughts in Scott Creek. Winter wet-season recharge causes the water table to rise between 1 and 2 m (Banks et al. 2009). A pluviometer in close proximity to the SCC, at the upslope Mount Bold Reservoir weather station, has an average annual rainfall of 801 mm/yr (BOM 2016). Mount Bold also has an average evaporation of 1,555 mm/yr, and therefore potential evaporation exceeds

rainfall from October to May (spring, summer and autumn; Bestland et al. 2009).

High salinity levels of Scott Creek at the Scott Bottom site relate to low stream flows and are associated with the groundwater-fed base-flow. Conversely, high flows have relatively low salinity that reflects mostly surface water run-off (James-Smith and Harrington 2002). Anderson et al. (2017) provides an understanding of the cause for a high salinity groundwater 'hotspot' observed on site and traces it to a tributary stream that flows into Scott Creek. Additionally, Kretchmer (2007) concluded that throughout harsh drought conditions (e.g. as arose in the summer of 2006–2007), Scott Creek diminished to a sequence of disconnected pools sourced from groundwater. Salinities on site fluctuate from 500 μS/cm in winter to above 2,000 μS/cm throughout the low-flow period from January to April. The seasonal salinity variations at

Scott Bottom were explained by evaporative enrichment; and groundwater input during the summer contrasting with runoff dilution during the winter wet season (Harrington 2004b). Comparatively, the nearby intermittent Mackreath Creek has much lower salinity than Scott Creek (200–500 µS/cm) and little salinity variation throughout its flow season, as revealed in Milgate (2007); Bestland et al. (2009); and Pichler (2009). This sub-catchment has significant areas of sandy soils. These investigations also disclosed that Mackreath Creek only flowed after significant Autumn–Winter rainfall; however, surface-water salinities at both Scott Creek and Mackreath Creek are not believed to be in a state of equilibrium (Banks et al. 2009), reinforcing the theory that stored salts are flushing from the system. Flushing is thought to occur through two mechanisms: (1) during water-table rise, stored salt is flushed from the unsaturated zone consisting of soil and regolith (Anderson et al. 2017); and (2) the accumulated stored salts from the ambient groundwater is mixed and flushed by fresher recharge (appendix A; Harrington 2004a). These mechanisms are illustrated in a conceptual hydrogeologic model (Fig. 2).

Geology and hydrogeology

Despite the relative geological complexity of this area, the geology is well studied and understood (Preiss 1987; Banks et al. 2009; Bestland et al. 2016). The lower one third of the SCC is underlain by the relatively homogenous Woolshed Flat Shale unit. Five 3-m-deep backhoe trenches were dug as part of this project (reported in Bestland and Stainer 2013) from valley bottom to ridge crest in order to characterize the saprolite and soil zone. From this information combined with drill logs (Banks et al. 2009), the thick, clayey nature of the regolith has been determined.

A sequence of shallow to moderate depth piezometer nests were drilled at the Scott Bottom site in 2005 (Cranswick 2005). The piezometer nests allowed an analysis of the hydrogeological structure and flow dynamics of the site (Banks et al. 2009); the drilling logs for these piezometers are documented in Cranswick (2005). This network added to the deeper bores described in James-Smith and Harrington (2002). Piezometer nests adjacent to Scott Creek demonstrate an upward hydraulic gradient, as expected from the presence of artesian deep bores. Piezometer nests up-slope from the

Fig. 2 Conceptual model of Mount Lofty Ranges catchment groundwater system **a** prior to land-clearing and **b** post land-clearing
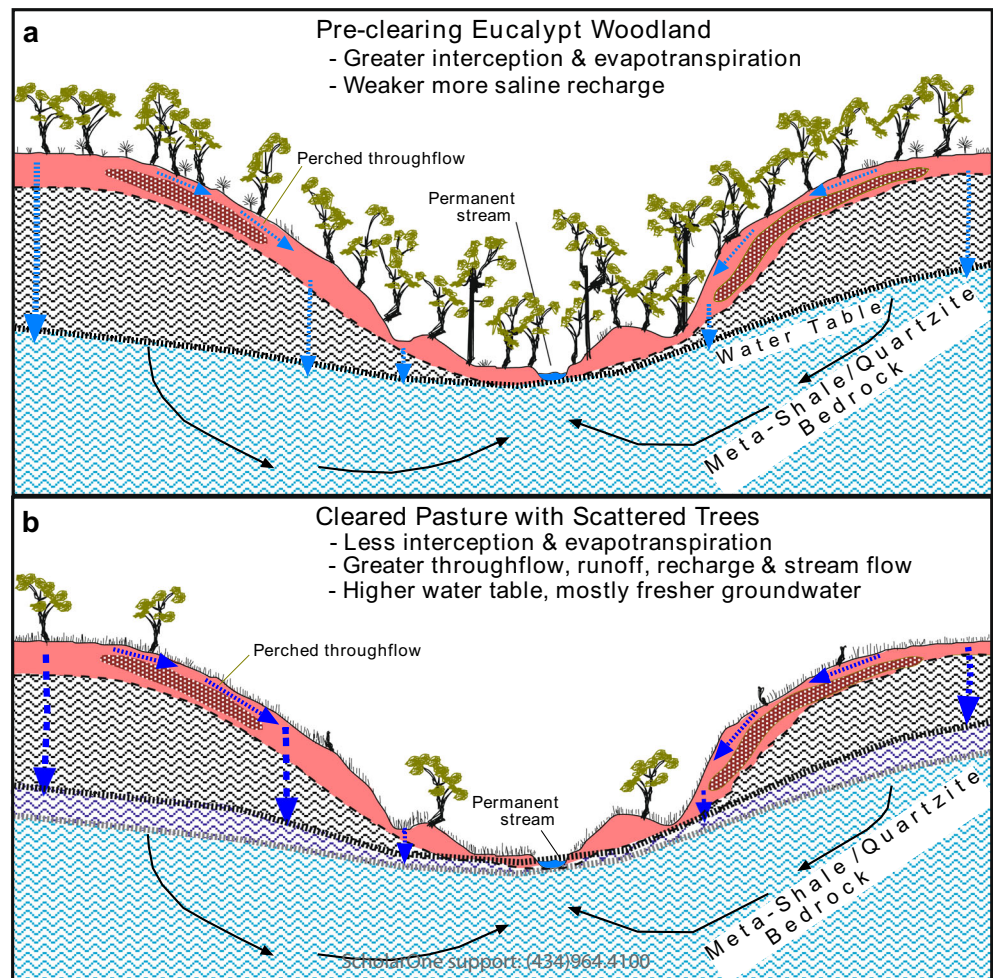
stream on the mid-slope of the hill demonstrate a downward gradient; thus, the conceptual model (Fig. 2), which shows the upward and downward gradient groundwater flow-paths, is supported by this data.

The regolith at the site plays an important role in groundwater flow and recharge and has been separated into zones. The deep, weathered bedrock saprolite zone of up to 15 m depth is generally very clayey with a massive structure (Cranswick 2005). Fractured bedrock underlies this zone. The degree and depth of weathering of the saprolite is vital in directing groundwater flow and recharge. Banks et al. (2009) outlined three zones that control groundwater flow at the site—the soil zone, saprolite zone and fractured bedrock zone. The soil zone is characterized as a duplex soil with a sandy-silty A horizon (10–20 cm depth) over thick clayey B and C horizons (Chittleborough et al. 1992).

The saprolite zone changes gradually from poorly structured (massive) clay down to the unweathered bedrock (Cranswick 2005; Bestland and Stainer 2013). Banks et al. (2009) found that the hydraulic conductivity of this zone ranged from 0.04 to 2.5 m/day and was usually less than the hydraulic conductivity of the fractured bedrock zone. The unweathered bedrock (Woolshed Flat Shale) consists of a grey siliceous slate. Hydraulic conductivity here ranged from 1.5 to 14 m/day. The fractured rock aquifer (FRA) is the most active part of the groundwater system with some deep bores being permanently artesian.

The thick clayey character of the saprolite developed from the meta-shale is responsible for the very low hydraulic conductivities found in this material (Banks et al. 2009). In addition, these low permeability zones cause widespread areas of perched through-flow in the Mount Lofty Ranges (Cox et al. 1996). Very low rates of groundwater recharge below these zones are thought to result in local areas of very high groundwater salinity (Anderson et al. 2017). Conversely, areas in the SCC, and elsewhere in the Mount Lofty Ranges, underlain by strata containing sandstones (quartzite) result in rocky and sandy soils, much higher rates of recharge, and much lower groundwater salinities.

