Appendix 56 On the Contribution of Groundwater to Streamflow in Laterite Catchments of the Darling Range, Southwestern Australia

Received: 22 April 2020 | Accepted: 29 September 2020

DOI: 10.1002/hyp.13928

RESEARCH ARTICLE

WILEY

On the contribution of groundwater to streamflow in laterite catchments of the Darling Range, south-western Australia

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Funding information
Alcoa of Australia; Department of Biodiversity, Conservation and Attractions

Abstract

In deeply weathered laterite catchments of the Darling Range in south-western Australia, the direct contribution (i.e., discharge) of permanent groundwater to streamflow has long been considered as minor. Instead, downslope shallow throughflow was thought to dominate, generating more than 90% of streamflow. We used a chemical hydrograph separation approach to estimate annual groundwater discharge for three catchments over periods of up to 39 years, and found that direct groundwater contributions to streamflow were far more variable across catchments and through time than has previously been acknowledged. The estimated proportion of annual streamflow sourced directly from groundwater ranged from 0 to 93% and was related linearly to the size of the groundwater discharge area in the catchment valley floor. In contrast, contributions from shallow sources including shallow throughflow varied primarily and linearly with annual rainfall. However, the response to rainfall was "amplified" in a predictable way by the size of the groundwater discharge area, consistent with the variable source area concept. We derived a functional relationship between catchment annual rainfall-runoff ratio and groundwater discharge area and successfully applied this to a further four catchments, inferring that the results were broadly applicable across the Darling Range. The implications for an improved understanding of streamflow generating processes in the study region, and for laterite catchments generally, are discussed.

KEYWORDS

catchment storage, groundwater discharge area, hydrograph separation, jarrah forest, shallow throughflow, stream salinity, streamflow generation

1 | INTRODUCTION

Laterite soils are widespread worldwide, yet their impact on catchment hydrology has received relatively little attention (Bonsor, MacDonald, & Davies, 2014; Cuthbert & Tindimugaya, 2010 but see Hughes, Petrone, & Silberstein, 2012). Laterite formation through deep weathering of geologically stable landscapes leads to distinctive horizonation featuring surface materials with characteristically high infiltration rates above clay-rich layers of much reduced permeability (McFarlane, 1976). Both the thickness of the weathered zone and the potential presence of preferred flowpaths which support rapid transfer of infiltrated rainfall to depth (Cuthbert & Tindimugaya, 2010; Johnston, 1987a), determine the partitioning of infiltrated rainfall between shallow sub-surface flow (throughflow) and groundwater recharge. As a result, streamflow responses can vary widely between laterite regions from "flashy" (Bonsor et al., 2014) to "sluggish" (Ruprecht & Schofield, 1990).

Laterite soils occur extensively across south-western Australia (Purdie, Tille, & Schoknecht, 2004) including the Darling Range near Perth (Figure 1). The Darling Range is an undulating elevated plateau of Archaean granite and gneiss that has weathered in situ to form a deep (up to 50 m) lateritic regolith supporting extensive areas of

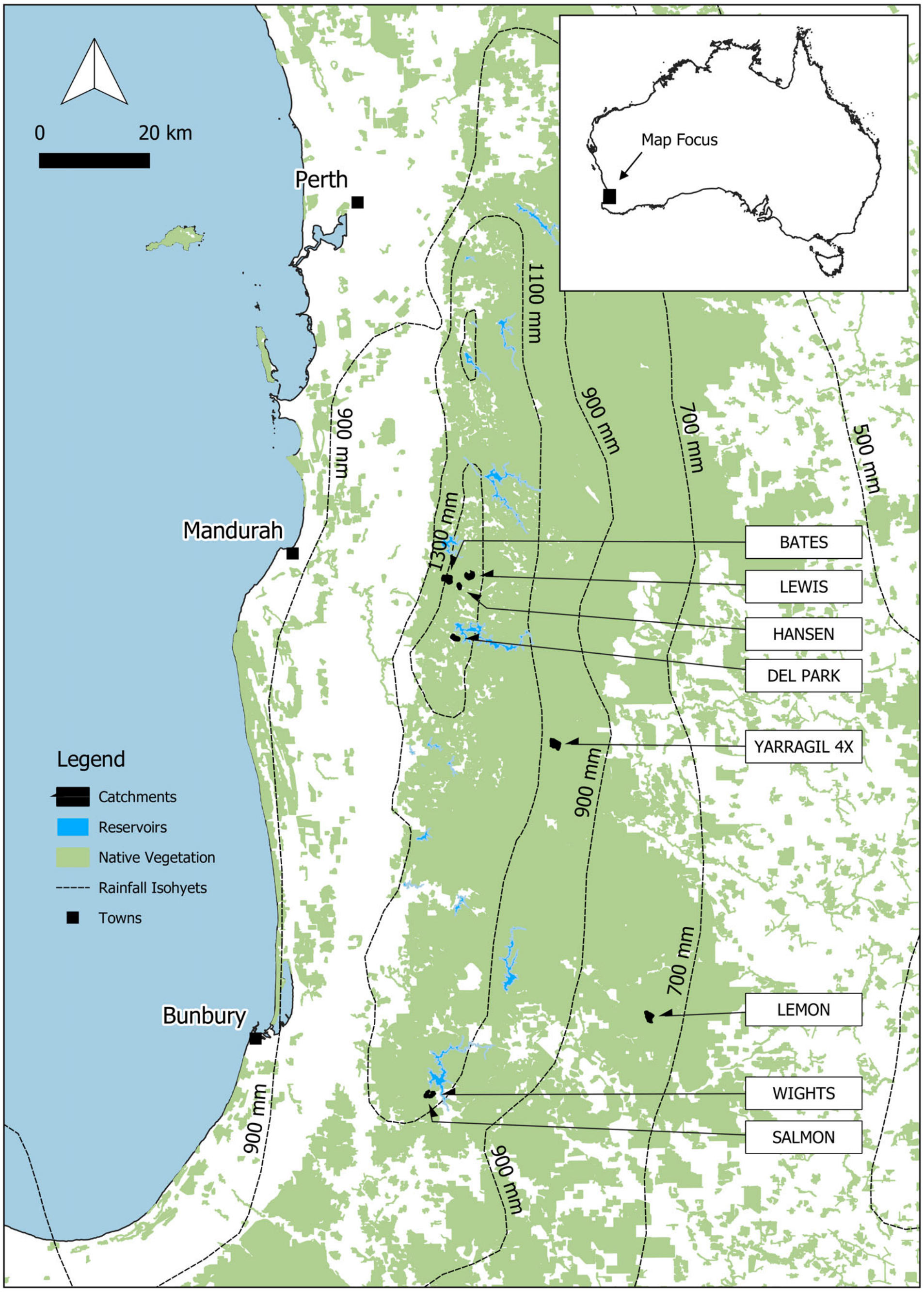

FIGURE 1 The Darling Range study area in south-western Australia showing the location of eight experimental catchments used in this study. Also shown are areas of native vegetation and long-term average annual rainfall isohyets

native forest. The regolith typically consists of surface gravels, sands and loams underlain by a discontinuous layer of cemented duricrust, a mottled zone enriched with iron and aluminium, and pallid zone clays down to partially weathered saprolite above the basement rock (Churchward & Dimmock, 1989). In upland parts of the plateau, relatively more of the laterite profile remains intact while valleys and lower slopes may be eroded or overlain by soils developed locally or transported from upslope (Churchward & Dimmock, 1989). Salt from oceanic spray transferred by rainfall and dry fallout is stored in the regolith (Hingston & Gailitis, 1976; Mazor & George, 1992), mostly in the mottled and pallid zones, with relatively little in the surface horizons (Johnston, McArthur, & Peck, 1980). Salt storage increases exponentially with decreasing rainfall (Schofield, Stoneman, & Loh, 1989; Tsykin & Slessar, 1985).

