Government of **Western Australia**
Department of **Water**

Water indicators for forest management

Assessment of forest management effects on streamflow and quality for the Forest Management Plan 2004–13 audit

Department of Water

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Department of Water
168 St Georges Terrace
Perth Western Australia 6000
Telephone +61 8 6364 7600
Facsimile +61 8 6364 7601

National Relay Service 13 36 77
www.water.wa.gov.au

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For more information about this report, contact Environmental Officer, Keren Raiter on (08) 6364 7867.

Cover photograph: A forested stream, affected by a long history of land use and climate changes. Photo: Keren G Raiter

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Summary

In the face of a drying climate and streamflow declines in south-west Western Australia, maintaining streams in forested areas has become a critical management challenge. Changes in runoff from multiple-use state forests, conservation reserves, and other lands vested in the Conservation Commission and managed by Department of Parks and Wildlife have implications for public water supplies, stream ecosystems, and the biodiversity that they support. Salinity has receded somewhat as a major issue of concern in these catchments, although ongoing monitoring of trends in this fundamental aspect of water quality is both important and enlightening – helping to reveal some significant shifts in catchment hydrology.

This technical report details an assessment of two key performance indicators (KPIs) submitted to the Conservation Commission and documented in their *Forest Management Plan 2004-13 End-of-Term Audit of performance report* (2012). This assessment was required by the Forest Management Plan 2004–2013 (FMP) and was undertaken jointly by the Department of Water and the Department of Parks and Wildlife, in consultation with Water Corporation and CSIRO. The performance indicators assessed are KPI 19: Stream salinity and KPI 22: Water Production. They relate to maintaining streamflow and low salinity in forested catchments managed under the FMP. This report is intended to serve as a reference for future Forest Management Plans.

Streamflow trends in 32 forested catchments across the south-west were assessed. In all but one (which was recently mined), streamflows were 12–50% lower in the period of the FMP analysed (2004–09) compared to the 1975–2003 average. The decline varied across the study area and was greatest in the northern jarrah forest. In addition, some streams shifted from perennial to intermittent flow regimes. Climate variability was found to be the dominant driver of streamflow variability and decline. In some catchments (particularly in the northern jarrah forest, where the metropolitan water supply and irrigation catchments are located) changes in forest structure have exacerbated streamflow declines, due to the higher water use of regrowth forests. This trend was strongest in forests regrowing after heavy timber harvesting in the early 20th century and rehabilitation after mining. Modern silvicultural practices, which often form a mosaic across catchments and tend to be lower in intensity, did not result in large, ongoing responses in catchment runoff.

The restricted availability of quality, long-term records for fully forested catchments limited our assessment of salinity trends, so some catchments with small amounts of clearing were analysed alongside fully forested catchments. We observed mixed salinity trends, with approximately half of the catchments studied showing higher salinities and half showing lower salinities, although the extent of change was often very small and comparable with the measurement error margin. The majority of catchments remain well within the fresh range. Salinity is not perceived to be a major cause for concern in forested catchments within the current context of a drying climate as declining groundwater levels caused by lower rainfall are associated with lower risks of saline groundwater discharge.

Groundwater, air temperature, evaporation and rainfall intensity trends were also analysed to understand their potential contribution to the observed declines. Silviculture for water and ecosystem health is approved but yet unfunded in the Forest Management Plan 2014–23.

1 Setting the scene

This report assesses the effects of forest management on streamflow and stream salinity in the south-west of Western Australia, using selected forested catchments with a variety of forest management histories. It also serves as a more detailed, technical foundation for the findings presented for key performance indicators 19 (annual flow-weighted mean salinity and the trend for streams in fully forested catchments) and 22 (water production) in the Forest Management Plan 2004–13 End of Term Audit (Conservation Commission 2012).

1.1 Forest management in south-west WA

Forest management planning

Forest ecosystems cover a large part of the south-west of Western Australia, and the Department of Parks and Wildlife currently manages almost 25 000 km^2 of these as state forest, timber reserves, national parks, and other reserves under the Forest Management Plan 2004–13 (FMP). The plan prescribes management for these areas based on multiple objectives that include ecosystem health, timber yield, soil, water, carbon cycling, socio-economic factors, and heritage. The area covered by the FMP is shown in Figure 1.

Key Performance Indicators of the 2004-13 Forest Management Plan

An overall objective of the Forest Management Plan 2004–2013 (FMP, Conservation Commission of Western Australia 2004) is 'to seek and protect soil and water resources on land to which the plan applies'. Under this, the forest management plan includes two key performance indicators (KPIs) that relate to water:

KPI 19: Salinity
KPI 22: Water production

The performance target of the former is for flow-weighted annual stream salinity trends in fully forested catchments to be neutral. The target of the latter is to maintain streamflow relative to rainfall.

The FMP was replaced in January 2014 by the Forest Management Plan 2014–2023 (Conservation Commission of Western Australia 2013), which took into account the performance of the FMP in fulfilling its objectives and KPIs. The Conservation Commission, in its *Mid-term audit of performance of the FMP* (2008) recommended that 'the government as a whole should address the question of whether it is reasonable to expect that forests can or should be managed to maintain or enhance water supply in the current drying climate'. More recently the panel reviewing silviculture in the south-west forests expressed the view that 'forest management to achieve a better water balance in a drying climate is a most critical issue facing forest managers now and in the future', and that a failure to address the acute water stress currently being experienced in parts of the south-west forests 'will likely compromise efforts to achieve ecologically sustainable forest management' (Burrows et al. 2011).

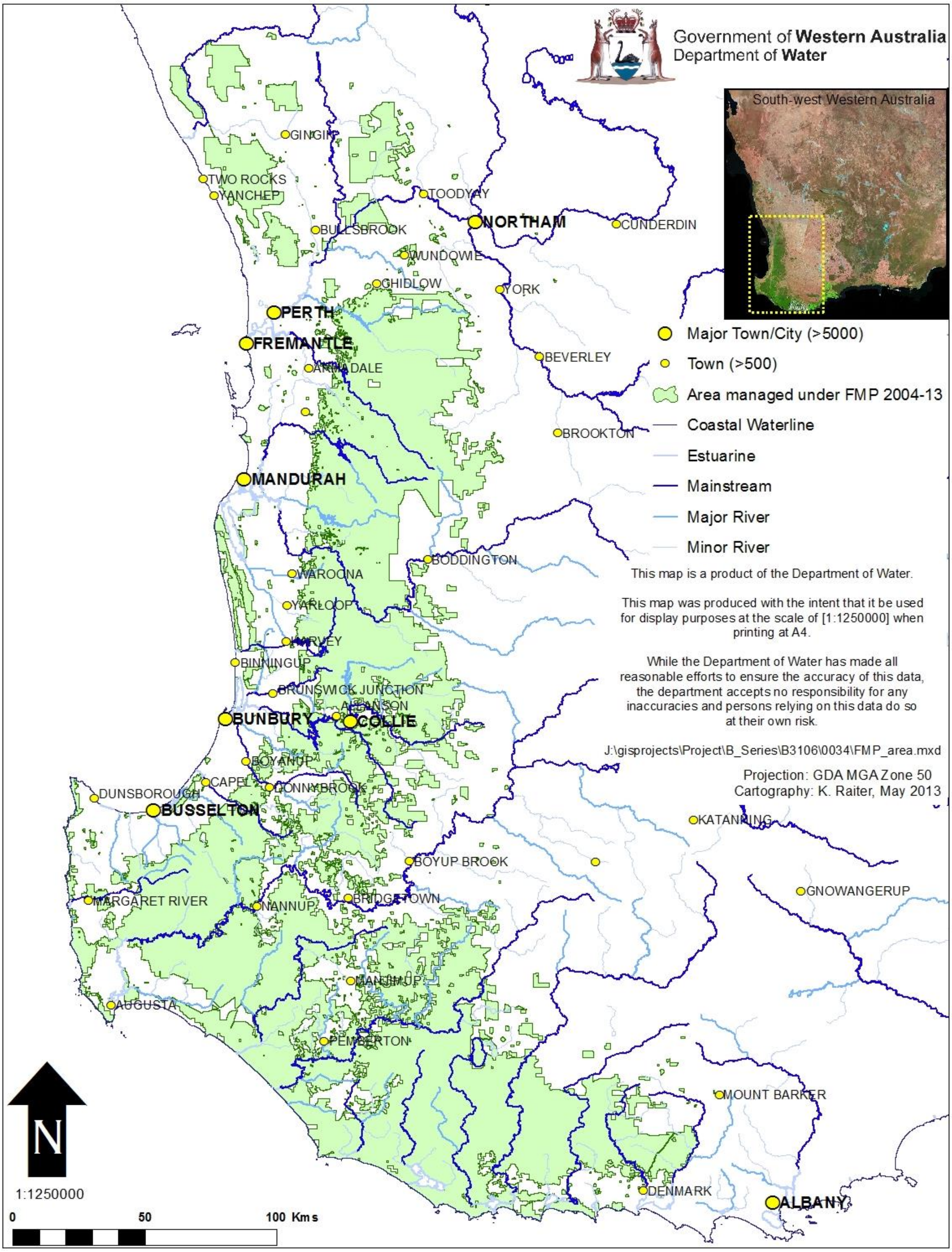


Figure 1 Area covered by the Forest Management Plan 2004–13

1.2 South-west streams overview

Climate and hydrology

The south-west region experiences a temperate climate with cool to cold wet winters and warm to hot dry summers (Stern et al. 2000). In general, mean annual rainfall decreases and mean annual evaporation increases inland and to the north.

Stream gauging with associated continuous rainfall measurements to better understand streamflow generation processes and water resources availability began in this region in about 1970. Several cooperative research programs also established a number of small experimental gauged catchments to assess the impact of clearing, forest treatments and bauxite mining on streamflow quantity and quality. Such monitoring, and the associated modelling that helps to elucidate insights into hydrologic processes and trends from the observed data, have enabled a sound understanding of the hydrology of the Northern Jarrah Forest.

A sharp decrease in winter rainfall occurred in the mid 1970s in the south-west of Western Australia. The Indian Ocean Climate Initiative (IOCI) has described it not as a gradual decline but more of a switching into an alternative rainfall regime. The rainfall decrease was only observed in early winter (May–July). Late winter rainfall has actually increased, although by a smaller amount, since 1975 (IOCI 2002).

Nicholls et al. (1999) concluded that the decline in rainfall has been accompanied by a decline in the volume of rain falling in high intensity rainfall events.

A step-decline in streamflow accompanied the drop in rainfall, with streamflow decreasing by approximately 50% between the periods 1911–74, and 1975–2005 (Bates et al. 2008).

The period since 2001 has been even drier than the preceding years, although statistical tests have failed to identify a statistically significant declining trend (Department of Water 2009; Petrone et al. 2010). A longer period is required to ascertain whether it is due to climate variability alone or represents a climate shift.

Evaporative demand, measured with evaporation pans, has been decreasing in the south-west. This can be explained by decreasing net radiation, wind speed, and vapour pressure despite rising temperatures (Donohue et al. 2010).

Department of Water (2009) surveyed a selection of south-west Western Australian streams and observed a decrease in streamflow in the majority, together with a shift in the peak flow month, with peak flows occurring about one month later in the '1997 to current' period compared with the 1975–96 period. It did not find a consistent regional step-decline further to that observed in 1975, although some streams displayed this trend (Department of Water 2009).

Petrone et al. (2010) and Silberstein et al. (2011) analysed gauged records and reported dramatic streamflow declines in their study catchments in the Darling Range: streamflows down by more than 50% and changes in flow characteristics. These changes included switches from perennial to intermittent flow regimes in 7 of the 18 streams studied and declines in flow durations. Changed rainfall-runoff relationships and ongoing non-stationarity[1] in runoff coefficients – the proportion of rainfall that becomes runoff – have also been observed. Historical runoff coefficients for the pre-1975 period of approximately 9–12% in the northern jarrah forest have recently tended to a new equilibrium of less than 3% where groundwater has permanently disconnected from stream zones (Stoneman & Schofield 1989; Silberstein et al. 2011; Hughes et al. 2012).

Petrone et al. (2010) and Hughes et al. (2012) concluded that the declines occurred as a response to below-average rainfall years creating deficits in soil moisture storage carried into future years, leading to smaller runoff coefficients and the development of a new hydrologic regime.

Hughes et al. (2012) examined the hydrological processes explaining non-stationarity in the relationship between rainfall, groundwater storage and runoff in 9 catchments within the Darling Range. They found a strong relationship between rainfall, changes in catchment storage, and runoff coefficients. An understanding of groundwater trends in other parts of the study area is limited by a scarcity of groundwater monitoring bores.

The South-West Sustainable Yields Project predicts a hotter, drier climate for the south-west of Western Australia with decreases in annual rainfall and runoff by an average of 8 and 25% respectively, a loss of perennial streams and an increase in runoff variability relative to 1975–2007 by 2030 (CSIRO 2009). Only three of the catchments assessed here lie within the area for which groundwater was assessed as part of the Sustainable Yields project (Whicher Range, Crouch Road, and Staircase Road). For these, many groundwater-dependent ecosystems are also predicted to experience severe stress (CSIRO 2009).

Extreme drought and heat conditions also precipitated a sudden forest canopy collapse in distinct patches within the northern jarrah forest over the 2010–11 summer (Evans & Lyons 2013; Matusick et al. 2013). Such collapses may become more frequent and/or widespread under projected future climates (Batini 2012). Decreased precipitation, coupled with raised temperatures, is also likely to severely affect flora and fauna, although many knowledge gaps regarding likely impacts, thresholds, and adaptation capacities remain (Dundas et al. 2014).

A brief physiography

The south-west of Western Australia has a complex geology which greatly affects the topography, soils, and consequently the hydrology of the area. The Darling Plateau, part of the Archaean Yilgarn Craton, is the geological centrepiece of the region. Coastal plains fringe the Darling Plateau to the west and south, and the Blackwood Plateau, of uplifted sedimentary rocks, lies to the south-west (CSIRO 2009).

Most rivers in the area arise on the Darling Plateau from major valleys, lateritic uplands and broad shallow valleys, and drain towards the coast via flatter coastal plains (Mauger et al. 1998; CSIRO 2009). Low hills and gently undulating uplands make up the Blackwood Plateau (CSIRO 2009).

[1] Non-stationarity refers to changes in the parameters of a system over time, such as the proportion of rainfall that recharges the groundwater or becomes flow.

The Yilgarn Craton has been remarkably stable for many millions of years, is deeply weathered, with a lateritic soil profile that is particularly deep (tens of metres) in the western part of the Darling Plateau, and provides a large soil salt and water store (CSIRO 2009). Above the igneous bedrock of granites and gneisses with doleritic intrusions lies a layer of kaolinitic sandy clay weathered from the bedrock. This acts as the lateral conducting layer for deep groundwater (Peck et al. 1980; Mauger et al. 1998). This is overlain by a thick, clayey pallid zone, a mottled zone, and a lateritic duricrust beneath the soil A horizon. Root channels penetrate the soil profile and are important in groundwater recharge.

Soils on the Darling Plateau vary significantly and include red, yellow, and brown soils; loams, gravels, sands and clays, interspersed by lateritic duricrust; and igneous rocky outcrops (Mauger et al. 1998). On the Blackwood Plateau, soils are alluvial and sandy with clayey material interspersed.

The CSIRO report (2009) describes the south-west’s physiography in greater detail.

Mechanisms of stream generation and decline

The disproportionate decline in streamflow relative to rainfall has been described as perplexing (Kinal & Stoneman 2012) and has prompted a re-evaluation of the mechanisms of streamflow generation in forested catchments, particularly regarding the role of groundwater in this process.

Catchment water balance

Evapotranspiration dominates the water balance in forested catchments in the south-west of Western Australia, due to the presence of a large soil water store that is available year-round to deep-rooted vegetation in deeply weathered lateritic profiles. Streamflow responses to rainfall are thus sluggish, and runoff is low (Mauger et al. 1998; Ruprecht & Pearcey 1999; Bari & Ruprecht 2003; Croton & Reed 2007). Silberstein et al. (2011) found that total evapotranspiration in 31 Mile Brook in the northern jarrah forest over the last seven years has approximately matched rainfall. Some streamflow is still generated during the wet winter months even while the soil moisture store is depleted by the perennial vegetation over the full course of the year. Hysteresis occurs in most catchments, with the streamflows of any given year influenced not only by the current year’s rainfall but also by the rainfall and subsequent streamflows of previous years (Rodgers & Ruprecht 1999; Petrone et al. 2010).

Evapotranspiration includes rainfall intercepted by vegetation surfaces. Where there is sufficient time and evaporative demand from the atmosphere, this water will evaporate and be lost from the catchment without reaching the ground. Interception in the jarrah forest may range from less than 10% to approximately 25% of rainfall (Silberstein et al. 2011); corresponding figures are not known for karri and wandoo and other vegetation types covered in this report.

Streamflow generation

Shallow throughflow, also called subsurface flow or interflow, was once considered the dominant source of streamflow on the Darling Plateau, occurring through the formation of a temporary perched aquifer above the relatively impermeable duricrust or clay horizon in winter (Ruprecht & Pearcey 1999). Correspondingly, groundwater discharge occurs primarily on the western margins of the catchments and was generally considered a relatively minor component of surface water yields in forested catchments (Mauger et al. 1998; Ruprecht & Pearcey 1999). Recent studies have challenged this thesis. Hughes et al. (2012) and Kinal & Stoneman (2012) found that catchment storage has a dominant effect on streamflows and concluded that this indicates that shallow perched layers are probably not dominant since they would not be affected by long-term changes in catchment water balance.

Where groundwater and surface water systems are connected, groundwater levels are strongly correlated with runoff coefficients and groundwater plays a dominant role in streamflow generation, albeit indirectly (Hughes et al. 2012). Where connected to the stream zone, groundwater amplifies saturated overland flow and throughflow processes, as well as directly contributing to streamflow via groundwater discharge (Hughes et al. 2012; Kinal & Stoneman 2012). Where the two systems are disconnected, runoff is significantly diminished, generally not exceeding 3% of annual rainfall (Hughes et al. 2012).

Saturation excess, also called direct runoff, dominates instantaneous flood peaks resulting from intense rain falling on saturated land. Saturation excess occurs more regularly where the groundwater is at or near ground level. Some catchment factors influencing flow generation in the south-west include longest flow path length, average slope, easting, northing, and catchment size (Silberstein et al. 2011).

Groundwater declines and streamflow impacts

Groundwater levels have generally fallen since 1975, particularly in the last decade, due to an emerging deficit between rainfall (which has declined) and evapotranspiration (which has not decreased to the same extent and, in some cases, has increased) (Croton & Reed 2007; Reed 2008; CSIRO 2009; Hughes et al. 2012; Croton et al 2013). There is a strong relationship between rainfall and changes in catchment groundwater storage, with groundwater acting as a catchment's 'memory' (Hughes et al. 2012). Where groundwater remains connected with the stream zone for at least part of the year, runoff coefficients reflect rainfall amounts from both current and recent years (Hughes et al. 2012). Silberstein et al. (2011) found that if annual rainfall in 31 Mile Brook catchment was less than a threshold value of 1000–1200 mm, the catchment's runoff coefficient in the following years declined further, primarily due to a fall in the riparian watertable.

This is in agreement with the findings of Mitchell et al. (2012) that a mixed species eucalypt forest shows relatively consistent rates of evapotranspiration despite years of low rainfall, and that this occurred at the expense of falling catchment storage, with little recovery following the drought period. In many areas in the northern part of the study area, evaporation has increased with vigorous growth and high leaf and sapwood areas in regrowth forests following timber harvesting and bauxite mining (Croton & Reed 2007; Macfarlane et al. 2010; Croton & Dalton 2011; Silberstein et al. 2011). Silberstein et al. (2011) suggest that, after rainfall, forest density is a major factor controlling the water balance and that approximately one third of the runoff decline in the 31 Mile Brook catchment is due to changes in forest structure since European colonisation. These trends have led to less groundwater recharge (less rain and a greater proportion of it used by vegetation) and, in some areas, greater net uptake of groundwater and/or soil moisture by deep-rooted vegetation.

The dominant role of groundwater levels in streamflow generation combined with their ongoing declines suggest that the disproportionate declines in streamflow relative to rainfall mostly reflect an aggregate loss of connectivity between groundwater and surface water systems (Kinal & Stoneman 2012).

Where groundwater levels decline so much that they disconnect from stream zones, streamflow may decrease in three ways: 1) throughflow, strongly influenced by groundwater and soil moisture levels, decreases 2) saturated areas, which would otherwise produce direct overland flow, contract and 3) groundwater no longer discharges into streams. In fact, some flow may actually be lost from the stream to the surrounding soil matrix (Reed 2008; Silberstein et al. 2011; Hughes et al. 2012).

Rainfall factors

Temporal patterns of rainfall, including intensity, duration of events and dry inter-periods, also influence the fate of rainfall within a catchment. The rate at which rain falls, the proportion intercepted by vegetative surfaces, and the potential for evaporation, soil infiltration, plant uptake, and groundwater recharge ultimately influence how much of it will become streamflow at each moment in time. Such instantaneous outcomes shape the water balance hourly, daily and monthly time scales, with ramifications at the annual time step and longer (Schofield 1984; Ruprecht & Pearcey 1999). Li et al. (2010) identified winter rainfall, total year rainfall, proportion of wet days, number and average length of dry events, average rainfall amount on consecutive rain days, and time of consecutive rain days as factors correlated with flow.

A number of studies have found that rainfall decreases over the last century were made up of decreases in the total numbers of rain days and high rainfall days, with the latter decline more marked than the former (Hennessey et al. 1999; Nicholls et al. 1999; Li et al. 2005; CSIRO 2009). However, these analyses have generally not included the recent decade, and trends in these indices have not always paralleled the trends in total rainfall, as noted by Nicholls et al. (1999).

Raiter (2012) assessed trends in rainfall intensity at both daily and hourly time intervals and found some contrasting results between the hourly and daily time steps. Hourly rainfall intensities were higher in the 2001–08 period than in the 1975–2008 period while there were fewer hours of rainfall on average indicating a trend toward more intense, shorter duration rain on the hourly scale. The daily timescale revealed a partially different trend: both rain days and daily rainfall intensity decreased in the recent period relative to the former (in agreement with Hennessey et al. 1999; Nicholls et al. 1999; Li et al. 2005; CSIRO 2009).

As noted earlier by Hennessey et al. (1999), trends in rain periodicity and intensity do not always mirror trends in total rainfall – 2007 is a good example: the wet season was wetter than average but rainfall at the hourly scale was notably less intense (Raiter 2012).

Salinity

Secondary salinity (salinity caused by human activities) has affected large parts of the south-west of Western Australia for a century due to rising saline groundwater caused by extensive clearing (Mayer et al. 2005).

This problem has not been a major problem in forested catchments due to the maintenance of deep-rooted perennial vegetation. Stream salinities have remained mostly fresh and stable, except where intense timber harvesting operations have occurred (Bari & Boyd 1993; Mayer et al. 2005).

The risk of secondary salinity in forested catchments is further diminished by the drying climate and resultant groundwater declines. Kinal and Stoneman (2012) observed a reduction in annual stream salinity and a reduction in its variability after groundwater disconnected from the stream zone in the Yarragil 4X sub-catchment within this report's study area.

1.3 Land management and stream responses

After rainfall, forest density is the most significant factor affecting streamflow trends in south-west forested catchments (Li et al. 2010; Silberstein et al. 2011).

The lands managed under the FMP include jarrah, karri, and wandoo-dominant sclerophyll forest ecosystems and other vegetation types. These forests are very variable in density, age and composition, with natural variation increased by a long history of timber harvesting, *Phytophthora* dieback, and both wild and controlled fire regimes that have changed over time (Stoneman & Schofield 1989; Croton & Reed 2007). In addition, some 100 km^2 have been mined for bauxite and are in progressive stages of rehabilitation, with 5–6 km^2 of additional rehabilitation established annually (Grigg 2009).

A large body of literature describes the history of land-use changes, forest management practices, mining and catchment experiments, and their effects on catchment hydrology, including salinity amelioration.

In summary, forest harvesting and thinning may temporarily raise groundwater levels and streamflow, as well as salinity in drier catchments (where groundwater salinities are generally higher anyway) while removal of perennial deep-rooted vegetation for agriculture can make such groundwater level, streamflow and salinity changes permanent (Ruprecht & Stoneman 1993). These are both hydrologic responses to temporary or permanent reductions in evapotranspiration: the dominant means by which water leaves a catchment (Stoneman & Schofield 1989; Davies et al. 1995; Bari & Ruprecht 2003; Croton & Reed 2007). The converse is often true for rehabilitated or regenerating forest and revegetated land: higher evapotranspiration leads to lower groundwater levels and lower runoff coefficients, often with lower salinity from groundwater discharge (Bari & Boyd 1993; Davies et al. 1995; Bari & Ruprecht 2003; Croton & Reed 2007). By reducing vegetation coverage, infection by *Phytophthora cinnamomi* (dieback) can also lead to significant and long-lasting increases in catchment runoff, particularly as areas in and adjacent to stream zones are the most prone to infection and are also the most significant parts of a catchment from a streamflow generation perspective (Batini et al. 1980).

The extent and duration of the hydrological response depends largely on the type and severity of the original treatment (e.g. thinning, coppicing), the type, root depth, density and health of the vegetation, the control of regrowth, the climatic regime during and preceding treatment, and the proximity of groundwater to ground level (Bari & Ruprecht 2003). The salinity risk in a catchment where vegetation is permanently removed is also related to the soil salt storage of the area where the vegetation has been removed, which in turn is related to the location's average rainfall (Stokes et al. 1980; Silberstein et al. 2003; Mayer et al. 2005).

Both rises and declines in flows following increases or decreases in evapotranspiration may occur in two stages. The first is the initial catchment response to the changed water balance. The second stage follows the connection or disconnection of groundwater to or from the stream zones, and is reached only where groundwater has been previously disconnected, or connected, as the case may be, and the change in catchment water balance and groundwater storage is sufficiently pronounced (Bari & Ruprecht 2003; Silberstein et al. 2003, Hughes et al. 2012, Kinal & Stoneman 2012). It consists of a response in the same direction as the first, but may have an increased magnitude.

Where the change in land use or vegetation cover results in a relatively stable new equilibrium, the altered flow regime may be maintained. If a new equilibrium is not reached (e.g. where thinned vegetation regains its density or evapotranspirative capacity), the original flow regime may return over time. A return to the original flow regime depends on the recovery trajectory of the vegetation, and other factors affecting the catchment water balance, such as rainfall (Ruprecht et al. 1991; Bari & Ruprecht 2003; Croton & Reed 2007; Grigg & Grant 2009). Inverse relationships have been reported between canopy or vegetation cover and streamflow, particularly in the high and intermediate rainfall areas (Ruprecht et al. 1991; Mauger et al. 1998).

Bruijnzeel & Vertessy (2004) emphasize, however, that a global suite of experiments attest to relatively muted streamflow responses to forest management practices that reduce vegetation density or coverage. According to their examples, the proportional change in streamflow is generally far less than the proportional change in vegetation stocking rate or cover, with 'large increases in leaf and sapwood areas of the remaining trees… [potentially] representing a tendency towards complete re-equilibration following a set of physiological relationships aimed at maximum site utilization', that is, trees in thinned areas tend to use more water than their densely stocked counterparts (Bruijnzeel & Vertessy 2004). In addition, streamflow increases due to forest management are generally lower with decreasing mean rainfall, and are transient where same-species regeneration occurs (Bruijnzeel & Vertessy 2004).

Macfarlane et al. (2010) and Vertessy et al. (2001) report that forests of different ages, even where basal areas are similar, may have different evapotranspirative capacities, with vigorous growth and high leaf and sapwood areas in younger, regrowth forests. Silberstein et al. (2011) reported transpiration in old growth jarrah forest to be about half that of a typical regrowth forest, and Vertessy et al. (2001) found that catchments covered with old-growth stands of mountain ash yield almost twice as much water annually as those covered with re-growth stands aged 25 years.

The impacts of forest management practices always manifest against the backdrop of the climatic regime, which as described in the previous section, can be a stand-alone driver of change in a catchment's water balance. Forest management practices may therefore compound hydrologic shifts caused by climate changes or climate variability or ameliorate them.

In the 31 Mile Brook catchment mature forest was estimated to transpire only half as much as a typical regrowth forest, the difference being approximately 18% of the annual rainfall (Silberstein et al. 2011). Here, therefore, forest management practices that result in high proportions of catchments being covered in regrowth forests increase the proportion of rainfall lost by evapotranspiration, exacerbating the hydrologic decline resulting from rainfall reductions.

1.4 Study catchments

Figure 2 shows the locations of the catchments studied in this investigation. They are scattered throughout the south-west of Western Australia, with a majority in the Darling Ranges to the east and south-east of Perth, two towards the south-west corner on the Blackwood Plateau, and five in the southern part of the Darling Plateau towards the south coast of Western Australia.

The study catchments range in size from less than one to more than 600 km^2 (Table 1). The two largest catchments, both of which span the lower rainfall zones, have some of the lowest average runoffs (Fig. 3). The combined area of the catchments is 3174 km^2 (excluding 6 nested catchments). The average total annual flow from all the catchments is 182 GL for the period 1975–2008. The abbreviated names indicated in the second column of Table 1 are used in figures and tables for the remainder of this report.

Twenty nine of the 32 catchments are in declared Public Drinking Water Supply Areas, with 16 of those 29 designated ‘Priority 1’ Public Drinking Water Supply Areas.

Thirty-four per cent (1236 km^2) of the combined area of the catchments has been inspected for the presence of dieback with 35% known to be infected. The proportion of each catchment inspected for dieback ranges from 0–100% and the proportion of inspected area in catchments identified as infected varies from 0–99%. Thus while dieback presence is generally significant in the study catchments, both the extent of infestation and our understanding of it vary widely.

Table 1 Locations of catchments used in this assessment

	AWRC name [a, b, c]	Short name [a]	River	Basin	AWRC ref	Lat[d]	Long[d]	Region[e]
Primary catchments	Beigpiegup	Beig	Mitchell River	Denmark coast	603005	–34.81	117.34	sc
	Blackbutt Point[b]	Black	Tallanalla Creek	Harvey River	613005	–33.11	116.12	cj
	Crouch Road	Crouc	Rosa Brook	Blackwood River	609001	–33.94	115.49	sw
	Dee Tee 59[b]	DT59	Falls Brook	Harvey River	613008	–33.04	116.00	cj
	Dingo Road[b]	Dingo	Harvey River	Harvey River	613002	-33.01	116.09	cj
	Hairpin Bend Rd[b]	Hairp	Little Darkin R.	Swan coast (Helena R.)	616010	-32.07	116.25	nj
	Ordnance Rd. Crossing[c]	Ordna	Weld River	Shannon river	606195	-34.72	116.51	sc
	Pine Plantation[b, f]	Pine	Darkin River	Swan coast (Helena R.)	616002	-32.14	116.46	nj
	Slavery Lane[b]	Slav	Pickering Brook	Swan coast (Helena R.)	616009	-32.03	116.19	nj
	Staircase Road[f]	Stair	Carey Brook	Donnelly River	608002	-34.36	115.89	sw
	Teds Pool[c]	Teds	Deep River	Shannon R. (Nornalup)	606001	-34.61	116.61	sc
	Wattle Block[c]	Watt	Weld River	Shannon R. (Nornalup)	606002	-34.66	116.54	sc
	Whicher Range[b]	Which	Margaret R. Nth	Busselton coast	610008	-33.82	115.48	sw
	Worsley[c]	Wors	Hamilton River	Collie River	612004	-33.28	116.06	cj
	Yarragil Formation[c]	Yarra	Yarragil Brook	Murray River	614044	-32.82	116.23	cj
Supplementary catchments	Bates Catchment[b, f]	Bates	Little Dandalup Trib.	Murray River (Dandalup)	614062	-32.58	116.03	nj
	Ceriani Farm[a, c]	More	More Seldom Seen Crk	Swan coast (Canning)	616022	-32.26	116.08	nj
	Cobiac[c]	Cobia	Wungong Brook	Swan coast (Canning)	616058	-32.33	116.2	nj
	Del Park[b, f]	DelPk	South Dandalup Trib.	Murray R (Dandalup)	614007	-32.67	116.04	cj
	Ernie's Catchment[c, f]	Ernie	Bingham River Trib.	Collier R	612008	-33.3	116.46	nj
	Gordon Catchment[b, f]	Gord	South Dandalup R. Trib.	Murray River (Dandalup)	614060	-32.63	116.25	nj
	Hansen's[b]	Hans	Little Dandalup Trib.	Murray River (Dandalup)	614019	-32.59	116.05	nj
	Jayrup[b, f]	Jay	Big Brook	Murray River (Serpentine)	614093	-32.59	116.23	nj
	Lewis[b, f]	Lewis	North Dandalup Trib.	Murray River (Dandalup)	614021	-32.57	116.07	nj
	Mount Curtis[a, c, f]	Water	Waterfall Gully	Swan coastal (Canning)	616023	-32.2	116.10	nj
	Ngangaguringuring[b, f]	Ngang	Helena River	Swan coastal (Helena)	616013	-31.94	116.51	nj
	O'Neil Road[b, f]	Oneil	Big Brook	Murray River (Serpentine)	614037	-32.55	116.24	nj
	Palmer[c, f]	Palm	Bingham River	Collie	612014	-33.23	116.41	cj
	Poison Lease[c, f]	Pois	Helena River	Swan coastal (Helena)	616216	-31.96	116.35	nj
	Travellers Arms[a, c, f]	Seld	Seldom Seen Creek	Swan coastal (Canning)	616021	-32.27	116.10	nj
	Trew Road[b]	Trew	Helena Brook	Swan coastal (Helena)	616012	-31.89	116.27	nj
	Vardi Road[c]	Vardi	Wungong Brook	Swan coastal (Canning)	616041	-32.29	116.16	nj

[a] Stations are referred to by their AWRC name, except for Travellers Arms (Seldom Seen Creek), Ceriani Farm (More Seldom Seen Creek), Mt Curtis (Waterfall Gully), which are referred to by their stream names, for consistency with the literature and practitioner use. AWRC = Australian Water Resources Council

[b] Declared public drinking water supply area – priority 1

[c] Declared public drinking water supply area – other than priority 1

[d] Centroid of catchment, used for SILO climate data drill query

[e] nj = northern jarrah forest, cj = central jarrah forest, sw = south-west, sc = south coast

[f] Salinity trends assessed under KPI 19 in addition to streamflow trends.