The nearby Mackreath Creek study site (Fig. 1) is underlain by similar geologic units to the Scott Bottom site and includes meta shales, sandstone-quartzite, and minor carbonate units (Preiss 1987). The site has 100–300 m of relief, reasonably steep slopes in many areas and narrow riparian-floodplain zones. The hydraulic head of the FRA is 2–3 m lower than the streambed at the gauging station on site, which demonstrates the disconnection between the surface water and the FRA.

The Mackreath Creek area has varying soil types as outlined in Bestland et al. (2016). In addition, three 3-m deep backhoe trenches were excavated and sampled for soil and regolith hydrochemical properties (Bestland and Stainer 2013). To summarize these soil properties, the regolith that

occurs over meta shale consists of a stony heavy clay, and where the regolith occurs over quartzite, it is composed of a silty stony sand with some clayey zones; additionally, minor quartzite outcrops are distributed along steep side slopes and narrow ridge tops.

Variation in flow and precipitation

Precipitation and stream flow at the SCC is representative of its Mediterranean climate, exhibiting high annual variability (Fig. 3). Most years have below 900 mm precipitation and less than 3,000 ML of flow; however, the maximum precipitation and flow over the 28-year period occurred in 2016, which had an annual precipitation above 1,200 mm, and flow that surpassed 9,000 ML. This vastly exceeded the annual mean for the years analysed of 804 mm of precipitation and 3,496 ML of flow. By contrast, the lowest annual flow occurred between the years 2002 and 2009 when most years were below 2,000 ML. In particular, 2006 was the driest year in this record with 1,057 ML of flow and 530 mm of precipitation. This was well below the average for the period of analysis. In addition, the standard deviation for flow was 2,000 ML and for precipitation 135 mm; this highlights the extent of the annual climatic variability of the site.

The variability in flow strongly correlates with the general climatic conditions for south-eastern Australia (BOM 2016; Murphy and Timbal 2008). Notable, in 2006 during the second worst drought in recorded history (Watkins 2005; Bettio 2006), the lowest flow was recorded at Scott Bottom. Moreover, between 1997 and 2006 (during 'the millennial drought') Southeastern Australia experienced a decade of record-breaking drought conditions (Murphy and Timbal 2008). This period also coincides with low flows on site. In contrast, flow on site in 2016 (the highest flow) concurred with the state of South Australia (including the Mount Lofty Ranges) having the highest September rain in recorded history with some sites in the Mount Lofty Ranges having had their highest annual rainfall (BOM 2016). Therefore, observed data from this investigation was consistent with the climatic conditions for the region and was therefore representative of overall climatic conditions of this area.

Methods

Flow and salinity data

Flow and surface-water-salinity-time-series data are available from hydrometric monitoring stations located adjacent to weirs at both the Scott Bottom and Mackreath Creek sites (Figs. 1d and 4). In addition, rainfall measurements are available from the nearby Mount Bold Reservoir weather station (Fig. 3). The Scott Creek data set has accumulated over many

Fig. 3 Monthly stream flow from Scott Creek and rainfall at Mt. Bold Reservoir station from 1989 to 2017
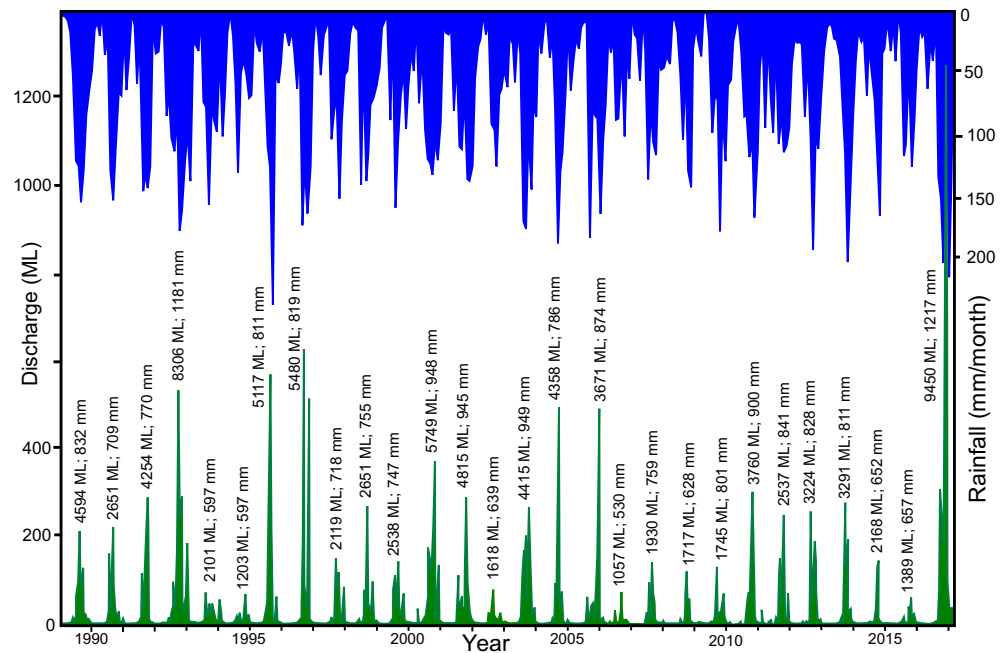
decades; whereas, the Mackreath Creek site was only in operation for the years 2001 to 2008. The data recorded for the Scott Bottom site over the last 5 years are available in SAW (2017) and the full data set available on request from the current custodian, SA Water (Scott Bottom) and DEWNR (Mackreath Creek).

Measurements of both electrical conductivity (EC; μS/cm) and the total daily volumetric flow (ML) were utilized during this investigation between the periods from 1989 to 2016. In addition to flow data, EC measurements at the Scott Bottom site were collected by acquiring samples of water passing through the site using the flow proportional composite sampling method (Nicholson and Clark 1992); thus, reported EC values represent the mean flow-weighted concentration for specified sampling periods (Fig. 4). In 2013, an in-situ-water-quality sensor was installed less than 5 m upstream of the weir; henceforth, the sensor recorded EC measurements every 5 min and data from this sensor were utilized instead of the composite sampling method for this study.

Despite these variations in EC sample frequency over the last 28 years, readings were usually taken on at least a fortnightly basis (approximately 90%). In the case measurements were missing in a month (less than 5%), a power regression between flow and EC (Fig. 5b) was used to estimate EC in

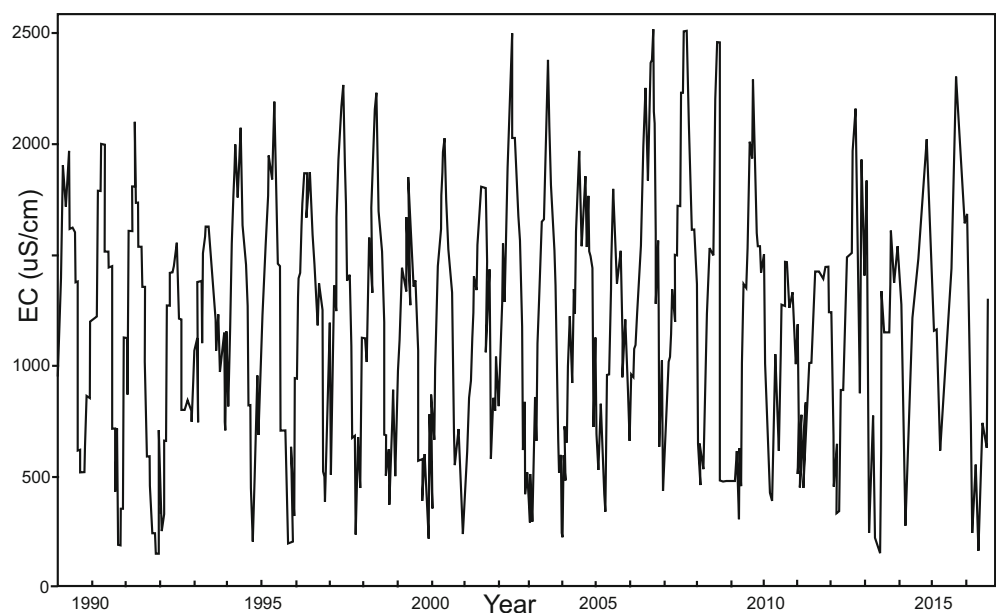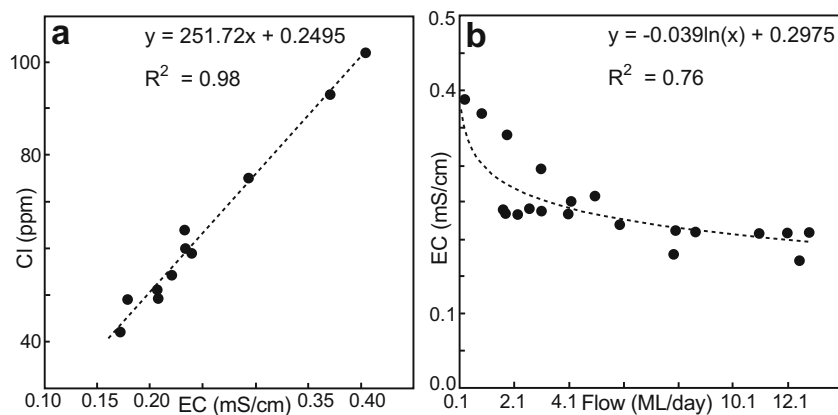**Fig. 4** Monthly salinity measurements from Scott Creek in 1989–2017