In the western parts of the Darling Range plateau where annual rainfall exceeds 1,100 mm (Figure 1), a permanent groundwater system is usually present as a single unconfined aquifer in the saprolite and lower pallid zone (Schofield et al., 1989). Due to a strongly seasonal pattern of rainfall and associated recharge, occurring as both matrix flow and via preferred flowpaths (Johnston, 1987a), groundwater levels can display an annual oscillation (e.g., McFarlane, George, Ruprecht, Charles, & Hodgson, 2020). Where groundwater is sufficiently close to the valley floors of headwater catchments it may contribute to streamflow (Hughes et al., 2012), with contributions varying in magnitude through the year in association with these seasonal oscillations (Ocampo, Sivapalan, & Oldham, 2006). Where the valley forms are broad and flat, particularly in the east of the Darling Range, a shallow perched aquifer over clay can also be present during the winter wet season (Fordyce, Gilkes, Loneragan, Beale, & Middleton, 2007; Ritson, Herbert, & Shea, 1981), although these do not usually confine the groundwater system below (Silberstein, Adhitya, & Dabrowski, 2003). Hence, streamflow consists of varying proportions of surface runoff, shallow throughflow and groundwater. Streamflows are usually ephemeral, with perennial flow restricted to those catchments where groundwater remains connected through the summer dry period (Schofield et al., 1989). In areas of native forest with annual rainfall less than 1,100 mm (Figure 1), groundwater is less extensive and is usually too deep below the valley floor to discharge directly to streams. Here, streamflow consists entirely of surface runoff and shallow throughflow from the perched aquifer if present. However, long-term reductions in the cover of native vegetation due to agricultural development can lead to rising groundwater levels and connection to the valley floor (Peck & Williamson, 1987), hence groundwater discharge to streams in inland areas as a result of clearing is associated with increases in stream salinity (Silberstein et al., 2003; Williamson, Stokes, & Ruprecht, 1987).

The contribution to total streamflow from groundwater across the Darling Range has long been considered minor. Instead, shallow throughflow in the upper gravelly soil horizons has been widely reported to dominate streamflow generation (Bari & Ruprecht, 2003; Kinal & Stoneman, 2011; McFarlane et al., 2020; Ruprecht, Schofield, Crombie, Vertessy, & Stoneman, 1991; Ruprecht & Stoneman, 1993; Schofield et al., 1989). Fundamental to this view is a conceptual model that contains a two-layered profile consisting of a highly conductive surface layer underlain by less conductive pallid zone clays (Sharma, Williamson, & Hingston, 1980), consistent with decreases in permeability with depth in laterite profiles worldwide (Bonsor et al., 2014). Conacher (1975) was the first to propose that infiltrated rainfall in the winter rainfall season formed a perched aquifer above the clay subsoil, generating shallow throughflow, which then travelled laterally and downslope to the stream. This conceptual pathway has been repeated in later literature (e.g., Bari & Ruprecht, 2003), and incorporated into process-based predictive models (Bari & Smettem, 2004; Croton & Barry, 2001). Two studies were pivotal to widespread acceptance of the shallow throughflow conceptual model. Both were short-term studies undertaken in Salmon experimental catchment (Figure 1) in the early 1980s. Stokes and Loh (1982), employing a hydrograph separation model using streamwater chloride concentrations, found that only 7% of annual flow in 1980 was sourced from groundwater while 91% was attributed to the shallow aquifer and the remaining 2% to surface flow. Subsequently, Turner, Macpherson, and Stokes (1987a) used a combination of stable isotope and chloride concentration approaches to show that over the course of four storm events in 1985, between 60 and 95% of streamflow was generated from shallow sources which they defined as shallow groundwater. Further, these authors found that the isotopic composition of streamflow matched that of shallow groundwater for almost the entire flow season. It is worth noting that, while both studies made no reference to downslope shallow throughflow as the pathway for shallow groundwater, this was implied from the conceptual model.

The dominance of the shallow throughflow conceptual model in the Darling Range has recently been challenged (Hughes & Vaze, 2015), with several studies drawing attention to the close correlation between streamflow and the state of the groundwater system (Grigg & Hughes, 2018; Hughes et al., 2012; Kinal & Stoneman, 2012). Kinal and Stoneman (2012), for example, found that disconnection of groundwater from the valley floor due to declining groundwater levels led to an abrupt and dramatic reduction in streamflow. Grigg (2017) showed that streamflow in three Darling Range catchments, including one where parts of the upper regolith had been disrupted by bauxite mining, was closely related to the dynamics of a groundwater discharge area. This finding echoed an earlier catchment clearing study by Ruprecht and Schofield et al. (1989) who also concluded that the permanent groundwater was instrumental in controlling streamflow response. Various authors have reported the presence of preferential flow paths in the laterite profiles of the Darling Range, both through the duricrust (Ruprecht & Schofield, 1993) and deeper into the regolith (Dell, Bartle, & Tacey, 1983; Johnston, 1987a), explaining relatively rapid responses of groundwater to rain events (Johnston, 1987a; Schofield et al., 1989). This pathway for infiltrated rainfall can play a significant role in the hydrology of laterite profiles (Cuthbert & Tindimugaya, 2010) and provides a possible mechanism for a greater or more variable contribution of groundwater to streamflow in the Darling Range.

In this study, we re-investigate the relative contributions of shallow throughflow and the permanent groundwater system to streamflow in the Darling Range. The aim is to quantify the direct contribution of groundwater to streamflow across multiple catchments and over extended periods of observation, in contrast to the short-term, single catchment studies that have been reported to date. In doing so, we aim to enhance our understanding of hydrological processes within the study region, and within laterite catchments more generally.

2 | METHODS

2.1 | Study area

The current study utilized published results from eight experimental catchments (Table 1) located across the Darling Range within approximately 200 km of the major city of Perth in south-western Australia (Figure 1). A permanent groundwater system was present in all catchments, while Lemon and to a limited extent Yarragil 4X also contained a transient perched aquifer in the valley floor. All catchments originally supported an open forest dominated by jarrah (*Eucalyptus marginata*) and a range of sclerophyllous shrubs and ground layer species (Bell & Heddle, 1989). Some of the catchments were subjected to different land use treatments (Table 1), with further details in the references supplied in the table. Both Lemon and Wights catchments

TABLE 1 Characteristics of experimental catchments in the Darling Range used in this study

Catchment	Area (ha)	Max. Relief (m)	Rainfall[a] (mm)	Treatment	Reference
Bates	230	70	1,205	Control—Open jarrah forest	Grigg (2017)
Del Park	131	60	1,205	Mining (32%) 1975–1979, 1987–1989, rehabilitation	Grigg and Hughes (2018)
Hansen	76	70	1,300	Intensively thinned 1985–1986	Ruprecht et al. (1991)
Lemon	344	110	820	Partially (53%) cleared 1976–1977	Ruprecht and Schofield (1991a)
Lewis	186	80	1,179	Mining (51%) 1996–2000, rehabilitation	Grigg (2017)
Salmon	82	110	1,120	Control—Open jarrah forest	Williamson et al. (1987)
Wights	94	100	1,120	100% cleared to pasture 1976–1977	Williamson et al. (1987)
Yarragil 4X	273	100	1,017	Moderate thinning 2000–2001	Kinal and Stoneman (2012)

[a] Long-term annual average reported in the cited studies.