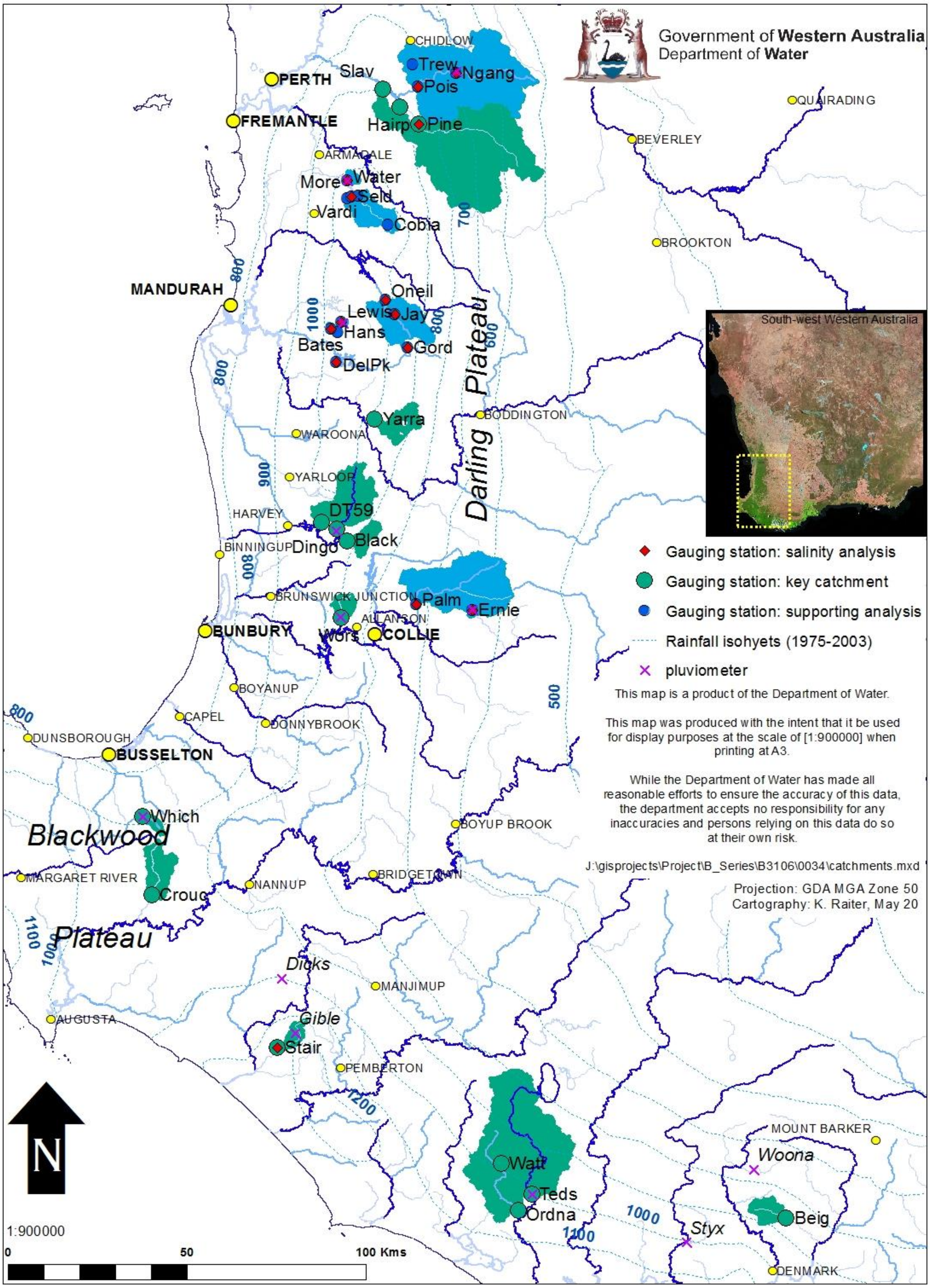


Figure 2 Catchments used in this study

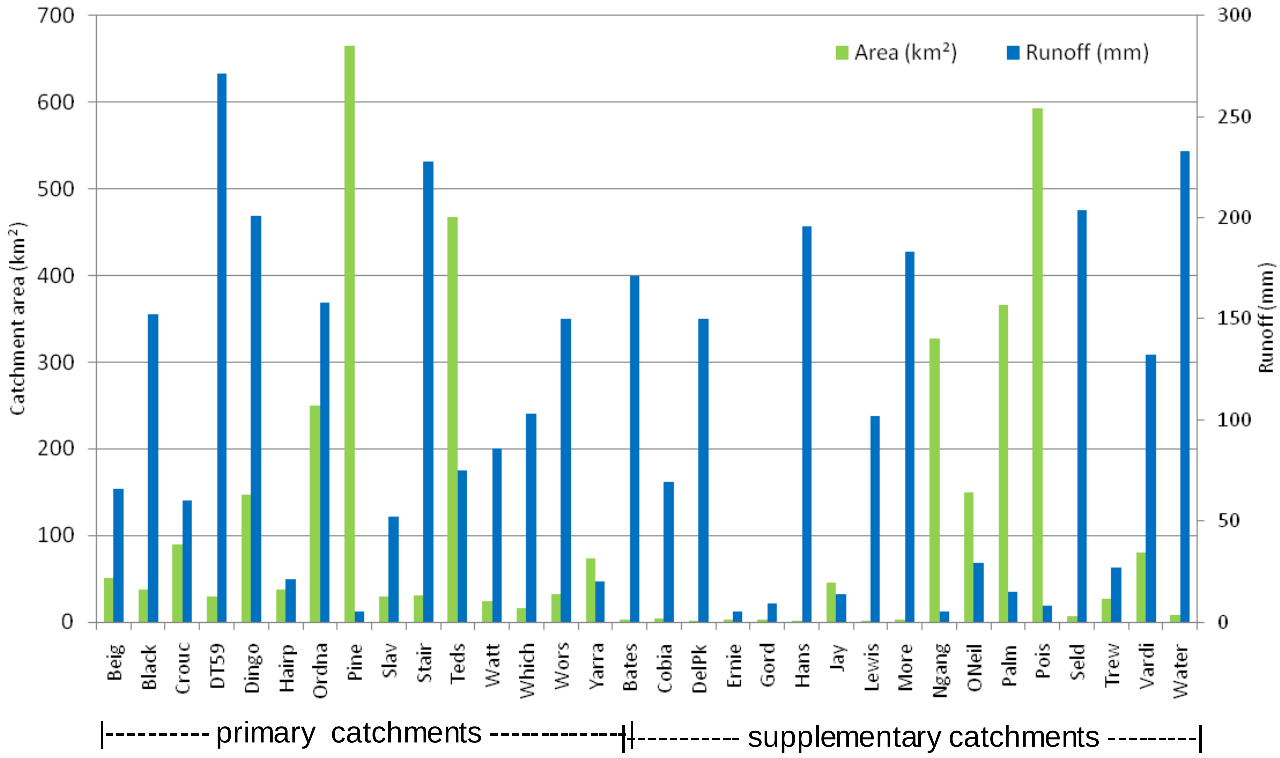


Figure 3 Study catchment area and average runoff for the period 1975–2008

History of the study catchments in the literature

The following provides a synopsis of some sources that have reported trends and hydrological manipulations in the study catchments, described in approximate chronological order.

Del Park

Twenty percent of Del Park catchment was mined and revegetated between 1974 and 1979, and the understorey of the revegetated areas was thinned in 1985. A further 10% of the catchment was mined between 1986-1989. The groundwater responded to the mining with a peak rise of 2–4 m before returning to about one metre above unmined levels six years following revegetation (Ruprecht et al. 1990). Streamflow also increased, peaking at an estimated 30 mm/yr in 1978 compared to an unmined scenario (equivalent to 41 ML or 23%), and returning to pre-mining levels by about 1988, after which they declined to a maximum of 20% below pre-mining levels (Croton 2004). Recent work has suggested that this catchment could be prioritised for experimental thinning.

Hansens

Hansens was uniformly thinned in the 1985/86 summer, reducing crown cover from 60% to 14%; basal area from 27.1 to 7 m^2/ha, and stand density from 700 to 110 stems/ha. In comparison with Lewis catchment, a nearby control of similar size and characteristics, the results were: runoff coefficient rose by 20% and average annual flow by 260 mm after 3 years; groundwater rose by 2 m adjacent to the swamp and 5 m in upslope areas, and reached equilibrium after 2 years; the duration of interflow increased from an average of

2 mo/yr to an average of 6 mo/yr, and flow became perennial. The crowns of individual trees became denser by 1989 but had not increased in size. Stump coppice became abundant and vigorous. Ground coppice did not increase significantly and remained similar to the control forest (Ruprecht et al. 1991).

Yarragil

A number of studies have reported the effects of thinning and harvesting in the Yarragil experimental catchments, nested within Yarragil formation catchment. In 1983 a trial thinning was undertaken in 4L subcatchment, involving a two-thirds reduction in canopy cover, basal area and stocking followed by extensive fires and coppice poisoning. This trial resulted in an increase in valley groundwater levels of 4.4 m, a large increase in streamflow of approximately 131 mm, and a jump in the runoff coefficient from 0.5% of annual rainfall to 10–12% relative to the control. This equates to a streamflow increase of more than 15-fold. The maximum streamflow increase was observed 9 years after treatment and was sustained for over 15 years, however no increases in stream salinity were recorded (Stoneman 1993; Moulds et al. 1994; Bari & Ruprecht 2003).

More recently, in the summer of 2000–01, a trial (described in full by Kinal & Stoneman 2011) consisting of two intensities of timber harvesting and silviculture resulted in some groundwater recharge relative to the control but no streamflow or salinity responses. These results were attributed to the fact that the stream zone was not treated, annual rainfall was very low during the trial duration, and groundwater levels were generally low and declining over the duration of the study (Kinal & Stoneman 2011).

Seldom Seen catchments

Loh et al. (1984), Davies et al. (1995) and Croton et al. (2005) all investigated the effects of bauxite mining and rehabilitation in the Seldom Seen and More Seldom Seen catchments, comparing them to Waterfall Gully as the control catchment. All three catchments were severely dieback affected. Aerial photographs and Department of CALM (Now Department of Parks and Wildlife) FMIS database records indicated that forest cover was already thin from timber harvesting and dieback, while Waterfall Gully had a small area cleared for agriculture (Croton et al. 2005). Thirty four and sixty two percent, respectively, of the Seldom Seen and More Seldom Seen catchments were mined starting in the late 1960s, and revegetation occurred progressively over the following 2–3 decades. Before 1988 eastern states species constituted much of the revegetation but some of the revegetation in the period 1978–87 and all after 1988 used WA native species, to resemble the jarrah forest ecosystem (Croton et al. 2005). Estimates of peak streamflow responses vary between source and calculation method, and range from 62–253 mm/yr for Seldom Seen and 90–255 mm/yr for More Seldom Seen (equivalent to increases in runoff coefficient of 6–23% and 7–21%, respectively; Davies et al. 1995; Croton et al. 2005). Following rehabilitation, streamflows declined, reaching pre-mined levels 20–32 years after their initial increase, and continuing to decline below pre-mining levels. Rising evapotranspiration of the forests in unmined areas within the catchments probably contributed to the decline (Croton et al. 2005). Stream salinity increased by 20–30 mg/L in both Seldom Seen and More Seldom Seen catchments during the period of mining and showed no signs of returning to pre-mining conditions in 1995 (Davies et al. 1995). In contrast, stream salinity at mean flow decreased over the study duration in Waterfall Gully. This may be associated with a gradual lowering of groundwater levels due to lower rainfall conditions in the last 20 years (Davies et al. 1995).

Ernies

Ernies catchment was retained as a forested control in an experiment involving land cleared to investigate salinity effects (Silberstein et al. 2003). Over the period 1974–2003, Silberstein et al. (2004) found that the runoff coefficient remained reasonably constant or slightly declining, at around 1%.

Wungong (incl Vardi, Cobiac, Waterfall Gully, Seldom Seen & More Seldom Seen)

The Wungong Catchment Trial was an operational thinning trial aimed at offsetting the effects of a drying climate and catchment management practices, and the consequent reduced inflows into the Wungong water supply reservoir. This trial covered the five study catchments: Vardi Road, Cobiac, Waterfall Gully, Seldom Seen and More Seldom Seen (McFarlane 2008). In the Cobiac catchment, 'full scale' catchment thinning at an operational level was performed in addition to the CSIRO research work mentioned above. Thinning in 2008 in Cobiac yielded positive responses in both groundwater and streamflowing in 2009, (Reed et al. 2012).

The hydrological modelling performed as part of the Wungong Catchment Trial demonstrates the contraction of the groundwater system in the catchments since the rainfall declines of the mid 1970s (Reed et al. 2012). It further demonstrated how a continuation of current low-rainfall conditions will likely result in continued falls in both groundwater levels and streamflows, with increasing disconnection of groundwater from stream zones. Reed et al. (2012) conclude that, to halt continuing groundwater declines and to return streamflows to late-1990s/early-2000s levels, forest treatment needs to be more intensive than previously anticipated.

Three transects in the Cobiac catchment were thinned by CSIRO as part of a research trial to investigate the impacts of thinning on forest structure, understorey microclimate, forest water balance (including changes to transpiration and soil moisture), modified flow pathways, water quality, nutrient dynamics, and habitat value for selected species. The thinning was carried out in late 2008 and consisted of commercial harvesting and notching to a density of 10 m^2 plus 5 retained habitat trees per ha. In 2009, some increases in soil moisture and groundwater were observed in treated transects, although this may be partly explained by the wet year (Silberstein et al. 2011). The Cobiac catchment was also treated as part of the Wungong Catchment Trial, described below. Hughes et al. (2012) investigated the correlation between rainfall and groundwater levels (for some catchments, this was estimated using baseflows). They found a strong correlation between rainfall and groundwater storage as well as between groundwater storage and runoff in Bates, Lewis and Del Park, where groundwater levels are still reasonably close to stream zones. Gordon was also studied, and was in a grouping of catchments where there is no strong correlation between groundwater level and runoff and runoff coefficients below 3% – with groundwater levels well below, and thus never intersecting, stream zones.

Region-wide

The Department of Water (DoW; 2009) observed a significant step-decline in the annual total flow at Carey Brook in 1999, decreasing but not significant trends at Ordnance Road Crossing, Yarragil Formation and Poison Lease; and a slight, insignificant increase at Palmer. Declines in flow duration have been observed at Ordnance Road Crossing, Yarragil Formation, Poison Lease, with the duration of flows at Yarragil Brook declining by 25% in the period 1975–96 compared with the pre-1975 period (Rodgers & Ruprecht 1999; DoW 2009).

Petrone et al. (2010) found significant step-declines at the following gauging stations. Parentheses indicate the change point, followed by the linear trend in mm/yr where it was found to be significant)[2]: Waterfall Gully (2001, –8.0), Vardi Road, Seldom Seen (1998, –9.8), More Seldom Seen (2001, –10.6), Bates (1998, –11.4), Del Park (1998, –10.5), and Worsley (1997, –9.0). They found no change point at Lewis, Gordon, and Dingo Road (although a significant linear trend of –3 was found for Dingo Road) for 1989–2008.

Between 1989 and 2008, the gauging stations at Seldom Seen, Vardi Road, Lewis, and Dingo Road also switched from perennial to intermittent flow regimes for at least some of the years in the latter part of the period (Petrone et al. 2010).

Salinity trends across the south-west

Mayer et al. (2005) reported trends in stream salinity, flow and salt input/output ratios across the south-west. Of 10 catchments common to their study and this one, 5 showed increases in salinity between the two periods 1983–92 and 1993–2002, 4 showed a decrease, and one remained constant on average. Of these 10 streams, 8 were fresh and 2 were brackish, with both brackish streams showing decreased average salinity between the two periods.

1.5 What is at stake?

The forested streams of south-western Australia support a rich variety of ecological communities which include a series of endemic and threatened species including some that are relics from Gondwanaland. In addition, many forested streams supply water that underpins the current prosperity and sustainability of human communities and economies or may be required for future water supplies. Ongoing declines in groundwater levels, streamflows, and/or water quality have devastating consequences for terrestrial, riparian and aquatic biodiversity, ecosystem health, water supplies and the social and economic benefits derived from them (Burrows et al. 2011; Reed et al. 2012). Silberstein et al. (2011) estimated that the replacement value of the water consumed by an unthinned regrowth forest is far greater than the opportunity cost of the timber production foregone by the thinning treatment.

Other groundwater-dependent ecosystems, including subterranean caves such as the Lake, Jewel and Easter caves of the Leeuwin–Naturaliste Ridge, are affected by declining rainfall and groundwater levels. Many of these provide habitat for critically endangered species and ecological communities (Subterranean Ecology 2010a & b).

[2] Stations are referred to by their AWRC name, except for Travellers Arms (Seldom Seen Creek), Ceriani Farm (More Seldom Seen Creek), Mt Curtis (Waterfall Gully), which are referred to by their stream names, for consistency with the literature and practitioner use. AWRC = Australian Water Resources Council.

2 Methods

2.1 Site selection

Thirty-two forested catchments were selected for the current study after considerable discussion between representatives of the Department of Water, Department of Parks and Wildlife and the Water Corporation.

Fifteen of the 32 catchments were analysed as primary catchments (Table 1). These were fully or almost fully forested, spread widely across the geographical and rainfall gradients of the area, and had streamflow records of good length and quality (> 15 years record where possible and quality code generally 1 or 2). Catchments were excluded from the main list if smaller than 15 km^2 in area. The remaining 17 catchments did not necessarily fit the criteria but were included in the analysis as supplementary catchments to help interpret trends and responses to climate and forest management. Some of these are experimental catchments which help to demonstrate various aspects of a catchment's hydrological responses to vegetation and climate changes.

Within the constraints of available data records, the set of catchments selected had the following characteristics:

- were generally less than 5% cleared
- were distributed as much as possible across the FMP area
- were distributed as much as possible across rainfall zones
- had historical streamflow records sufficient to calculate trends
- were predominantly within FMP tenure
- represented a range of forest management histories.

The catchments were grouped into four 'regions' to facilitate comparisons of trends within the study area: the 'northern jarrah forest' region (roughly the northern half of the IBRA[3] Northern Jarrah Forest JF1 subregion, from east of Perth down to just south of Mandurah); the 'central jarrah' region (just north of Waroona down to Collie, incorporating roughly the southern half of the IBRA Northern Jarrah Forest JF1 subregion); the 'south-west' region (Busselton to Pemberton, covering parts of the Southern Jarrah Forest and Warren IBRA subregions) and the South Coast (north of Broke Inlet to Albany, also covering parts of the Southern Jarrah Forest and Warren IBRA subregions; Department of Sustainability, Environment, Water, Population and Communities 2012).

Throughout this report, stations are referred to by their AWRC name, except for Travellers Arms (Seldom Seen Creek), Ceriani Farm (More Seldom Seen Creek), Mt Curtis (Waterfall Gully), which are referred to by their stream names, for consistency with the literature and practitioner use.

[3] Interim Biogeographic Regionalisation of Australia

Table 2 Characteristics of study catchments

	Short name	Catchment area (km²)	Region	Av. Rainfall[a]	Gauge custodian[b]	Salinity data[c]	% cleared	% old growth	Dieback %[d]	Other history[e]	Last harvest %[f]				Exotics %[g]
											70s	80s	90s	00s	
Primary catchments	Beig	51.4	sc	951	DoW	–	0	20	74 (100)	35	30	15	0	0	0
	Black	38.1	cj	1020	WC	–	0	2	76 (3)	35	10	43	0	5	7
	Crouc	89.2	sw	886	DoW	–	0	10	66 (59)	10	50	5	15	10	4
	DT59	29	cj	1064	WC	–	0	0	99 (65)	70	20	0	0	10	0
	Dingo	147.2	cj	1072	DoW	–	1	3	94 (70)	15	45	10	< 5	20	1
	Hairp	37.8	nj	956	DoW	–	0	2	0 (39)	60	0	3	35	0	0
	Ordna	250.2	sc	1033	DoW	–	1	35	37 (54)	10	15	10	10	10	<1
	Pine	665.3	nj	1021	DoW	disc+cont	4	7	4 (16)	25	3	3	5	25	1
	Slav	29.4	nj	1018	DoW	–	0	0	42 (54)	20	5	3	0	20	2
	Stair	30.3	sw	1185	DoW	disc+cont	1	70	29 (12)	0	3	7	0	0	0
	Teds	467.8	sc	877	DoW	–	0	30	27 (51)	15	15	15	5	15	0
	Watt	24.2	sc	961	DoW	–	0	90	18 (13)	0	0	0	0	0	0
	Which	15.5	sw	878	DoW	–	0	0	99 (33)	2	50	0	0	2	3
	Wors	32.3	cj	975	DoW	–	5	0	92 (25)	30	60	0	0	30	1
	Yarra	73.5	cj	946	DoW	–	1	5	14 (98)	5	5	40	25	5	2
Supplementary catchments	Bates	2.2	nj	1181	DoW	disc+cont	<1	0	74 (100)	30	0	70	10	1	0
	Cobia	3.6	nj	1059	DoW	–	0	0	48 (100)	60	20	20	0	0	0
	DelPk	1.4	nj	1192	DoW	disc+cont	0	0	61 (39)	40	50	10	0	0	10
	Ernie	2.7	cj	674	DoW	cont	0	0	0 (39)	94	0	0	3	3	0
	Gord	2.1	nj	959	DoW	cont	0	0	4 (100)	0	0	15	0	0	0
	Hans	0.7	nj	1181	DoW	–	0	0	77 (100)	0	0	100	5	30	0
	Jay	45.5	nj	972	Alcoa	–	12[f]	0	20 (100)	20	3	5	55	25	<1
	Lewis	2	nj	1161	DoW	disc+cont	1	0	57 (100)	50	0	5	45	0	0
	More	3.4	nj	1081	DoW	–	3	0	67 (58)	3	85	20	3	0	46
	Ngang	327	nj	652	DoW	disc+cont	6	3	- (0)	90	7	0	0	0	<1
	Oneil	149.4	nj	974	DoW	disc+cont	0	<1	32 (94)	15	20	2	40	35	<1
	Palm	366.1	cj	693	DoW	disc+cont	5	15	2 (32)	70	10	< 5	8	< 5	1
	Pois	592.9	nj	785	DoW	–	4	3	56 (0.5)	81	10	0	2	< 1	2
	Seld	7.2	nj	1081	DoW	disc	2	0	66 (65)	10	85	5	1	0	18
	Trew	26.7	nj	855	DoW	–	10	0	82 (13)	79	10	0	1	0	7
	Vardi	80.8	nj	1090	DoW	–	7	0	56 (97)	20	45	15	15	5	11
	Water	8.6	nj	961	DoW	disc	7	0	84 (75)	20	80	0	0	0	0

[a] Average water year (April to March) rainfall for the period 1975–2008
[b] DoW= Department of Water, WC = Water Corporation, Alcoa = Alcoa of Australia Limited.
[c] Reference is made only to data used in this report. disc = discrete data (manual sampling); cont = continuously gauged data
[d] Percentage of area interpreted for dieback that was found to be infected. Note: for some catchments this is a small fraction.
[e] Other timber harvesting history: areas not harvested after 60s, and also not old growth forest. Includes forest logged prior to 1960 and non forest types e.g. heathland.
[f] Decade of last harvest – percentage of catchment most recently harvested in the decades shown. More details in Appendix C.
[g] Percentage of catchment covered by exotic vegetation; includes plantations and bauxite revegetation from before 1988.
[h] 14% of Jayrup catchment is currently being mined. Maximum area cleared and with <4 year old rehabilitation is 12%.

A further seven catchments were identified for future analysis as part of the FMP KPIs but excluded from the current analysis due to insufficient available recent data records. They are (with AWRC reference numbers) Yarragil Brook Tributaries 4X, 6C and 4L (614048, 614049, and 614057), 31 Mile Brook – 31 Mile Road (616026), North Dandalup River – North Road (614036), Canning River – Gleaneagle (616065) and 39 Mile Brook –Jack Rocks (614031).

Overviews of catchment characteristics and trends, including summaries of their forest management histories and information from the literature, are presented in Appendix A.

2.2 Data

All data was reported to the start of the period, with each period beginning at 9 am on the relevant day to correspond with some rainfall stations that are read daily at this time. A 'water year' (April to March of the following year) was used for all analyses. Historical period averages are calculated based on available data from the period 1975 to 2008. This period differs from that recommended by the United Nations World Meteorological Organisation (1961–90) due to the change in rainfall regime that occurred around 1975 (IOCI 2002) and the need to include recent data in order to address a key objective of this report – to assess data for the period within the FMP in the wider temporal context.

Catchment characteristics and histories

Average catchment slope and the lengths of the longest stream flow path in each catchment were calculated using the ArcHydro plug-in tool for ArcGIS, in ArcMap, version 10.0.

Vegetation, harvesting records, dieback, and fire histories were provided in spatial format and summarised numerically by the Department of Parks and Wildlife.

The data consisted of:

- Forest structure and dominant species as described by Bradshaw et al. (1997), non-forest vegetation components, regeneration age
- Timber harvesting history including (where available) silvicultural outcome, intensity, proportion of catchment and frequency of harvest
- Fire history including fuel age and, where available, season and intensity of burn
- Forest health including (where available) data on dieback presence, history and impact
- Leaf area index data for whole catchments and specific parts of catchments of interest due to their harvesting, fire, or dieback history were supplied by Geographic Information Analysis Pty. Ltd. These data are based on Landsat TM and MSS satellite scenes taken in January of each given year, and were derived in 2011 by the method described by Mauger et al. (in prep).

Climatic

A set of SILO data drill climatic data for the centroid of each catchment (see Table 1) was purchased from http://www.longpaddock.qld.gov.au/silo. This included rainfall, average daily maximum temperature and Class A pan evaporation data spatially interpolated using ground-based observational data and latitude, longitude and elevation as independent variables (Jeffrey et al. 2001).

Rainfall intensity was calculated separately using pluviometer records extracted as hourly rainfall totals from the Department of Water's Hydstra database (see Table 3).

Table 3 Pluviometers used for the rainfall intensity analysis

BOM ref	AWRC river	AWRC name	Short name[1]	Region[2]
510017	Helena River	Ngangaguringuring	Ngang	NJ
509271	Waterfall Gully	Mt Curtis	Water	NJ
509349	North Dandalup Trib	Lewis Catchment	Lewis	NJ
509119	Harvey River	Dingo Road	Dingo	CJ
509249	Bingham River Trib	Ernies Catchment	Ernies	CJ
509109	Hamilton River	Worsley	Wors	CJ
509296	Carey Brook	Giblett	Gible	SW
509355	Margaret River North	Whicher Range	Which	SW
509053	Barlee Brook	Dickson Tower Road	Dicks	SW
509300	Deep River	Teds Pool	Teds	SC
509022	Yate Flat Creek	Woonanup	Woona	SC
509278	Kent River	Styx Junction	Styx	SC

[1] Used for figures.

[2] NJ = northern jarrah forest; CJ = central jarrah forest; SW = south-west SC = south coast

Streamflow

Figure 4 shows the period of record for the gauging stations in this study (as extracted in daily time steps from the Department of Water's Hydstra database[4] and provided by the Water Corporation in December 2010). Missing data for periods of less than 8 months (but mostly less than 1 or 2 months) were patched as follows: where a stream with streamflow that correlated highly with the stream in question was found, the missing data points were estimated using a linear regression relationship with the correlated stream. Where no highly correlated stream was available, the missing data was estimated from the rainfall for that year and the relationship between rainfall and runoff for that gauging station for the whole period of data post-1975, using the best fitting of a tanh (Grayson et al.1996), polynomial, or linear trend line.

Annualised data, daily flows and minimum daily flows are synthesised in the folder 'results summaries'.

Salinity

This investigation employed both continuous and discrete salinity data extracted from the Department of Water Hydstra database and provided by the Water Corporation.

To maximise the data and periods of records available for analysis, all three discrete variables representing stream salinity were included in the analysis. These were in-situ TSS (Hydstra code 6165; available predominantly from the recent decade), laboratory TSS (Hydstra code 6163; available mainly from mid 1970s to late 1990s), and soluble chloride (Hydstra code 284; used mostly in records prior to 1970s). Where data was calculated from

[4] Flow and salinity records for most gauged catchments in Western Australia are now available for free via the Department of Water's Water Information Portal, accessible at http://wir.water.wa.gov.au

conductivity measures, the conductivity was adjusted to compensate for temperature variation and converted to a measure of salinity using the south-west gen rating relationship (Appendix B) or a site-specific conductance–salinity relationship, where it existed (about 1/3 of the sites; O'Malley pers. comm. 2011, Department of Water: Water Information Section). Where two or more variable data points existed for a given day, in-situ salinity and then laboratory salinity were prioritised. Discrete in-situ and laboratory salinity data generally did not differ by more than 3 mg/L for one sample although in some cases differed by up to 32 mg/L.

Salinity measurements taken on days when no flow was recorded were excluded from the analysis.

Annual salinity data was estimated from discrete data by deriving the relationship between flow and salinity for each catchment for the days on which discrete data was available, and using this relationship together with continuous flow records to estimate daily salinity and salt load (Box 1).

Trends in daily and flow-weighted salinity were calculated and are presented for each catchment.

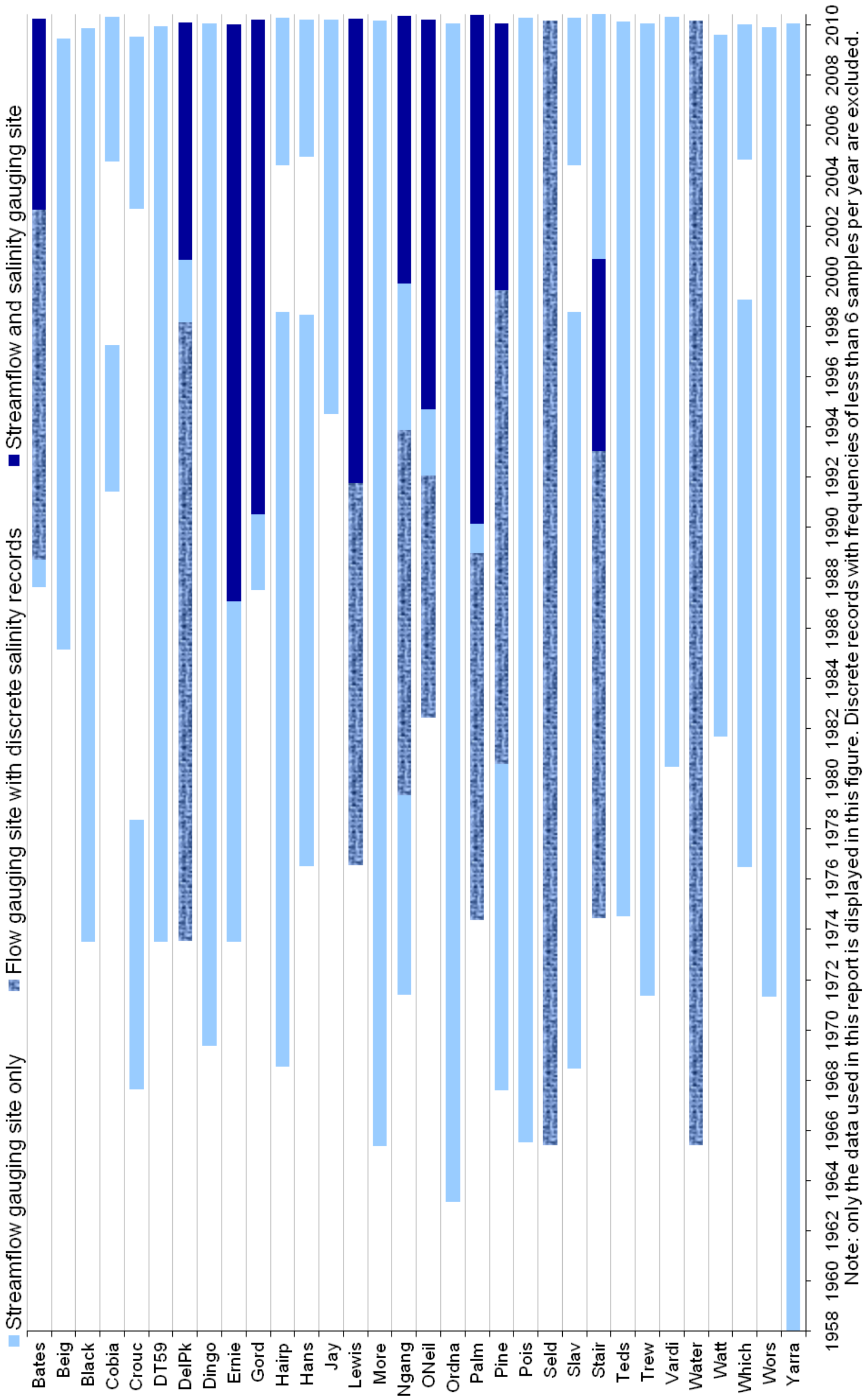


Figure 4 Periods of record for the gauging stations used in this study to mid 2010

Box 1 Calculation of annual flow-weighted data from discrete salinity samples

Annual flow-weighted salinity was estimated using discrete salinity data where continuous flow data were available.

The first step consisted of calculating the relationship between salinity and flow for each day in which a discrete data point was taken, based on the formula Salinity = a × $flow^b$ (Mayer et al. 2005). Values for the parameters ‘a’ and ‘b’ were calculated using a 5-point centred moving regression between the discrete salinity and correspondent daily flow values.

Estimated daily salinity values were then calculated for the days for which there was no discrete value available, based again on the formula Salinity = a × $flow^b$, and using the parameters calculated based on the five discrete data points that had the most recent discrete sample in their centre.

Where flow was zero, no salinity data was estimated, as this calculation is destined to enable the calculation of flow-weighted salinity which relies on total salt load, rather than instantaneous salinity estimates.

Once daily estimates for salinity were complete, daily estimated salt load was calculated using flow data, and the water-year totals of salt load, streamflow, and hence flow-weighted salinity were estimated.

The flow-weighted salinity was calculated by dividing total salt load by total flow for each year, as described by Mayer et al. (2005).

An example of discrete data, daily salinity data based on discrete data, and continuous data from a period in which both types of data were available is shown in Figure 5. This method provides a coarse but effective means for estimating flow-weighted annual salinity where no continuous salinity data is available.

It is assumed that more frequent sampling increases data reliability: reliability was attributed as high (mostly continuous measurements or more than 100 discrete samples per year, medium (30–100 samples per year) or low (fewer than 30 samples per year; adapted from Mayer et al. 2005). Where there were fewer than six samples per year, flow-weighted salinity was calculated but given a very low reliability was attached to the result. The assumption of increased reliability with higher frequency may not hold true where other factors influence the reliability of the results, such as the quality of the discrete data. For example, parallel salinity records based on discrete and continuous sampling methods at Bates catchment show low conformity prior to 1999 and increased conformity since (Fig. 5).

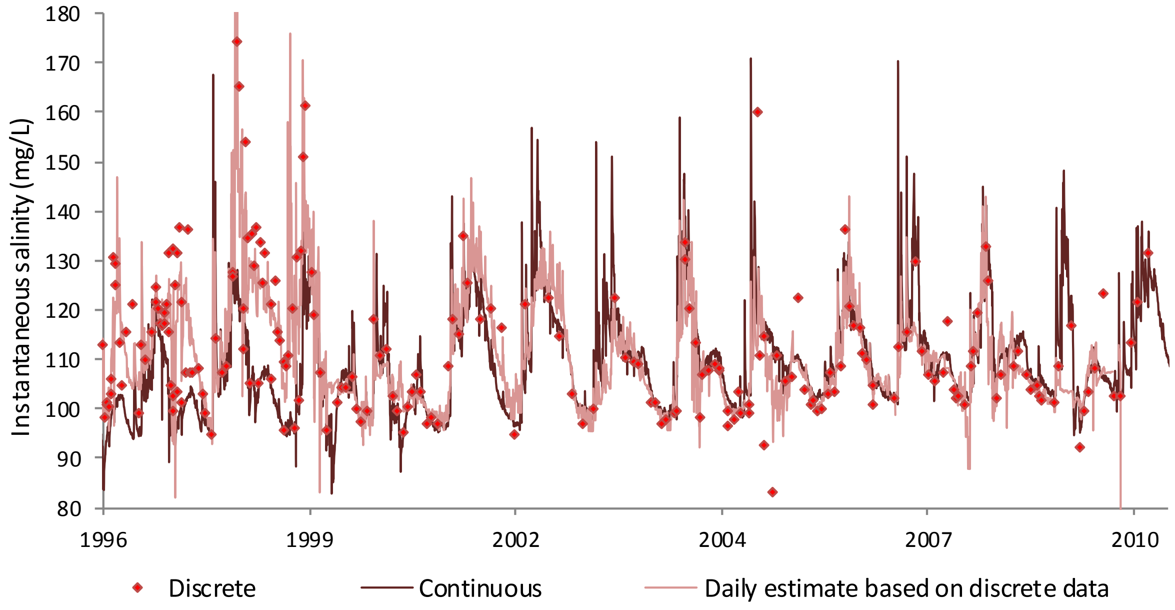


Figure 5Continuous, discrete, and daily salinity estimates based on discrete data for Bates

A mistake found in the Hydstra database led to miscalculated continuous salinity records for Del Park gauging station prior to 2007. This has been corrected.

The salinity of water is categorised according to a series of thresholds (Table 4).