Fig. 5 **a** Mackreath Creek chloride (Cl) measurements correlated to electrical conductivity (EC) measurements using a linear equation. **b** EC correlated to flow measurements using a logrithmic equation

Results and discussion

Stream salinity hydrograph and trends

Salinity and chloride budget calculation

Based on EC measurements, a salinity load was calculated for Scott Creek at the Scott Bottom site (Fig. 6a). Salinity or total dissolved solids concentration (TDS, mg/L) of Scott Creek was thereby estimated from EC (in μS cm) measurements multiplied by a conversion factor of 0.64 (Mackay et al. 1988; Ali et al. 2012). Daily salinity loads were quantified by multiplying salinity concentration by the total daily stream flow. These were then summed to provide monthly and annual salinity loads from the two stream systems. Additionally, chloride concentration data for Scott Creek and Mackreath Creek were correlated with EC in order to generate time series of chloride concentration (Fig. 5a, b). The monthly totals for atmospheric deposition of chloride were based on average chloride concentrations (4.45 mg/L) in bulk rainfall for the area (Guan et al. 2010b), the rainfall from Mount Bold station and the area of each catchment (28.4 and 3.3 km^2 respectively). The monthly totals of chloride load in Scott Creek were based on flow measurements from the gauging station and estimated using an exponential relationship with EC for the Mount Lofty Ranges (Guan et al. 2010a). At the Makcreath Creek site, chloride load was calculated by multiplying flow with the concentration correlation equations shown in Fig. 5a,b. Two different sets of correlation equations for the two streams were necessary because of the very different character of the streams: one is permanent, fed by groundwater and higher in salinity, and one is intermittent, fed by runoff and soil water through-flow, and lower salinity.

In this strongly Mediterranean climate although there is a good seasonal correlation between rainfall, stream flow, and stream salinity (Figs. 3 and 4), there are however times when groundwater input to surface flows has had a delayed response to rainfall on a year to year basis. This interpretation is supported by the contrast in flow that occurred between 1993 and 1994, both low rainfall years. The year 1993 followed the anomalously wet year 1992 and had considerably more flow (>40%) with the same rainfall totals. This lag time in flow response to rainfall is assumed to be reflective of significant groundwater recharge during wet years. Such pulses of recharge generating stream flow is the mechanism envisioned to cause more saline groundwater to flush. Loh and Stokes (1981) found similar variations in flow and salinity following changes in flow in south-western Australia.

Similar to the aforementioned flow data, the EC data at the Scott Bottom site are highly variable (Fig. 4), with a standard deviation of 503 μS/cm over the 28-year period. In addition, seasonal variation during this sampling period ranges from above 1,500 μS/cm in the summer months (Dec–Feb) to below 400 μS/cm during the winter months (June–Aug). Furthermore, the wettest years (e.g. 1992, 1995, 1996, 2000, and 2016) had much lower than average salinity minimums (below 220 μS/cm). Conversely, during the millennial drought (during the years 1997–2006) there is a visually obvious trend of higher salinities, with maximums reaching over 2,000 μS/cm; therefore, it has been well established that there is strong correlation between flow and salinity. The variability in annual flow and salinity of Scott Creek is of critical importance to concepts of salinity flushing from the groundwater system. The seasonal salinity variation is caused by mixing of precipitation-induced runoff and groundwater input. During the drier summer months groundwater contribution to stream-flow

cases where flow data existed but EC data were missing. In general, where in-situ-water-quality data were available, this was used in preference to composite samples; however, limitations of the sensor method included equipment malfunction. EC of less than 150 μS/cm were assumed to be due to faulty equipment or low flow and in this case, data from the composite sample method were employed instead.

Fig. 6 **a** Yearly salinity load (total dissolved solids, TDS, in tonnes) and **b** yearly mean salinity concentration (kg/ML), plotted against flow from Scott Creek
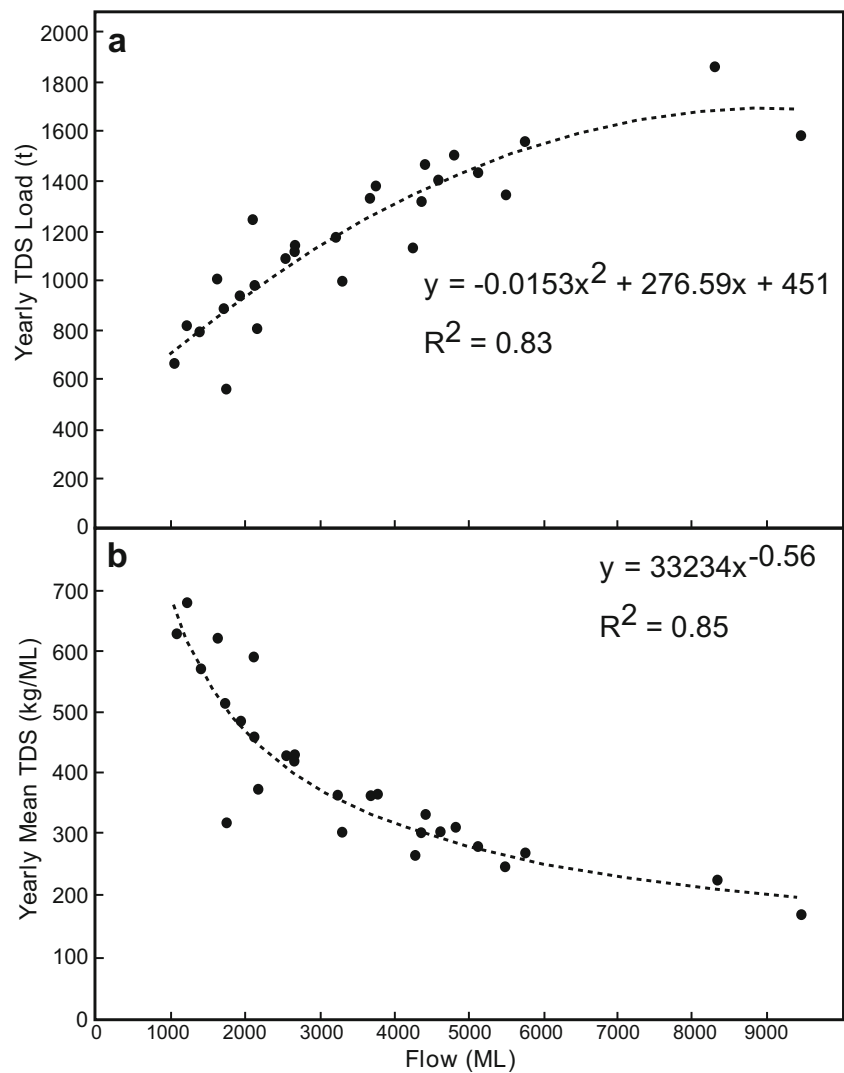
is dominant (Kretchmer 2007), which dramatically increases the EC. During wetter winter months there is freshwater dilution from precipitation and runoff lowering the EC (Banks et al. 2009).