TABLE 2 Mean tracer concentration of groundwater and water from shallow sources, and years of streamflow and stream salinity records in three catchments used to estimate the contribution of groundwater to annual streamflow

		Streamflow component			
Catchment	Tracer (mg/L)	Groundwater	Shallow sources	Period of stream/salinity records	Reference(s)
Lemon	TDS	2,200	29	1974–1998	Ruprecht and Schofield (1991a), Silberstein et al. (2003)
Wights	Cl-	500	65	1974–1987	Williamson et al. (1987)
Yarragil 4X	TDS	686	113	1975–2013	Kinal and Stoneman (2012), this study

experienced rising groundwater levels and an expanded discharge area in response to partial (Lemon) or complete (Wights) deforestation. Streamflow in these catchments changed from seasonal to perennial as groundwater attained and remained at the surface, with reports of piezometric surfaces above the ground (Ruprecht & Schofield, 1989; Ruprecht & Schofield, 1991a). The climate of the region is Mediterranean, with cool wet winters and hot dry summers. Approximately 80% of annual rainfall occurs in the period from May to October (Gentilli, 1989) and there is a strong rainfall gradient inland from the western margin of the plateau (Figure 1).

2.2 | Model development

In this study, measured total annual streamflow (Qt) was divided into two source categories, being direct contributions from groundwater (Qd) and contributions from all other sources including shallow throughflow and saturated overland flow (Qs) (Equation (1)).

$$Qt = Qd + Qs. \tag{1}$$

We used a chemical hydrograph separation approach (described below) to estimate Qd for three "test" catchments, Lemon, Yarragil 4X and Wights (Figure 1; Table 1). Qs was then calculated from Equation (1). This was completed for each year of available record in the catchments, spanning periods of 25 years for Lemon, 14 years for Wights and 39 years for Yarragil 4X (Table 2). We developed linear regressions between annual Qd and an estimate of a groundwater discharge area in the valley of each catchment in each year (see below), and between annual Qs and catchment annual rainfall, from which a functional relationship between catchment annual rainfall runoff ratio and groundwater discharge area was derived. We then compared predicted values from this relationship with measured annual runoff ratios and groundwater discharge areas in four "validation" catchments (Hansen, Lewis, Bates, Del Park: Figure 1; Table 1) for which no suitable tracer data were available to undertake chemical hydrographic separation directly. The goodness of fit in the "validation" catchments was used to infer broader applicability of the estimates of deep groundwater contribution to streamflow for laterite catchments across the Darling Range.

2.3 | Chemical hydrograph separation

The tracer used in the chemical hydrograph separation step was either the chloride anion, or total dissolved salts (TDS) derived from stream conductivity measurements. Chloride is commonly used as a tracer in hydrological studies (Herczeg & Edmunds, 2000), including the estimation of groundwater discharge to streams (Cook, 2013; Kalbus, Reinstorf, & Schirmer, 2006). Chloride has previously been used as a tracer in process studies in the Darling Range (Stokes & Loh, 1982; Turner et al., 1987a), with Turner, Macpherson, and Stokes (1987) noting good concurrence between chloride and isotopic approaches. TDS is less commonly used as a tracer, however, sodium chloride dominates the solute composition of Darling Range soils, accounting for approximately 93% by weight of solutes, and chloride accounting for approximately 95% of anions (Johnston, 1987b; Johnston, Williamson, & Trotter, 1982). This reflects the marine aerosol origin of the soil salts (Hingston & Gailitis, 1976; Mazor & George, 1992). Therefore, it is reasonable to assume a strong correlation between chloride and TDS signatures in groundwater and streamflow in this region.

We adopted a two-component mixing model for the chemical hydrograph separation step, composed of a groundwater end-member and the second end-member representing all other sources including shallow throughflow and saturated overland flow (hereafter termed “shallow sources”). Annual flow-weighted mean stream salinities were assumed to be linear combinations of these two sources. Since the success of the approach relies on adequate differentiation of source waters and quantification of end-member concentrations (Cook, 2013), the three “test” catchments were selected primarily on their generally elevated groundwater salinities and large differences between the two sources (Table 2). Annual flow-weighted mean stream salinities can bias estimates of the contribution of groundwater where significant evaporative concentration of salts occurs. In Lemon catchment where rainfall exceeds evaporation for only 4 months of the year (Ruprecht & Schofield, 1991b), we found that mean flow-weighted salinities for the main winter flow period (May–October: data not shown) were indeed lower than the reported full-year values but that the uncertainty introduced was well within the variability in groundwater salinities across the catchment. Similar examination of the other two “test” catchments found no evidence for significant evaporative concentration, therefore we did not consider the issue further. Input data shown in Table 2 were collated from published values, as follows. In Lemon catchment, the groundwater end-member was estimated as the mean of multiple conductivity measurements of six bores sampling the permanent groundwater system reported in Silberstein et al. (2003), avoiding shallow bores also reported in that study. The end-member for shallow sources was assumed to equal the mean annual flow-weighted stream chloride for the 3 years prior to treatment reported in Ruprecht and Schofield (1991b). In these years, groundwater was more than 15 m below the stream channel and all flow was generated from shallow sources (Ruprecht & Schofield, 1991b). In Wights catchment, the groundwater end-member was assumed to equal the mean chloride concentration of streamflow during the summer drought when streamflow primarily comprises groundwater discharge, as was done by Williamson et al. (1987). The end-member for shallow sources of streamflow in Wights was assumed to equal the mean annual stream chloride concentration in 1974. In this year, the groundwater discharge area in the catchment was estimated to be only 0.5% of the catchment area (Williamson et al., 1987) and hence the groundwater contribution would have been minimal (see Kinal & Stoneman, 2012). In Yarragil 4X, the groundwater end-member was estimated as the mean TDS of seven deep (mean piezometer depth 26.2 m) monitoring bores in the catchment (Kinal & Stoneman, 2012), while the end-member for shallow sources was assumed to equal the mean annual stream TDS for years from 1999 through to 2013 (excluding 2001) when stream salinities were relatively constant and groundwater connection was minimal (Kinal & Stoneman, 2012).

Annual total streamflow data for Lemon catchment were sourced from the Western Australia Department of Water and Environmental Regulation database (www.wir.water.wa.gov.au/) (Station 612009). Annual flow-weighted mean stream salinity data for Lemon, calculated from continuous electrical conductivity measurements, were drawn from Ruprecht and Schofield (1991b) and Silberstein et al. (2003). For Wights catchment, annual streamflow and mean annual stream chloride (based on daily sampling) up to 1983 were taken from Williamson et al. (1987), with data for additional years 1984 to 1987 sourced from the Western Australia Department of Water and Environmental Regulation database (Station 612010). Data for Yarragil 4X catchment were drawn from the study by Kinal and Stoneman (2012), with data for three extra years, 1975, 2012 and 2013 sourced from more recently available records. Flow-weighted annual stream salinity was estimated from periodic grab samples up to 1990, weighted by flow rate at the time of sampling, and from continuously measured conductivity from 1991 to 2013. Annual catchment streamflow and rainfall data for the four “validation” catchments were drawn from the studies reported by Grigg (2017) and Grigg and Hughes (2018).

2.4 | Estimation of groundwater discharge area

Estimates of the groundwater discharge area in each year of record for the three “test” catchments were determined as follows. For Lemon and Wights catchments, previously published estimates were available (Bari, Smettem, & Sivapalan, 2005; Ruprecht & Schofield, 1989; Silberstein et al., 2003). For Yarragil 4X, groundwater discharge areas were estimated from bore dip readings following the method used by Grigg (2017), as follows. Mean annual depths to groundwater for each of seven deep bores in the catchment (Kinal & Stoneman, 2012) were regressed for each year of record against UPNESS, a topographic index variable within the model FLAG that has been used to predict water accumulation in the landscape (Summerell, Dowling, Wild, & Beale, 2004). The index is calculated as the set of 25 m grid cells above any given point in the grid that is connected by a monotonic continuous uphill path (Roberts, Dowling, & Walker, 1997). A quadratic regression model of the form $y = a - bx - cx^2$ was fitted to the set of seven average annual bore readings for each year, with all correlation coefficients >.98. There were insufficient bore readings in the years 1992–1994 and 1997–1999 to calculate average annual values and these years were omitted from the analysis. A grid of estimated mean annual depth to groundwater was then generated, from which maps of annual depth to groundwater were derived using kriging within the mapping software Surfer 8.0©. The extent of the groundwater discharge area was delineated by areas of the valley floor where the mean annual groundwater level was within 2 m of the topographic surface, following Grigg (2017).