Table 4 Salinity category thresholds (adapted from Hillel 2000)

Salinity (mg/L TDS)	Salinity status	Category
≤ 500	Fresh	Drinking and irrigation
500–1000	Marginal	Irrigation
1000–2000	Brackish	Irrigation with caution
2000–5000	Moderately saline	Primary drainage
5000–10 000	Saline	Secondary drainage and saline groundwater
10 000–35 000	Highly saline	Very saline groundwater
≥ 35 000	Brine	Seawater

Groundwater

Depth to groundwater data for 3 catchments was obtained from the Water Corporation and Alcoa of Australia Ltd. For 9 catchments with near-perennial flow, estimated groundwater storage over time was calculated in the statistical software *R*, by J Hughes of Alcoa (Feb 2011), using the method described by Brutsaert (2008). Estimated groundwater storage, *S*, is an estimate of groundwater storage in upstream aquifers above the zero-flow level for a stream at a given location i.e. the annual minimum catchment groundwater storage that can be a water source for the stream. This method assumes that the lowest daily flow rate (the 'baseflow') for each year is due only to groundwater discharge and that the total groundwater storage in a basin can be approximated as a power function of flow rate at the basin outlet (Brutsaert 2008; Hughes et al. 2012). The calculation of *S* involves using recessions of daily streamflow series to calculate a characteristic timescale for each catchment's drainage process (or storage coefficient) that depends upon the physical characteristics of the basin in question (Brutsaert 2008). The method generally uses the annual lowest seven-day flows to increase reliability, but in this case the lowest average daily runoff for a continuous 21-day period in the first six months of each year was used in order to include catchments with short no-flow periods, and to ensure that a consistent dry season score was attained (Brutsaert 2008; Hughes pers. comm. 2011).

2.3 Exploratory data analyses

Exploratory data analyses provided the foundation for identifying trends and possible causes and associated factors. This analysis included graphing time series of annual and monthly catchment rainfall, average maximum temperature, annual pan evaporation, streamflows, runoff, runoff coefficients, and residuals and cumulative residuals of these values based on differences from predicted variables based on a series of approaches for estimating the rainfall–runoff relationship. The approaches were: a simple linear regression, 2-order polynomial, exponential, and tanh curves, with the latter based on the function described by Grayson et al. (1996).

The differences between precipitation and FAO 56 reference evapotranspiration values were plotted as a surrogate for the potential volume of excess water in the catchment that may have been available for streamflow generation, together with the residuals (difference from the period average) and the cumulative residuals of these values.

'Runoff at mean rainfall' (Q at mean P) was calculated as a proxy for removing the effect of rainfall variability from runoff, and thus revealing changes in the rainfall–runoff relationship that may be caused by changes in vegetation cover, temperature, evaporation, and/or rainfall patterns. It was calculated by creating a centred 5-point regression between rainfall and runoff for each data point, calculating a linear relationship between rainfall and runoff for those 5 points, and then calculating the flow at mean rain based on that regression and the mean rainfall for the overall period. Plotting runoff at mean rainfall is a means to explore trends in the rainfall-runoff relationship, but there is overlap between this method and that consisting of calculating runoff coefficients (or moving averages of runoff coefficients); the latter approach was adopted for further analysis and presentation in the KPI reports.

Streamflow records were further analysed for flow duration (number of flow days), peak flows (maximum daily flows), and changes in these aspects of the streamflow regime over time.

2.4 TREND data analyses

The Trend and Change Detection Software (TREND; Chiew & Siriwardena 2005) was used to detect statistical trends and step-changes, where present, in the rainfall, runoff, evaporation, and temperature records. TREND consists of 12 tests including parametric and non-parametric trend and change detection (with and without pre-specified change point) as well as two tests for randomness and autocorrelation. The data were initially analysed using all tests but priority was given to the more powerful[5] non-parametric test results in this report. TREND produced results at the 1, 5 and 10 per cent significance level; all results up to the 10 per cent significance level ($p = 0.1$) are presented here.

Streamflow data was 'pre-whitened' prior to analysis as per the method described by Yue et al. (2002) in the statistical software *R*, by J. Hughes of Alcoa, Feb 2011 to remove autocorrelation. Serial correlation can increase the probability that the Mann-Kendall non parametric test detects a significant trend where the null hypothesis is actually true (ie a false detection; Yue et al. 2002). The pre-whitening procedure removes serial correlation and thus prevents such false detections. Data for Cobiac and Crouch Road could not be pre-whitened due to breaks in the data record.

2.5 Rainfall intensity analyses

The statistics of the total number of rain hours, average rainfall per rain hour, and the proportion of total rainfall that fell above a range of intensity thresholds were calculated for all of the stations in Table 2. The rainfall thresholds tested were 5, 10 and 20 mm thresholds, and the analysis was conducted both for full water years (April to March the following year) and for wet seasons only, in order to reduce the influence of summer rain events which may skew intensity trends but often contribute little to streamflow. The total number of rain hours, average rain-hour rainfall, and percent of total rain that fell at or above threshold amounts (per cent HIR) were also summarised for the decades 1980–89, 1990–99, and 2000–09 to elucidate trends in these parameters over time. These analyses were performed in MATLAB by Muhammad Alam (Shafiq) and summarised in Excel.

Further analyses of temporal patterns of rainfall may have been useful but were beyond the scope of this investigation. Possible further work in this area could include an analysis of trends in frequency, intensity and duration of rainfall events, the dry periods between them, their timing within seasons, correlation with temperature, and how these may affect interception, infiltration and other hydrological processes relevant to streamflow generation.

A useful example of such a method is the analysis of rainfall patterns conducted by Andrew Grigg and others at Alcoa Australia Ltd, as part of a canopy interception study targeting native and regrowth jarrah forests in Alcoa's mining tenement (A. Grigg pers. comm. 2014). That study assessed 'rain events' (periods of rain preceded by 4 or more dry hours) and 'storms' (one or more events preceded by 12 or more dry hours). While that study did not assess trends over time (beyond the four-year investigation period), it highlighted the strong potential for evaporation between *and* during storms and events, and the potential for temporal patterns of rainfall to influence runoff coefficients.

[5] There are two possible types of errors in statistical determination of trends; Type I error is when H_0 is incorrectly rejected. Type II error is when H_0 is accepted when H_1 is true. A test with low Type II error is said to be powerful.

3 Climate trends

3.1 Annual rainfall

Rainfall varied considerably across the study area and over time. Figure 6 shows the decline in average rainfall during 2004–09 (the years of the FMP included in this study) relative to 1975–2003 average. Figure 6 also shows the approximate delineation of the regions that the study area was broken up into: 'northern jarrah forest', 'central jarrah forest', 'south-west', and 'south coast' regions.

Rainfall during the study years of the FMP (2004–09) was lower than during the preceding record in a majority of catchments in all regions except the south coast region, which experienced slightly higher rainfall during this period.

The widely reported lower rainfall period since either 1997 or 2001 partly overlaps the period of the FMP study reported here but several catchments with rainfall declines in the 2001–09 period do not show declines during the recent FMP period.

Figure 7 shows how 5-year moving rainfall averages have varied by region.

The relatively high rainfall across all of the catchments before 1975 was followed by a period of relatively low rainfall in the late 1970s (northernmost regions) and early 1980s (south coast). The step-decline in average rainfall that occurred during the mid 1970s has been widely reported in the literature (although in some cases it is reported to have happened in the late 1960s) and is associated with observed changes in atmospheric circulation (IOCI 2002). Rainfall also varied considerably prior to 1975 but analysis and discussion of this is beyond the scope of this report.

In most areas rainfall was relatively high around the 1990s compared with the preceding and following periods, although trends can vary between regions as well as across rainfall zones. The period of lower rainfall since 2000 in the northernmost regions is comparable to the period of low rainfall in the late 1970s/early 1980s but in most cases the more recent period has been more protracted.

Trends in the south coast region are partly at odds with the trends observed elsewhere. Although the rainfall decline during the mid 1970s was consistent, the increase noted in the mid 1980s in other regions did not occur in the south coast region.

The decline in rainfall since 2001 compared with the 1990s was greatest in the northern jarrah forest, moderate in the central jarrah forest and south-west region, and absent on the south coast (where the period since 2001 is actually slightly wetter than the 1990s). Figure 8 summarises some of these observations. Note that the trends differ slightly according to period selected; periods averaged in Figure 8 were selected as best representing the apparent trends observed in the data and do not reflect predetermined analysis windows.

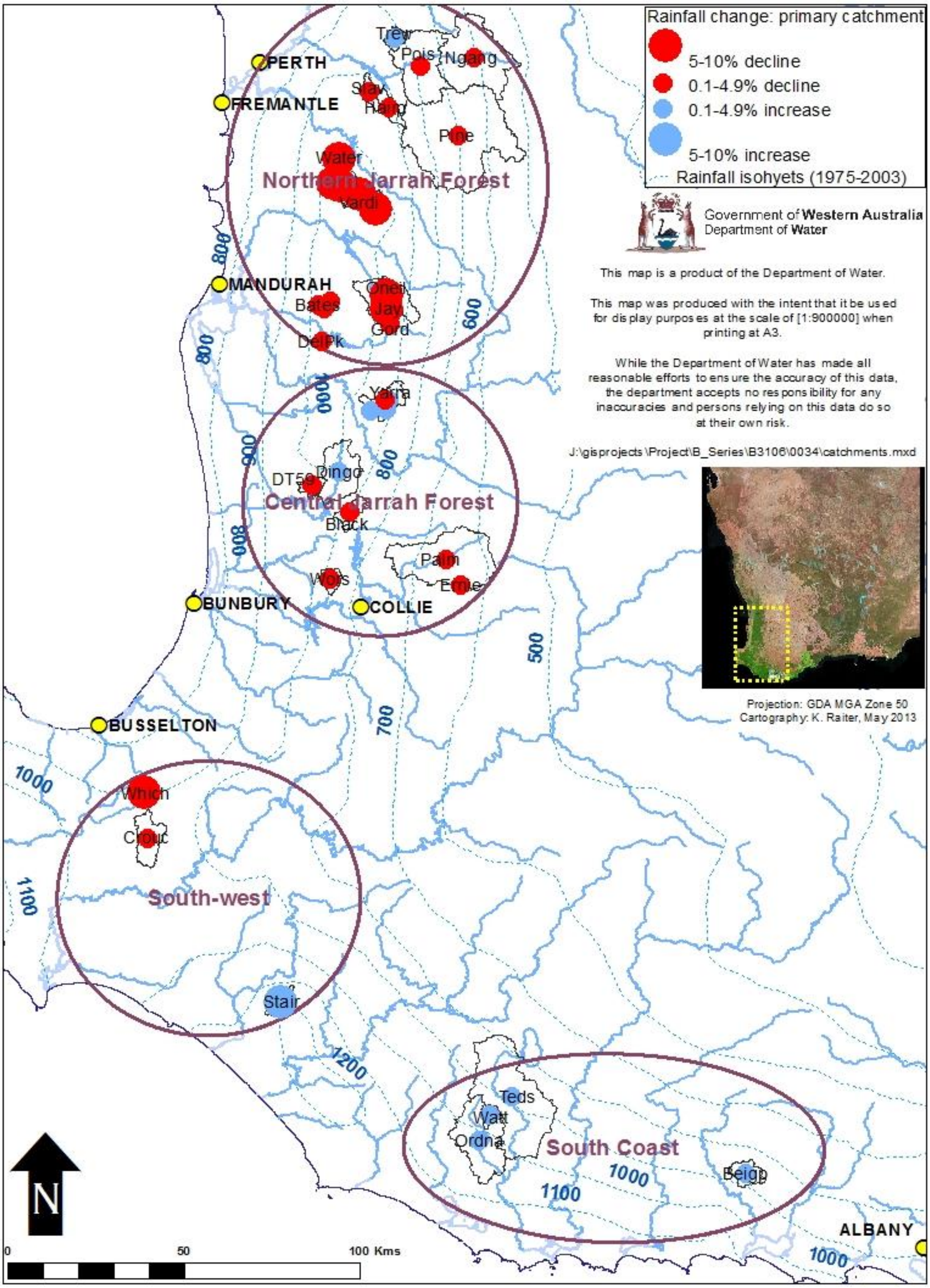
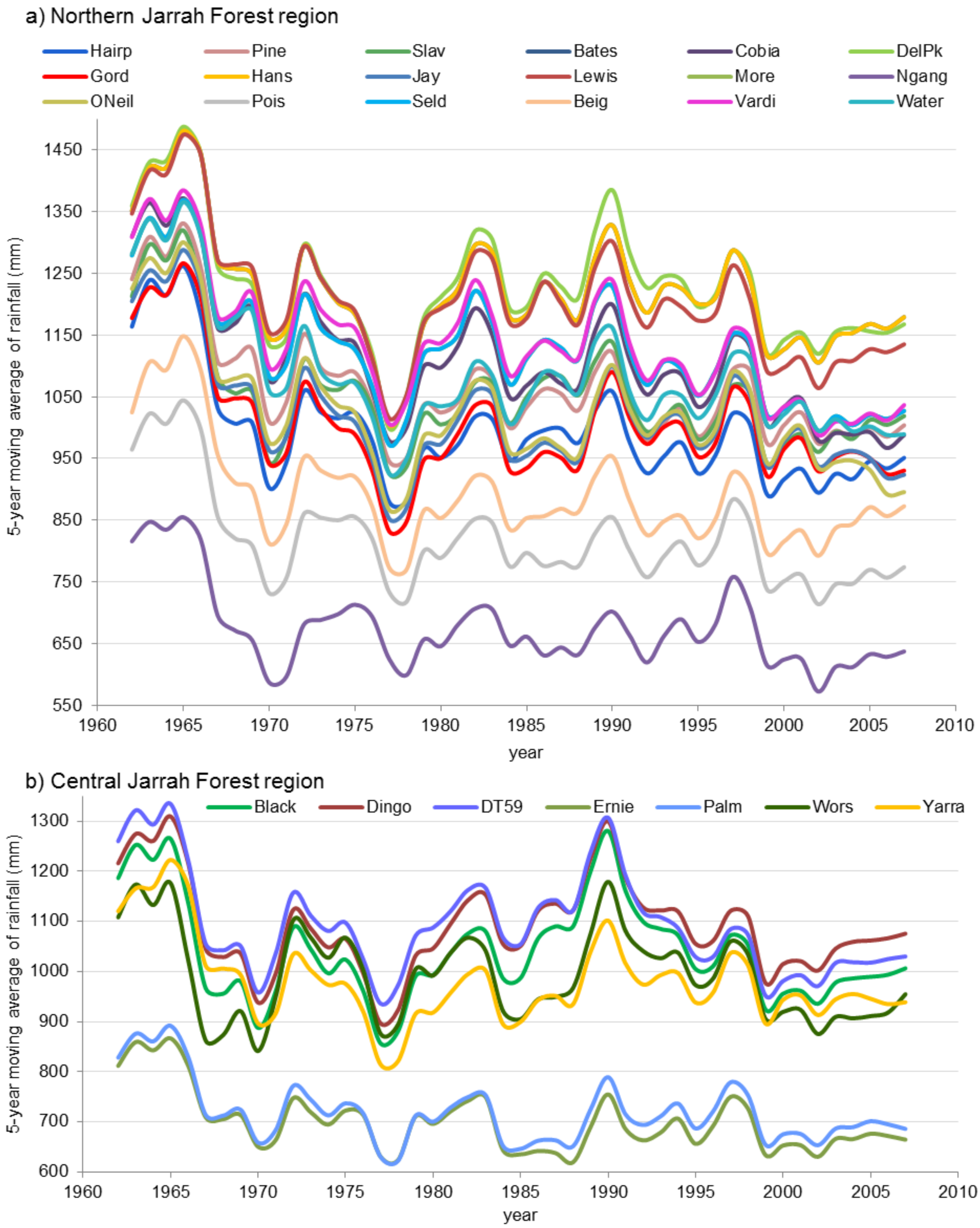


Figure 6 Differences in rainfall in the 2004–09 vs 1975–2003 periods across the study area


a) Northern Jarrah Forest region
Hairp
Pine
Slav
Bates
Cobia
DelPk
Gord
Hans
Jay
Lewis
More
Ngang
ONeil
Pois
Seld
Beig
Vardi
Water
5-year moving average of rainfall (mm)
1450
1350
1250
1150
1050
950
850
750
650
550
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
year
b) Central Jarrah Forest region
Black
Dingo
DT59
Ernie
Palm
Wors
Yarra
5-year moving average of rainfall (mm)
1300
1200
1100
1000
900
800
700
600
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
year

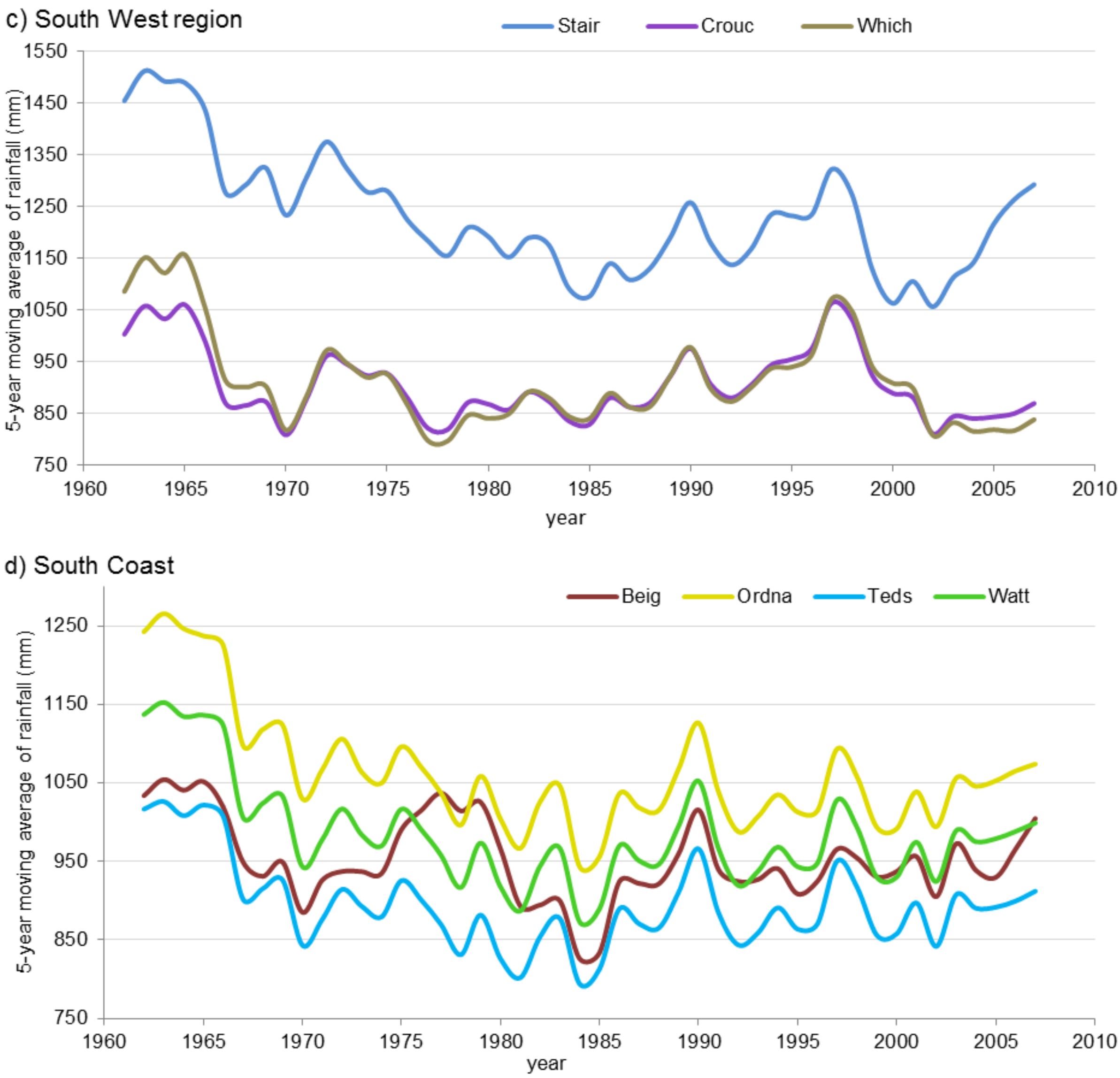


Figure 7 5-year moving rainfall averages across the study area

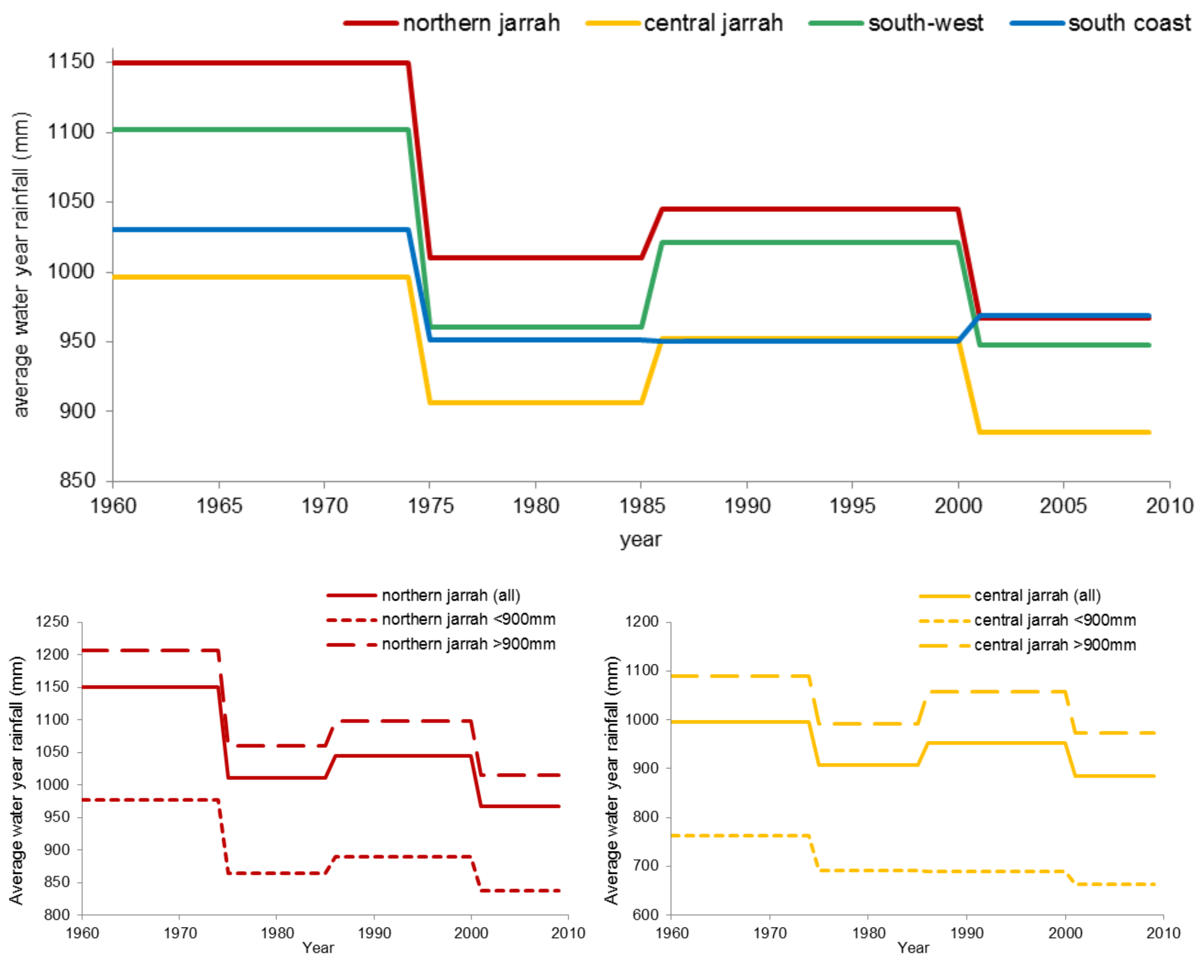


Figure 8 Annual rainfall averages for selected periods across the study regions

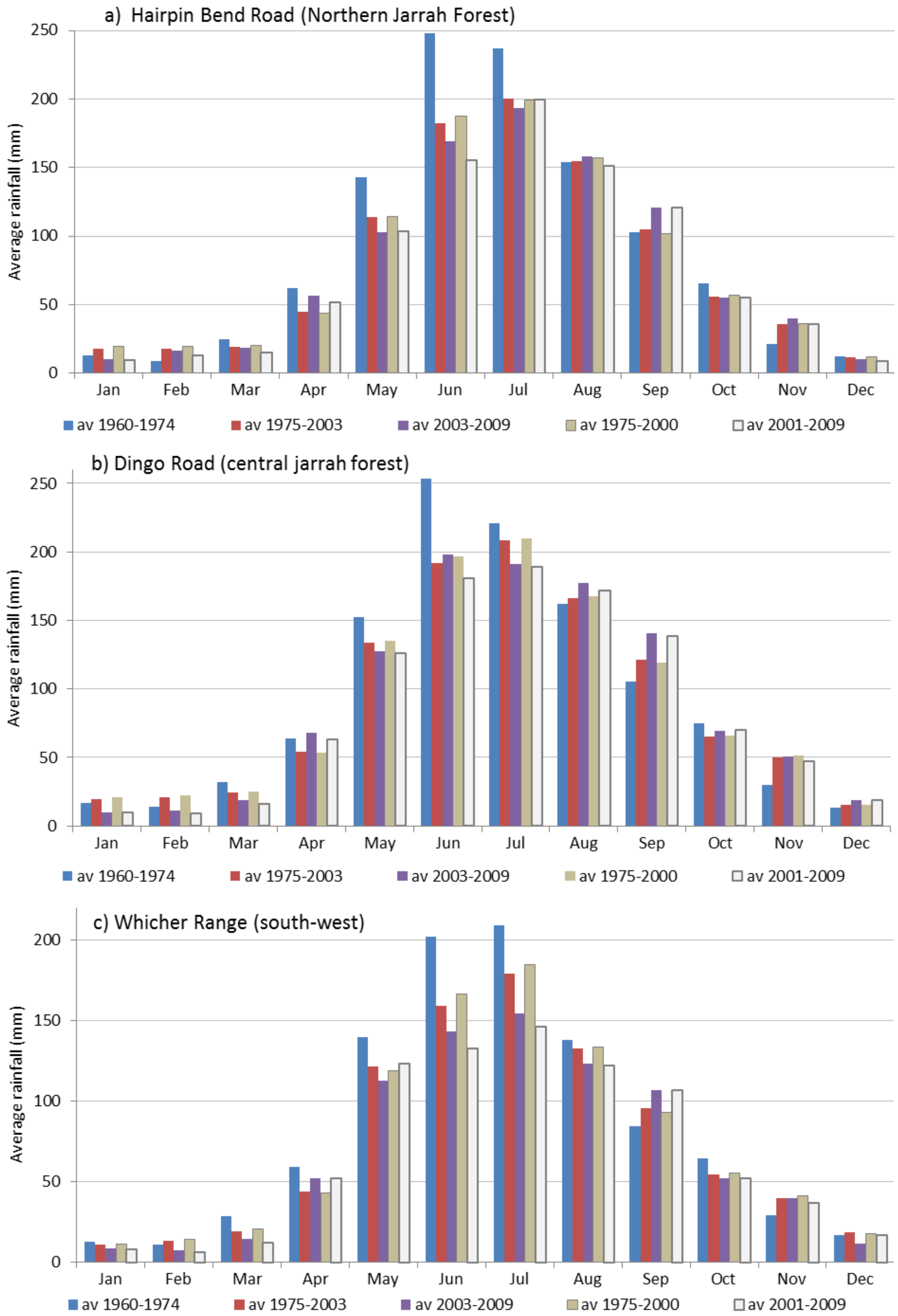
3.2 Temporal patterns of rainfall

Monthly rainfall distributions

Figure 9 shows the monthly patterns of rainfall for four selected catchments across the study area. The decline in early winter (May–July) rainfall in the mid 1970s reported by IOCI (2002) is obvious in most cases. In all cases, April and September were wetter in the recent period (2003–09 and 2001–09) compared with the preceding period. These increases resulted in a partial reversal of the April declines observed since 1975 and a continuation of the slight increases observed for September since 1975.

The May, June and July decline reported since the mid 1970s was followed in most areas by a further decline in average rainfall for those months in the recent period. January, February and March were drier in the recent period relative to the preceding period, while December was somewhat wetter. August and October showed conflicting trends across the geographical distribution of the catchments, and November was generally stable.

For comparison the periods displayed in Figures 9a–d reflect both management timeframes (2003–09) and periods with streamflow declines (1975–2000 and 2001–09).


a) Hairpin Bend Road (Northern Jarrah Forest)
Average rainfall (mm)
0
50
100
150
200
250
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
av 1960-1974
av 1975-2003
av 2003-2009
av 1975-2000
av 2001-2009
b) Dingo Road (central jarrah forest)
Average rainfall (mm)
0
50
100
150
200
250
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
av 1960-1974
av 1975-2003
av 2003-2009
av 1975-2000
av 2001-2009
c) Whicher Range (south-west)
Average rainfall (mm)
0
50
100
150
200
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
av 1960-1974
av 1975-2003
av 2003-2009
av 1975-2000
av 2001-2009

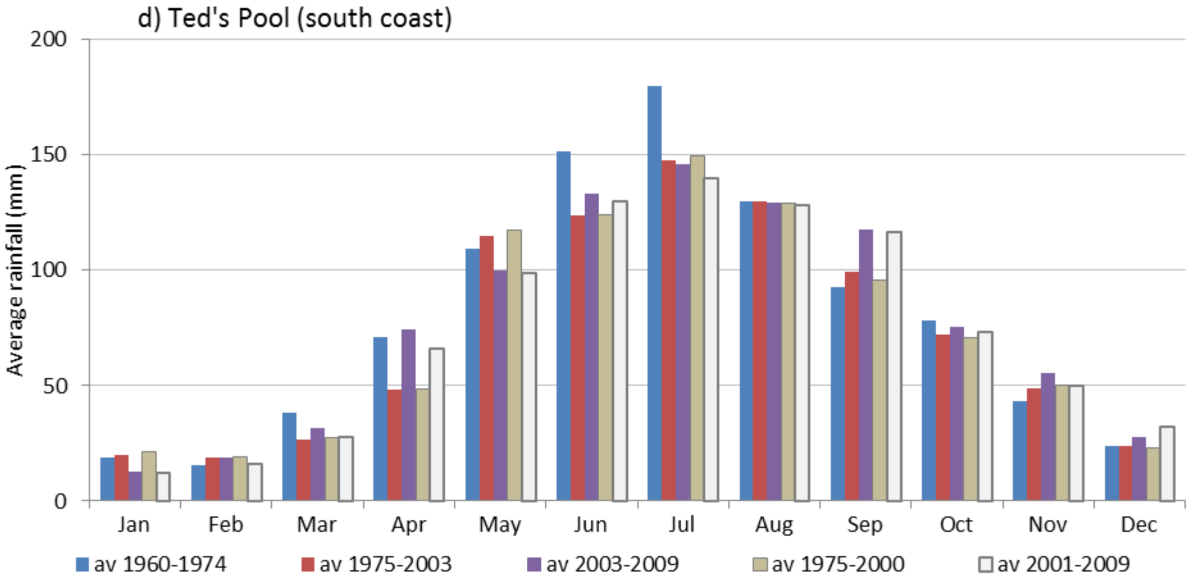


Figure 9 Monthly rainfall distributions for a selection of catchments across the study area

Rainfall intensity and periodicity

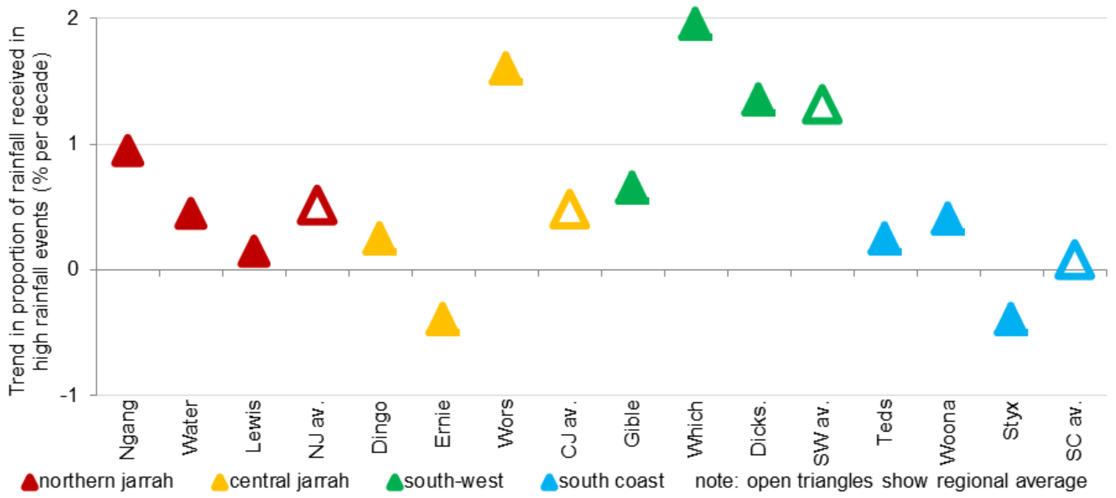
Three continuously operating rainfall gauges (pluviometers) in each region were selected to maximise data availability and spread, geographically and across rainfall zones, while minimising distance from the study catchments (Fig. 2, Section 1 & Table 3, Section 2). Trends in the proportions of high intensity rain, hourly rainfall intensity, and rain hours were assessed for the full water year and for the 'wet season' – April to October of each year. Both sets of analyses revealed generally similar trends and only wet season trends are reported here as wet season rainfall is more significant for streamflow generation.

The proportion of total higher intensity rainfall (above 5 and 10 mm/hr) showed a positive trend in 83% of pluviometers over the recent three decades, with an average increase of 0.6% per decade for the 10 mm threshold (Fig. 10a). Average rainfall intensity also increased (Fig. 10b), particularly between the periods 1980–89 and 1990–99 (Fig. 10). This finding is in agreement with those of Raiter (2012) but in contrast with most other findings in the literature of decreases in rainfall intensity. However, these findings are based on hourly-scale analyses which have been found, in the case of intensity trends, to contrast with findings at the daily time scale (Raiter 2012).

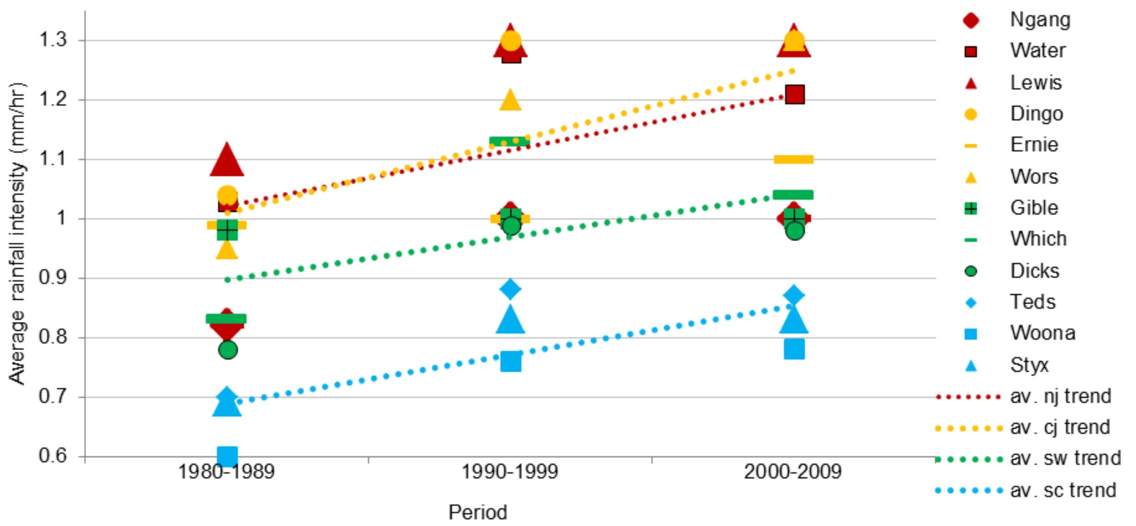
This increase in hourly intensity was matched by a reduction in the rain hours during the wet season, decreasing by approximately 200 hours from 1980 to 2009 – a drop of more than 20% (Fig. 10c).