As anticipated, both the highest salinity load and flow occurred in winter (June–Aug) followed by spring (Sep–Nov; Fig. 7). The lowest flow and salinity load occurred in summer (Dec–Feb) and autumn (March–May), which are, approximately equivalent. The highest flow occurred in spring; however, even with similar flow, a higher salinity load is flushed in winter compared to the spring period. Flushing of salinity, however, continues during the spring, but then declines by summer. By this time, flows have dropped off and the water table has lowered, unless during years when tropical moisture is present in South Australia (BOM 2016) as in the case of the September 2016 period. During these periods, transient flows can be high; thus, the change in season plays an important role in the amount of historical salinity flushed from the catchment.

Deep groundwater salinity flushing

Critical to the discussion of catchment-scale salinity mass balance is the consideration and description of the groundwater flow system. As mentioned, the Scott Creek experimental site has numerous nested piezometers as well as several deep open bores from which groundwater salinity profiles have been obtained (Fig. 8). Groundwater salinity measurements surrounding the streambed (piezometer nests D and E; Banks et al. 2009) are similar to the summer time stream salinity (between approximately 2,000 and 3,000 µS/cm; Banks et al. 2009). However, in this upward hydraulic gradient area in the valley bottom there is good evidence of groundwater mixing of fresher soil water with more saline deep groundwater (Banks et al. 2009; Bestland and Stainer 2013), which is thought to be the path for considerable salinity flushing from the groundwater system.

Deep open bores (up to 120 m) with groundwater EC profiles reveal an increase in salinity with depth (Fig. 8). There
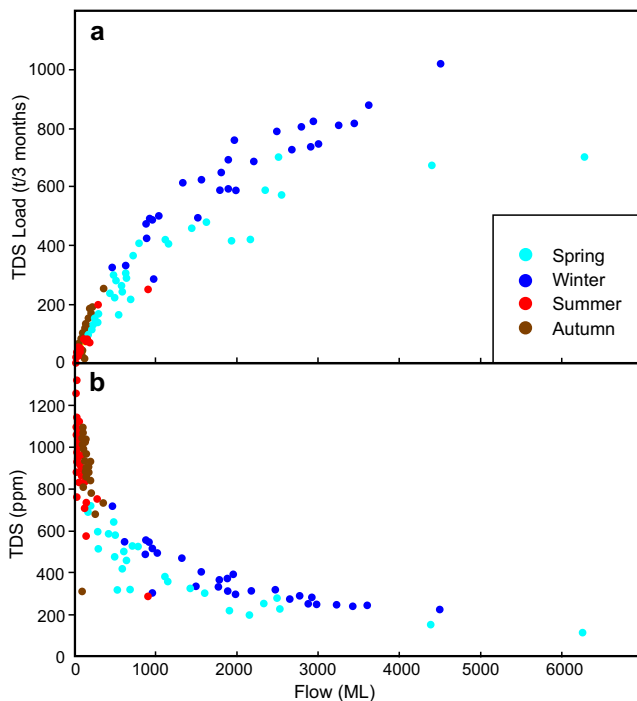
Fig. 7 Total dissolved solids **a** load and **b** concentration, calculated for each season (spring, winter, summer, and autumn) over the time span of 1989–2017

are obvious steps in the salinity increase with depth in most bores (Harrington 2004b)—bore PN 57830 (black profile in Fig. 8), which has a step in salinity at about 20 m and again at approximately 40 m, also bore PN 57830 (blue profile) has a salinity step increase at 40 m, while bore PN 57830 (red profile) shares this step at 20 m. Similarly, bore PN 57835 reveals a step but not to the extent of the other bores, whereas bore PN 58095 (green profile) does have an increasing step, but at 100 m, much deeper than the other bores.

The salinity rise observed at 20–60 m below the ground surface is interpreted as historic groundwater salinity that is flushing due to increase and freshening of recharge. The groundwater system in this valley has a strong upward gradient with several deep bores being artesian (Cranswick 2005; Banks et al. 2009). Banks et al. (2009) describes how the fractured bedrock zone at this site plays an important role in groundwater flow. Variation in the depths of these salinity steps are probably due to the locations of fractures that both access deeper more saline water as well as provide pathways for fresh recharging groundwater. Therefore, the steps in salinity found in most of these bores are interpreted as the result of historic salinity flushing.

The salinity increase in bore PN 58095 at over 100 m presumably represents the deep, unflushed ambient groundwater system. Carbon 14 dating of deep bores within close proximately to the Scott Bottom site (within 8 km) by Harrington (2004b) reveal the apparent age was over 1,000 years. Similarly, Radon-222 data by Cranswick (2005) suggest that
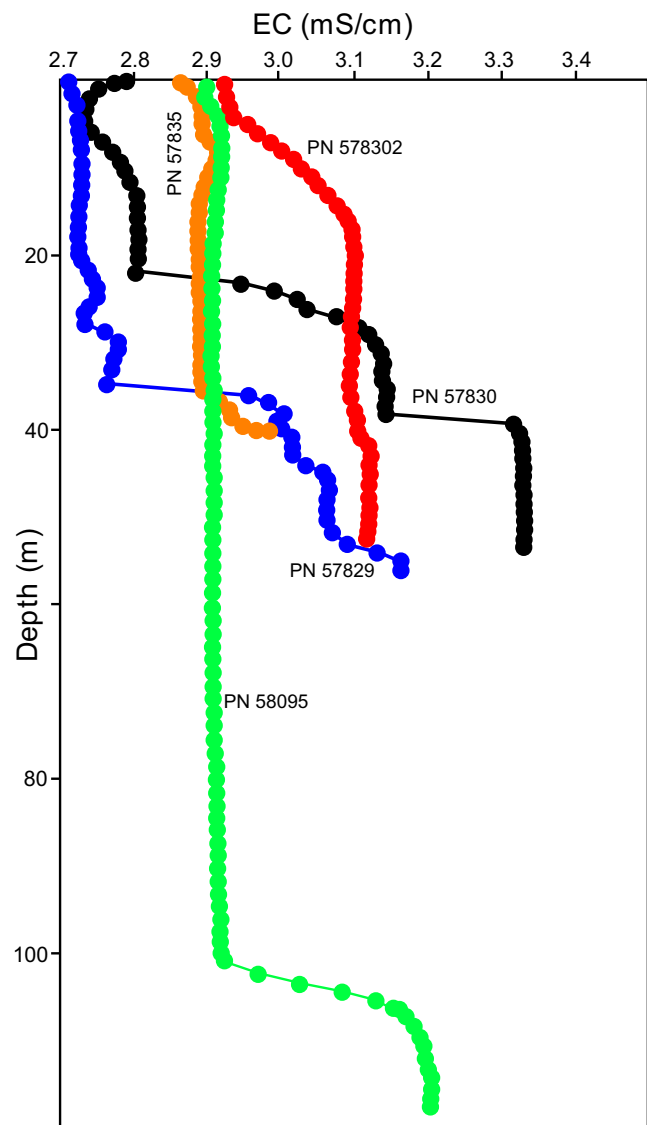
Fig. 8 Electrical conductivity (EC) depth profiles from open bores at the Scott Bottom site (data from Harrington 2004a)

water from deeper piezometers has considerably longer residence times. In addition, age dating by Banks et al. (2009) based on CFC-12 and CFC-13 found the shallower groundwater (< 30 m) to be a few decades old, considerably younger than that of the deeper bores. Therefore, as land clearing initiated in the 1840 and 1850s, the stored salinity discharging into the stream would have commenced post this era.