TABLE 3 Measured annual rainfall, streamflow and mean stream salinity (TDS or Cl-) for Lemon and Wights catchments, with estimates of the proportional contribution to annual flow from groundwater (Q*d*) and from shallow sources (Q*s*)

Year	Rainfall (mm)	Streamflow (mm)	TDS/Cl- (mg/L)	Q*d* (mm)	Q*d* (%)	Q*s* (mm)	Discharge area (%)
Lemon							
1974	976	48.5	28	0.0	0.0	48.5	0
1975	680	4.7	36	0.02	0.3	4.7	0
1976	659	0.7	22	0.0	0.0	0.7	0
1977	631	7.1	37	0.03	0.4	7.1	0
1978	788	25.2	34	0.06	0.2	25.1	0
1979	547	3.5	37	0.01	0.4	3.5	0
1980	731	13.9	35	0.04	0.3	13.8	0
1981	696	28.6	36	0.09	0.3	28.5	0
1982	740	29.0	42	0.2	0.6	28.8	0
1983	834	57.4	33	0.1	0.2	57.3	0
1984	670	25.1	35	0.1	0.3	25.0	0
1985	669	31.2	29	0.0	0.0	31.2	0
1986	580	20.5	37	0.1	0.4	20.4	0
1987	516	8.8	60	0.1	1.4	8.7	0
1988	847	69.4	98	2.2	3.2	67.2	0.6
1989	716	54.4	286	6.5	11.8	48.0	2
1990	770	71.7	1,000	32.1	44.8	39.6	4.7
1991	804	98.1	1,250	55.2	56.3	42.9	5.7
1992	770	107.5	1,400	67.9	63.2	39.6	6.4
1993	726	116.7	1,600	84.5	72.4	32.2	7
1994	584	78.4	1,700	60.4	77.0	18.0	7.3
1995	736	129.2	1,650	96.5	74.7	32.6	7.6
1996	858	213.9	1,450	140.1	65.5	73.8	7.7
1997	476	96.2	2,050	89.6	93.2	6.6	8
1998	814	137.0	1,820	113.1	82.6	23.9	8
Wights							
1974	1,326	317.2	65	0.00	0.0	317.2	nd
1975	1,027	80.2	171	19.5	24.4	60.6	nd
1976	822	19.0	418	15.4	81.2	3.6	3.0
1977	877	163.6	158	35.0	21.4	128.6	3.5
1978	943	215.1	201	67.3	31.3	147.9	7.0
1979	781	125.9	340	79.6	63.2	46.3	9.3
1980	1,165	349.0	216	121.2	34.7	227.8	9.5
1981	1,347	423.3	207	138.2	32.6	285.1	14.0
1982	837	330.1	288	169.2	51.3	160.9	16.0
1983	1,147	557.4	205	179.4	32.2	378.0	14.2
1984	1,050	417.8	301	226.7	54.3	191.1	17.0
1985	1,105	415.5	295	219.7	52.9	195.8	18.0
1986	770	254.1	367	176.4	69.4	77.7	17.0
1987	790	229.9	355	153.3	66.7	76.6	16.5

Note: Estimated mean annual groundwater discharge area is also indicated (see Section 2).
Abbreviation: nd, data not available.

3 | RESULTS

3.1 | Groundwater contribution to streamflow

Estimates of Q*d* in the three "test" catchments are listed in Tables 3 and 4 and shown in Figure 2. In Lemon, groundwater contributions commenced around 1988 when rising groundwater levels first expressed at the surface as a result of the partial deforestation treatment (Silberstein et al., 2003), and appeared to attain an equilibrium of approximately 80% of annual flow in the final 4 years of record (Table 3, Figure 2a). Contributions were relatively higher in lower rainfall years (e.g., 1997) and relatively

TABLE 4 Measured annual rainfall, streamflow and mean stream TDS for Yarragil 4X, with estimates of the proportional contribution to annual flow from groundwater (Q*d*) and from shallow sources (Q*s*)

Year	Rainfall (mm)	Streamflow (mm)	TDS (mg/L)	Q*d* (mm)	Q*d* (%)	Q*s* (mm)	Discharge area (%)
1975	822	24.3	282	7.2	29.6	17.1	nd
1976	790	3.2	622	2.8	88.8	0.4	nd
1977	767	9.7	444	5.6	57.8	4.1	nd
1978	873	15.6	358	6.7	42.9	8.9	nd
1979	721	6.1	582	5.0	81.9	1.1	nd
1980	971	9.9	396	4.9	49.5	5.0	nd
1981	1,046	31.7	195	4.6	14.5	27.1	nd
1982	824	7.3	389	3.5	48.3	3.8	nd
1983	1,020	44.3	148	2.8	6.3	41.5	nd
1984	1,027	11.6	291	3.6	31.2	8.0	nd
1985	921	16.4	215	3.0	17.9	13.5	1.70
1986	762	2.3	439	1.3	57.0	1.0	1.33
1987	730	4.0	303	1.3	33.3	2.7	1.25
1988	1,184	39.1	196	5.7	14.6	33.4	1.21
1989	882	3.7	289	1.2	30.8	2.6	1.20
1990	937	10.4	nd	nd	nd	nd	0.99
1991	1,081	24.1	143	1.3	5.4	22.8	0.86
1992	1,060	32.2	131	1.1	3.3	31.1	nd
1993	813	3.7	370	1.7	45.0	2.1	nd
1994	708	4.5	244	1.0	23.0	3.5	nd
1995	950	11.9	159	1.0	8.2	11.0	0.81
1996	1,104	28.8	119	0.3	1.1	28.4	0.66
1997	729	2.4	177	0.3	11.4	2.1	nd
1998	884	4.5	145	0.3	5.7	4.3	nd
1999	972	13.2	131	0.4	3.3	12.8	nd
2000	991	17.3	98	0.0	0.0	17.3	0.62
2001	526	0.1	41	0.0	0.0	0.1	0.05
2002	928	5.0	126	0.12	2.5	4.8	0.04
2003	1,052	8.6	123	0.16	1.9	8.5	0.05
2004	884	6.4	109	0.0	0.0	6.4	0.04
2005	1,046	5.4	124	0.12	2.2	5.3	0.04
2006	639	0.3	91	0.0	0.0	0.3	0.02
2007	1,056	6.0	125	0.14	2.3	5.9	0
2008	927	2.8	106	0.0	0.0	2.8	0
2009	986	11.3	93	0.0	0.0	11.3	0
2010	468	0	nd	0.0	0.0	0.0	0
2011	933	1.1	114	0.0	0.3	1.1	0
2012	980	0.8	118	0.01	1.0	0.8	0
2013	970	4.9	99	0.0	0.0	4.9	0

Note: Estimated mean annual groundwater discharge area is also indicated (see Section 2).
Abbreviation: nd, data not available.

lower in wetter years (e.g., 1996). In Wights, the contributions from groundwater in the small number of years prior to clearing were around 20% (except for the dry year 1976 when it was more than 80%), increasing to approximately 50% after clearing (Table 3, Figure 2b). In Yarragil 4X, contributions ranged from nil to almost 90% of streamflow, with an overall declining trend for the period of records (Table 4; Figure 2c) consistent with declining groundwater levels in the catchment and disconnection from the valley floor after about 1999 (Kinal & Stoneman, 2012). For the period of groundwater connection, the contribution of groundwater to annual streamflow averaged approximately 30%. Contributions were relatively higher in lower rainfall years (e.g., 1976, 1979) and conversely relatively lower in years of above-average rainfall (e.g., 1983, 1988).