Overall, rainfall intensity also tended to be lower on the south coast (0.8 mm/hr), highest in the northern and central jarrah forest regions (both 1.1 mm/hr) and moderate in the south-west region (1.0 mm/hr). The proportion of rain received in higher intensity events followed the same trends.

a) Trend in proportion of high intensity (>10 mm/h) rainfall events



b) Average rainfall intensity



c) Trends in average number of rain hours per wet season over time

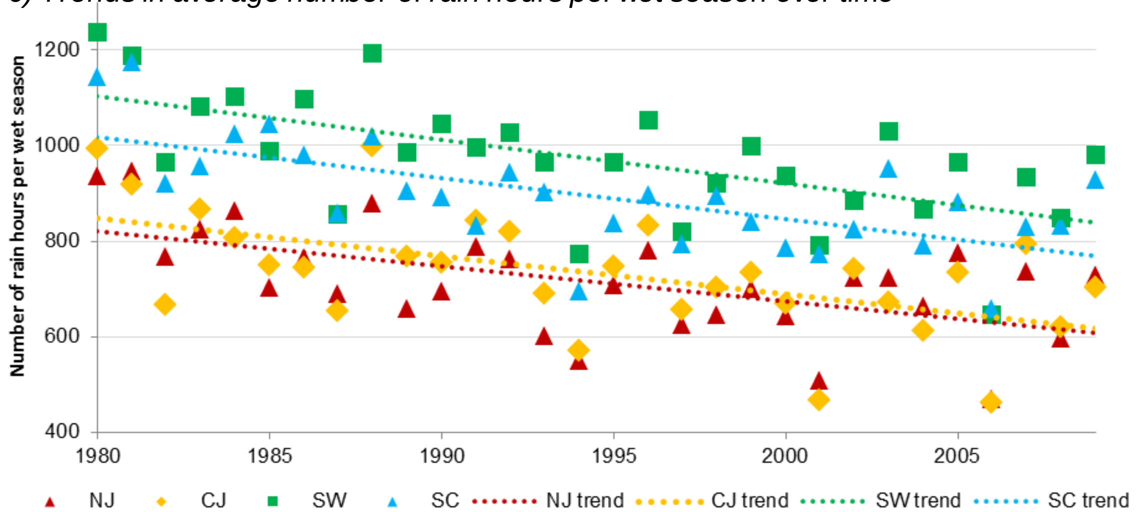


Figure 10 Trends in proportions of high intensity rainfall, av. rainfall intensity, and rain hours

The number of rain hours per wet season was highest in the south-west region, moderate on the south coast, and lowest in the central and northern jarrah forest regions.

Taken alone, the trends of increasing rainfall intensity and decreasing rain hours suggest the potential for increased runoff generation. When more rain falls within a set duration, a smaller proportion will be lost to interception and transpiration from the unsaturated zone and a greater proportion will consequently be available to infiltrate into the soil or flow overland if the soil is saturated. Increased infiltration results in increased groundwater recharge, formation of temporary perched aquifers and/or shallow throughflow and increased streamflow. Conversely, when rain falls over longer periods, and/or falls at lower intensities, more can be lost to interception or used from the unsaturated zone, with a smaller proportion likely to recharge groundwater and reach the stream. Rain was intercepted in tree canopies and on other vegetation surfaces and exposed to wind and sunshine and the evaporative demand of the atmosphere for an average of 200 fewer hours in 2009 than at the beginning of the 1980s. The extent to which the observed trends affect overall runoff generation is unknown but the effect of increasing rainfall intensity and fewer rain hours on streamflow is likely to be positive, if anything.

Thus, trends in rainfall intensity and periodicity may have somewhat ameliorated the effects of declining rainfall and a drier early-winter period on runoff coefficients and streamflows.

More work on understanding the distribution of rain events across the wet season, including the frequency and duration of intervening dry periods and in light of trends in total rainfall (see previous section), evaporation and temperature (see next section) would further elucidate the consequences of these trends for runoff coefficients, and thus streamflow.

Note that the time periods and sites assessed in this analysis vary from those used elsewhere in this report. This is due to the availability of pluviometer data – which was generally limited to the period from 1980 to the present, and to sites where rainfall is measured with a pluviometer, as opposed to being read daily.

3.3 Temperature and evaporation

Average daily maximum temperatures across the study area rose by about 0.5 °C during 1975–2009 while pan evaporation decreased slightly (Fig. 11). These findings agree with those of current literature on this subject (Donohue et al. 2010; Indian Ocean Climate Initiative 2012). It should be noted though that other trends have been observed for other aspects of temperature; for example, the mean maximum summer temperatures have also risen along the west coast of the south-west but decreased along the south coast (Indian Ocean Climate Initiative 2012).

The observed increases in temperature would most likely have increased transpiration as plants use transpiration to cool their leaves when water is available. This increased water use may have well exceeded the reduction in total catchment evapotranspiration resulting from the decline in evaporation.

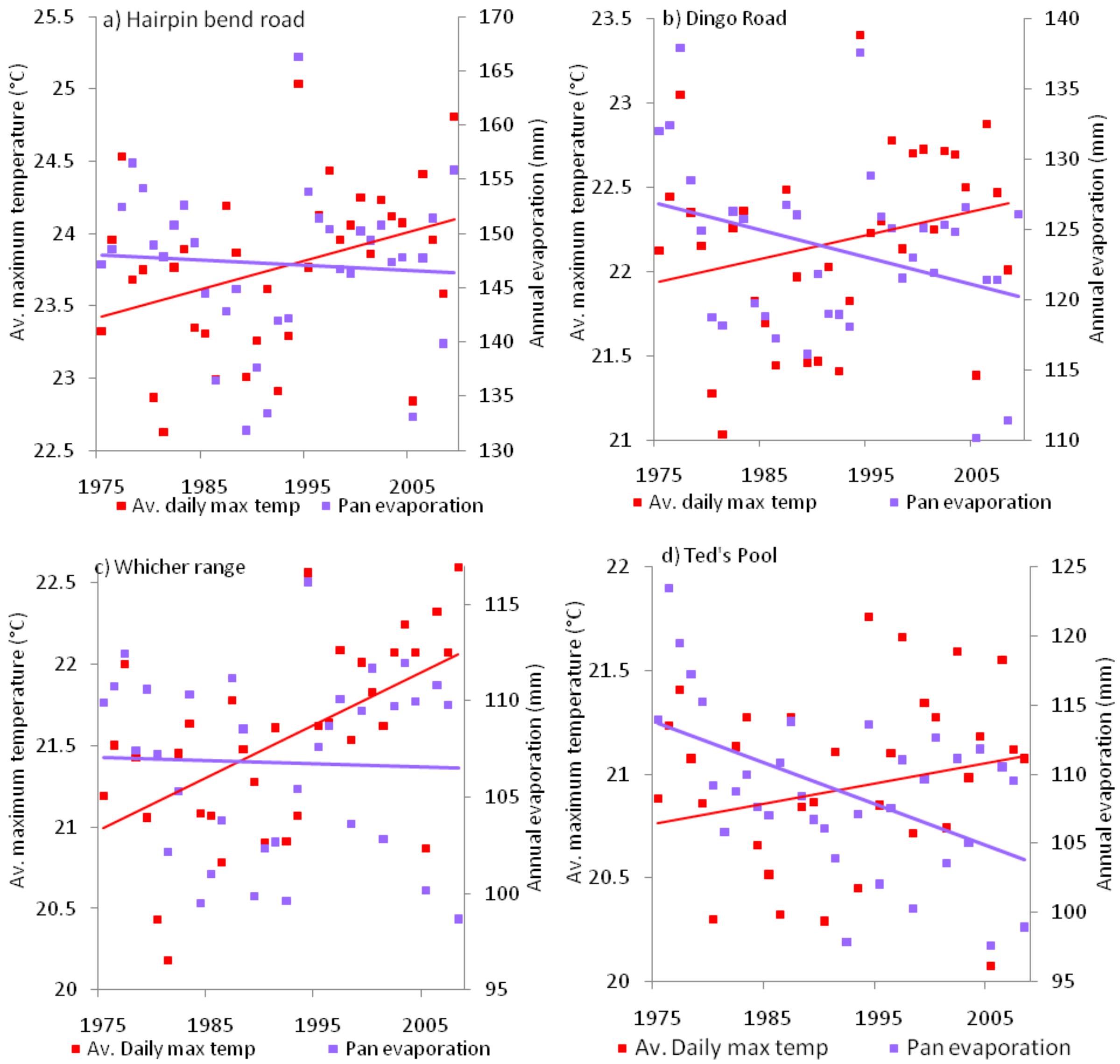


Figure 11 Temperature and evaporation trends at four catchments across the study region

3.4 Vegetation coverage

Changes in average catchment leaf area indices (remotely sensed) over the last three decades in all of the study catchments for which data was available are shown in Figure 12.

The leaf area index (LAI) is defined as the ratio of leaf surface area to unit ground surface area and is closely associated with transpiration and other water-use attributes of eucalypt forests (Hatton et al. 1998, Vina et al. 2011).

LAIs varied substantially over the years and across the catchments. Some catchments showed 'humped' or no overall trends, some showed decreasing trends and others showed increases.

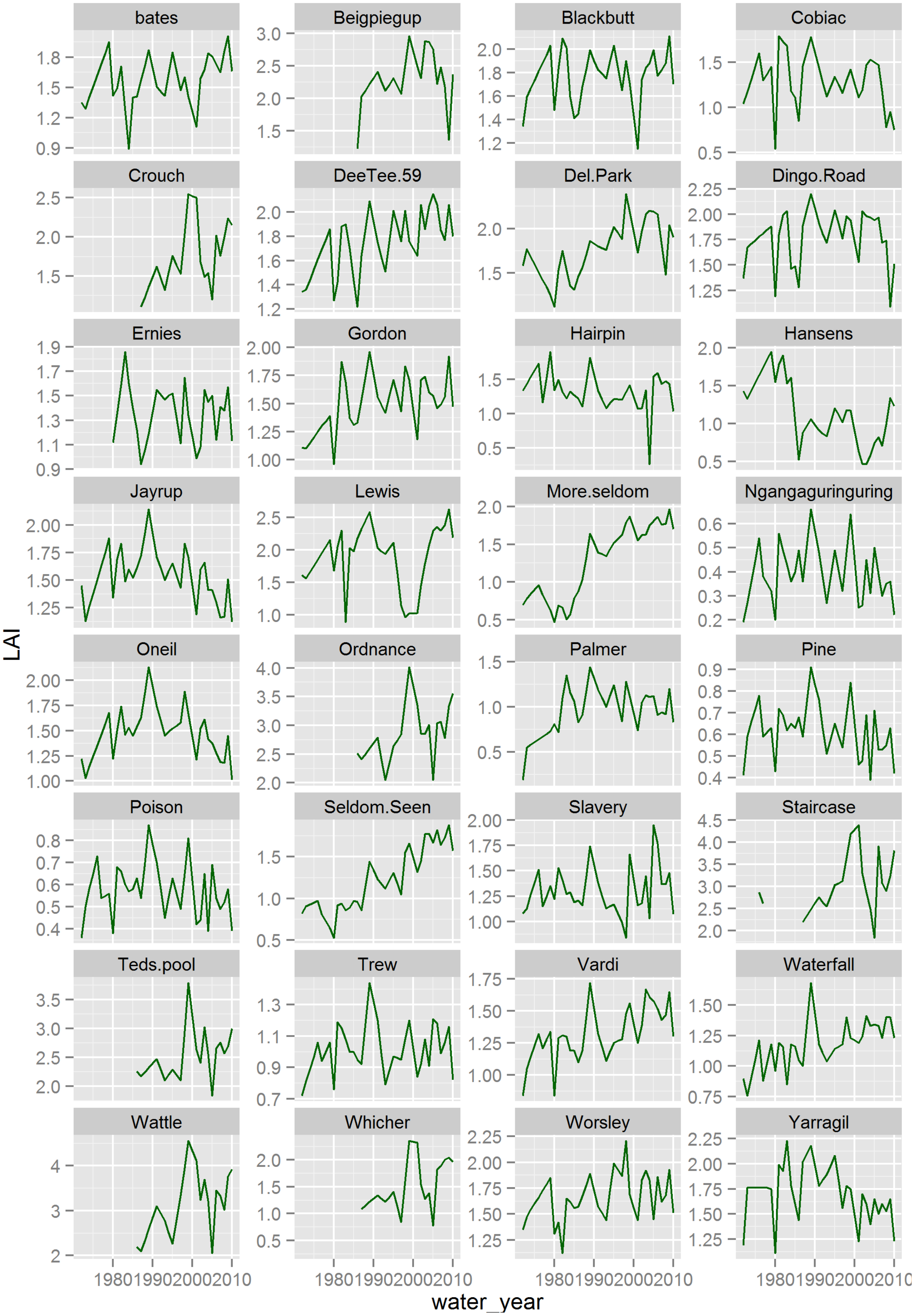


Figure 12 Average catchment leaf area indices over time in selected study catchments

4 Streamflow and groundwater trends

4.1 Total annual streamflow

Average annual streamflow during the period of the current FMP (2004–13) was 26% and 37% lower than during 1975–2003 in the primary and supplementary catchments respectively, with a range of 12–50% in the primary catchments. The one exception is a small supplementary catchment (Hansens) which was extensively mined and subjected to forest thinning and where average annual streamflow increased by 29% during the 2004–09 period compared with 1975–2003 (Fig. 13).

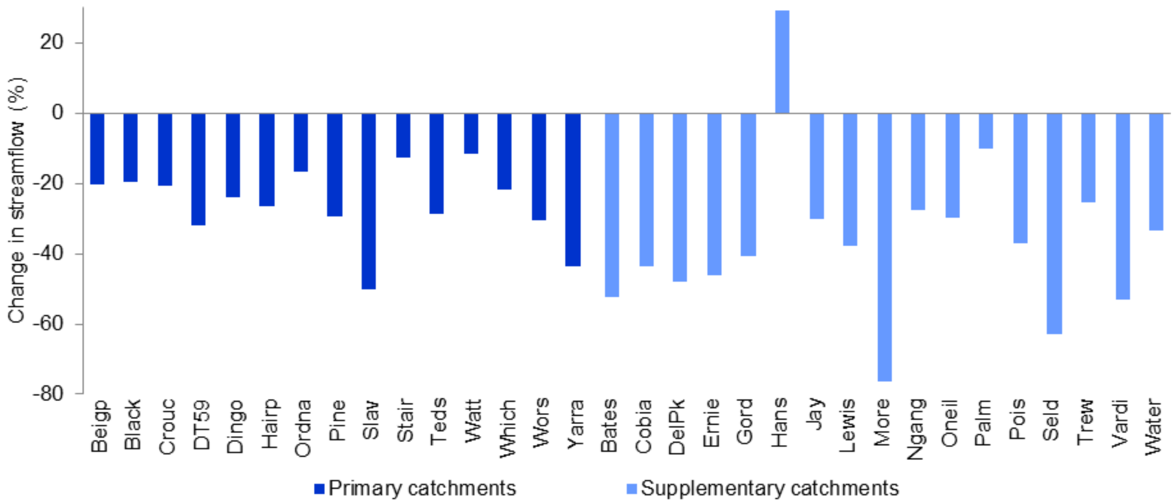


Figure 13 Streamflow changes between the 1975–2003 av. and 2004–2009 periods

Average annual streamflows in all regions declined: declines were greatest (averaging 47%) in the northern jarrah region, 29% in the central jarrah region, and 23 and 25% respectively in the south-west and south coast regions.

Average annual streamflows have varied considerably from decade to decade. Most catchments had relatively high annual streamflows in the pre-1975 period (where records exist), low flows associated with low rainfall in the late 1970s and early 1980s and medium to high flows in the late 1980s to early 1990s, followed by low flows since the late 1990s and into the period of the FMP. This widespread pattern mirrors the pattern in the rainfall record and indicates that climate variability is, in most cases, the dominant driver of streamflow variations and the recent streamflow declines (Fig. 14). Groundwater levels mirrored the climatic pattern in streamflow records and declined in the recent decade. Other factors, including increasing vegetation coverage in some catchments, are discussed below.

In many catchments, streamflows in the recent decade are the lowest recorded. While streamflows during the FMP period are, in most cases, lower than the 1975–2003 average, a statistically significant declining trend (Table 5) cannot always be identified because the large variations in annual streamflow reflect large annual variations in rainfall.

For some catchments, successive changes in forest structure and rising LAI (remotely sensed) indicate that historical forest management practices may have exacerbated climate-influenced streamflow decline. These tend to be the catchments where large proportions of their areas were harvested intensively early last century (before the regulatory controls were introduced in the 1930s by the former Forests Department) and subsequently thinned in the 1960s or 1970s. Their earlier management has resulted in extensive areas of regrowth forests still in immature to early mature stages of growth with relatively high leaf area and consequently relatively high water use (D Maher pers. comm. Senior Silviculturalist, Department of Environment and Conservation 2010).

Although most catchments have experienced declining streamflows in recent times, and climate is considered to be the major driving influence, they have not responded uniformly and the presence or strength of trends has varied over time. To show the broad differences between the streamflow responses and suspected influences, the catchments are broadly grouped into the categories shown in Table 5.

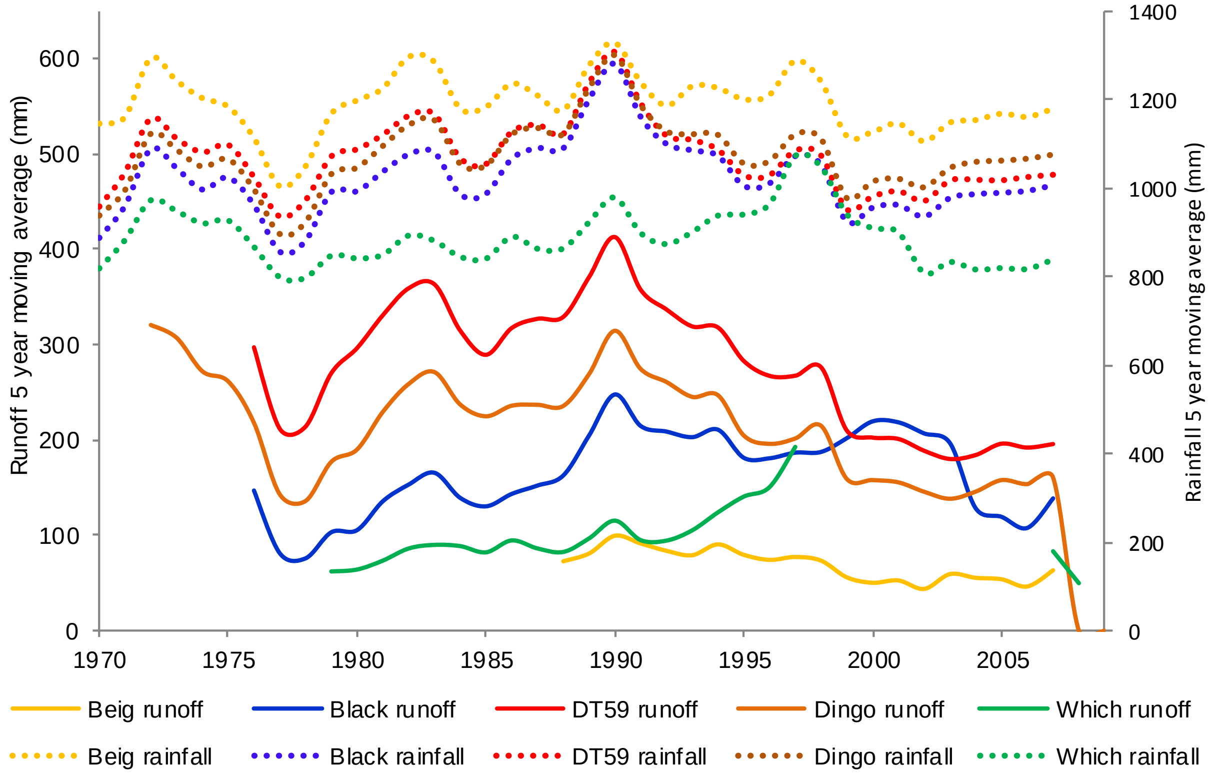


Figure 14 Moving averages showing trends in rainfall and runoff for selected catchments

Table 5 Summary of flow trends and groupings for the study catchments

Primary catchments (15)	Streamflow 1975–2003 (ML)	No-flow days 1975–2003	Stream-flow 2004–09 (ML)	No-flow days 2003–09	Trend (direction, type*, significance)	Trend category
Black	6351	12	5107	11	-, -, -	Climate pattern dominant – no overall streamflow trend
Crouc	6472	174	5125	192	-, -, -	
Hairp	823	233	605	246	-, -, -	
Pine	3255	216	2300	232	-, -, -	
Watt	2182	144	1930	139	-, -, -	
Beig	3656	89	2913	124	↓ -, -	Climate pattern dominant – streamflow decline observed
Ordna	41085	46	34208	48	↓ -, -	
Stair	7119	0	6231	0	↓ -, -	
Teds	37308	80	26659	108	↓ -, -	
Wors	5132	63	3576	100	↓ -, -	
Yarra	1615	181	911	212	↓ b, 0.05	
Dingo	30882	3	23459	3	↓ c, - -	Climate pattern present, streamflow decline possibly exacerbated by increasing vegetation cover
DT59	8256	0	5627	9	↓ abc, 0.1	Climate pattern present, streamflow decline exacerbated by increasing vegetation cover.
Slav	1682	183	840	210	↓ b, 0.1	
Which	1656	176	1294	183	-, -, -	Further investigation required – unusual similarity in rainfall – runoff relationship over time. Appears to follow rainfall pattern.
Supplementary catchments (17)						
Jay	770	241	539	256	-, -, -,	Climate pattern dominant – no overall streamflow trend.
Bates	429	0	204	<1	↓ abc, 0.01	Climate pattern dominant – streamflow decline observed.
Cobia	322	204	181	242	↓ b, 0.01	
Ernie	14	327	7	333	↓ - , -	
Trew	755	217	564	237	↓ -, -	
Water	2101	0	1402	0	↓ ab, 0.1	
DelPk	231	53	120	139	↓ ab, 0.01	Climate pattern present, streamflow decline exacerbated by increasing vegetation cover
Gord	22	272	13	290	↓ -, -	
More	702	18	165	183	↓ abc, 0.01	
Seld	1619	0	599	11	↓ ab, 0.01	
Vardi	11846	0	5567	73	↓ ab, 0.01	
Hans	135	29	174	0	↑ ab, 0.01	Climate pattern present, clearing and/or intensive thinning have stabilised or increased streamflows.
Lewis	217	12	135	38	↑ a, 0.1	
Ngang	1755	0	1273	0	-, -, -	
O'Neil	4571	211	3211	238	-, -, -	
Palm	5447	232	4902	234	-, -, -,	
Pois	4949	191	3118	202	-, -, -,	

* a = Significant trend detected by Mann-Kendall or Spearman's Rho tests (Chiew & Siriwardena 2005)
b = Significant step-change, detected by Rank Sum or distribution-free CUSUM tests
c = Shift from perennial to intermittent flow observed

Note: based on past observations. Some catchments have been mined recently or their forests thinned and their categorisation might change in coming years. Some catchments in which the climate trend is dominant have forest that have actually been thinned or otherwise significantly harvested, but these actions have had little extended impact on streamflows.

The sustained decreases in rainfall over the past three decades is the dominant, although not sole, factor driving the observed streamflow declines and the trend observed over the FMP period is a continuation of the well documented overall trend which began in the mid 1970s. Under the current climatic regime, the catchments are all likely to be at different stages of groundwater–stream zone disconnection. This disconnection is a major factor implicated in streamflow decline and supported by a growing body of scientific research and the groundwater data. Groundwater connection to the stream zone is first lost high in the landscape. This may explain the larger streamflow declines observed in the northern jarrah forest supplementary catchments which are generally first-order catchments high in the landscape.

After rainfall, the next most significant factor implicated in the observed streamflow declines is increased vegetation cover in some catchments within the northern jarrah forest. Increasing vegetation cover is largely associated with changed forest structure due to historical timber harvesting practices (mainly before the 1930s) and mine-site rehabilitation (Silberstein et al. 2011) and is indicated by increases in the derived estimates of LAI. The streamflow decline in the north of the FMP area, where there has been bauxite mining and a longer and more intensive history of timber harvesting, is thus greater than in the south.

In the south of the FMP area, evaporation is lower and there is generally a shorter and less intense history of timber harvesting. In addition, the southern rainfall decline was weaker than in the north, and the south coast appears to have even experienced increased rainfall in the recent decade (Fig. 6, Section 3).

In many catchments, particularly in the north, streamflow decline has been characterised by groundwater systems disconnecting from streams, longer no-flow periods, and/or a transition from perennial to intermittent flow regimes (Kinal & Stoneman 2012). Streamflow generation is a complex process and for each catchment results from a different combination of influences which include geology, topography, soil type, vegetation type, health, structure and management history.

In addition to the gradient from north to south, there is also a gradient of increasing streamflow decline from higher rainfall areas in the west to lower rainfall areas further east. The mechanism driving this trend is considered to be the disconnection of streams from groundwater systems (Hughes et al. 2012).

4.2 Relationship between runoff and rainfall

The differences in the relationships between runoff and rainfall are illustrated in Figures 15–18 for a selection of catchments. The runoff for a given volume of rainfall in the period 2004–09 is, in most cases, lower than the runoff for that same volume of rainfall during 1975–2003. Also illustrated are changes in the runoff coefficient, rainfall, and LAI where data is available. A full overview of each catchment is presented in Appendix A.

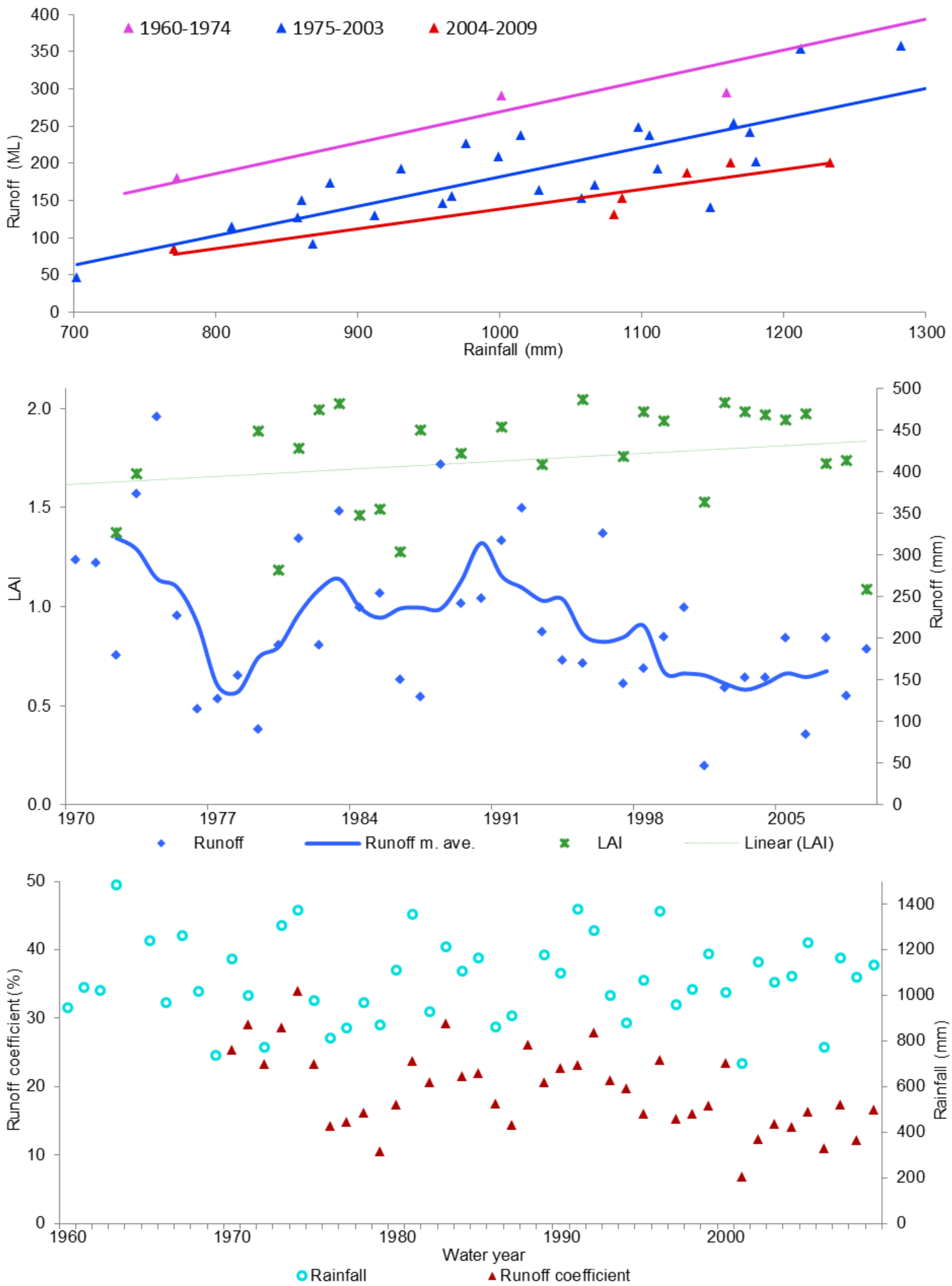


Figure 15 Rainfall-runoff relationships, runoff trends, and coefficients for Dingo Road

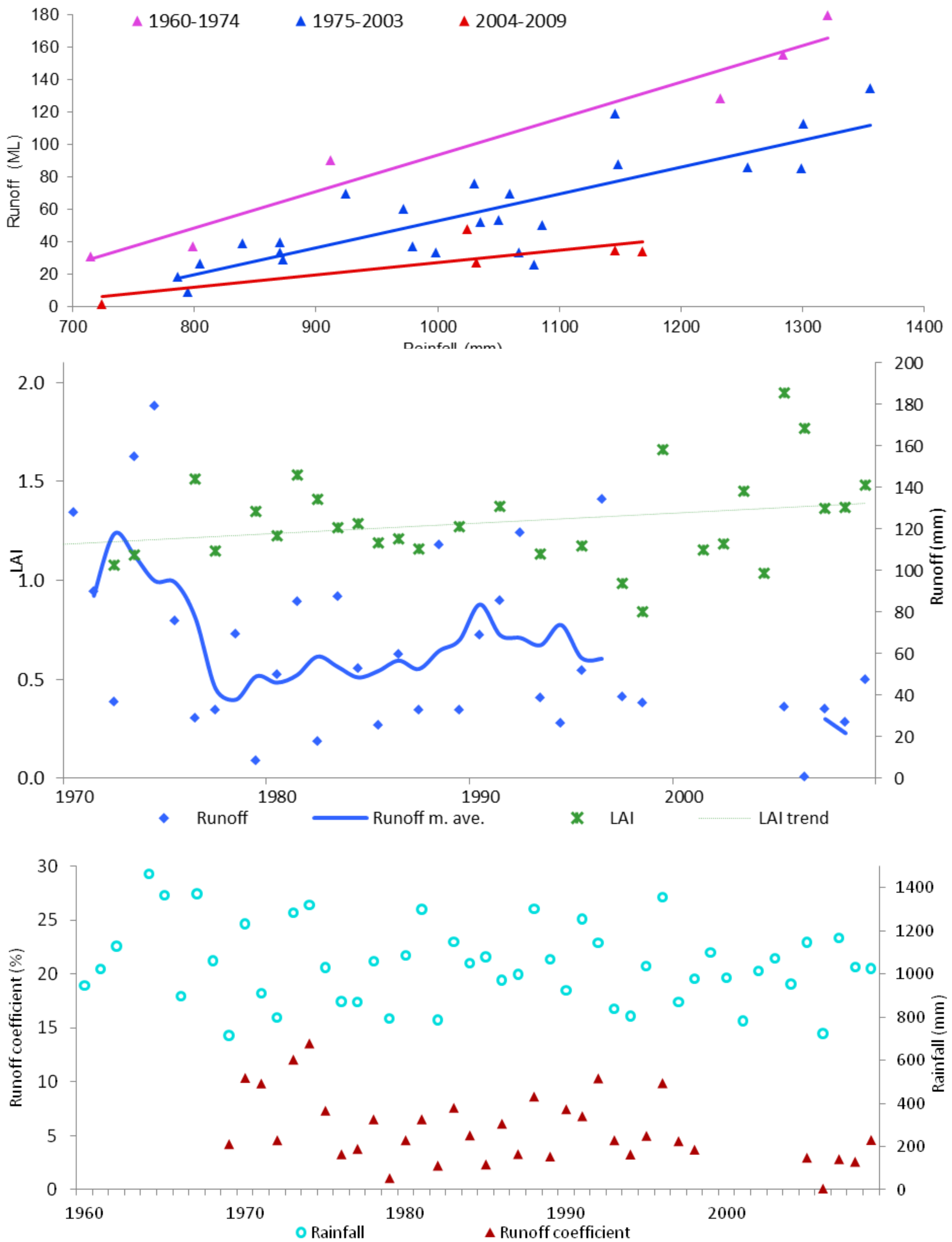


Figure 16 Rainfall-runoff relationships, runoff trends, and coefficients for Slavery Lane

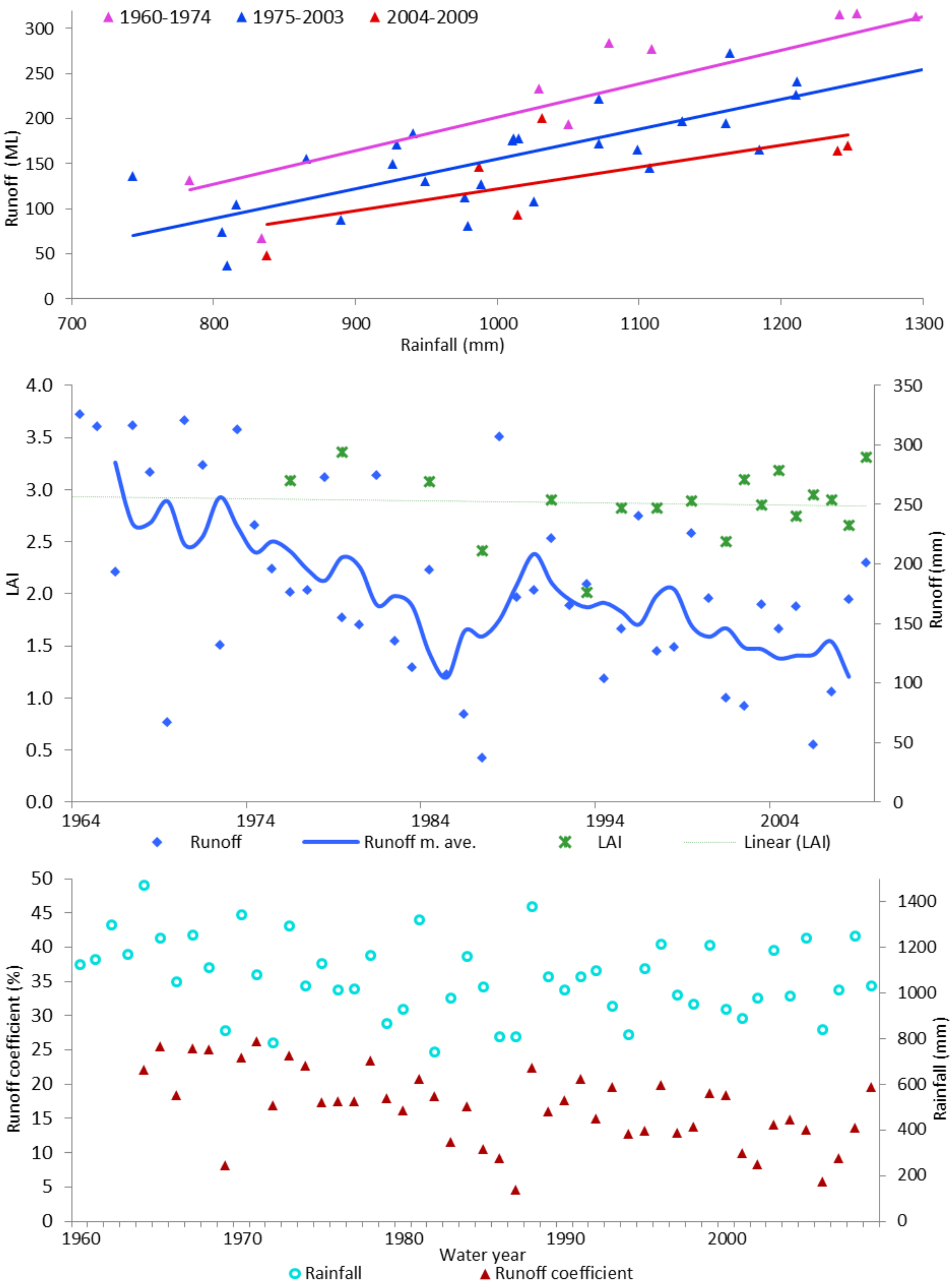


Figure 17 Rainfall-runoff relationships, runoff trends, and coefficients for Ordnance Road

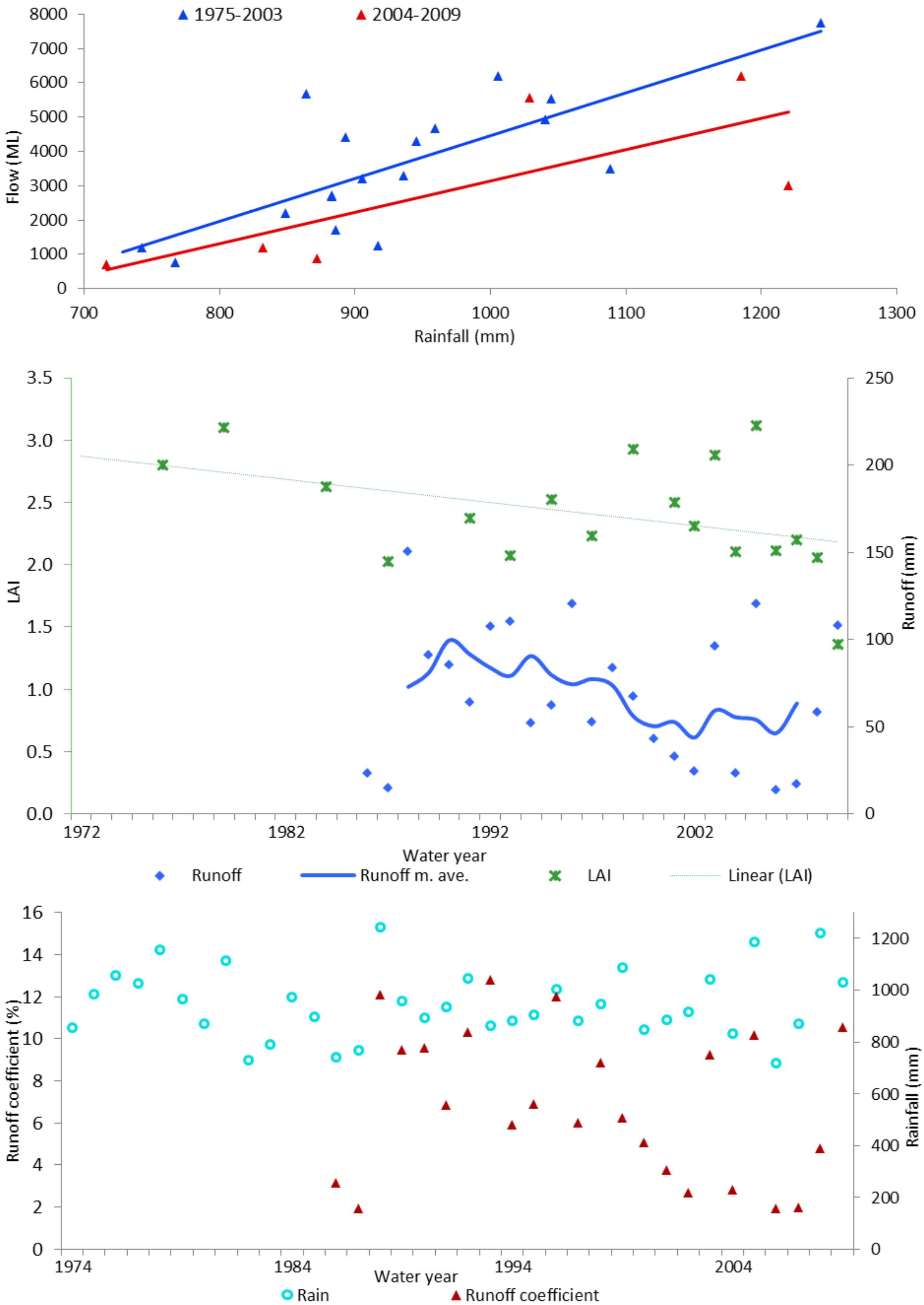


Figure 18 Rainfall-runoff relationships, runoff trends, and coefficients for Beigpiegup

4.3 Flow regime

Flow duration curves, based on daily distribution of flow, can show changes in other ecologically significant aspects of the flow regime that are masked by summing daily flows into annual totals.