The export and accumulation of chloride

For the Scott Creek catchment, defined from the Scott Bottom gauging station, analysis of the monthly chloride deposition and load reveals periods of both export and accumulation (Fig. 9). Overall, during most years, there is over two times more chloride exported from the system than deposited by atmospheric chloride deposition; i.e. on average per month

Fig. 9 Catchment-scale chloride export or accumulation data (black line) calculated from monthly atmospheric chloride deposition (blue line) subtracted from monthly averaged stream chloride load (not shown)
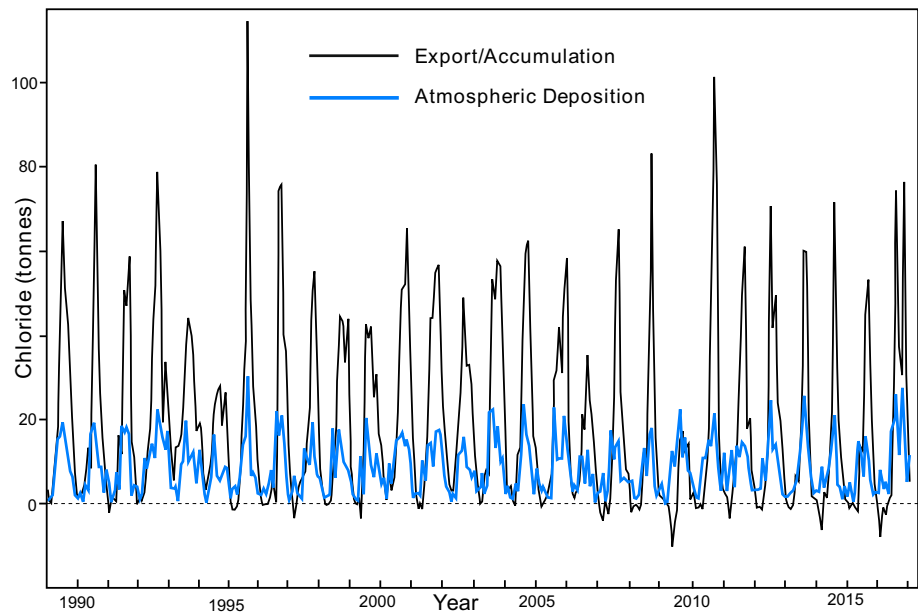
8.5 tonnes (t) of atmospheric chloride is deposited and 19.6 t of chloride is exported. It should be noted, however, that any groundwater export from the catchment that does not involve measured surface water flow has been omitted from this analysis. More stored chloride is generally exported during periods of higher flow, which supports the regression in Fig. 6a—for example, the month with the highest amount of chloride export is July 1995, with over 110 t exported. This occurred during a monthly flow of approximately 3,000 ML, which is about 10 times higher than the average monthly flow of 291 ML. Conversely, accumulation of chloride occurs during some summer months that have low stream flow but significant rainfall—for example, for the month of January 2007, 4.2 t of chloride were deposited while flow was only 6 ML. In such an extreme Mediterranean climate with large summer moisture deficit even moderate summer precipitation events can result in little runoff; therefore, these calculations and trends are consistent. Furthermore, January 2016 had the highest chloride accumulation of the years under investigation. Eight tonnes of chloride accumulated during this month, following two of the driest years on record (2014 and 2015). Overall, the data illustrate that the amount of chloride exported is highly variable with a standard deviation per year of 22.7 t. The variance was thereby dependent on both time and flow with more stored salinity accessed and exported when water tables rise during periods of high precipitation and flow. During these periods, more historical salinity discharged into the surface waters; however, during dry, summer and autumn months (Dec–April) chloride accumulation occurred during rainfall events, expressed as negative values in chloride load (Fig. 9; Table 2). Remarkably, there are higher, longer periods of chloride accumulation in more recent years, probably due to drought years with low flow accompanied by some summer

rainfall. Overall, however, the data suggest that the highest contributions to surface water salinity are stored historical salinity rather than salinity recently deposited from precipitation.

Importantly however, higher rates of salinity export are not only related to flow, but are also related to time. For instance, 30.6 t of chloride were exported during September 2016, the month exhibiting the highest flow (approximately 4,600 ML; Fig. 3) during the 28-year time series. However, this was significantly less than the chloride exported during the next highest flow month of July 1995, with 114.9 t of chloride exported despite less flow.

Given the strong correlation between salinity and flow within the SCC, there is an obvious and expected correspondence between the amount of the annual salinity load and the flow volume (Fig. 6a). An increase in salinity load is observed with a logarithmic increase in flow. Additionally, this relationship has a confidence level of nearly 100% (p value = 4.7 × 10^{-11}) and a significant coefficient of determination (R^2) of 0.83 (Table 3). Similarly, salinity concentration in mg/L exhibits a high correlation with flow in which lower salinities are correlated to higher flow (Fig. 6b; R^2 = 0.85).

In addition to correlations between salinity and flow, statistical trends are also apparent between time and flow. While there is no significant correlation regarding a decrease in salinity with time alone, a logarithmic regression with salinity load as a function of both time and flow exhibits a strong correlation (Table 3). This had an R^2 value of 0.85 with <1% likelihood that it occurred by chance (significance of F = 6.89E-11). This regression reveals that 6.4 t less salinity was exported each year from the 110 t being exported annually on average (p value = 0.04). This strong relationship of a decrease in salinity exported from the system each year is consistent with the theory that this site is reaching a new salinity

Table 2 Chloride load regression statistics. *SE* standard error

	Coefficient	SE	*t*-stat	*p* value	95% confidence interval	
					Lower	Upper
Chloride load	−229.9 t	96.7 t	−2.377	0.0254	−429.1 t	−30.7 t
Reduction in chloride load per year since 1989	−1.8 t	0.8 t	−2.254	0.0331	−3.45 t	−0.16 t
Logarithmic flow	140.7 ML	27 ML	5.202	2.21×10^{-5}	84.97 ML	196.3 ML

balance. The gradual freshening of the catchment over the 28 years of record, expressed through a reduction of 6.4 t of discharging salinity annually, indicates a decrease in salinity flowing into the stream presumably from increased recharge and freshening of the groundwater.

Analogous to the trend in annual salinity load, the annual chloride load for SCC also shows a decreasing trend with time (Fig. 10a). Chloride is not being exported consistently at the average observed rate (approximately 22 t/year), as depicted in Fig. 10 and summarized in Table 4. The observed cumulative load is estimated by regression to decrease over time with chloride export declining by 1.8 t of chloride per year (Fig. 10b). Unlike the historic chloride exported from the stream, the trend in atmospheric chloride deposition remains relatively linear throughout the analysed period. Therefore, whilst there is a relatively long-term steady value for chloride deposition, the amount exported is decreasing and indicates the site is attaining a new salinity balance, consistent with the study by Guan et al. (2010a).

Intermittent stream export and accumulation of chloride

Having established the overall salinity trend in the SCC, it is noteworthy that significant differences in the mass of chloride accumulated or exported are evident from the intermittent Mackreath Creek (Fig. 11). The Mackreath Creek catchment with its intermittent surface-water flow had no winter flushing in the years 2002 and 2006. Chloride accumulated during these years according to the mass balance based on chloride deposition and stream flow (Fig. 11). These differences between the annual chloride masses exported or accumulated for these two catchments is expressed as a mass per time per area (t/yr/km^2; Table 4). Markedly, Mackreath Creek exported

0.21 t of stored chloride per km^2/yr averaged over the 8-year monitoring period. In comparison, perennial Scott Creek exported 8.1 t/ km^2/yr averaged over the same 8-year period indicating that far more of this historical salinity is exported each year through the perennial steam. Additionally, the amount of chloride exported at Mackreath Creek only exceeded accumulation in three of the 8 years monitored. In contrast, the mass of chloride exported from Scott Creek was greater than the amount accumulated every year throughout the 28-year monitoring period. Furthermore, over the 8-year period Mackreath Creek had a maximum annual export of 3.7 t/km^2 in 2003 compared to Scott Creek which has a maximum of 10.3 t/km^2 in 2001. Over this 8-year period, the most extreme year in terms of chloride mass balance for Mackreath Creek was 2002 when 2.2 t/km^2 of chloride accumulated (no export occurred). The most extreme year in terms of chloride mass balance for Scott Creek was 2006 with a minimum chloride export of 4.9 t/km^2. Furthermore, the amount of chloride exported per km^2 from Mackreath Creek is only 2.6% of that from Scott Creek. Overall, this study revealed that there were vast differences when comparing the amount of chloride discharging from the intermittent stream compared to the perennial stream.

It is evident that the intermittent Mackreath Creek catchment, which is representative of most of the landscape of the SCC, has a low rate of chloride export compared to the SCC as a whole. This is due to the fact that most intermittent streams are losing streams where the groundwater does not rise enough to flush the stored salinity into the stream. During drier years there are extended periods of chloride accumulation with no apparent winter flushing. Specifically, this occurs during drought when the low rainfall causes low stream flow.