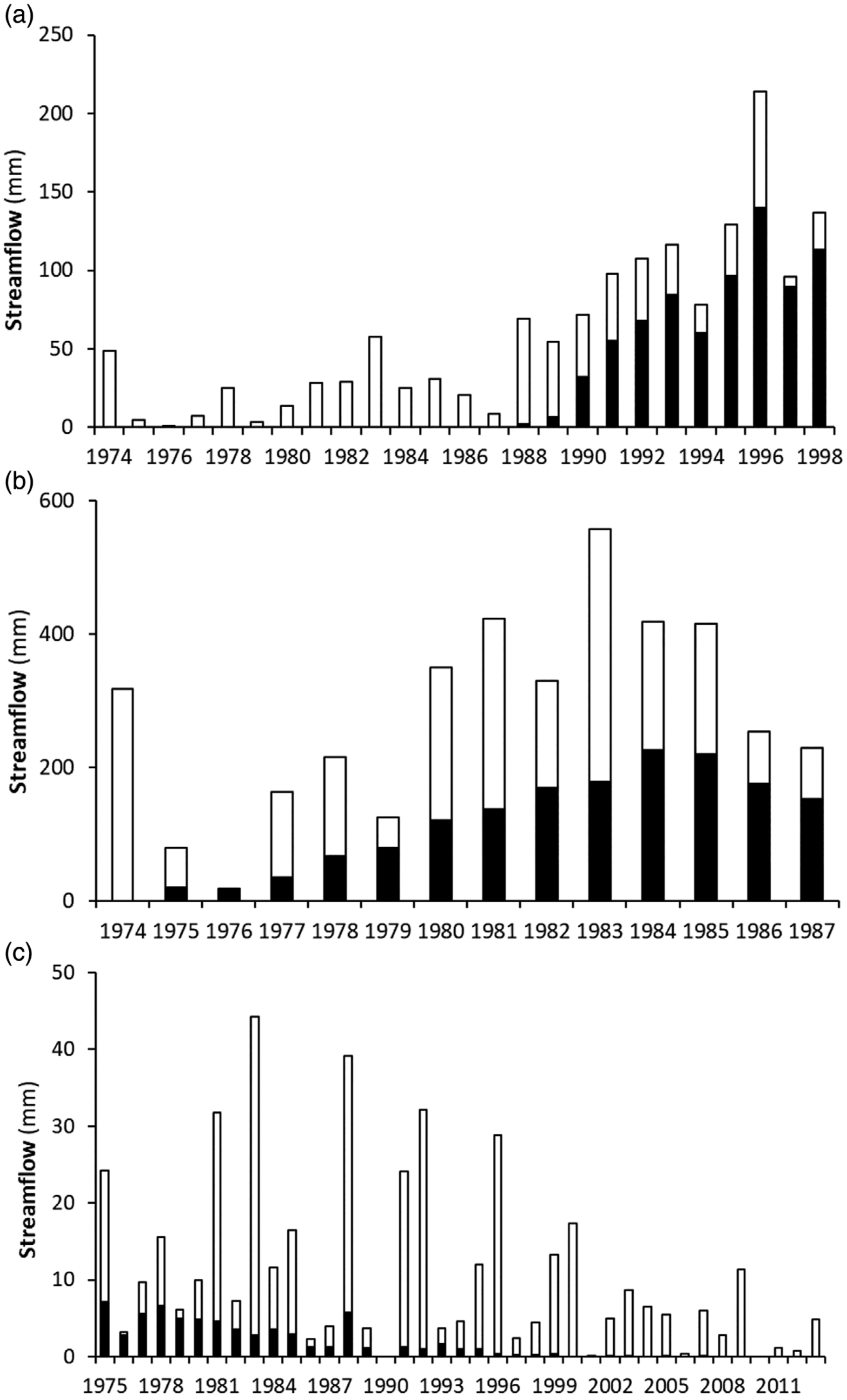

FIGURE 2 Measured annual streamflow (combined open and filled bars) and estimated contribution from groundwater (filled bar) for (a) Lemon, (b) Wights and (c) Yarragil 4X catchments. * indicates in (a) the approximate year of connection of rising groundwater in Lemon, and in (c) the approximate year of disconnection of declining groundwater in Yarragil 4X

Annual estimates of Q*d* across all three catchments were linearly related to the groundwater discharge area (Figure 3) according to the equation:

$$Qd = 11.2 * Ag \quad \left(R^2 = 0.95\right), \tag{2}$$

where A*g* is the groundwater discharge area expressed as a percentage of the total catchment area. The regression is constrained through the origin on the basis that there will be no groundwater contribution to streamflow where there is no contact between groundwater and the valley floor.

3.2 | Shallow source contributions to streamflow

Shallow sources of streamflow (Q*s*) were positively and linearly related to annual rainfall, described by an equation of the form:

$$Qs = \alpha P + \beta, \tag{3}$$

where *P* is annual rainfall and α and β are coefficients.

The magnitude of Q*s* for a given annual rainfall was strongly contingent upon the size of the groundwater discharge area (A*g*), demonstrated for two classes of groundwater discharge area in Figure 4. These classes were selected based on natural groupings within the range of observed groundwater discharge areas (Tables 3 and 4), displaying small standard errors (Table 5) and with minimal overlap. Correlation coefficients for each class were ≥.60 except where there was no discharge area (Table 5). The classes of discharge area divided to some extent along catchment lines (e.g., larger discharge areas occurred mostly in Wights, while the smaller discharge areas were mostly in Yarragil 4X; Tables 3 and 4) due to the status of the groundwater system at each location. However, linear regression coefficients α and β varied systematically with increasing A*g* (Table 5), therefore the size of the groundwater discharge area rather than catchment characteristics was considered to be the driving factor. Excluding cases where there was no groundwater connection

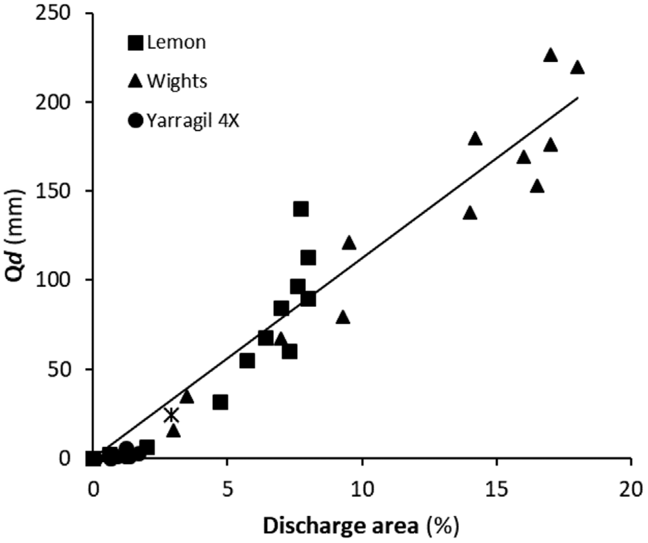

FIGURE 3 Estimated contribution of groundwater to annual streamflow (Q*d*) in the three "test" catchments in relation to groundwater discharge area (*n* = 59). The estimated position of Salmon catchment (*), for a single year 1985 was not used in the regression (see Section 4)