Important aspects of the flow regime include maximum flows and high-flow periods (important for scouring out river pools), no-flow periods, and low-flow periods.

Flow duration curves for each catchment are shown in Appendix A. Key points include the shift from perennial to intermittent flow regime in some streams and changes in the annual number of no-flow days per year as indicated in Table 5 (Section 4.1).

Several streams have experienced major changes in streamflow pattern. One primary stream, DeeTee59, shifted from perennial to intermittent in 2004–09 (Fig. 19). A second primary stream, Dingo Road, became intermittent in 2001 (before the FMP; Fig 20). Three supplementary streams, Bates, Seldom Seen, and Vardi Road, shifted from perennial to intermittent flow during the FMP, and another (More Seldom Seen) lost its perennial flow in 1998. Streams in one primary catchment (Pine plantation) and in four supplementary catchments (Cobiac, Ernies, Gordon and Poison Lease) did not flow at all in 2010, although this year was not included in the analysis as the full water year data was not available when the analysis was undertaken. Flow duration curves and other representations of flow for all catchments are presented in Appendix A. The no-flow period increased by an average of about two weeks across the catchments, and average annual daily maximum flow decreased by 22%.

While trends vary, the flow decline is evident regardless of location or management history from Wattle block in the south, an almost entirely old-growth forest dominated by karri trees, to the jarrah forest in the north which has a history of disturbance from timber harvesting, mining and public access spanning more than a century.

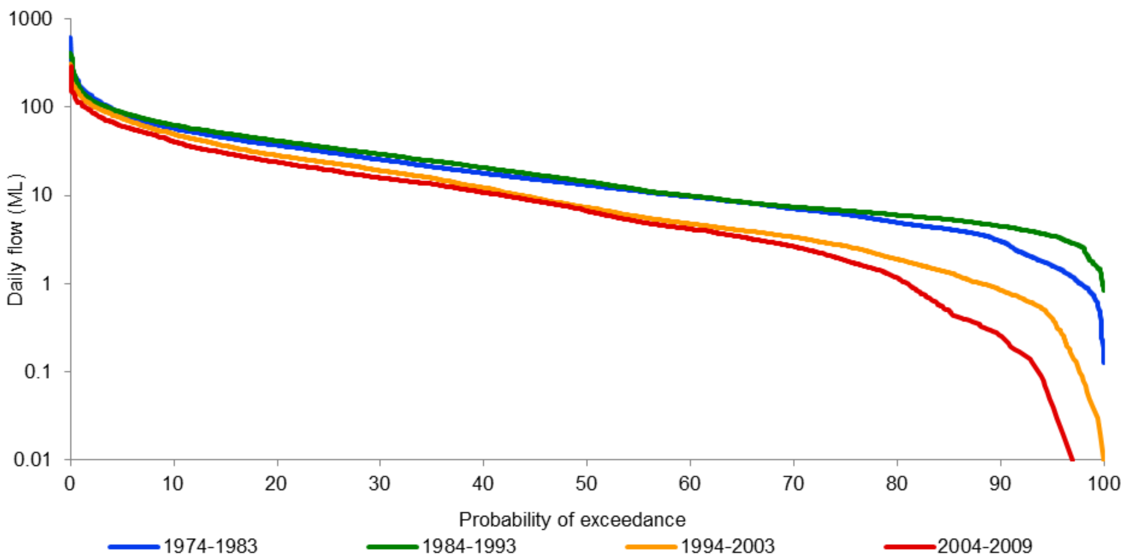


Figure 19 Flow duration curve for DeeTee 59 showing shift from perennial to intermittent

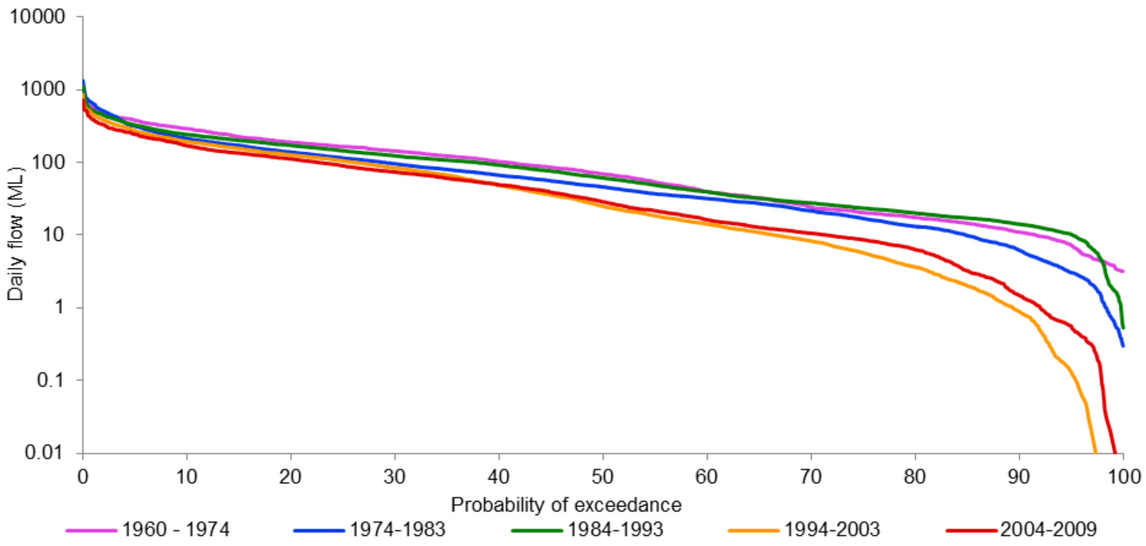


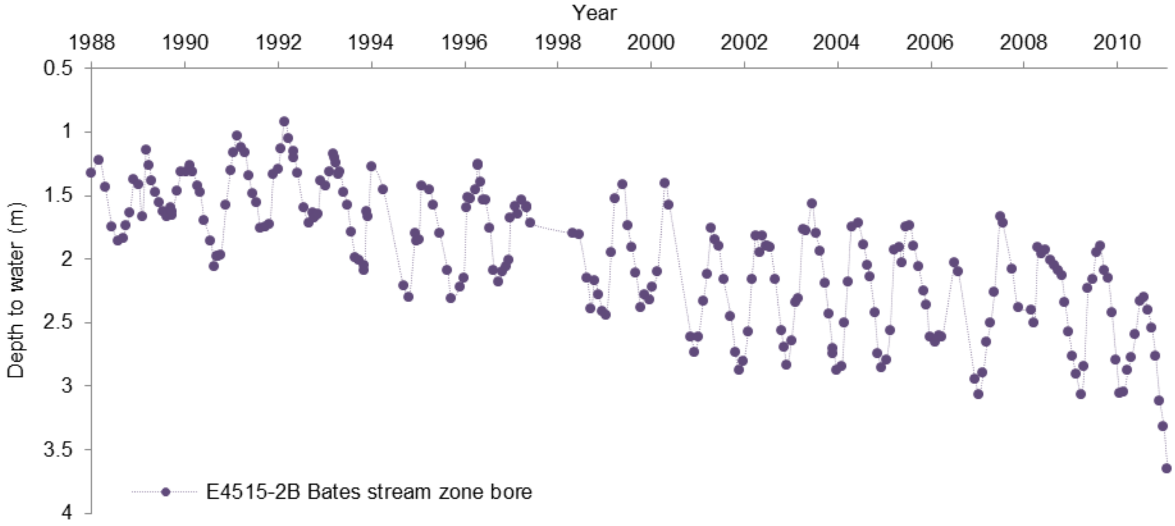
Figure 20 Flow duration curve for Dingo Road showing shift from perennial to intermittent

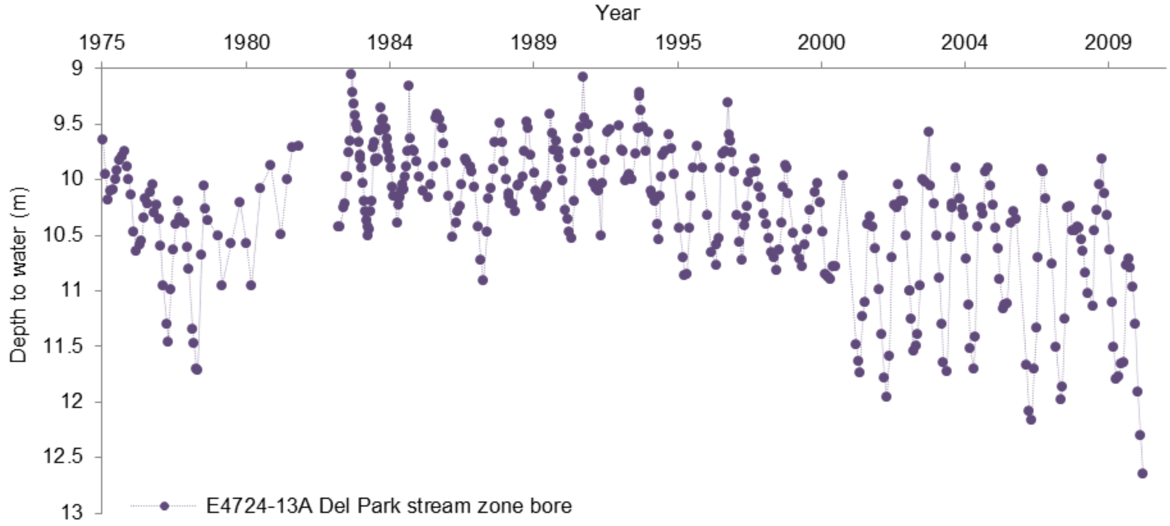
4.4 Groundwater

Groundwater data were extremely limited. Stream zone bore levels for the three supplementary catchments shown come from data supplied by Alcoa of Australia (Fig. 21). Groundwater trends in all cases followed respective catchment trends for streamflow and/or runoff coefficient while the rising groundwater levels in Del Park during the late 1980s and early 1990s followed mining in the catchment.

Estimated groundwater storage was calculated for the nine catchments with perennial or near-perennial flow (average no-flow period <30 days), using the technique described by Brutsaert (2008). This technique calculates groundwater storage above a zero-flow level, and therefore requires perennial or near-perennial flow; only seven catchments from the northern jarrah region, one from the central jarrah region, and one from the south-west region fit this criteria.

Groundwater storage estimates generally followed similar trends to those observed from actual groundwater data and streamflow although there was some variation (Fig. 22). Estimated storage declined in all except Hansens catchment, which had been mined. The decline estimated for Staircase Road, the only south-west catchment, appeared less than for the other catchments. The south-west region generally experienced only a slight decrease in rainfall compared with the 1975–85 period (Section 3.1) and smaller decreases in streamflow than those observed in the northern jarrah and central jarrah regions. It should be noted that Brutsaert groundwater storage estimates do not indicate actual groundwater levels but rather the minimum volume of water stored above the zero-flow level of the stream during each year. This volume, although reported in mm, does not directly refer to the groundwater level above the zero-flow level, as it does not incorporate catchment porosity, and refers to a theoretical average across the catchment.





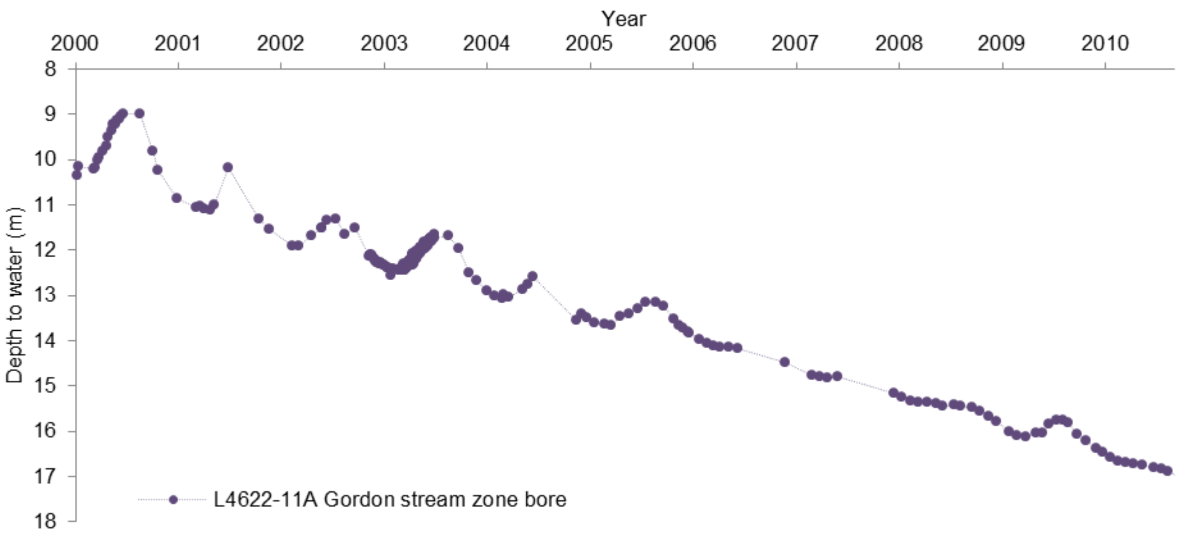


Figure 21 Depth to groundwater over time at three stream-zone bores

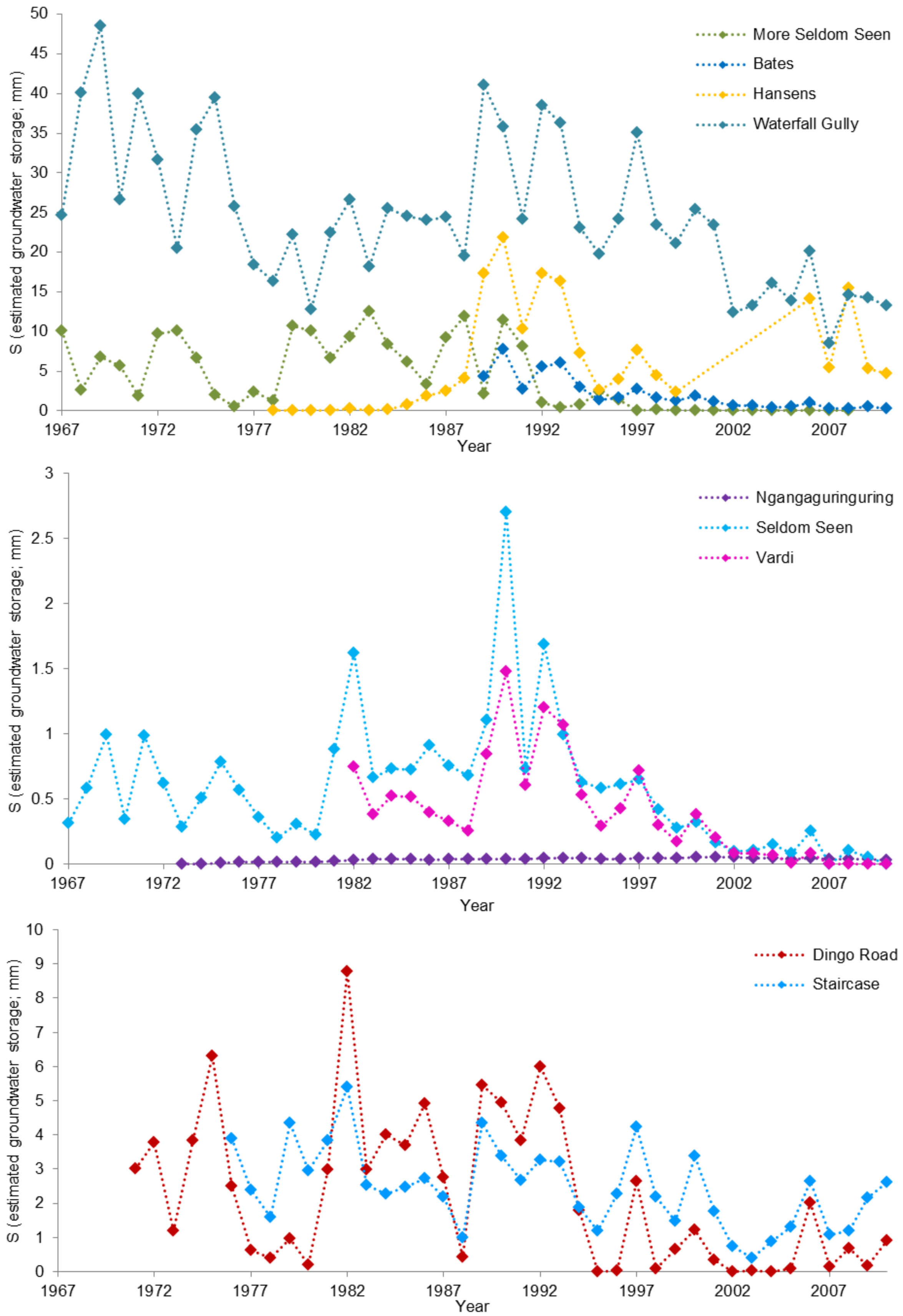


Figure 22a–c Groundwater storage estimated using the Brutsaert technique

5 Salinity trends

5.1 Trends in annual flow-weighted salinity

The selection of catchments in this analysis was initially targeted at catchments with long-term continuous records, almost no permanent clearing, and areas larger than 15 km^2. In the context of this KPI, areas of forest that have been harvested and regenerated or areas that have been mined and rehabilitated are not considered to have been permanently cleared. Catchments with 2% or less of their area permanently cleared are considered to be close to fully forested. Low salinity or 'fresh' water is defined as having less than approximately 500 mg/L TDS. A change of salinity less than 30 mg/L between periods was considered 'no change' to allow for measurement error.

The availability of good quality data presented a challenge in reporting on this KPI. Many stations with near-complete, long records were closed during the last 20 years and while a proportion were reopened some years later, gaps in observations remain. Others remain closed and we couldn't use their records at all. Under current budget cuts additional stations may be closed, which may limit the availability of data records for future assessment purposes.

Although continuous data provide the most accurate calculations of flow-weighted salinity, discrete data (a series of 'once off' measurements) were used in the absence of continuous data. With the scarcity of good salinity records, some catchments with more than 2% permanently cleared areas or smaller than 15 km^2 in area were included (Fig 23).

The low salinity in streams within fully forested catchments has been maintained, meeting the target for salinity trends to be neutral. Figure 24 shows that these streams are fresh with salinity well below 500 mg/L. Although statistically significant trends exist, the magnitude of these is very small – with differences between the FMP and the historical period generally less than 40 mg/L. All streams that were consistently fresh at the start of monitoring remained fresh for the monitored period. Although all the catchments have a history of timber harvesting spanning more than 100 years, there was no detectable impact of timber harvesting or other forest management activities on stream salinity in the fully forested catchments.

In streams with more than 2% of the catchment area permanently cleared, the salinity was often higher (Table 6) and more variable (Fig. 25). Catchments with clearing on the lower slopes (even if only a small percentage of the total catchment area) have higher stream salinities: higher than 200 mg/L, and up to 2000 mg/L, while fully forested catchments have stream salinities around 100–200 mg/L. The salinity is due to mobilisation of salts in the soil by rising groundwater. The variability is most likely to be related to seasonal–decadal changes in these salts being accumulated or flushed from the catchments. The Palmer catchment, 5% cleared, has streamflow that has oscillated around the freshwater limit for most of its record but has been well below this limit since 2002. The two most northern catchments, Ngangaguringuring and Poison Lease, have had marginal–brackish stream salinities for most of their recorded histories.

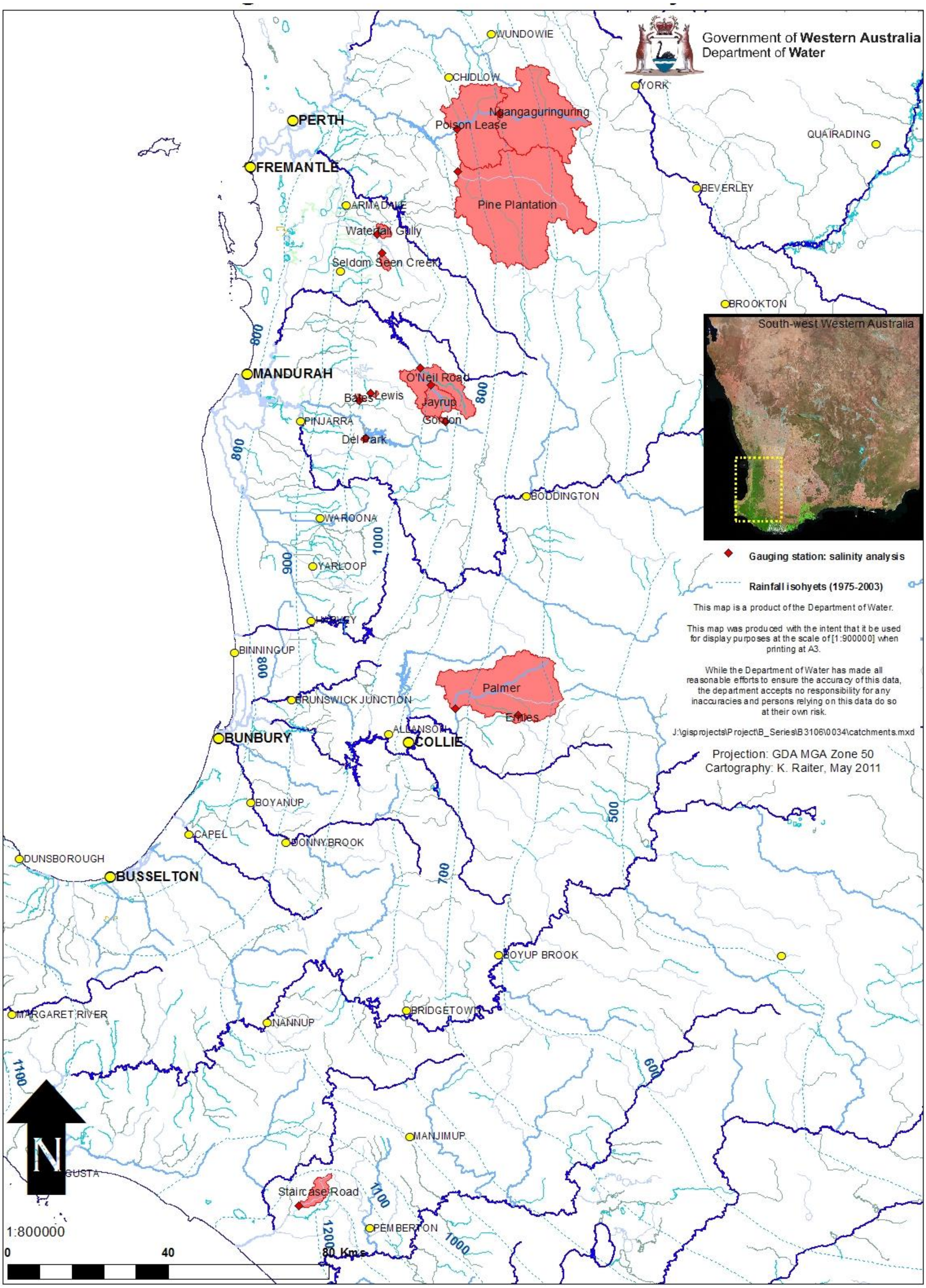


Figure 23 Catchments included in salinity trends analysis for KPI 19

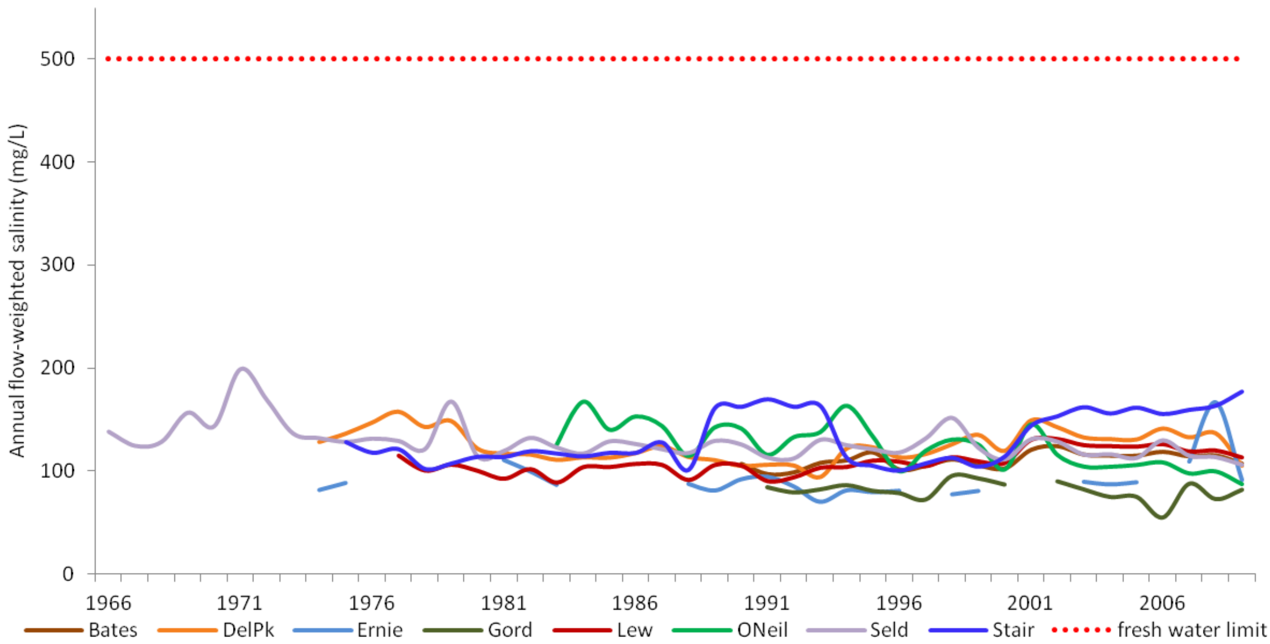


Figure 24 Flow-weighted salinity for catchments with less than 2% permanent clearing

These catchments are both approximately 6% cleared, and extend eastward into the low rainfall zone where soil salt stores can be very high. The salinity in the Poison Lease catchment appears to have stabilised in the recent decade. Salinity at Ngangaguringuring catchment steadily rose in recent decades but appears to have stabilised and may even be decreasing in recent years.

Table 6 shows salinity trends for the assessed catchments, data reliability and possible reasons for the observed trends. In catchments where stream salinity is falling, this is generally considered to result from falling groundwater levels caused by decades of below-average rainfall. When the groundwater level falls below the stream level, the saline groundwater contribution to streamflow is reduced or ceases.

In catchments where stream salinity has risen, this may be because there is less fresh surface flow and interflow to dilute the saline groundwater.

A lower confidence was attributed to data derived from discrete sampling records. Where discrete and continuous salinity data are available for an overlapping period, the two types were compared. Their similarities varied. This confirmed the importance of bearing reliability codes in mind when interpreting trends. A summary of the statistical analyses is shown in Table 7.

Overall, statistically significant increases in salinity were detected in 6 streams (43%), statistically significant decreases were detected in 7 streams (50%), and no statistically significant change was detected in 1 stream (7%). Disregarding changes of absolute magnitude of less than 30 mg/L between the 1975–2003 and 2004–09 periods (Table 6) leaves only two catchments with significant increases and four with decreases in annual flow-weighted salinity (Tables 6 & 7).

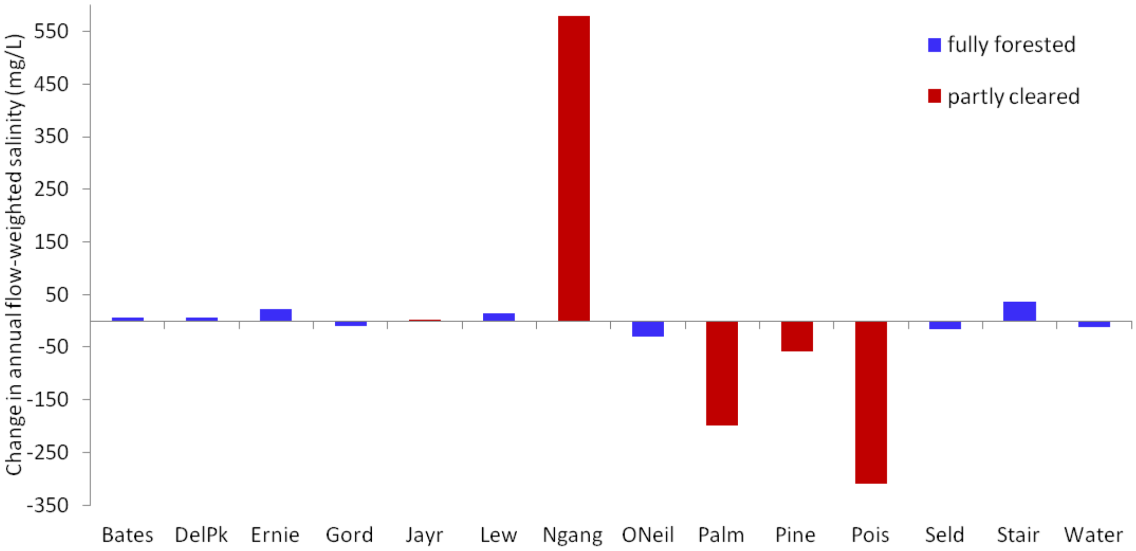


Figure 25 Flow-weighted salinity changes between 1975–2003 and 2004–09 averages

Table 6 Catchment clearing, salinity and possible reasons for trends

Catchment	Percentage permanently cleared (%)	Salinity 1975–2003 (mg/L)	Salinity 2004–09 (mg/L)	Salinity change between FMPs (mg/L)	Data reliability	Comments
Bates	0	109	114	+5	High	LAI increased.
Del Park	0	123	129	+6	High	Slight increase may be due to change from discrete to continuous data.
Ernies	0	86	109	+23	Medium	Unreliable trend, many no-flow years.
Gordon	0	84	75	–10	High	Vegetation coverage increasing'
Jayrup	4	76	76	0	High	Short period of record, streamflow appears to follow rainfall variation.
Lewis	1	106	121	+15	High	Mining. Salinity decreasing since 2001, soon after rehabilitation began.
Nganga-guringuring	6	1563	2143	+580	2000+: high, previous: medium	Affected by clearing in the catchment, which raised groundwater levels prior to 2000 (groundwater levels have fallen since 2001).
O'Neil	0	131	100	–31	1995+ high, Low previous	Possible disconnecting groundwater. Catchment recently mined.
Palmer	5	408	208	–200	1991+: high, previous: medium	Possible diluting effect from clearing in stream zones on stream salinity
Pine Plantation	4	246	188	–58	2000+: high, previous: medium	Possible declining groundwater. Streamflows follow rainfall variation.
Poison Lease	6	1153	843	–310	High	Possible declining groundwater.
Seldom Seen	2	131	116	–15	Medium	Declining groundwater
Staircase Road	1	126	162	+36	2000+: medium, previous: high	1% cleared. Possible dilution effect of increased rainfall-derived streamflow relative to groundwater discharge
Waterfall Gully	7	128	116	–11	Medium	Declining groundwater. Streamflows follow rainfall variation.

Table 7 Results of statistical analyses performed on salinity data

Catchment (period of record)	Average salinity (mg/L)	Mann-Kendall slope (max p value)	Spearman's Rho slope (max p value)	CUSUM (year of step change, max p value)	Rank Sum 1975-2003 vs 2004–09 (max p value)
Bates (1990–2009)	110	↑ (0.05)	↑ (0.05)	↑ (2000, 0.05)	-
Del Park (1974–2009)	112	-	-	↑ (1997, 0.1)	-
Ernies (1974–2009, no-flow years skipped)	91	-	-	-	↑ (0.05)
Gordon (no-flow in 2001 skipped)	81	-	-	-	↓ (0.05)
Jayrup	76	-	-	-	-
Lewis (1977–2009)	109	↑ (0.01)	↑ (0.01)	↑ (1994, 0.01)	↑ (0.01)
Ngangaguringuring (1975–2009)	1738	↑ (0.01)	↑ (0.01)	↑ (2000, 0.01)	↑ (0.01)
O'Neil (1983–2009)	124	↓ (0.01)	↓ (0.01)	↓ (2001, 0.1)	↓ (0.01)
Palmer	368	↓ (0.05)	↓ (0.05)	↓ (1994, 0.05)	↓ (0.05)
Pine Plantation (1975–2009)	228	↓ (0.01)	↓ (0.01)	-	-
Poison (1975–2009)	1140	↓ (0.05)	↓ (0.05)	-	-
Seldom Seen (1975–2009)	124	↓ (0.05)	↓ (0.05)	-	↓ (0.05)
Staircase Road (1975–2009)	132	↑ (0.05)	↑ (0.05)	↑ (2000, 0.01)	↑ (0.01)
Waterfall Gully (1975–2009)	121	↓ (0.1)	-	↓ (1982, 0.1)	-

5.2 Salinity trends by catchment

Figures 26 to 39 show trends in daily salinity for the salinity study catchments based on discrete and/or continuous data (where available), annual flow-weighted salinity estimates and corresponding trends in flows and salt loads for each catchment.