The considerably lower rate of historical chloride exporting into the surface water at Mackreath Creek is emphasized by

Table 3 Salinity load regression statistics. *SE* standard error

	Coefficient	SE	*t*-stat	*p* value	95% confidence interval	
					Lower	Upper
Salinity load	−2,589 t	360 t	−7.191	1.550×10^{-7}	−3,330 t	−1,847 t
Reduction in salinity load/yr since 1989	−6.38 t	2.98 t	−2.145	0.042	−12.51 t	−0.253 t
Logarithmic flow	1,105 ML	100.637 ML	10.980	4.702×10^{-11}	898 ML	1,312 ML

Fig. 10 **a** Yearly chloride export
from Scott Creek catchment from
1989 to 2017 showing trend line
of decreasing chloride export
(1.8 t/yr). **b** Monthly cumulative
chloride export (blue line)
compared to cumulative mean
chloride export (averaged over
years 1989–2016) and cumulative
mean chloride export minus
observed chloride export decrease
of 1.8 t/yr
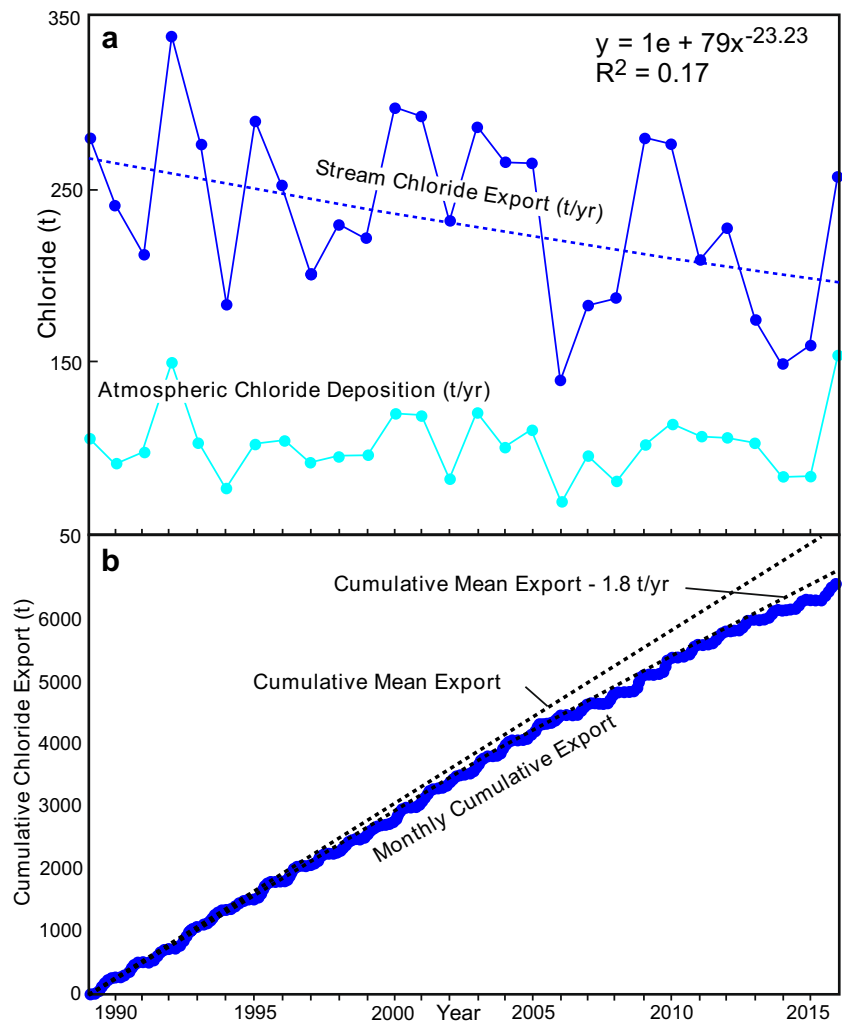
the significantly lower salinity in the stream (Milgate [2007]; Bestland et al. [2009]; Pichler [2009]). Presumably, recharge is moving salinity to the water table where flow toward the permanent stream allows this salinity to be flushed. Another consideration is the significant areal extent of sandy soil present in the Mackreath Creek catchment (Bestland et al. [2009]) compared to the thick, clayey soil of much of the SCC (Banks et al. [2009]; Bestland et al. [2016]). Anderson et al. ([2017]) observed that the soil at Scott Bottom can retain high salinity due to low rates of infiltration and recharge. When geology and porosity of the soil restrict drainage, shallow saline groundwater can occur (Cartwright et al. [2013]). Therefore, as more salinity has

been historically stored, there is more salinity available to flush. Considering the variation in salinity load exported between the perennial and intermittent streams within the subcatchment, the perennial stream proves to be by far the more important means of exporting these historical salts.

## Timeframe to reach new chloride equilibrium

The quantification of flushed salinity loads over a time interval can be used to approximate the timeframe for the catchment's restoration to a new salinity equilibrium (Fig. [12]). Results from this investigation allowed the development of a conceptual model similar to that of Guan et al. ([2010a]) and Jolly et al. ([2001]). However, the model in this study has a plethora of data to support the theory of reaching a new salinity equilibrium. To do this, an approximate period was calculated on a linear scale, whereby, remarkably, this determined that the site would reach equilibrium by 2090.

Findings from this investigation support findings by Guan et al. ([2010a]) who reported that catchments in the Mount Lofty Ranges with an annual rainfall of >900 mm would have

Table 4 Descriptive statistics of chloride load at the Mackreath and Scott Bottom catchments

Descriptive statistic	Mackreath Creek	Scott Bottom
Minimum chloride load (t/yr/km^2)	−2.2	4.9
Maximum chloride load (t/yr/km^2)	3.7	10.3
Mean chloride load (t/yr/km^2)	0.21	8.1

Fig. 11 Time series of chloride data from Mackreath Creek catchment for years 2001–2008. Export or accumulation of chloride is calculated from monthly atmospheric deposition subtracted from monthly chloride load in stream flow
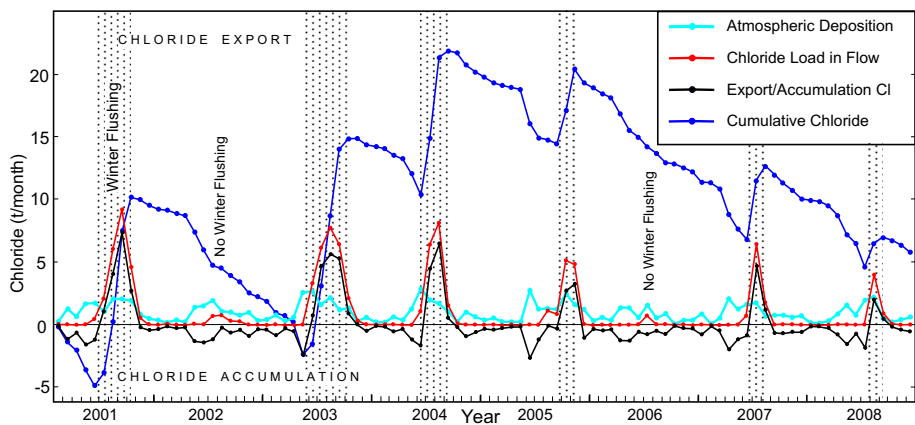
already reached equilibrium by the year 2008. Therefore, it is understandable that a catchment such as the SCC, with an average annual rainfall of 800 mm, would be approaching equilibrium by the year 2090. Although, Jolly et al. (2001) found that catchments in the Murray Darling Basin with annual rainfall of above 800 mm revealed minimal changes in their salinity balance; furthermore, in the Murray Darling Basin, catchments with an annual rainfall of 500–800 mm displayed a rising trend in the salinity balance. However, these catchments were only analysed over a 10-year period from data collected 20 years prior to the last values in this current investigation; furthermore, clearing began in the Murray Darling Basin several decades prior to clearing in the SCC (Walker et al. 1993). Therefore, various factors would come into effect causing this variation and for these reasons, the Murray Darling Basin of similar annual precipitation would understandably precede the SCC in the achievement of salinity equilibrium.