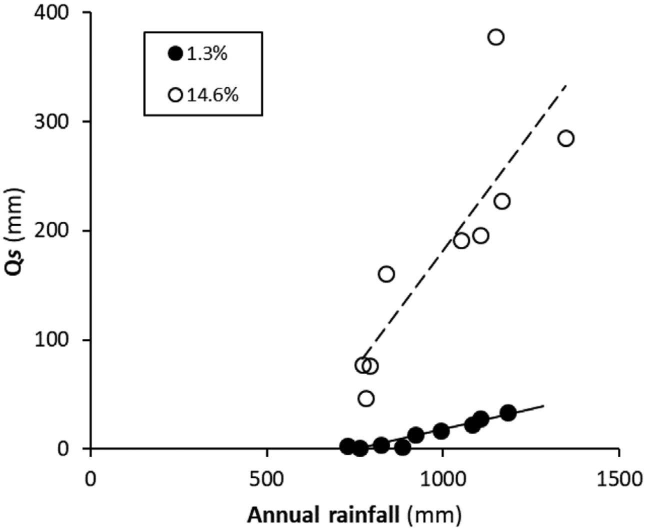

FIGURE 4 Estimated contribution to annual streamflow from shallow sources (Q*s*) in relation to annual rainfall, under two widely differing classes of groundwater discharge area (% of catchment) in the three "test" catchments. Details of the fitted regression lines are given in Table 5

TABLE 5 Regression statistics for the relationship between Q*s* and annual rainfall for five groundwater discharge area classes

Mean (±SE) discharge area (%)	Sample size (*n*)	Slope α	Intercept β	R^2	*P*	Predicted annual rainfall for zero flow (mm)
0 (0)	21	0.007	10	0.01	0.73	na
0.15 (0.04)	7	0.016	−9	0.67	0.024	556
1.3 (0.08)	9[a]	0.075	−56	0.93	<0.001	750
6.2 (0.16)	12	0.264	−147	0.60	<0.001	557
14.6 (0.36)	9	0.433	−250	0.72	<0.001	577

Note: Input data are contained in Tables 3 and 4.
Abbreviation: na, not applicable as regression not significant.
[a]Lemon catchment in 1988 appeared as an outlier and was not included.

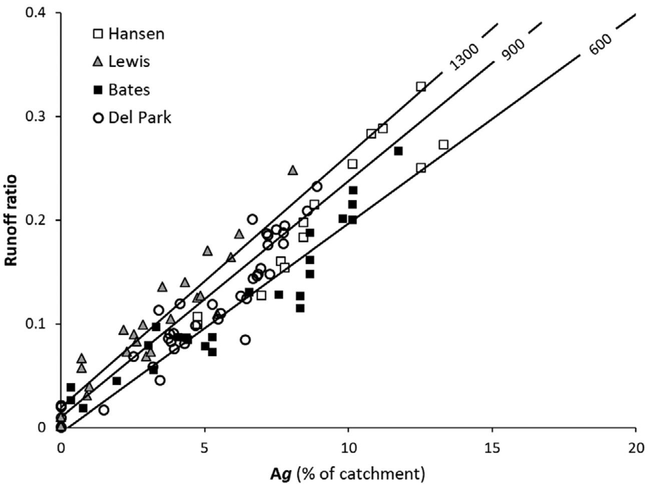

FIGURE 5 Predicted catchment annual rainfall runoff ratio in relation to groundwater discharge area (A*g*) for three selected annual rainfalls, using Equation (6). Data for four catchments not used in model development, reported by Grigg (2017) and Grigg and Hughes (2018), are also plotted for comparison

(i.e., A*g* = 0) on the basis the regression was non-significant, the relationship could be separately described by the equations:

$$\alpha = 0.028 * \mathrm{A}g + 0.04 \quad \left(R^2 = 0.97\right), \tag{4}$$

$$\beta = -15.9 * \mathrm{A}g - 27 \quad \left(R^2 = 0.97\right). \tag{5}$$

Equations (1) to (5) were rearranged and collapsed to estimate the proportion of a catchment with a groundwater discharge zone, given a knowledge of annual flow and rainfall:

$$\mathrm{A}g = \frac{\mathrm{Q}t - 0.04 * P + 27}{0.028 * P - 4.7}. \tag{6}$$

Equation (6) indicates a functional relationship between annual rainfall runoff ratio, catchment groundwater discharge area and annual rainfall, demonstrated in Figure 5.

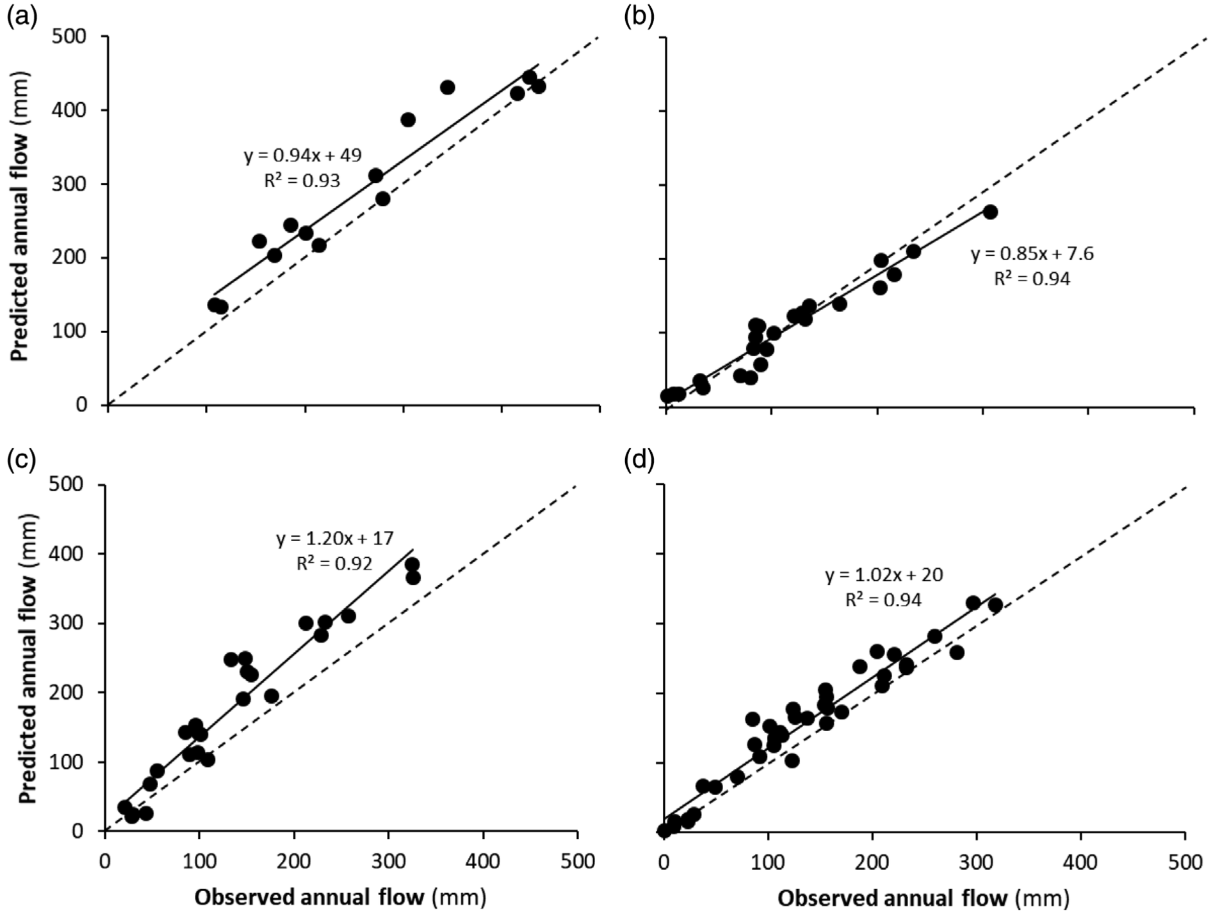

FIGURE 6 Comparison of observed and predicted annual streamflow for (a) Hansen, (b) Lewis, (c) Bates and (d) Del Park catchments. The dotted line is the 1:1 line