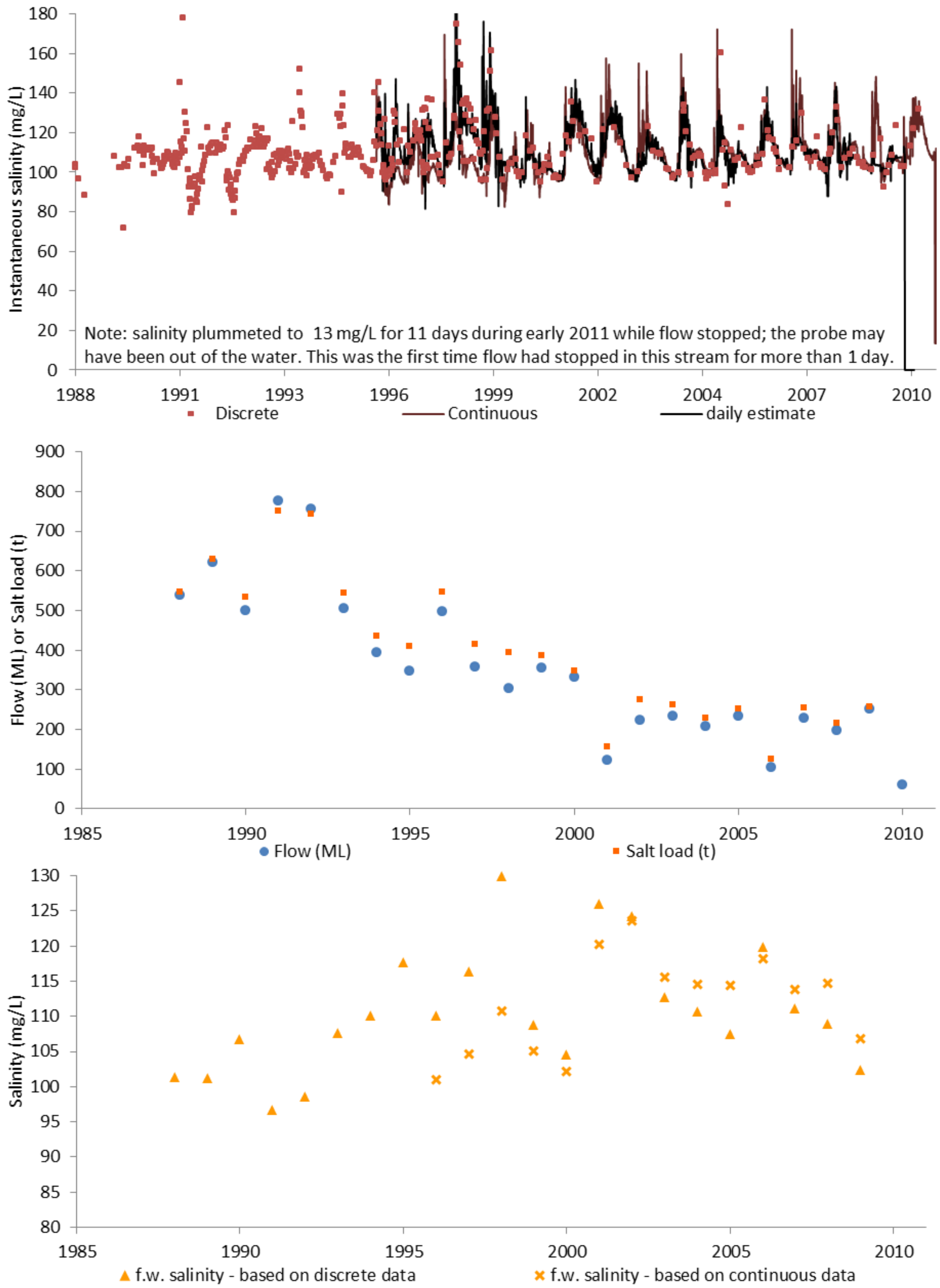


Figure 26 Salinity trends for Bates catchment

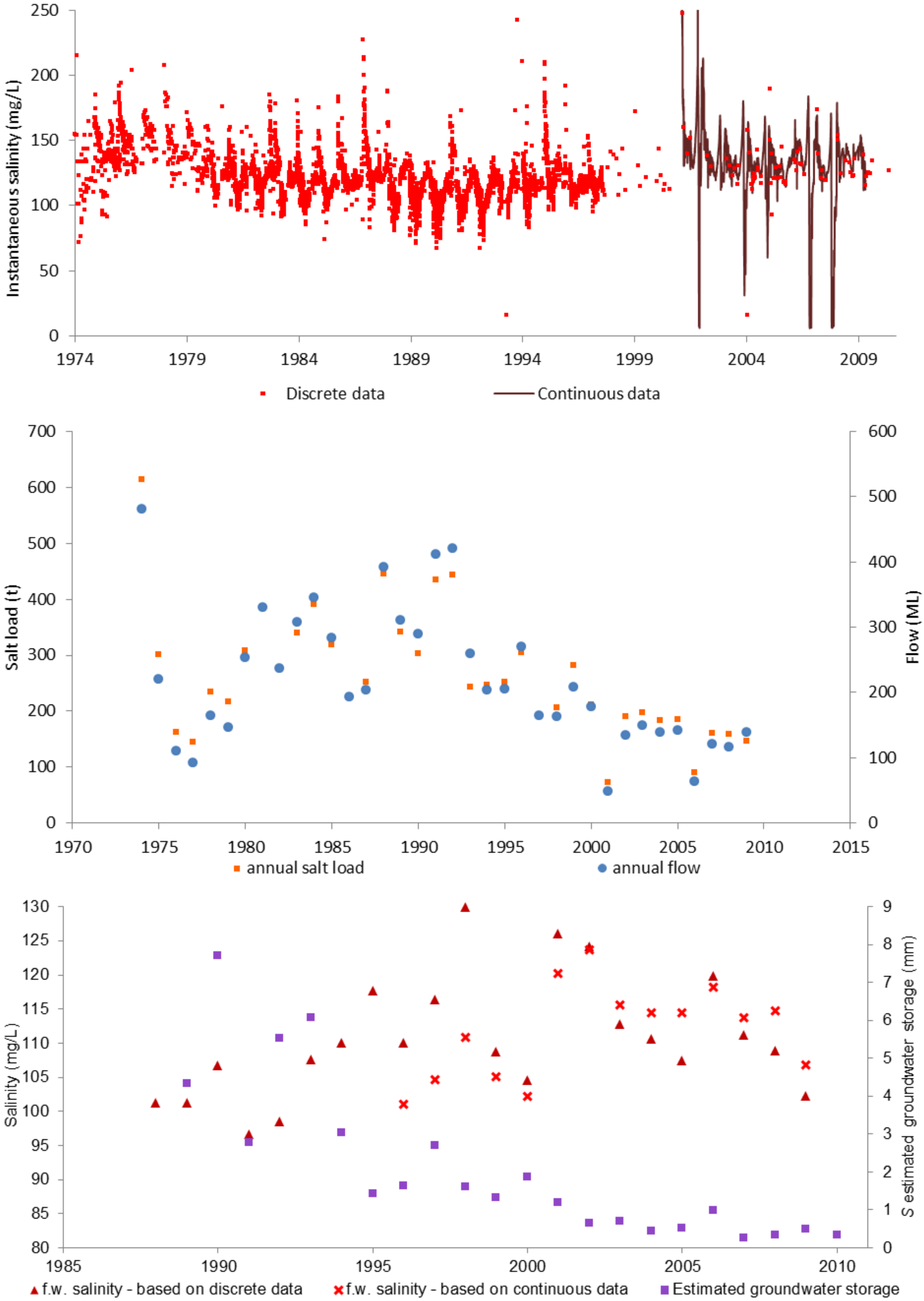


Figure 27 Salinity trends for Del Park catchment

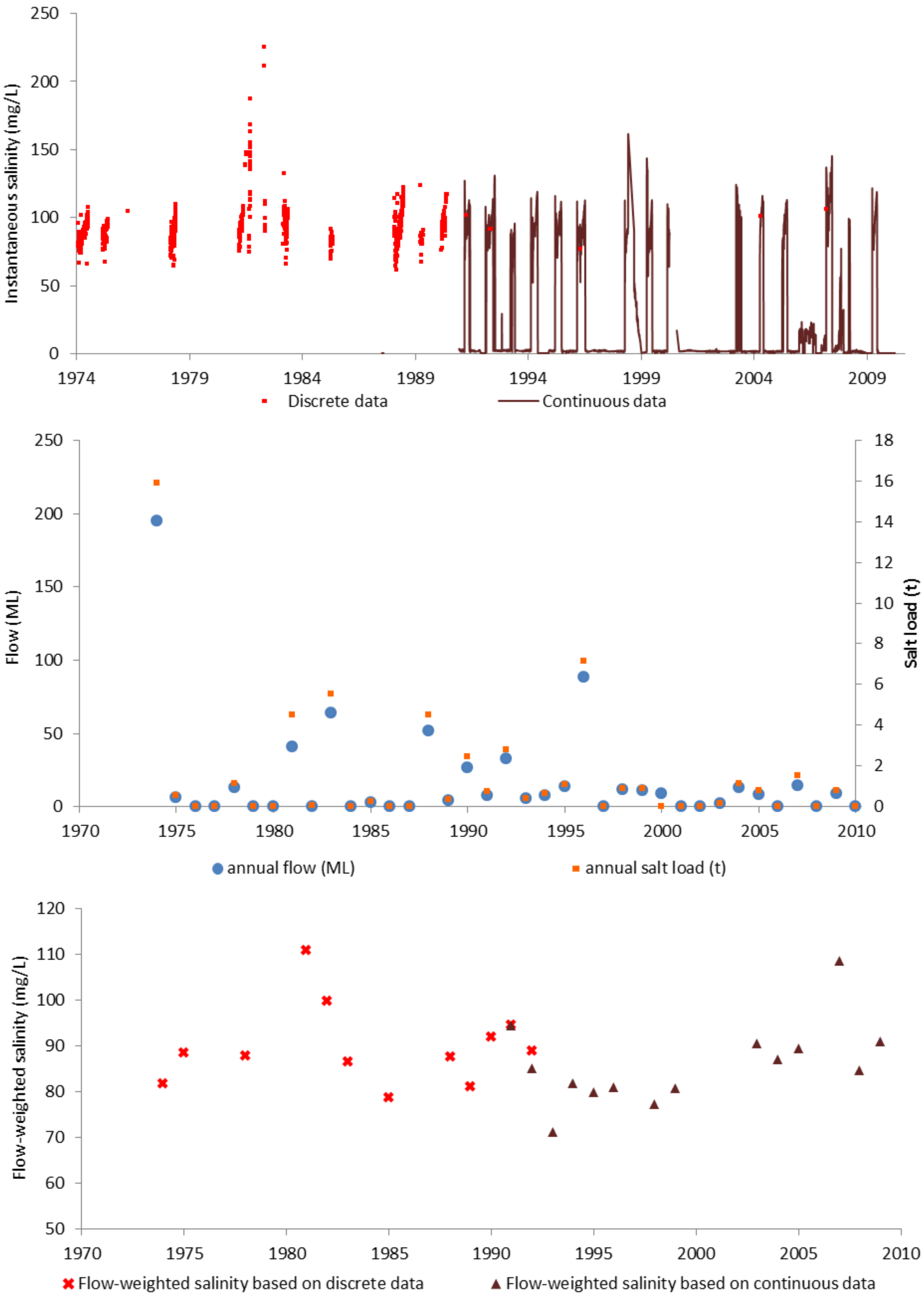


Figure 28 Salinity trends for Ernies catchment

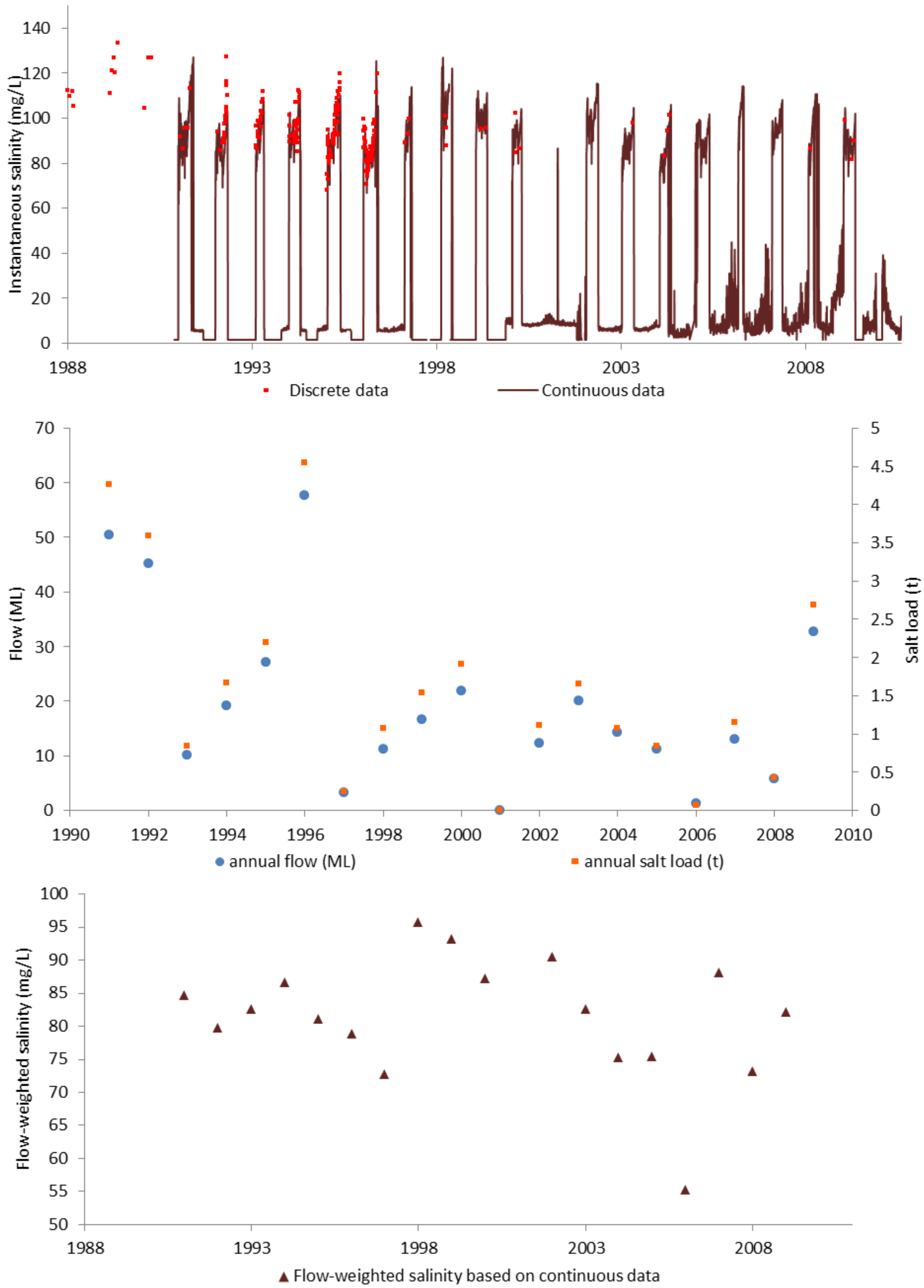


Figure 29 Salinity trends for Gordon catchment

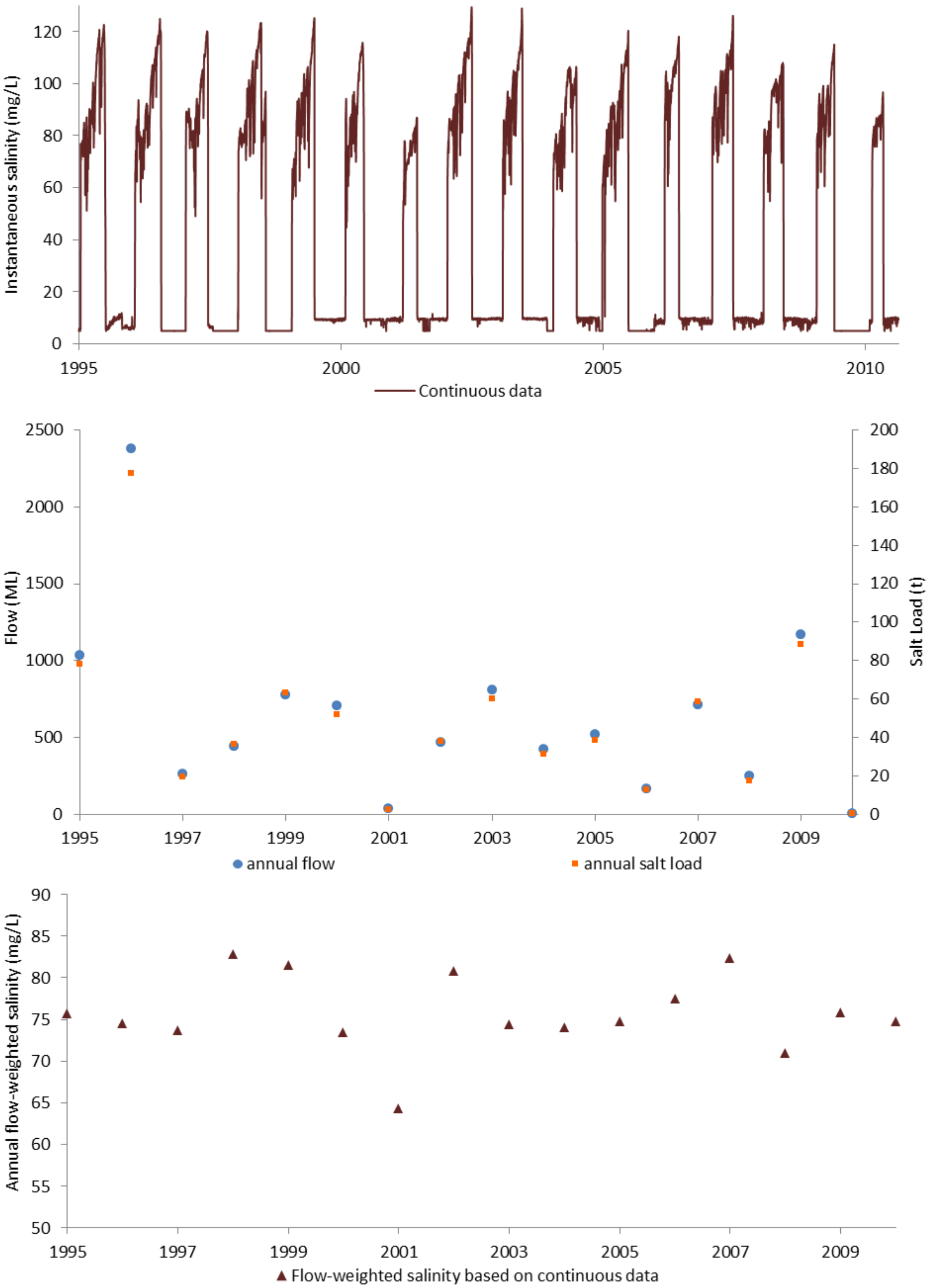


Figure 30 Salinity trends for Jayrup catchment

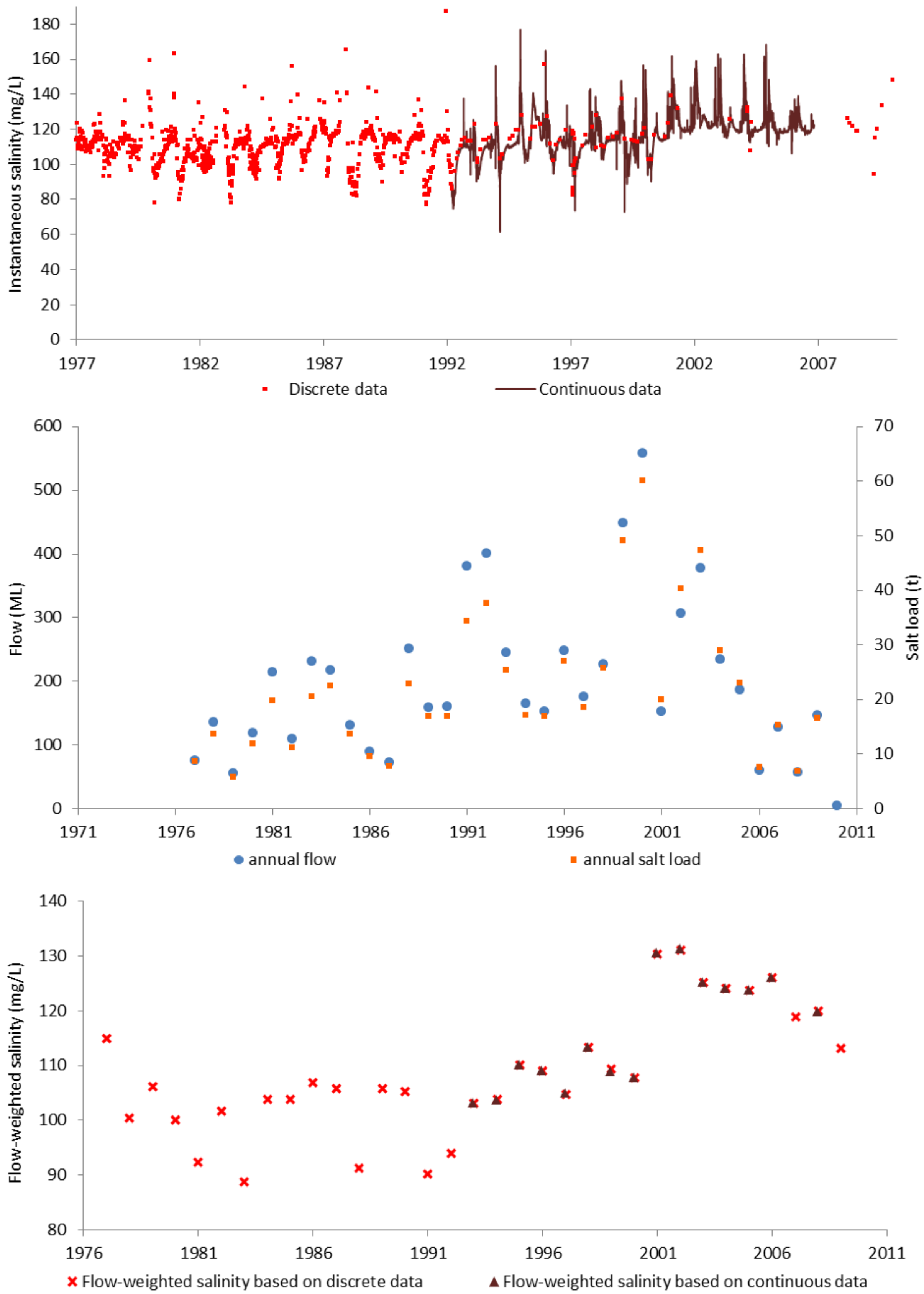


Figure 31 Salinity trends for Lewis catchment

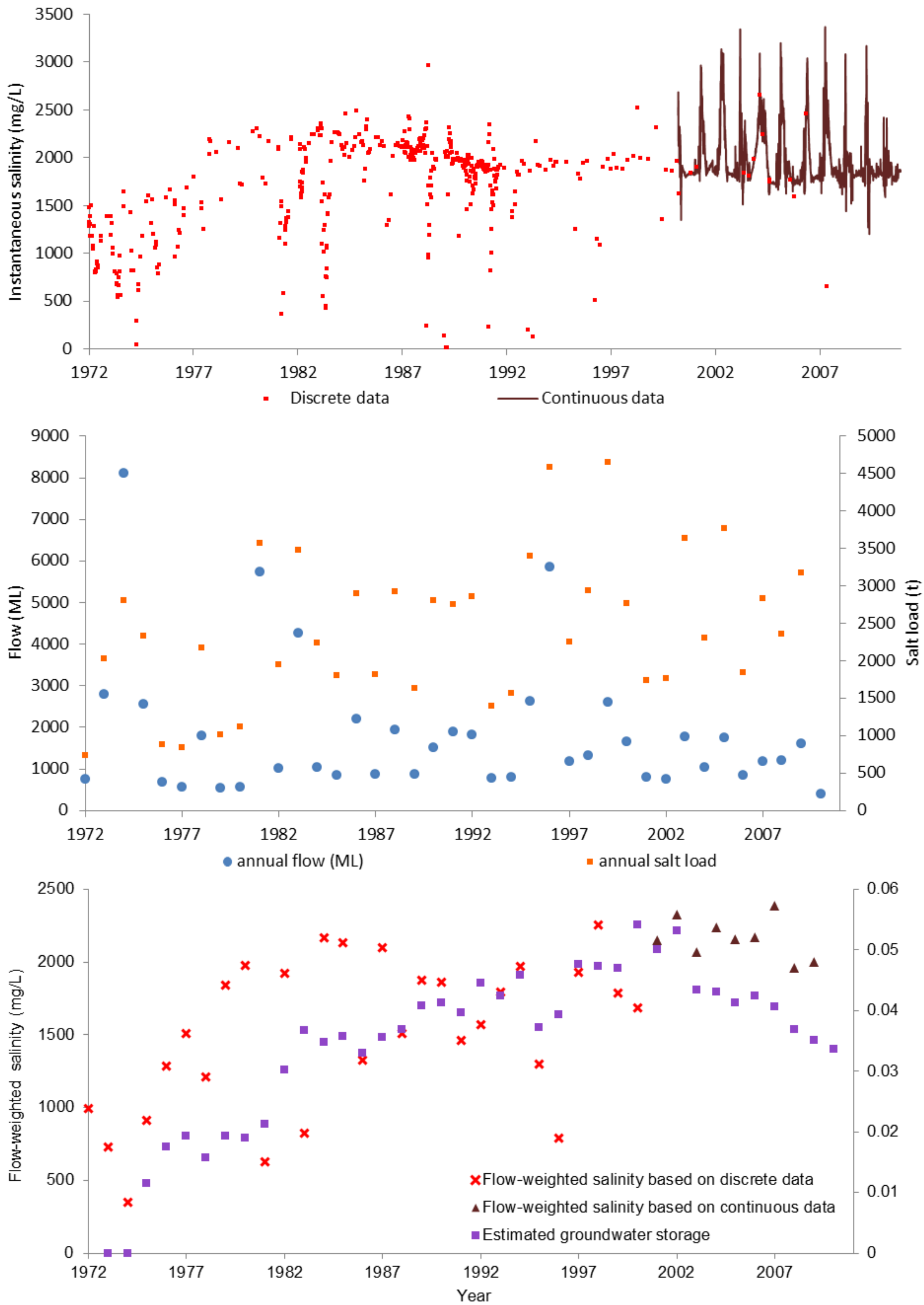


Figure 32 Salinity and groundwater trends for Ngangaguringuring catchment

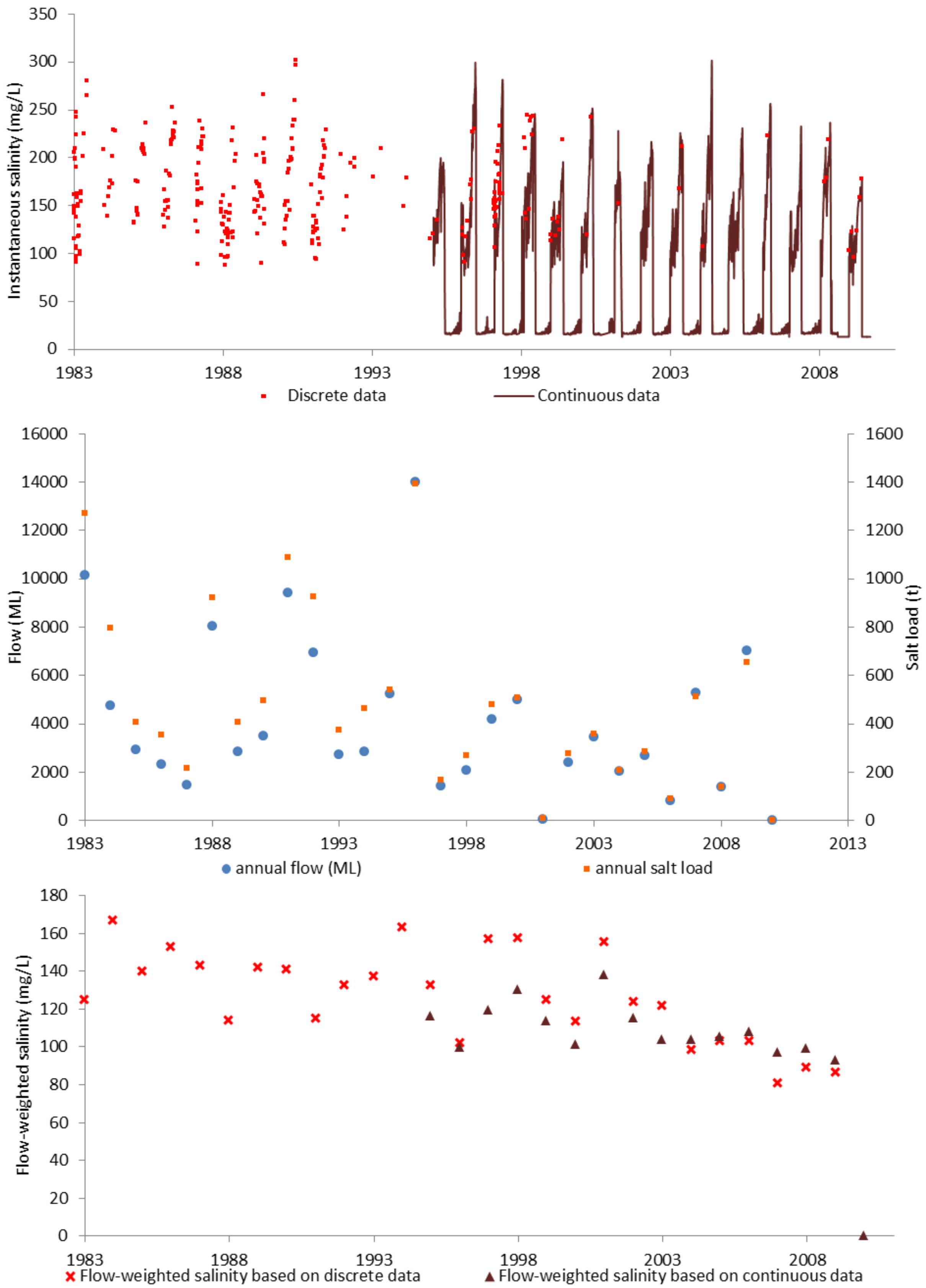


Figure 33 Salinity trends for O'Neil catchment

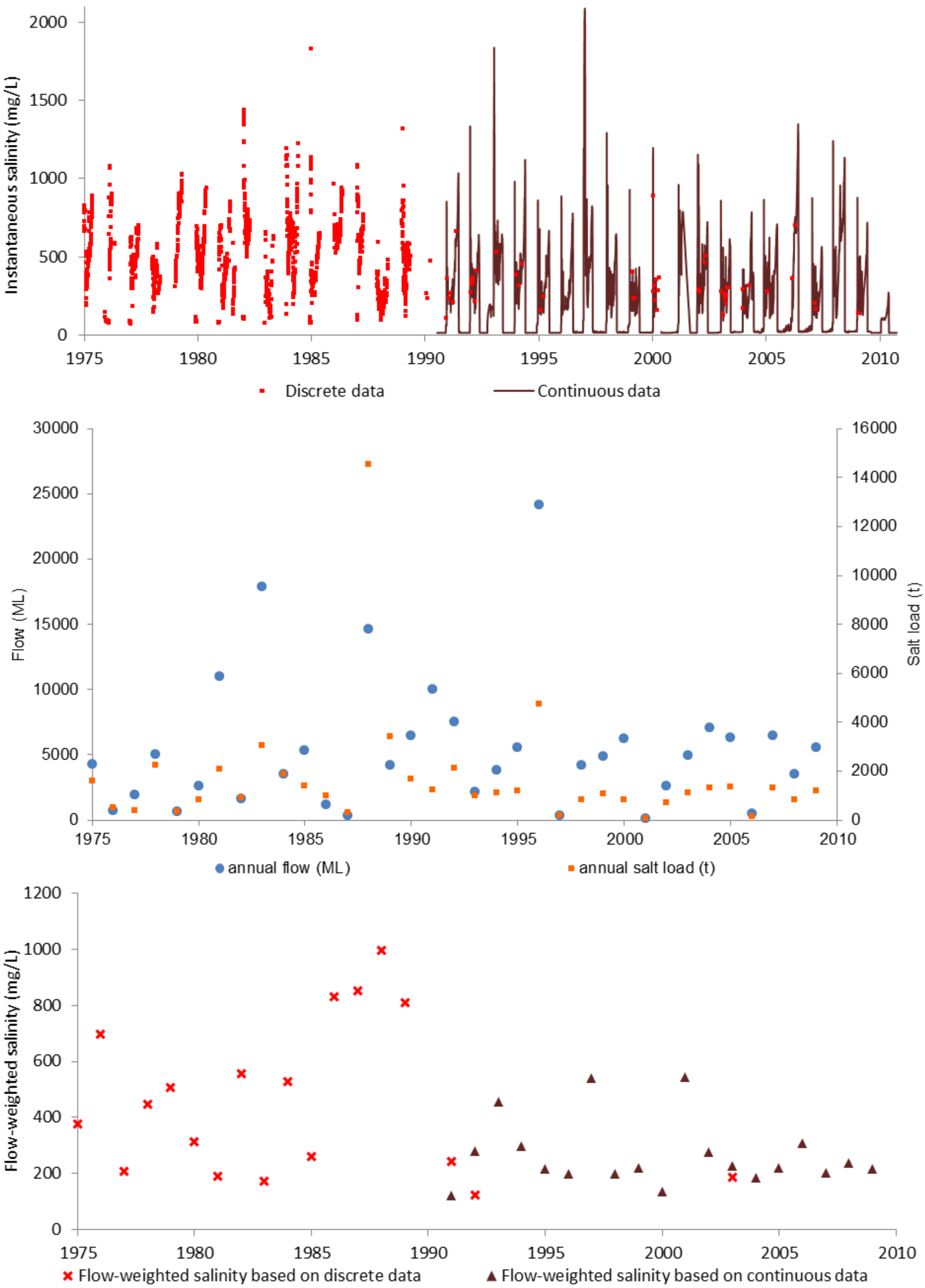


Figure 34 Salinity trends for Palmer catchment

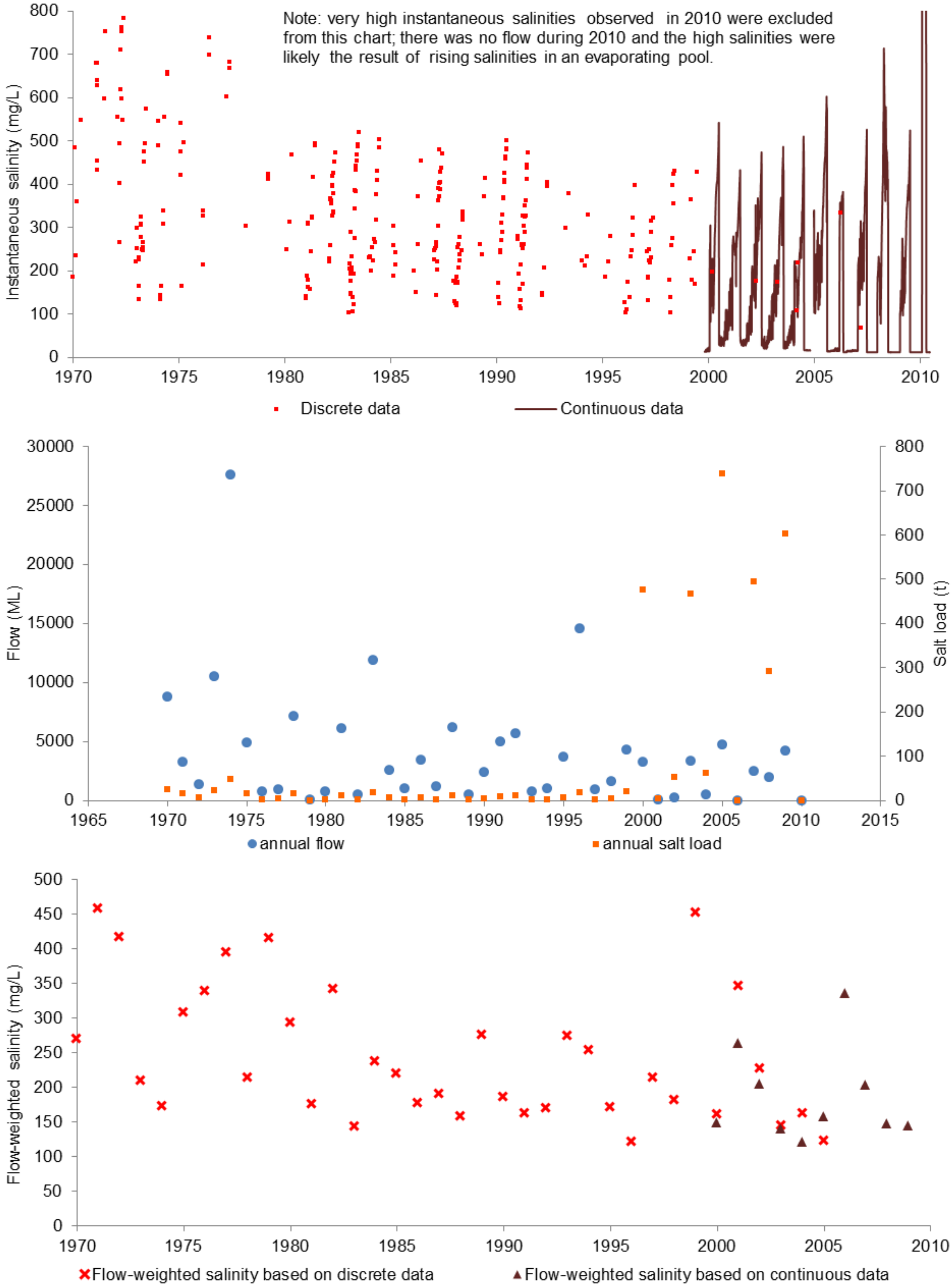


Figure 35 Salinity trends for Pine Plantation catchment

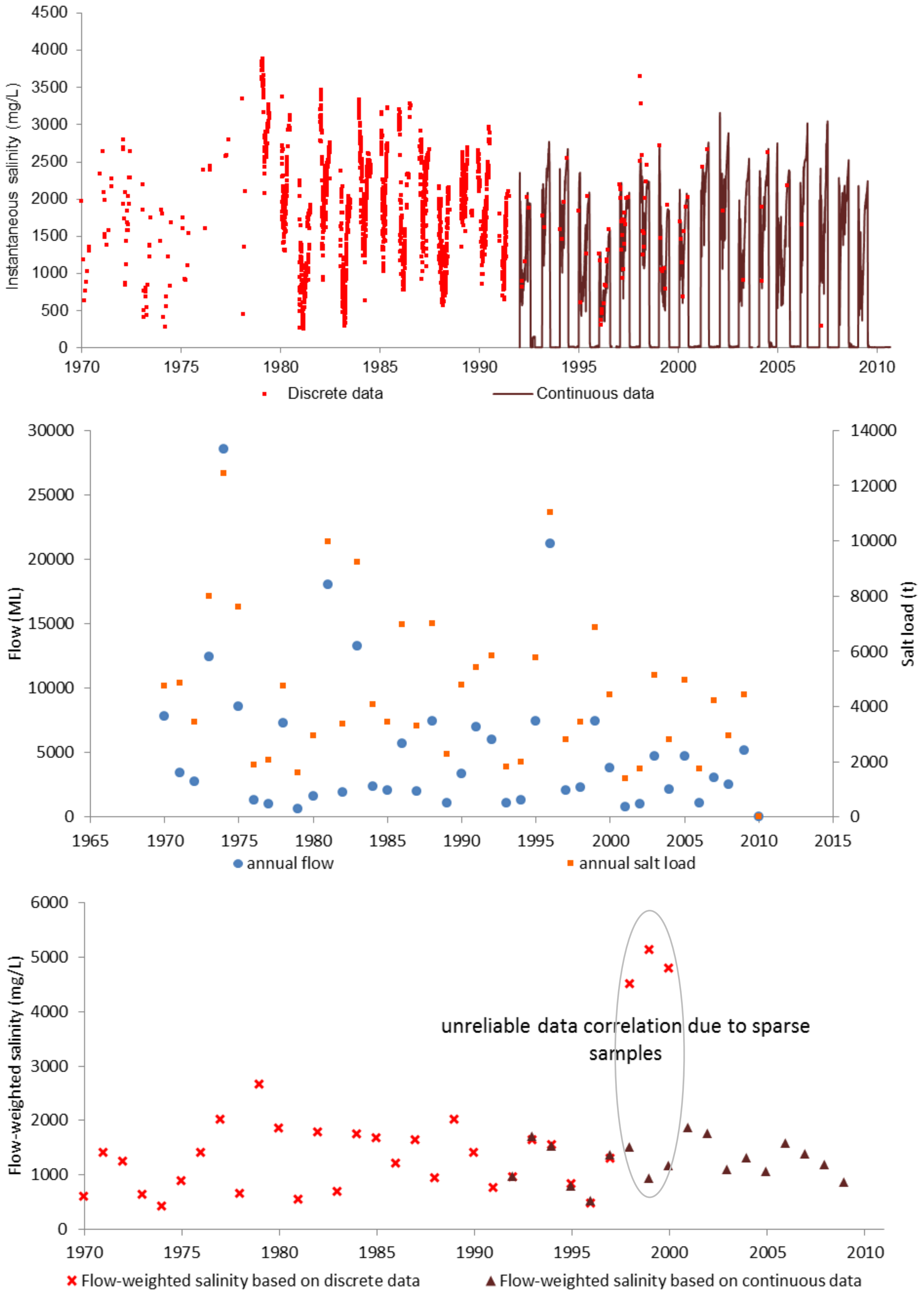


Figure 36 Salinity trends for Poison Lease catchment

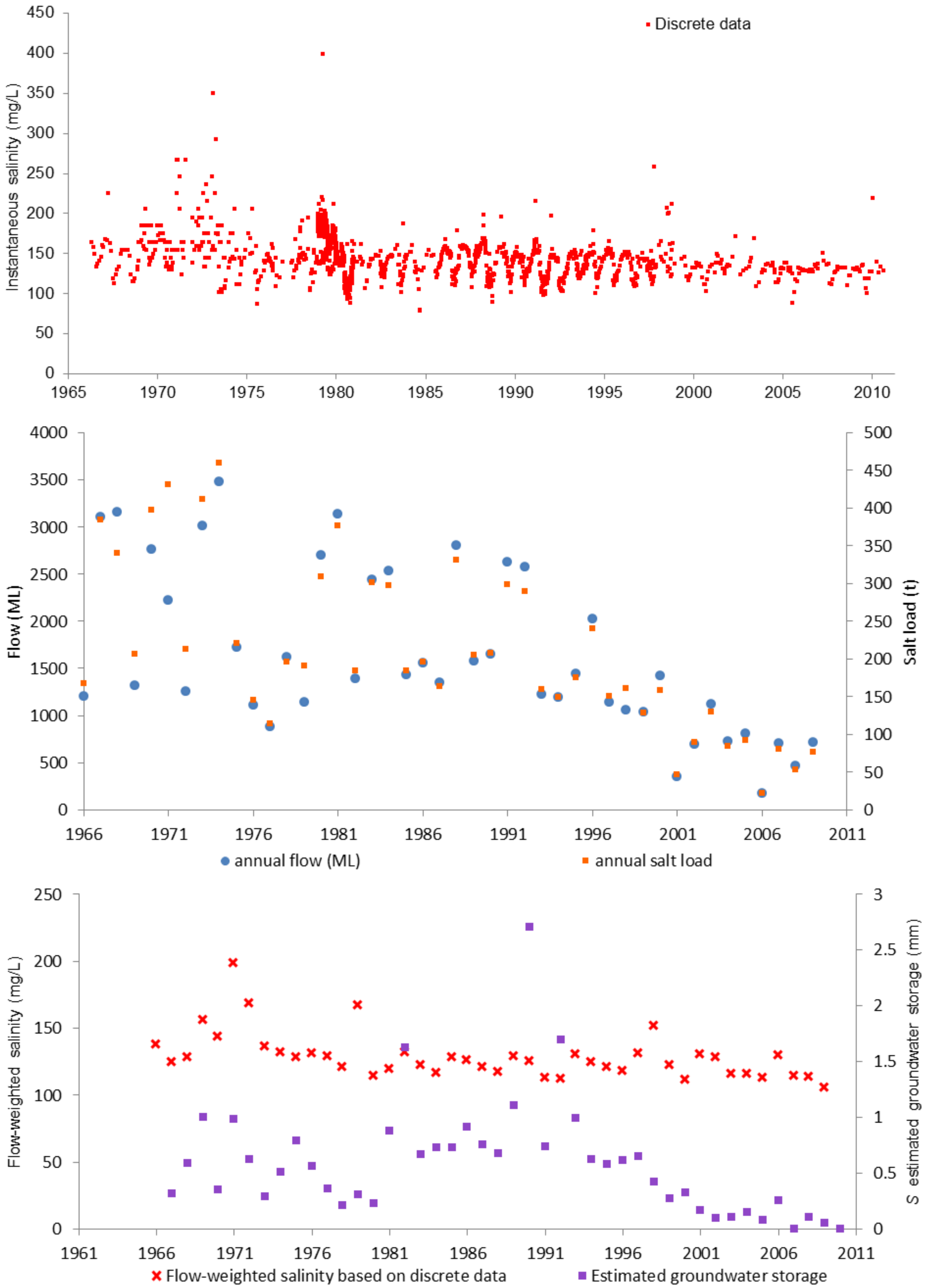


Figure 37 Salinity trends for Seldom Seen catchment

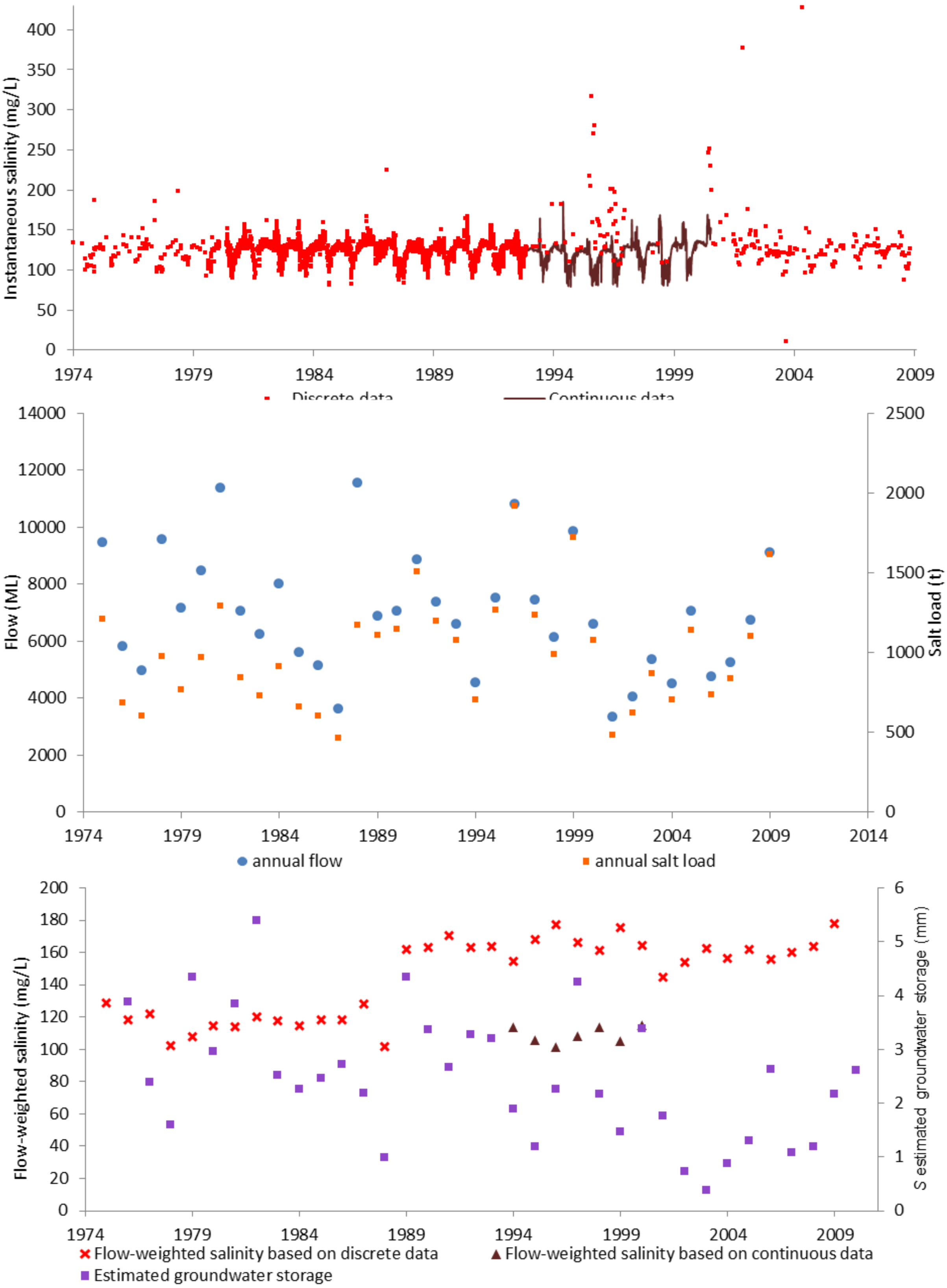


Figure 38 Salinity trends for Staircase Road catchment

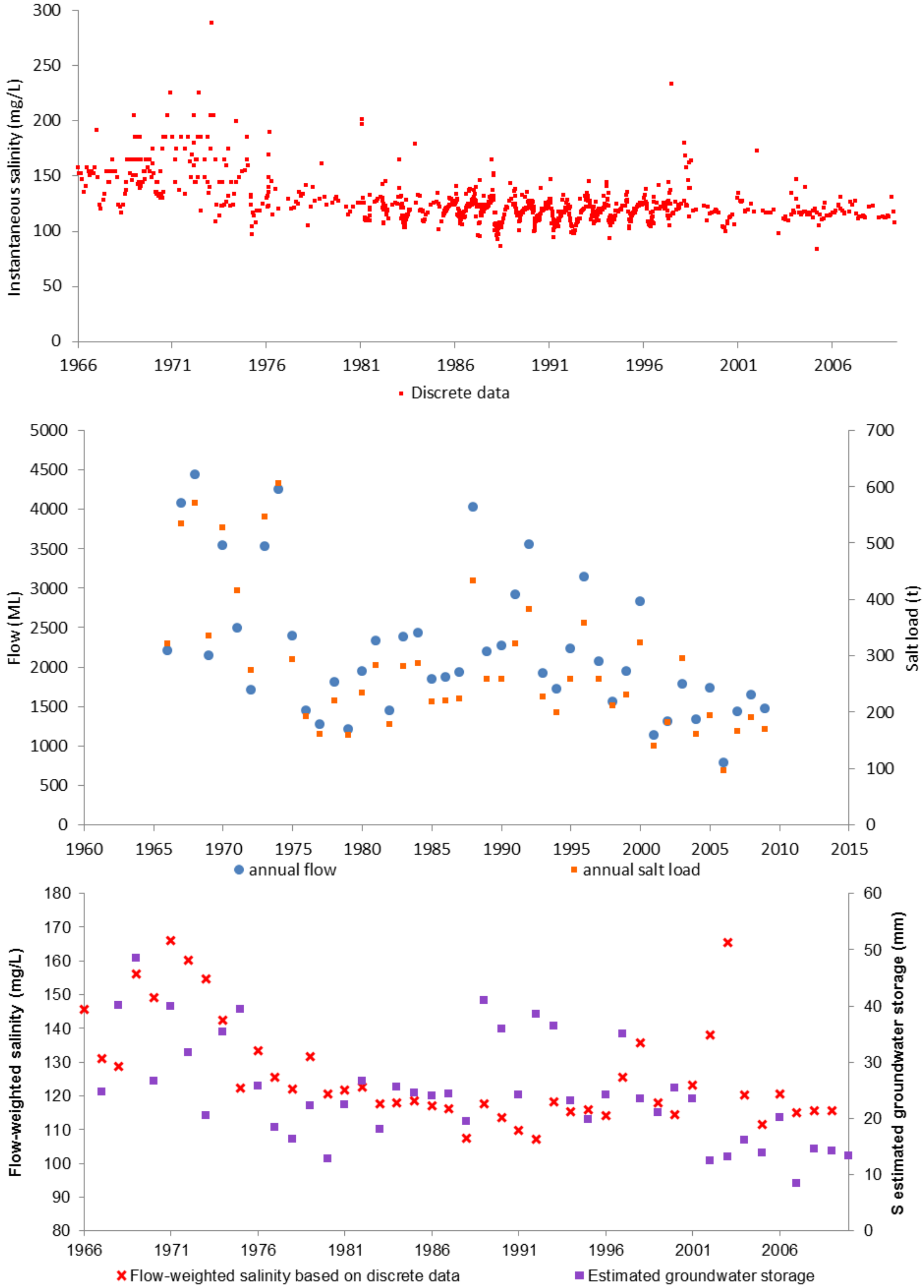


Figure 39 Salinity trends for Waterfall Gully

6 Discussion

6.1 Streamflows and climate

Dominant effect of trends in annual rainfall

In the majority of cases, both streamflow and runoff coefficients have declined severely in the last decade of analysis, and this trend has continued since. In many cases the small streamflows observed in the last decade were similar to those observed in the late 1970s, but the severity and/or duration of the recent declines was often greater. Groundwater levels based on both measurements and derived estimates generally followed similar patterns.

The dominant streamflow trend observed across most of the catchments was what we called a 'climate pattern' – approximately mirroring the observed rainfall trends. This consisted of relatively high rainfall prior to 1975 (the main year in which a step-decline is said to have taken place), very low rainfall in the late 1970s in the northern regions and in the early 1980s in the south coast region, a period of relatively high rainfall from the mid 1980s to the late 1990s, and another period of very low rainfall since 2000 or slightly before.

The climate pattern was a little different in the south coast region with the late 1970s dry period in other regions appearing later (early 1980s) and the most recent decade of data showing a slight rise in rainfall. This rise was not reflected in the runoff, with declines observed in most catchments.

Effects of silvicultural legacy

The second most prominent streamflow trend observed was attributed to the early 20th century silvicultural legacy that left large areas of maturing jarrah forests with increasing vegetation coverage in some of the catchments. Such catchments (e.g. Dee Tee 59, Slavery Lane, and Dingo Road) showed stronger declines in streamflow and runoff coefficients in the recent decade.

To show the broad differences between streamflow responses and the possible reasons for these, the catchments were broadly grouped into the following trend categories based on plotted data and statistical analyses:

- Catchments with a dominant climate pattern and no overall streamflow trend
- Catchments with a dominant climate pattern and observed decline in streamflow
- Catchments with a climate pattern and streamflow decline which may have been exacerbated by increasing vegetation cover
- Catchments with a climate pattern and a streamflow decline with a high likelihood that this decline was exacerbated by increasing vegetation cover
- Catchments with a climate pattern but where clearing, mining and/or intensive thinning have stabilised or increased streamflows
- Catchments requiring more investigation due to an unusual similarity in the rainfall-runoff relationship over time.

Table 8 summarises the categorisation of catchments.

Table 8 Categories of trends observed with the study catchments

Trend category	Primary catchments	∑ primary	Supplementary catchments	∑ supplementary
Catchments with a dominant climate pattern and no overall streamflow trend	Blackbutt Point, Crouch Rd, Hairpin Bend Rd, Pine Plantation, Wattle Block	5	Jayrup	1
Catchments with a dominant climate pattern and an observed decline in streamflow	Beigpiegup, Ordnance Rd, Staircase Rd, Ted's Pool, Worsley, Yarragil	6	Bates, Cobiac, Ernie's, Trew Rd, Waterfall Gully,	5
Catchments with a climate pattern and streamflow decline which may have been exacerbated by increasing vegetation cover	Dingo Rd	1	N/A	0
Catchments with a climate pattern and a streamflow decline with a high likelihood that this decline was exacerbated by increasing vegetation cover	Dee Tee 59, Slavery Lane	2	Del Park, Gordon, More Seldom Seen, Seldom Seen, Vardi Road	5
Catchments with a climate pattern but where clearing, mining and/or intensive thinning have stabilised or increased streamflows	N/A	0	Hansens, Lewis, Ngangaguringuring, O'Neil, Palmer, Poison Lease	6
Catchments requiring more investigation due to an unusual similarity in the rainfall-runoff relationship over time	Whicher Range	1	N/A	0
Total		15		17

All catchments with exacerbated declines in streamflow considered likely to be caused by increasing vegetation cover were in the northern or central jarrah regions.

Effects of evaporation and temperature

Evaporation generally decreased by varying degrees over the study period. This would have had either negligible effects on the streamflow declines observed or possibly counterbalanced them slightly. Average daily maximum temperature increased by about 0.5 °C over the study period; this is likely to have increased transpiration by vegetation across the study area. Estimating the effects on catchment water balance of the increased transpiration attributable to the rising daily maximum temperatures is beyond the scope of this study but may be significant given that transpiration is essential for cooling plant surfaces and evapotranspiration constitutes a large part of the catchment water balance.

Effects of vegetation disturbances

Some bushfires had discernible effects on streamflow (e.g. for Hairpin Bend Road, an extensive summer bushfire was followed by a 120% increase in streamflow compared to what would have been expected (Batini & Barrett 2007) but it was often difficult to distinguish bushfire effects from natural streamflow variability, particularly when the fire affected a small proportion of a catchment.

We were not able to discern dieback (*Phytophthora cinnamomi*) effects but this is largely due to the limited nature of the data. Many of the catchments had not been comprehensively interpreted for the presence of the disease and it was not clear from the available data when known dieback infections had spread.

Mining and subsequent rehabilitation temporarily increased and then decreased streamflows; trends which agree with the literature for this area.

In the Palmer catchment, clearing near the stream zone appears to have stabilised streamflow to some degree despite generally increasing vegetation coverage in the catchment indicated by increases in the leaf area index.

The effects on streamflow of recent silvicultural activities tended to be difficult to discern against the backdrop of natural variability, rainfall, groundwater and streamflow decline. More detailed analysis, including catchment modelling, might be required to ascertain if and to what extent recent forest management practices alone have influenced streamflow, although there remain numerous unknowns that would make this a challenging pursuit. Existing models, including those used by Croton et al. (2014), are a significant contribution to this area.

Effects of rainfall seasonality and intensity

Rainfall decline during May, June, and July in most areas in the recent decade added to the decline observed since the mid 1970s and may have also contributed to streamflow declines. However, increases in April and September rainfall across all regions would have meant that the catchments would not necessarily have begun the rainy season with drier than normal antecedent conditions (unless the additional April rainfall had increased transpiration from vegetation) and that late winter rains were often more substantial in the recent period.

There was a large (over 20%) drop in the number of rain hours per wet season in the last decade of analysis and corresponding increases in average hourly rainfall intensity and the proportion of rainfall that fell at higher intensities (above 5 and 10 mm/hr). These findings are in contrast with a number of published papers on the subject although these papers investigated daily (not hourly) rainfall trends and did so over different time periods. Raiter (2012) found conflicting trends between the hourly and daily time scales. Higher rainfall intensity is likely to be associated with higher runoff coefficients as a larger proportion of the rain is likely to run off as saturation excess or infiltrate into the groundwater rather than remain on vegetation and soil surfaces and within the shallow root zone to be evaporated or quickly used by plants. It is possible that rising rainfall intensities may have somewhat counterbalanced other factors causing a decline in streamflow. Further investigation is needed on the effects of the reduced rain hours, the differences between the effects of trends at hourly and daily time steps and the temporal distribution of rain events.

Flow regimes