This study has determined that the SCC is returning to equilibrium in terms of salinity input/output following clearing of the native vegetation over 100 years ago. Following
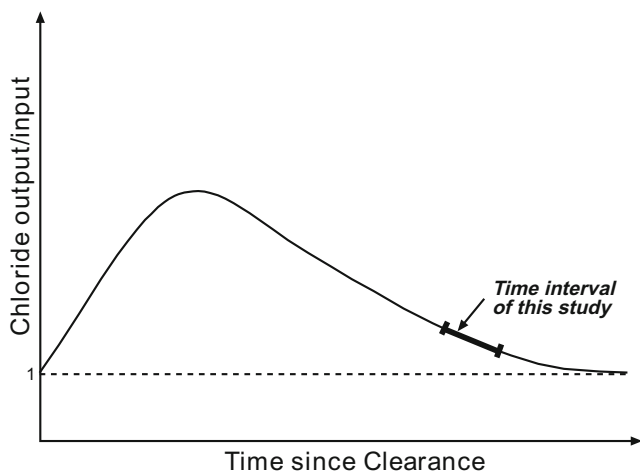

Fig. 12 Conceptual model of chloride output/input ratio change following land clearing (modified from Jolly et al. 2001 and Guan et al. 2010a)

clearing, increased recharge and water-table rise has flushed stored salinity. Eventually, an equilibrium will be reached between salinity export and salinity deposition (Jolly et al. 2001). Then, as the salinity is leached from the system, the salinity will drop until a new equilibrium is achieved.

Conclusions

Human-induced salinization, in particular dryland salinity, has had devastating impact on the hydrology of catchments in southern Australia and elsewhere. Notably, cases of salinity imbalance occurred following clearances of native vegetation; however, this study has focused on a catchment that is returning to a new salinity equilibrium. Following the land clearance at the SCC, evidence indicates that stored salinity is flushing into the surface water, driving the catchment to a new equilibrium. Two flushing mechanisms are envisioned: (1) the rising water table flushes salinity stored in the unsaturated zone and also flushes ambient groundwater, (2) increased recharge flushes salinity from the soil-regolith. Additionally, there is a considerable difference between the perennial and intermittent stream on site in the amount of salinity exported. Whilst the perennial Scott Creek had periods of salinity accumulation during dry months of certain years, the intermittent Mackreath Creek had entire drought years of salinity accumulation. Ultimately, this study reveals trends in salinity for this cleared catchment, using methods that are transferable to other catchments within the Mount Lofty Ranges and elsewhere.

The results presented here give conclusive evidence that the SCC is returning to a new salinity balance. Furthermore, it has revealed that despite the long-term variability in flow, salinity, and rainfall, significant trends were able to be determined. Thus, this study has exposed a decreasing trend in salinity with time, achieved through a multiple regression of a 28-year data set. Additionally, the amount of surface-water salinity that originates from atmospheric deposition and that from stored sources was able to be determined. Three times

more salinity derives from stored sources as affirmed by the chloride analyses. In fact, at the rate the salinity load is decreasing, an estimated new salinity equilibrium will occur by approximately 2090.

References

Ali NS, Mo K, Kim M (2012) A case study on the relationship between conductivity and dissolved solids to evaluate the potential for reuse of reclaimed industrial wastewater. KSCE J Civ Eng 16(5):708–713

Allison G, Cook P, Barnett S, Walker G, Jolly I, Hughes M (1990) Land clearance and river salinisation in the western Murray Basin, Australia. J Hydrol 119(1–4):1–20

AMLRNRM (2013) Adelaide and Mount Lofty Ranges natural resources management plan, strategic plan 2014–15 to 2023–24. Adelaide and Mount Lofty Ranges Natural Resources Management Board, Adelaide, Australia

Anderson TA, Bestland EA, Soloninka L, Wallis I, Banks EW, Pichler M (2017) A groundwater salinity hotspot and its connection to an intermittent stream identified by environmental tracers (Mt Lofty Ranges, South Australia). Hydrogeol J 25:2435–2451

Banks EW, Simmons C, Cranswick R, Love A, Werner A, Bestland E, Wood M, Wilson T (2009) Fractured bedrock and saprolite hydrogeologic controls on groundwater/surface-water interaction: a conceptual model (Australia). Hydrogeol J 17(8):1969–1989

Bestland EA, Stainer G (2013) Down-slope change in soil hydrogeochemistry due to seasonal water table rise: implications for groundwater weathering. Catena 111:122–131

Bestland EA, Milgate S, Chittleborough D, Vanleeuwen J, Pichler M, Soloninka L (2009) The significance and lag-time of deep through flow: an example from a small, ephemeral catchment with contrasting soil types in the Adelaide Hills, South Australia. Hydrol Earth Syst Sci 13:1–14

Bestland EA, Liccioli C, Soloninka L, Chittleborough DJ, Fink D (2016) Catchment-scale denudation and chemical erosion rates determined from 10Be and mass balance geochemistry (Mt. Lofty ranges of South Australia). Geomorphology 270:40–54

Bettio L (2006) Seasonal climate summary southern hemisphere (autumn 2005): an exceptionally warm and dry autumn across Australia. Aust Meteorol Mag 55(1)

Biggs AJ (2006) Rainfall salt accessions in the Queensland Murray–Darling basin. Soil Res 44(6):637–645

Biggs AJ, Silburn DM, Power RE (2013) Catchment salt balances in the Queensland Murray–Darling basin, Australia. J Hydrol 500:104–113

Blackburn G, McLeod S (1983) Salinity of atmospheric precipitation in the Murray-Darling drainage division, Australia. Soil Res 21(4):411–434

BOM (2016) Climate statistics for Australian sites. Bureau of Meteorology. http://www.bom.gov.au/climate/averages/tables/ca_sa_names.shtml. Accessed 22 September 2016

Brown P, Halvorson A, Siddoway F, Mayland H, Miller M (1983) Saline seep diagnosis, control and reclamation. USDA Conservation research report no. 30, US Department of Agriculture, Washington, DC

Cartwright I, Gilfedder B, Hofmann H (2013) Chloride imbalance in a catchment undergoing hydrological change: upper Barwon River, Southeast Australia. Appl Geochem 31:187–198

Chittleborough D, Smettem K, Cotsaris E, Leaney F (1992) Seasonal changes in pathways of dissolved organic carbon through a hillslope soil (Xeralf) with contrasting texture. Soil Res 30(4):465–476

Cox J, Fritsch E, Fitzpatrick RW (1996) Interpretation of soil features produced by ancient and modern processes in degraded landscapes: VII. water duration. Soil Res 34(6):803–824

Cranswick R (2005) Hillslope scale geological controls on surface water–groundwater interaction: evidence of active recharge to a fractured rock aquifer. Honours Thesis, Flinders University South Australia, Adelaide, Australia

Currell M, Gleeson T, Dahlhaus P (2016) A new assessment framework for transience in hydrogeological systems. Ground Water 54(1):4–14

Dahlhaus P, Cox JW, Simmons CT, Smitt C (2008) Beyond hydrogeologic evidence: challenging the current assumptions about salinity processes in the Corangamite region, Australia. Hydrogeol J 16(7):1283

Dawes WR, Gilfedder M, Walker GR, Evans W (2004) Biophysical modelling of catchment-scale surface water and groundwater response to land-use change. Math Comput Simul 64(1):3–12

DEHAA (1999) Scott Creek conservation park management plan. Dept. for Environment, Heritage and Aboriginal Affairs, Adelaide, Australia

EPA (2013) Scott Creek, Scott Bottom aquatic ecosystem condition report. Environmental Protection Agency. http://www.epa.sa.gov.au/reports_water/c0244-ecosystem-2013. Accessed 5 October 2016

Eriksson E (1959) The yearly circulation of chloride and sulfur in nature: meteorological, geochemical and pedological implications, part I. Tellus 11(4):375–403

Eriksson E (1960) The yearly circulation of chloride and sulfur in nature: meteorological, geochemical and pedological implications, part II. Tellus 12(1):64–109

Fitzpatrick RW, Boucher S, Naidu R, Fritsch E (1994) Environmental consequences of soil sodicity. Soil Res 32(5):1069–1093

George R, McFarlane D, Nulsen B (1997) Salinity threatens the viability of agriculture and ecosystems in Western Australia. Hydrogeol J 5(1):6–21