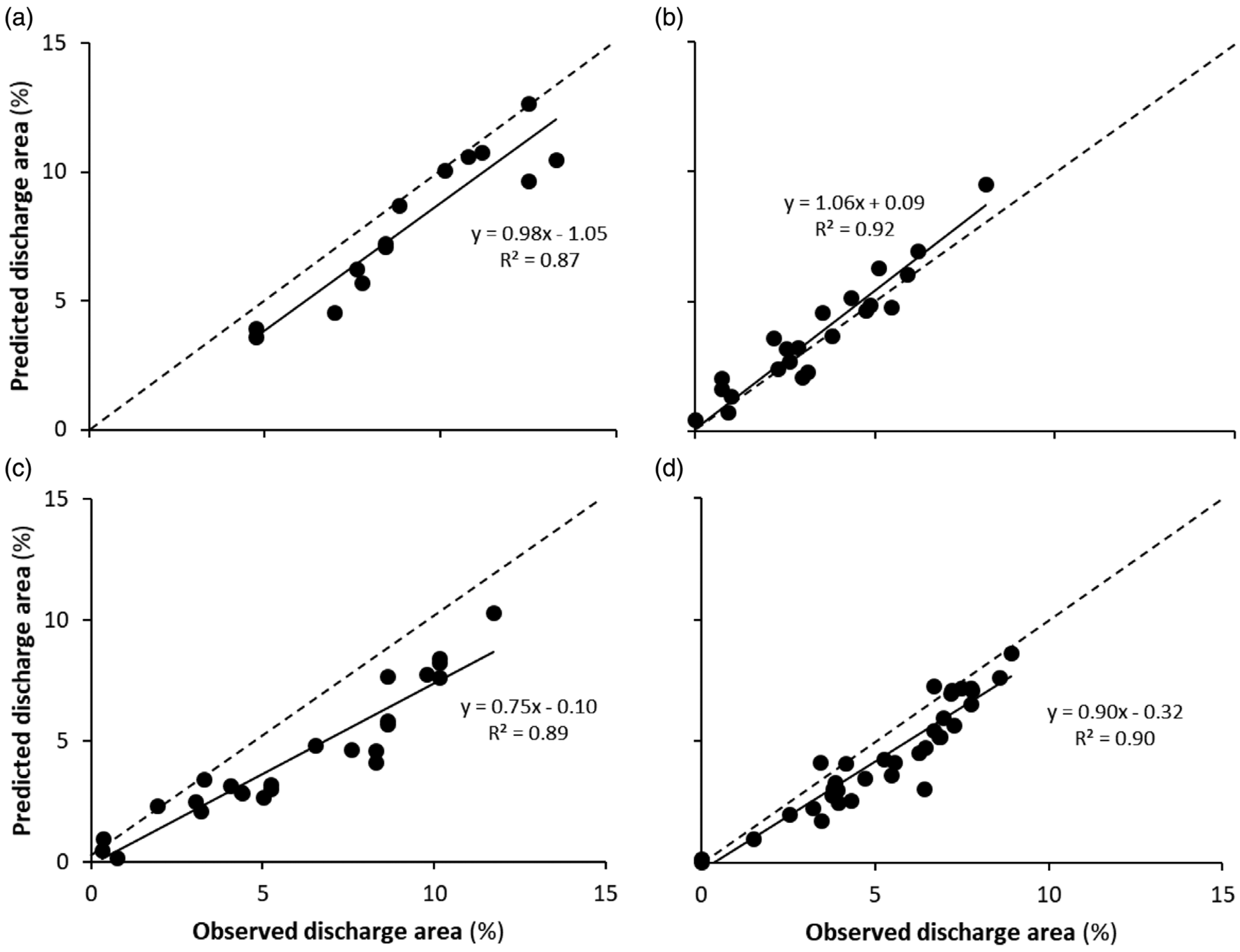

FIGURE 7 Comparison of observed and predicted groundwater discharge areas for (a) Hansen, (b) Lewis, (c) Bates and (d) Del Park catchments. The dotted line is the 1:1 line

Regardless of whether a groundwater discharge area was present in the catchment, a zero contribution from shallow sources was either predicted (Table 5) or observed (Tables 3 and 4) if annual rainfall was less than approximately 550 mm.

3.3 | Validation catchments

Predictions of annual flow using Equations (2) to (5) were very good for all four "validation" catchments, with correlation coefficients ≥.92 in all cases (Figure 6), although flows tended to be over-predicted in Hansen and Bates (Figure 6). Predictions of groundwater discharge area were also satisfactory (Figure 7) although with slightly lower correlation coefficients than for annual flow. Over-prediction of streamflow was associated with under-prediction of the groundwater discharge area in Hansen and Bates, which could arise if actual discharge areas in these catchments were smaller than those estimated by Grigg (2017).

Estimated contributions of groundwater to total annual flows in the "validation" catchments using Equations (3) to (5) are shown in Figure 8. The proportional contribution in the catchments, all located in the higher rainfall areas of the study area (Figure 1) where groundwater connection was historically strong, was typically in the range 30–40% during much of the available record. However, the contribution declined to below 20% in Bates and Lewis in the latter parts of the record. The contribution of groundwater rose to 50% or more of total flow in strong drought years 2001, 2006 and 2010. Conversely, higher rainfall years such as 1988, 1991 and 1992 show a relatively greater contribution from shallow sources.

4 | DISCUSSION

The current study has shown that the direct contribution of groundwater to streamflow in laterite catchments of the Darling Range in south-western Australia is far more variable across catchments and