The declines in streamflows mentioned above have been coupled with changes in flow regimes, with many streams shifting from perennial to intermittent flows, more no-flow days for historically intermittent streams, and changes in both low- and high-flow periods which are likely to have significant consequences for the formation and maintenance of in-stream pools and the ability of water-dependent species to inhabit streams.

6.2 Salinity

Streams in fully forested catchments remained fresh, although some changes were apparent. Assessing changes in salinity over time was difficult with the data limitations; very few fully forested catchments have been continuously monitored for stream salinity over long enough periods for such analyses. Therefore the analysis was expanded to include discrete data (where they were enough to calculate annual salinity with some reliability) and catchments with some clearing.

No catchments in the south coast region and only one in the south-west region had enough data to include in this analysis.

Statistically significant trends in annual flow-weighted salinity were detected for most catchments, with approximately half showing increases and half showing decreases. Many trends were small enough to be considered negligible or within measurement error. When catchments with absolute changes >30 mg/L in annual flow-weighted salinity between the 2004–09 and 1975–2003 periods are considered, then only two catchments showed statistically significant salinity increases and four showed declines.

The declines are likely to be due to salty groundwater discharges into streams that have fallen or stopped as a result of declining groundwater levels. The increases may be due to a reduction in the dilution of salty groundwater by fresh surface water, and are likely to be temporary.

6.3 Conclusions and recommendations

Changes in the climate, particularly rainfall, appear to be the largest factors influencing streamflow and rainfall-runoff relationships in fully forested catchments in the area managed under the FMP. In some cases, streamflow declines appear to have been exacerbated by increased vegetation cover associated with forest responses to the silvicultural land-use legacy. Streamflows have generally declined across the south-west in the recent decade, and rainfall projections suggest that this situation will continue to deteriorate. Declines in total annual streamflows have often been accompanied by shifts in streamflow regime from perennial to intermittent, longer no-flow periods, and changes in high and low flows. These changes are strongly associated with falling groundwater levels, and may have serious consequences for stream ecosystems as well as water supplies (Dundas et al. 2014).

Salinity is generally less of a concern now in forested catchments as groundwater levels fall but ongoing monitoring can a) help to detect disconnection between groundwater and stream zones, b) provide baseline data and address continuing salinity concerns (e.g. specific areas where saline groundwater is close to the surface; mining) and c) assess threats and risks and plan appropriate responses in the case that the climate becomes wetter (even temporarily), as the catchments are now accumulating far more salt than previously.

Stream gauging and meteorological stations with long data records are very valuable in providing high-quality information for assessing, evaluating and implementing actions in long-term government strategies, such as addressing the hydrological changes that the south-west will continue to face.

Forest management policies need to take these changes in forest hydrology into account. Forest management practices may be the key way in which society can assist forested streams and their associated catchments to adapt to climate changes. Some options and potential solutions, with a range of objectives, are already being trialled and investigated, and the Forest Management Plan 2014–23 takes some of these into account, although these activities largely remain unfunded.

As such, this report also recommends that the key performance indicators covered here are included in future FMPs, with the following changes:

- Include measures of flow regime with annual streamflow for the KPI addressing streamflow.
- Include measures of inter-annual salinity variations (e.g. 95th percentile daily salinity) with the annual flow-weighted mean for the KPI addressing salinity trends.
- Include an additional KPI which directly assesses trends in depth to groundwater with the target of no declines in groundwater as a result of management activities, and some mitigation of any declines caused by other factors (e.g. climate).

Glossary and shortened terms

Autocorrelation	A property displayed by some sequences of adjacent items not being independent of each other; similarity between observations as a function of the time separation between them.
Climate change	Natural and/or anthropogenic long-term, directional trends in climate averages and variability (e.g. in the frequency, severity and duration of extreme events).
Climate variability	Natural, shorter term (daily, seasonal, annual, inter-annual, several years) variations in climate, including the fluctuations associated with El Niño (dry) or La Niña (wet) events. Natural variation does not consist in long-term directional changes in climate averages or variability.
Flow duration curve	A cumulative frequency curve that shows the proportion of time specified flow rates were equalled or exceeded during a given period.
FMP	Forest Management Plan 2004–13
Hysteresis	The lagging of an effect behind its cause. The phenomenon by which an effect in a system depends not only on the present stimulus but also on the previous state of the system.
m AHD	Australian Height Datum, based on the mean sea level around Australia for 1966–68, measured in metres
Foliage projective cover	Per cent of ground surface covered by vegetation. The cover would equal the shadow cast if the sun was directly overhead.
Non-stationarity	A condition whereby the parameters of the system change over time; the probabilistic behaviour of every collection of values is not identical to that of any time-shifted set (Hughes et al. 2012). For example, the relationship between rainfall and runoff during one time period is different to that in a different period. Non-stationarity is a widespread issue in hydrological prediction and is related to changes and cycles in climate and land use.
PDWSA	Public Drinking Water Source Area – a registered area from which public drinking water is sourced or may be sourced in the future.
Percentile	A percentile is the value of a variable below which a certain percent of observations fall; i.e. 90% of a series of data fall under the 90th percentile of that series
Rainfall intensity	The amount of rain falling per unit of time (here: an hour)

Runoff	All the water in a catchment that makes its way to the stream (equivalent to streamflow, but normalised by catchment area; 1 mm is equivalent to 1 ML/km^2)
Runoff coefficient	The proportion of rain that reaches the streams and 'runs off' a catchment
Streamflow	The water that flows in streams; the combination of surface runoff (infiltration excess and saturation excess), subsurface lateral throughflow (also called throughflow), and groundwater discharge. Streamflow is measured volumetrically (litres).
Stream zone	The interface between a stream or river and dry land, may be characterised by the presence of riparian vegetation or defined as a set distance from the stream.
Wet season	The months during which most of the rain falls: in this report, April–October

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Appendices

Appendix A Catchment overviews

Bates Little Dandalup Tributary (Murray River basin) 614062

Historically perennial stream. Stopped flowing for one day for the first time on record on 12 March 2010; it has since dried up on multiple occasions. Significant decreasing trend and step declines observed in streamflow; flow in current FMP is significantly lower than in prior FMP.

Public Drinking Water Source Area (PDWSA) Priority 1. Unmined control catchment for Warren, Benetts and Hansens (McFarlane 2008). 10% harvested twice 80s and 90s. Hughes (2012) found linear correlation between the annual change in the groundwater level and annual rainfall, with 1.3 mm decline in groundwater for every 1 mm that rainfall is below the threshold (1312 mm), indicating that the response is greater than the cause.

Assessment	Supplementary catchment
Size & location	2.2 km^2 (small); 32.58°S, 116.03°E
Av. rainfall	1179 mm/a for 1975–2008, (nearby met station 509579)
Tenure	State forest
Clearing	<1%; 0% exotics
Vegetation type	90% jarrah forest, 9% jarrah woodland, 1% shrub, herb & sedgeland
Timber harvest	100% harvested pre-1920. 65% in 1920s, 35% in 30s, 69% in 80s, 10% in 90s.
Fire history	10% last burnt in spring 1989, 90% last burnt in winter 2001–02.
Dieback	100% interpreted for dieback presence; 74% infested.
Flow trends	Significant declines in streamflow, and rainfall-runoff relationship observed. Progressive decline in flow regime over recent decades. Catchment categorised as ‘climate pattern present, streamflow decline observed’.
Salinity data	Some discrete and continuous data available; Reliability code: 2 (mostly continuous measurements with very small (<2 days) estimated gaps or more than 100 discrete samples per year)
Salinity trends	Salinity is low (~110 mg/L) but shows statistically significant rising trends

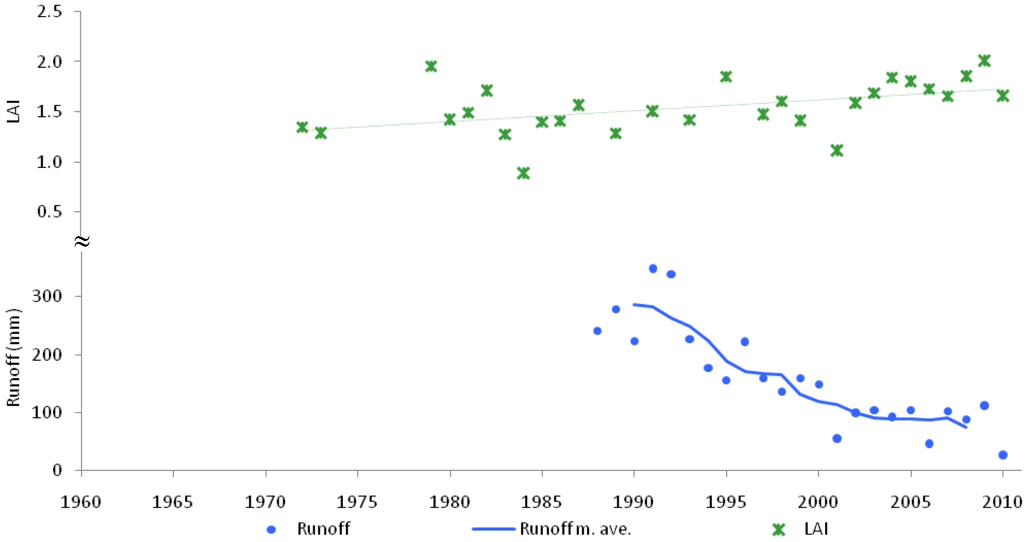

Figure A1 Annual streamflow, moving average, and leaf area index for Bates catchment

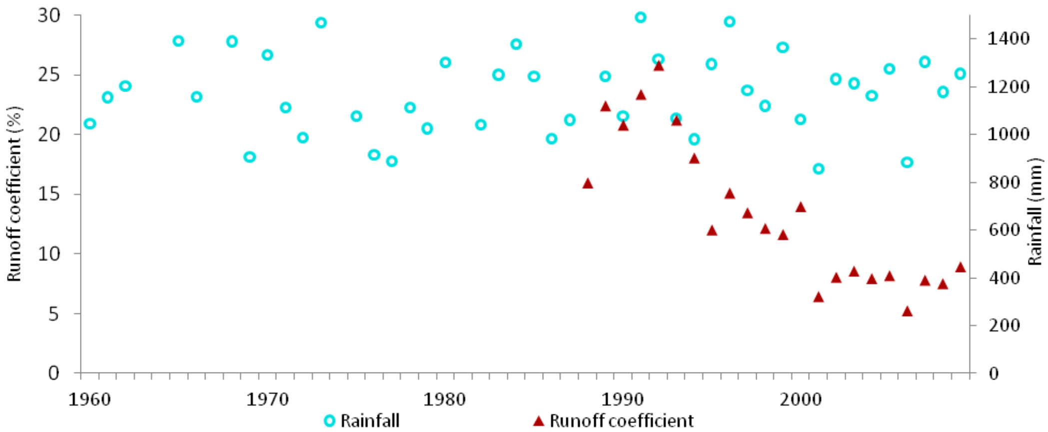

Figure A2 Annual rainfall and runoff coefficient for Bates catchment

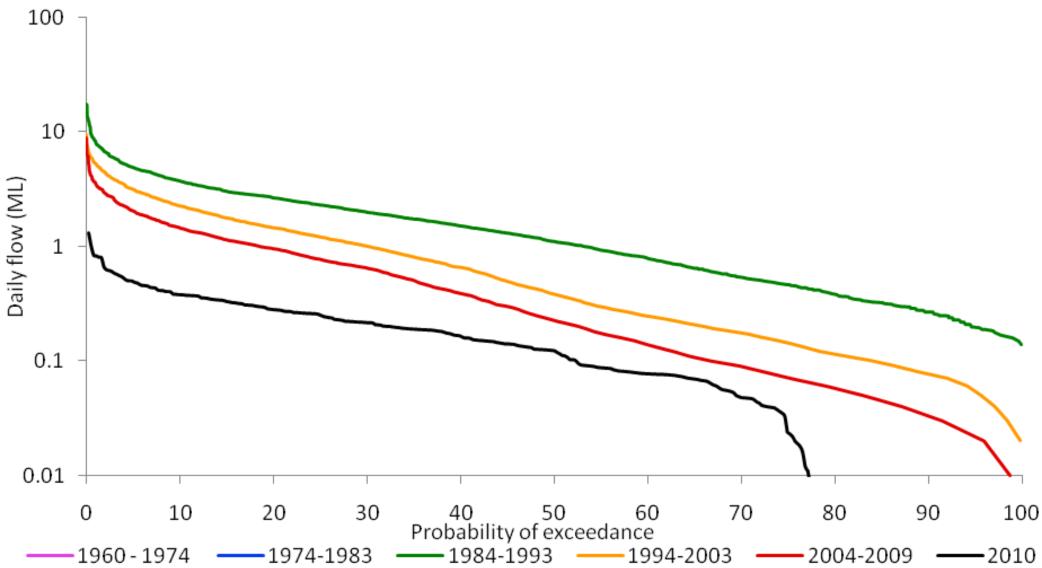

Figure A3 Flow duration curves for Bates catchment showing shift from perennial to intermittent flow, and progressive declines in flows throughout the year.