Gilfedder M, Walker GR, Dawes WR, Stenson MP (2009) Prioritisation approach for estimating the biophysical impacts of land-use change on stream flow and salt export at a catchment scale. Environ Model Softw 24(2):262–269

Greeff G (1994) Ground-water contribution to stream salinity in a shale catchment, RSA. Ground Water 32(1):63–70

Guan H, Love A, Simmons C, Hutson J, Ding Z (2010a) Catchment conceptualisation for examining applicability of chloride mass balance method in an area with historical forest clearance. Hydrol Earth Syst Sci 14(7):1233

Guan H, Love A, Simmons C, Makhnin O, Kayaalp A (2010b) Factors influencing chloride deposition in a coastal hilly area and application to chloride deposition mapping. Hydrol Earth Syst Sci 14(5):801

Harrington G (2004a) Hydrogeological investigation of the Mount Lofty Ranges, progress report 3: Borehole water and formation characteristics at the Scott Bottom research site, Scott Creek Catchment. Report DWLBC 2004/03, Dept. of Water, Land and Biodiversity Conservation, Adelaide, Australia

Harrington G (2004b) Hydrogeological investigation of the Mount Lofty Ranges, progress report 4: groundwater–surface water interactions in the Scott Creek, Marne River and Tookayerta Creek Catchments. Report DWLBC 2004/03, Dept. of Water, Land and Biodiversity Conservation, Adelaide, Australia

Hatton T, Ruprecht J, George R (2003) Preclearing hydrology of the Western Australia wheatbelt: target for the future. Plant Soil 257(2):341–356

James-Smith J, Harrington G (2002) Hydrogeological investigation of the Mount Lofty Ranges, progress report 1: hydrogeology and drilling phase 1 for Scott Creek catchment. Dept. for Water, Land and Biodiversity Conservation, Adelaide, Australia

Jayawickreme DH, Santoni CS, Kim JH, Jobbágy EG, Jackson RB (2011) Changes in hydrology and salinity accompanying a century of agricultural conversion in Argentina. Ecol Appl 21(7):2367–2379

Jolly I, Walker G, Stace P, van der Wel B, Leaney R (2000) Assessing the impacts of dryland salinity on South Australia's water resources. CSIRO technical report 9/00, CSIRO Land and Water, Adelaide, Australia

Jolly I, Williamson D, Gilfedder M, Walker G, Morton R, Robinson G, Jones H, Zhang L, Dowling T, Dyce P (2001) Historical stream salinity trends and catchment salt balances in the Murray–Darling basin, Australia. Mar Freshw Res 52(1):53–63

Keywood M, Chivas A, Fifield L, Cresswell R, Ayers G (1997) The accession of chloride to the western half of the Australian continent. Soil Res 35(5):1177–1190

Kretchmer P (2007) Determining the contribution of groundwater to stream flow in an upland catchment using a combined salinity mixing model and modified curve number approach. Honours Thesis, Flinders University South Australia, Adelaide, Australia

Loh I, Stokes R (1981) Predicting stream salinity changes in South-Western Australia. Dev Agric Eng 2:227–254

Mackay N, Hillman T, Rolls J (1988) Water quality of the river Murray: review of monitoring 1978 to 1986. Murray-Darling Basin Commission, Canberra, Australia

Marchesini VA, Giménez R, Nosetto MD, Jobbágy EG (2017) Ecohydrological transformation in the Dry Chaco and the risk of dryland salinity: following Australia's footsteps? Ecohydrology 10(4):e1822

Meinzer OE (1923) Outline of ground-water hydrology, with definitions. US Government Printing Office, Washington, DC

Milgate SA (2007) Hydrochemical investigation of flow pathways through quartz-sand and duplex soils during a storm event: Mackreath Creek, Mount Lofty Ranges. Honours Thesis, Flinders University South Australia, Adelaide, Australia

Murphy BF, Timbal B (2008) A review of recent climate variability and climate change in southeastern Australia. Int J Climatol 28(7):859–879

Nicholson BL, Clark RD (1992) Nutrient loads in the Onkaparinga River system. EWS report no. 92/17. Dept. of Engineering and Water Supply, Adelaide, Australia

Norman C (1995) Effect of groundwater pump management on reclaiming salinised land in the Goulburn Valley, Victoria. Aust J Exp Agric 35(2):215–222

Pannell DJ (2001) Dryland salinity: economic, scientific, social and policy dimensions. Aust J Agric Resour Econ 45(4):517–546

Peck A, Hurle DH (1973) Chloride balance of some farmed and forested catchments in southwestern Australia. Water Resour Res 9(3):648–657

Pichler M (2009) Characterization of spatial and seasonal changes of dissolved organic carbon in the soils of a South Australian catchment. Honours Thesis, Flinders University South Australia, Adelaide, Australia

Poulsen DL, Simmons CT, Le Galle La Salle C, Cox JW (2006) Assessing catchment-scale spatial and temporal patterns of groundwater and stream salinity. Hydrogeol J 14(7):1339–1359

Preiss WV (1987) The Adelaide Geosyncline: Late Proterozoic stratigraphy, sedimentation, palaeontology and tectonics. Govt. Printer, South Australia, Adelaide, Australia

Ranville JF, Chittleborough DJ, Beckett R (2005) Particle-size and element distributions of soil colloids. Soil Sci Soc Am J 69(4):1173–1184

Ruprecht J, Schofield N (1989) Analysis of streamflow generation following deforestation in Southwest Western Australia. J Hydrol 105(1–2):1–17

Ruprecht J, Schofield N (1991) Effects of partial deforestation on hydrology and salinity in high salt storage landscapes: I. extensive block clearing. J Hydrol 129(1–4):19–38

SAW (2017) SA Water data set: Scott Creek @ Scott Bottom, A5030502AA. http://wds.amlr.waterdata.com.au/StationDetails.aspx?sno=A5030502AA. Accessed 12 January 2017

Scanlon BR, Reedy RC, Stonestrom DA, Prudic DE, Dennehy KF (2005) Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. Glob Chang Biol 11(10):1577–1593

Schofield N (1992) Tree planting for dryland salinity control in Australia. Agrofor Syst 20(1–2):1–23

Sivapalan M, Ruprecht JK, Viney NR (1996) Water and salt balance modelling to predict the effects of land-use changes in forested catchments: 1. small catchment water balance model. Hydrol Process 10(3):393–411

Smitt C, Gilfedder M, Dawes W, Petheram C, Walker G (2003) Modelling the effectiveness of recharge reduction for salinity management: sensitivity to catchment characteristics. CSIRO technical report 20/03, CSIRO Land and Water, Canberra, Australia

Stevens D, Cox J, Chittleborough D (1999) Pathways of phosphorus, nitrogen, and carbon movement over and through texturally differentiated soils, South Australia. Aust J Soil Res 37(4):679–679

Tyagi N (2003) Managing saline and alkaline water for higher productivity. In: Kijne JWBR, Molden D (eds) Water productivity in agriculture: limits and opportunities for improvement. CABI, Wallingford, UK, pp 69–87

USGS (2018) United States geological survey water data for the nation. https://waterdata.usgs.gov/nwis. Accessed 16 August 2018

Walker J, Bullen F, Williams B (1993) Ecohydrological changes in the Murray-Darling basin: I. the number of trees cleared over two centuries. J Appl Ecol 30:265–273

Walker GR, Gilfedder M, Williams J (1999) Effectiveness of current farming systems in the control of dryland salinity. CSIRO Land and Water, Canberra, Australia

Watkins A (2005) The Australian drought of 2005. World Meteorol Org Bull 54(3):156–162

Williams J, Hook RA, Gascoigne HL (1998) Farming action: catchment reaction: the effect of dryland farming on the natural environment. CSIRO, Collingwood, Australia

Williamson D, van der Well B (1991) Quantification of the impact of dryland salinity on water resources in the Mt Lofty Ranges, SA. Int. Hydrology and Water Resources Symp. Challenges for Sustainable Development, Perth, WA, October 2–4, 1991, National Conf. Publ., Inst of Eng. Aust., Barton, Australia, pp 48–52

Williamson D, Stokes R, Ruprecht J (1987) Response of input and output of water and chloride to clearing for agriculture. J Hydrol 94(1–2):1–28

Wood WW (1999) Use and misuse of the chloride-mass balance method in estimating ground water recharge. Ground Water 37(1):2–5