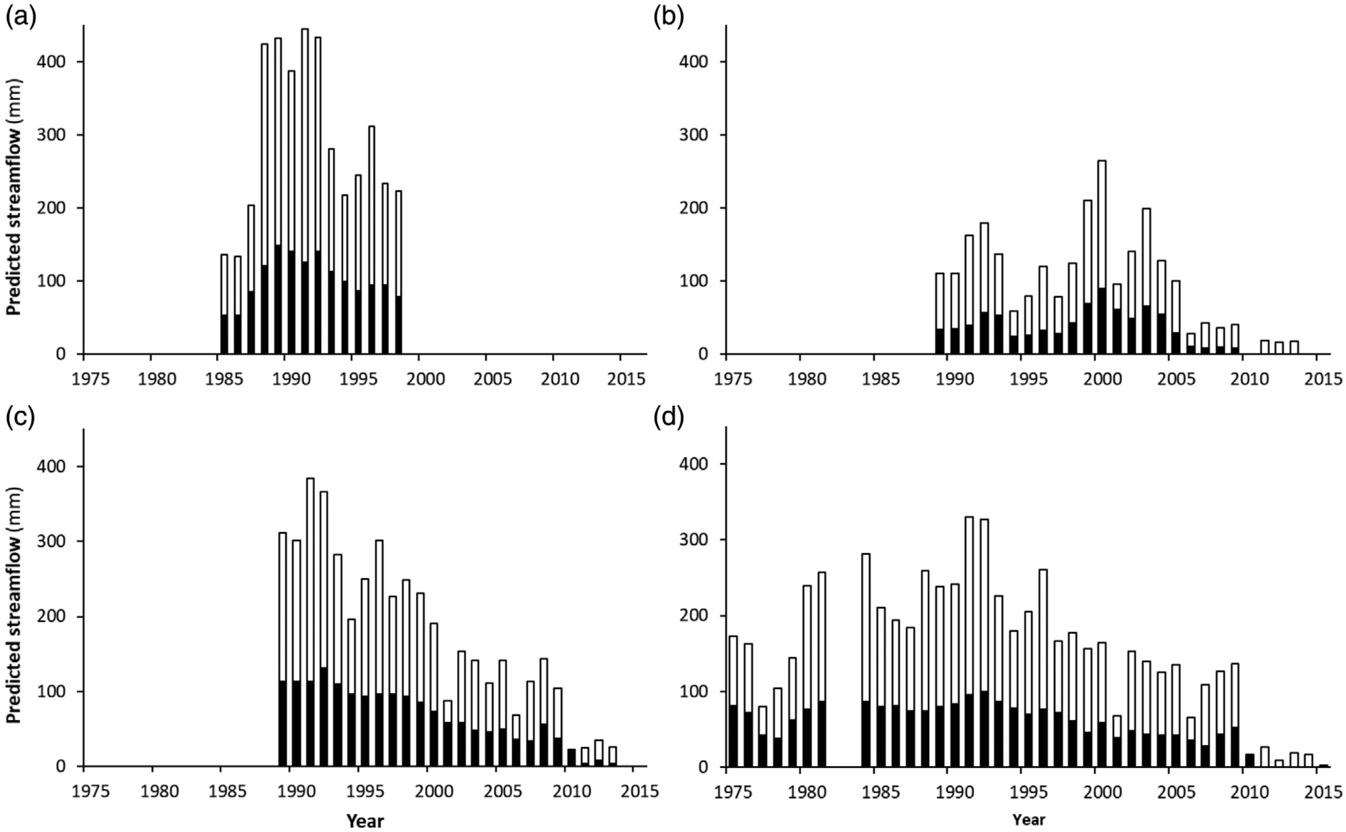

FIGURE 8 Estimated annual streamflow (combined bars) and contribution from groundwater (filled bars) for (a) Hansen, (b) Lewis, (c) Bates and (d) Del Park catchments. Flows could not be estimated for Del Park in 1982 to 1983 due to lack of groundwater data in those years

through time than has previously been acknowledged. In this study, estimates of the direct contribution of groundwater ranged from nil to more than 90% of annual streamflow. The range reported here encompasses the estimated contribution of less than 10% reported by Stokes and Loh (1982) in Salmon catchment but contradicts later authors who assumed that the minor contribution observed in Salmon catchment could be applied more generally to the Darling Range (Bari & Ruprecht, 2003; Ruprecht & Stoneman, 1993; Schofield et al., 1989). At timescales of several years to decades observed here, the contribution of groundwater varied with the degree of connection of the permanent groundwater system, which in turn is associated with the status of catchment storage within the deeply weathered regolith (Grigg & Hughes, 2018). Thus, declining groundwater contributions in Yarragil 4X, Bates and Del Park are consistent with declines in groundwater levels (Grigg, 2017; Grigg & Hughes, 2018; Kinal & Stoneman, 2012) driven largely by declines in regional rainfall (Hughes et al., 2012; Petrone, Hughes, Van Neil, & Silberstein, 2010). Conversely, increases in contributions from groundwater were indicated in Hansen, Lemon and Wights catchments where increases in groundwater storage and expansion of a saturated discharge area occurred as a consequence of increased recharge resulting from reductions in catchment vegetation cover (Grigg, 2017; Ruprecht et al., 1991; Silberstein et al., 2003).

While the relative contribution of groundwater to streamflow was variable, annual groundwater discharge for each percentage area of a catchment occupied by the groundwater discharge zone was remarkably uniform across the three “test” catchments (Equation (2), Figure 3). The estimated position of Salmon catchment in 1985 (Figure 3), using a simple average of the estimated contribution for four storms reported by Turner et al. (1987b) and an estimate of discharge area from Equation (6), sits comfortably within and extends the relationship to a fourth catchment, and clearly sets the context for the earlier study. Expansion and contraction of a groundwater discharge area takes place along the stream channel from the catchment outlet (e.g., Ruprecht & Schofield, 1989) and is related linearly with overall catchment storage (Grigg & Hughes, 2018). Thus, changes in catchment storage will influence the length of channel directly discharging groundwater in a similarly linear way, with groundwater gradients between the riparian zone and adjacent hillslopes providing the driving mechanism (Ocampo et al., 2006).

The contribution to streamflow from shallow sources was more variable than groundwater from year to year (Figures 2 and 8) and was primarily dependent on the annual rainfall amount. However, this study has highlighted the indirect role of groundwater in “amplifying” other streamflow-generating processes (Figure 5) including shallow throughflow and surface runoff from saturated areas, previously described in detail by Kinal and Stoneman (2012). A larger groundwater discharge area not only provides more channel length upstream of the catchment outlet for direct discharge, but also a larger area of saturation for perching to occur, in turn facilitating shallow throughflow and saturation excess runoff. The findings support the conceptual model proposed by Stokes and Loh (1982) of a seasonal aquifer perched on groundwater in the valley floor and extending upslope and away from the stream channel during the winter wet season, following the variable source area concept (Walter et al., 2000). Interestingly, Schofield et al. (1989) dismissed variable source areas as a significant streamflow generating mechanism for streams in the Darling Range, based on the small saturated area within Salmon catchment at the time of the study reported by Stokes and Loh (1982).

By supporting the variable source area concept, and highlighting a far more significant contribution from direct discharge of groundwater, this study calls into question shallow lateral downslope throughflow as a dominant process for streamflow generation in the Darling Range. This is consistent with the study by Grigg (2017) who found that removal of the upper ~4 m of the regolith across more than half of an experimental catchment arising from bauxite mining did not fundamentally alter streamflow generating processes. Further, Grigg and Hughes (2018) showed that, for Del Park catchment, seasonal streamflow was strongly correlated with periods of contact between groundwater and the stream channel: if downslope shallow throughflow was important, then streamflow would have been expected during the winter rainfall season irrespective of the status of deep groundwater. Instead, the current study suggests that groundwater recharge may be the more important hydrological pathway in this environment, facilitated by root channels and discontinuities in the regolith that have been observed to act as preferential flowpaths (Dell et al., 1983; Johnston, 1987a). Cuthbert and Tindimugaya (2010) have reported the important role that preferential flowpaths can play in laterite hydrology in Africa, but their significance for streamflow generation in the Darling Range appears not to have been fully appreciated. Cuthbert and Tindimugaya (2010) pointed to the implications of underestimating recharge in predictive models, especially where climate change impacts are evident or possible, and there are parallels in this study. In particular, model results may be misleading if insufficient weight is given to the dynamics of the permanent groundwater system (Grigg & Hughes, 2018; Hughes & Vaze, 2015) and, for process-based models, the pathways leading to groundwater recharge.

5 | CONCLUSION

The present study has indicated a more variable, and overall a more significant, contribution by groundwater to streamflow in laterite catchments of the Darling Range in south-western Australia than has been previously acknowledged. In this study, the proportion of total flow contributed by groundwater was found to be dependent on (a) the degree of connection of groundwater to the valley floor, as enumerated by the size of the groundwater discharge area, and (b) the amount of rainfall within any given year. The second factor affects the generation of shallow groundwater sources of streamflow which is "amplified" by the deep groundwater discharge area, consistent with the variable source area concept. The conceptualization of downslope shallow throughflow as the dominant process for streamflow generation in laterite catchments of the Darling Range is not supported by this study. Instead, processes leading to groundwater recharge are more important for streamflow generation. The results are useful for understanding hydrological processes in laterite landscapes worldwide.

ACKNOWLEDGEMENTS

This study was supported by Alcoa of Australia and the Western Australia Department of Biodiversity, Conservation and Attractions.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Grigg AH, Kinal J. On the contribution of groundwater to streamflow in laterite catchments of the Darling Range, south-western Australia. *Hydrological Processes*. 2020;34:5070–5084. https://doi.org/10.1002/hyp.13928