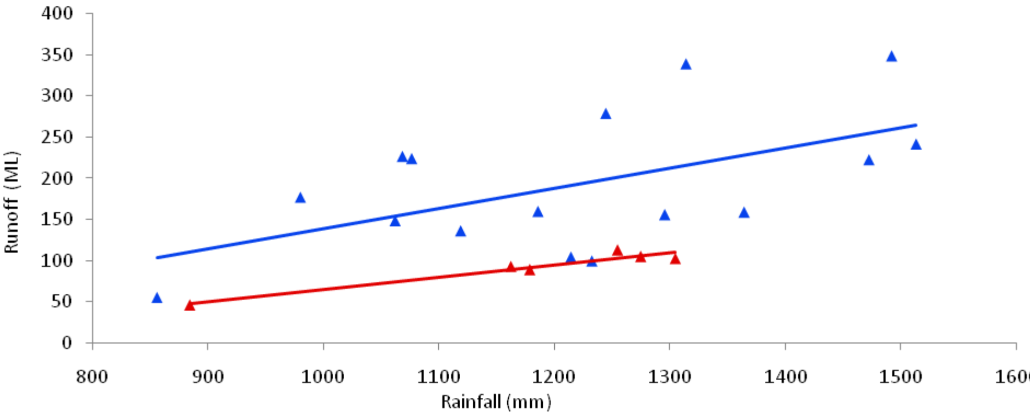

Figure A4 Annual runoff plotted by annual streamflow for Bates, showing a decline in the rainfall-runoff relationship.

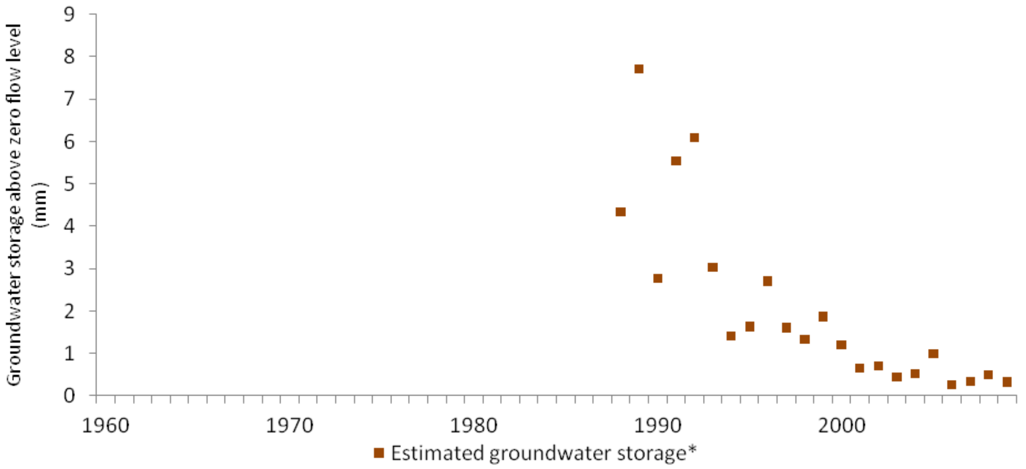

Figure A5 Estimated groundwater storage for Bates catchment

Beigpiegup Mitchell River (Denmark River basin) 603005

Intermittent stream. Runoff coefficient declined by almost 50% around the year 2000 and flow duration has decreased. Light harvesting in the 70s and 80s, and no harvest since. Vegetation coverage declined until mid 1980s.

Mean annual salinity in 1983–92 was 280 mg/L, and in 1993–2002 was 350 mg/L. During same period average flow decreased from 3.9 to 3.2 GL. Salt input was lower than output – catchment appeared to be leaching salt Mayer et al. (2005).

Assessment	Primary catchment
Size & location	51.4 km^2 (medium); 34.81°S, 117.34°E
Av. rainfall	948 mm/a
Tenure	100% National Park
Clearing	0% cleared
Vegetation type	50% jarrah forest, 49% shrub, herb and sedge land, 1% rock outcrop
Geomorphology	Proterozoic origins. Granitoid gneiss, in some places porphyritic and even grained, minor metamorphic rock and quartzite, generally weathered to clay or clayey sand. Minor, local aquifers.

Timber harvest	Not harvested for the last 24 years. Always harvested at low intensity. Last sawlog harvests were 11% in 1987 and 1% in 1985. Prior to this approx. 31% was harvested in the '70s and 3% in '60s. No record of harvesting before '60s.
Fire history	80% burnt Jan 1996, 36% burnt by wildfire in 2001/2, 61% spring burn in 2009/10
Flow trends	Non-significant decline in streamflow and rainfall-runoff relationship observed, despite no recent decline in rainfall. Categorised as 'climate pattern dominant, streamflow decline observed'.
Salinity data	Insufficient recent data to include in current analysis, but was included in Mayer et al. (2005). Data reliability code: 5 (Mostly continuous measurements with very large estimated gaps (>3 months) or fewer than 6 discrete samples per year or data estimated from flow)
Dieback	3% interpreted for dieback presence, of this 76% infested
Trends	No statistically significant trends observed

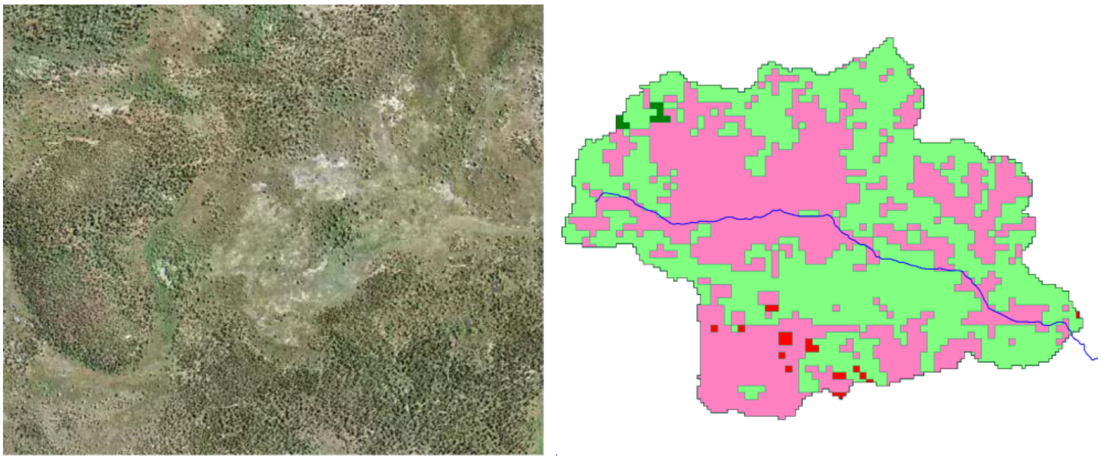

Figure A6 Beigpiegup catchment views: L) Aerial photograph showing approximately half non-forest. R) Vegetation types (pink = non forest; green = >30% jarrah; red = rock outcrop)

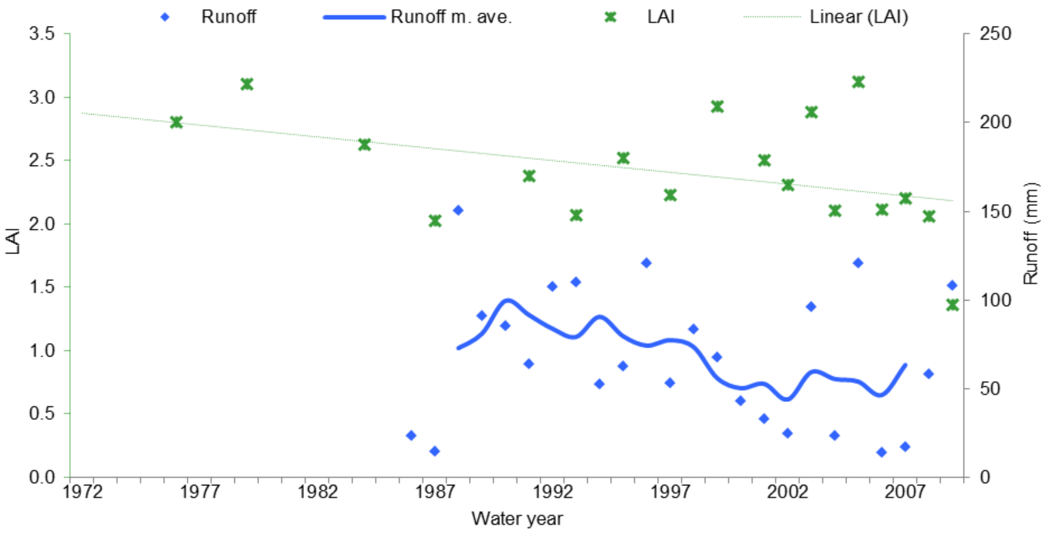

Figure A7 Annual streamflow, moving average, and leaf area index for Beigpiegup catchment

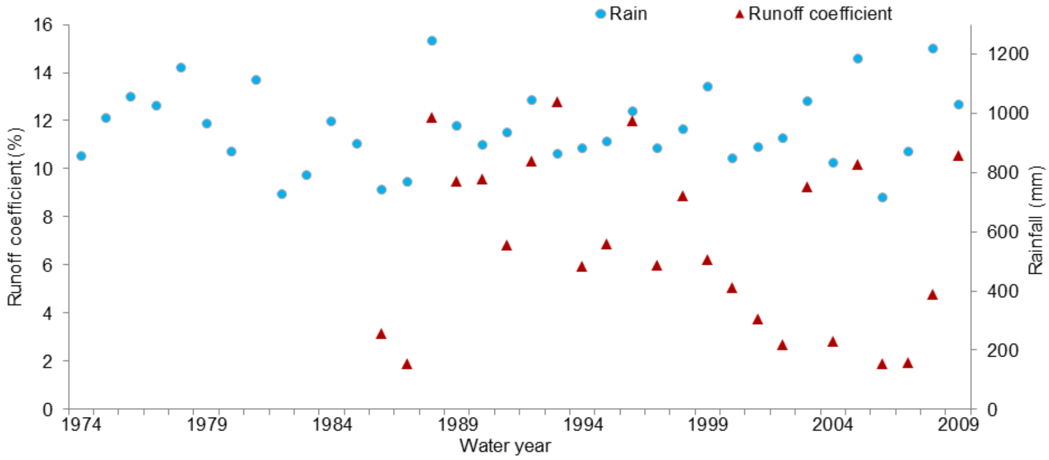

Figure A8 Annual rainfall and runoff coefficient for Beigpiegup catchment

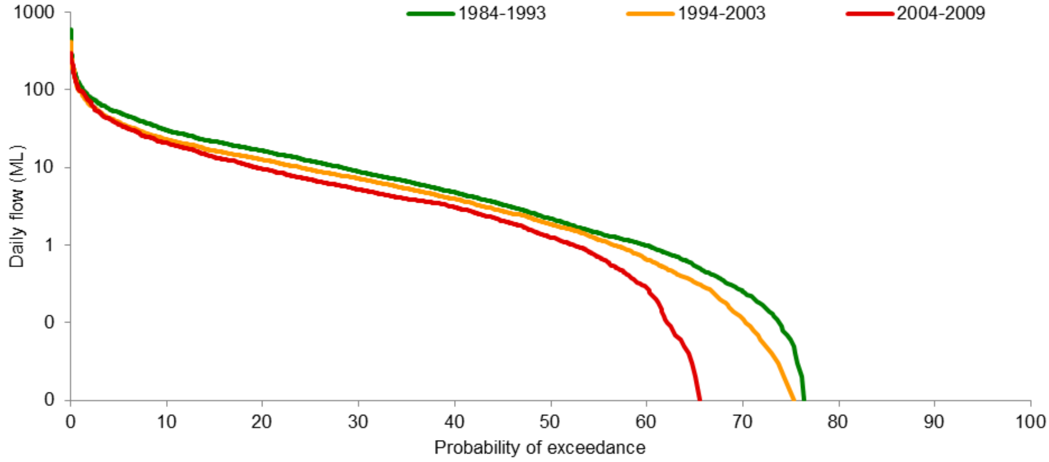

Figure A9 Flow duration curves for Beigpiegup catchment

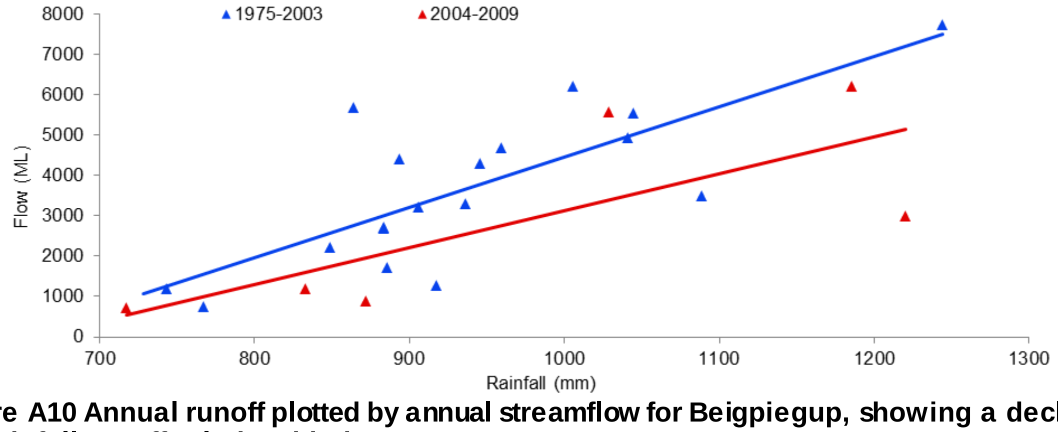

Figure A10 Annual runoff plotted by annual streamflow for Beigpiegup, showing a decline in the rainfall-runoff relationship in recent years.

Blackbutt Point Tallanalla Creek (Harvey River Basin) 613005

PDWSA Priority 1 catchment. This catchment appears to be on the perennial–intermittent border, and takes a few years to respond to changes. It was perennial till 1977 following the wet 1975 climate, intermittent till mid/late 1980s with the drier climate of the late 70s/early 80s, perennial again following harvesting of half the catchment and the slightly wetter climate of the late 80s/early 90s, and finally intermittent again since 2008 with little forest harvesting, increasing vegetation coverage, and successive years of below-average rainfall. Strong, but short-lived, increase in runoff coefficient in 2001 possibly related to clearing of plantations adjacent to stream. No significant trends detected.

Assessment	Primary catchment
Size & location	38.1 km^2 (medium); 33.11°S, 116.12°E
Av. rainfall	1018 mm/a
Tenure	100% state forest
Clearing	2% cleared (power line and roads)
Vegetation type	2% old growth, 83% jarrah with forest, 7% jarrah woodland, 7% pine plantation
Geomorphology	Low to moderate relief; undulating plateau – moderate dissection, lateritic soils over Archaean granitic and gneissic rocks.
Timber harvest	Significant proportions harvested at low intensity in the '20s (50%), '30s (26%), '60s (41%), 70s (10%) and '80s (49%). Plantation clear felled 1999 & 2000 on 7% of catchment on lower slope immediately upslope from gauging station.
Fire history	Spring burnt in 1981 (5%), 1990 (3%), 1998 (11%), 1999 (5%), 2001 (22%), 2002 (13%) 2003 (4%), 2006 (8%) & 2009 (7%), 14% Autumn burnt in 2010. No significant wildfires.
Dieback	54% has been interpreted for dieback, 65% of this area was infected.
Flow trends	No statistically significant trends observed. Categorised as 'climate pattern dominant – no overall streamflow trend'.
Salinity data	Average TSS 190 mg/L to 1982 (WRB 1984b). Data reliability code: 5 (Mostly continuous measurements with very large estimated gaps (>3 months) or fewer than 6 discrete samples per year or data estimated from flow).

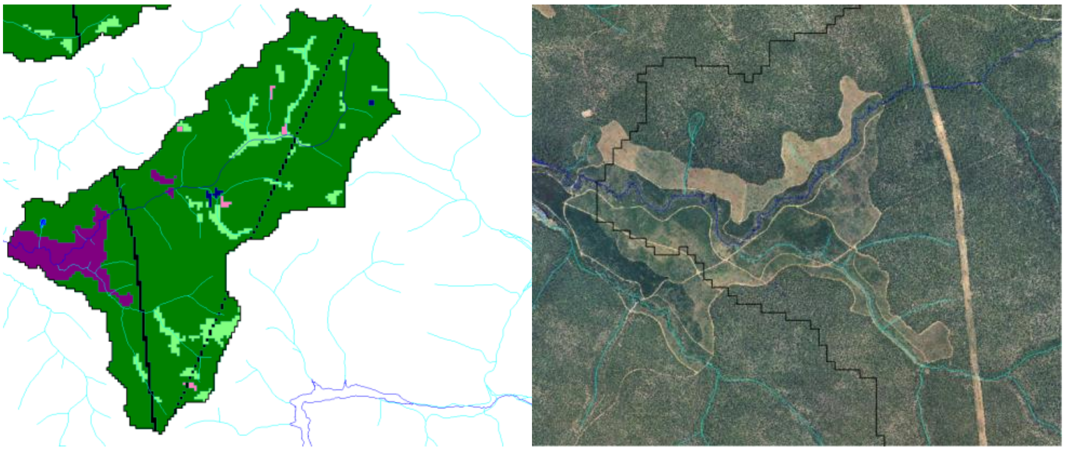

Figure A11 Blackbutt Point catchment views. L: Vegetation type showing jarrah forest in dark green, woodland light green, cleared infrastructure corridors in black and pine plantation in purple. R: Aerial photo showing clear fell and newly established plantation adjacent to gauging station

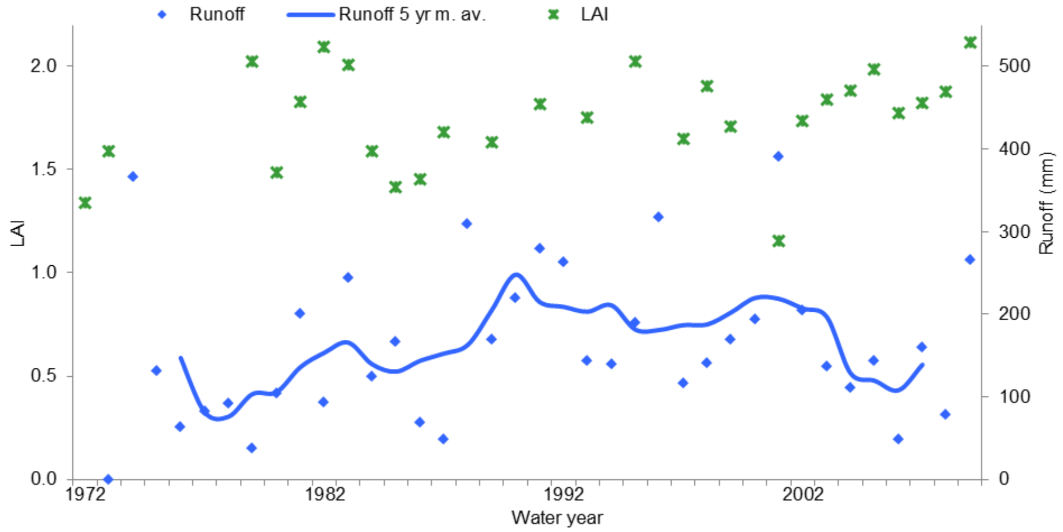

Figure A12 Annual streamflow, moving average, and leaf area index for Blackbutt Point

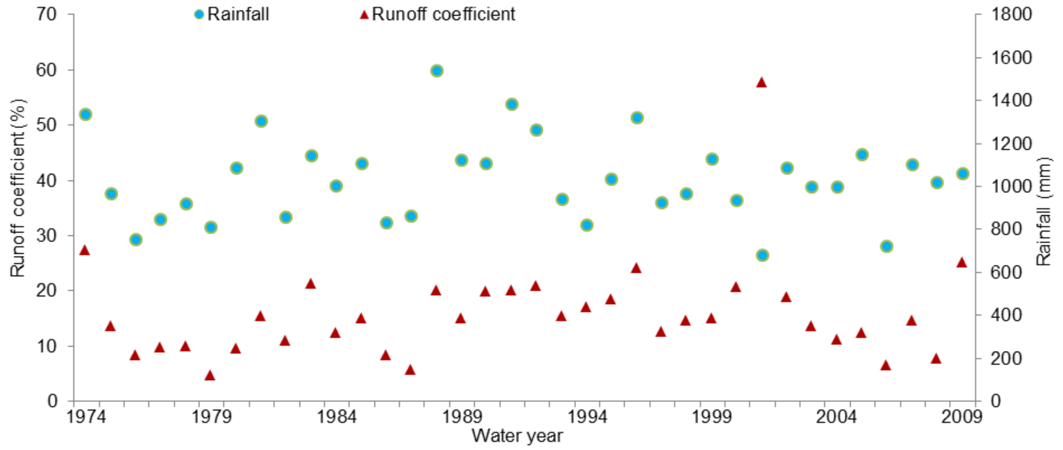

Figure A13 Annual rainfall and runoff coefficient for Blackbutt Point catchment

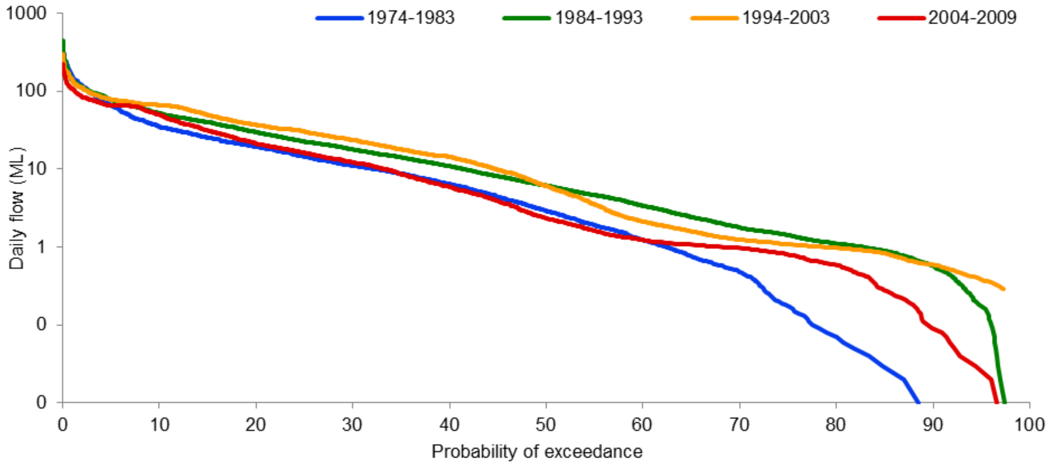

Figure A14 Flow duration curves for Blackbutt Point catchment showing oscillation between perennial and intermittent flow regimes

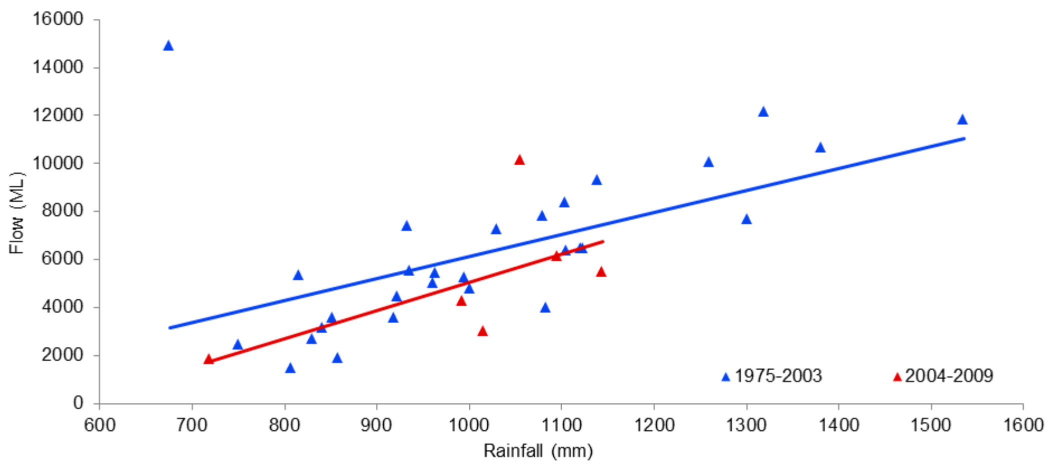

Figure A15 Annual runoff plotted by annual streamflow for Blackbutt Point, showing a decline in the rainfall-runoff relationship in recent years.

Cobiac Wungong Brook (Canning-Swan Coastal basin) 616058

PDWSA. Initially part of Alcoa's research with an extensive groundwater monitoring network (approx. 180 bores), installed and monitored by Alcoa from 1992–98, then mothballed after Alcoa's decision to close the Jarrahdale mine site. Very small proportion mined by Alcoa before 1998 (Water Corporation 2005).

Gauging station and some bores reinstated by Water Corporation for Wungong trial; since late 2006, Water Corporation has continued monitoring on a seasonal basis (McFarlane 2008). Thinned from 25–30 to 15 m²/ha total basal area in early 2008.. Average groundwater levels have declined by an average of 4 m over the 10 years to 2008 – 2 m drop in near stream levels, 6 m drop in upslope levels.

As part of the Wungong catchment thinning trial, three transects were commercially thinned and notched to a density of 10 m² plus 5 retained habitat trees per ha in late 2008, to assess the impacts on forest structure, understorey microclimate, forest water balance incl. changes to transpiration and soil moisture, modified flow pathways, water quality, nutrient dynamics, and habitat value for selected species. Piezometers and neutron moisture meter access tubes were installed along each transect.

Increases in soil moisture and groundwater were observed may be partly explained by the wet year (Silberstein et al. 2011). A streamflow response to thinning – 50 mm not the predicted 24 mm –observed in the second winter (2009) after thinning, and groundwater intersected the stream zone for the first time in over 10 years. The gain vanished in 1–2 years. Cobiac didn't flow in 2010.

Assessment	Supplementary catchment
Size & location	3.6 km² (small); 32.33°S, 116.20°E
Av. rainfall	1059 mm for 1975-2008
Tenure	State Forest
Clearing	0%
Vegetation type	79% jarrah forest, 21% jarrah woodland

Timber harvest	100% harvested in 1940s, 16% in 1960s, 17% in 1970s, 20% in 80s, 4% in 1990s, 68% in 2000s.
Fire history	35% last burnt spring 1986, 58% last burnt autumn 2003, 7% burnt winter 2006–07.
Dieback	100% interpreted for dieback; 48% was found to be infested.
Flow trends	Significant declines in streamflow, and rainfall-runoff relationship observed. Catchment categorised as 'climate pattern present, streamflow decline observed'.
Salinity data	Insufficient data for analysis. Data reliability code: 5 (Mostly continuous measurements with very large estimated gaps (>3 months) or fewer than 6 discrete samples per year or data estimated from flow)

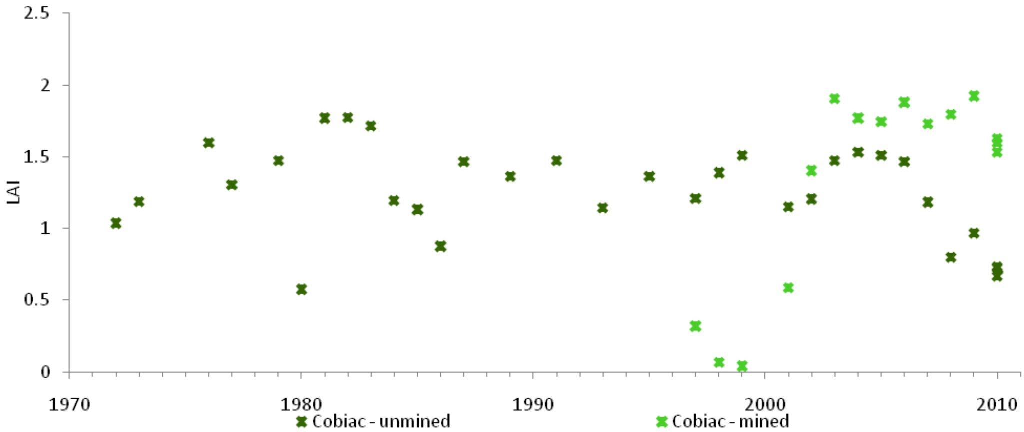

Figure A16 Leaf area index data shown separately for mined and unmined parts of Cobiac catchment

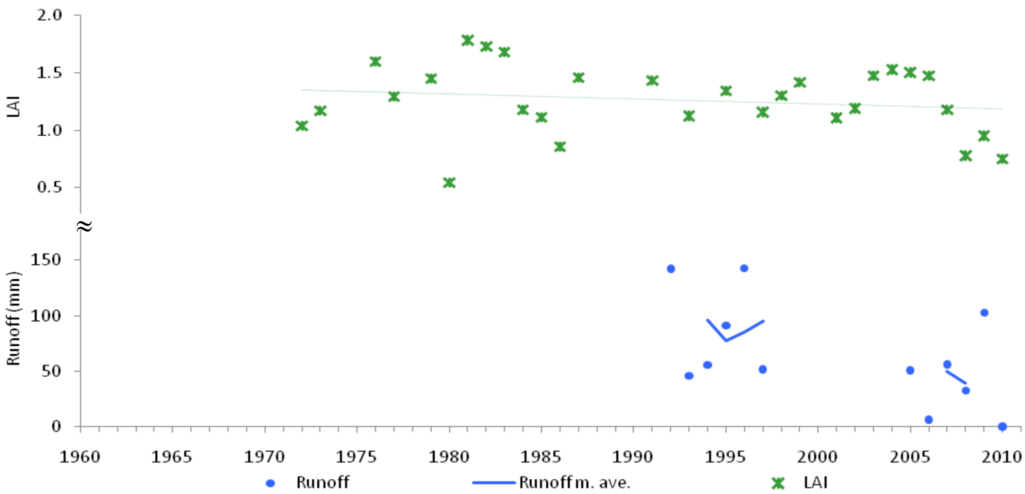

Figure A17 Annual streamflow, moving average, and catchment average leaf area index for Cobiac catchment

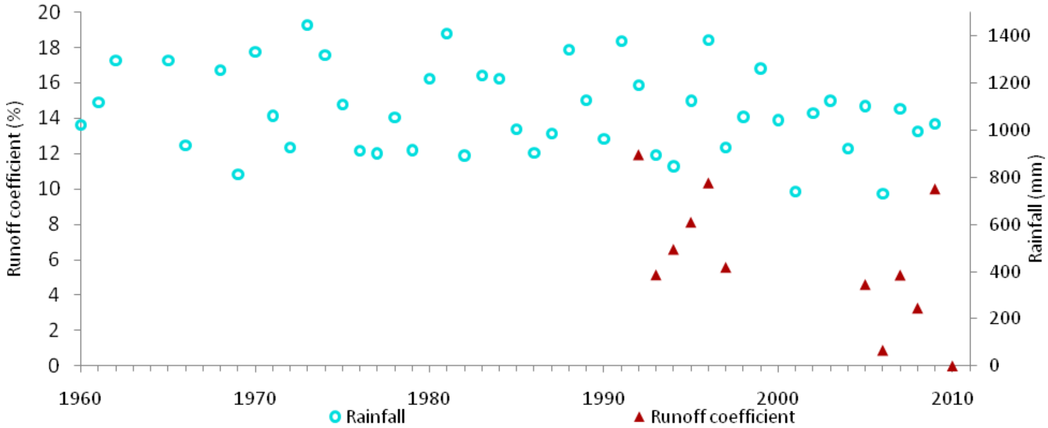

Figure A18 Annual rainfall and runoff coefficient for Cobiac catchment

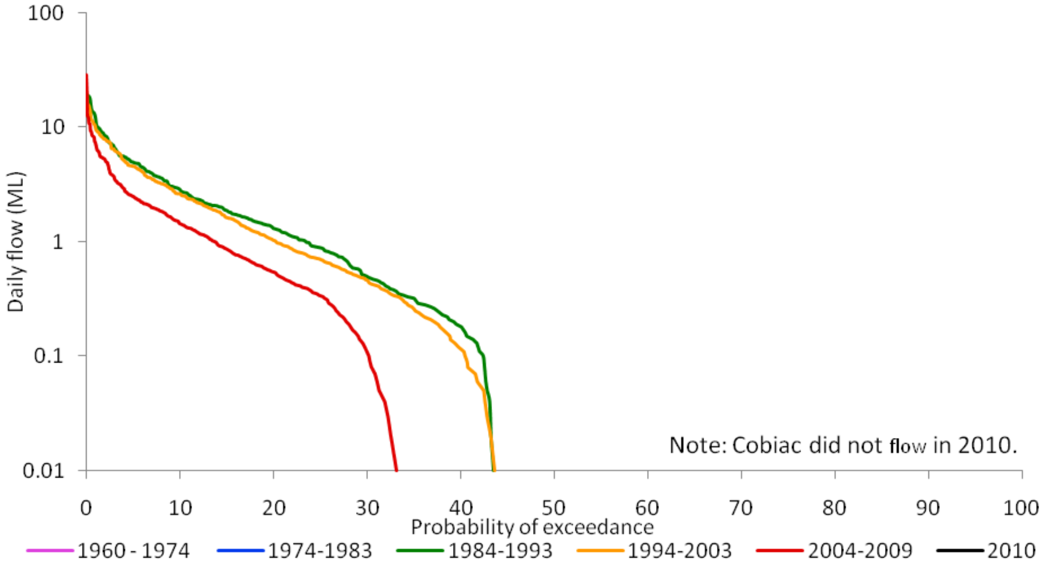

Figure A19 Flow duration curves for Cobiac catchment

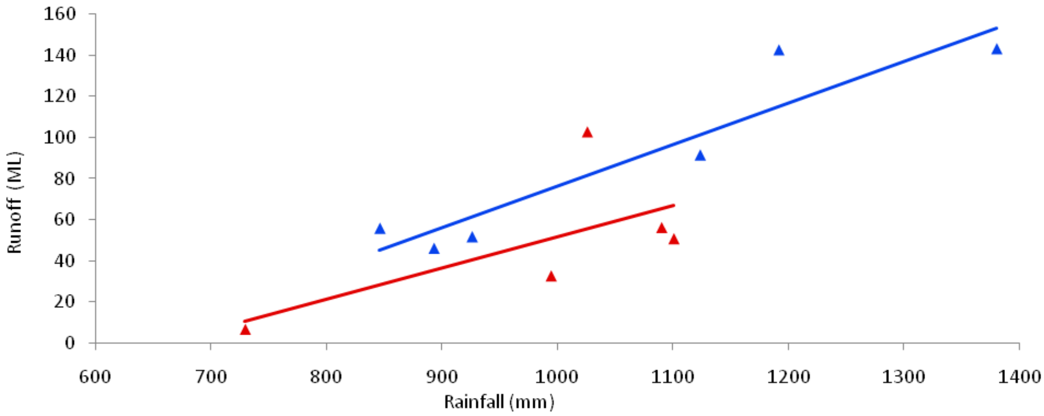

Figure A20 Annual runoff plotted by annual streamflow for Cobiac, showing a decline in the rainfall-runoff relationship in recent years.

Crouch Road Rosa Brook, Blackwood River Basin 609001

Intermittent stream with limited streamflow data. Mostly jarrah forest, lightly harvested and dieback infected. Low flows and runoff coefficients in recent period correspond with those in 1970s, but high flows/coefficients are absent altogether. No statistically significant trends detected. LAI decreased till 1997 and has increased steadily since, possibly aided by regeneration following some moderate and high intensity harvesting in 90s.

Assessment	Primary catchment
Size & location	89 km^2 (medium); 33.94°S, 115.49°E
Av. rainfall	886 mm/a
Tenure	92% State forest, 8% National Park. Entire catchment falls within petroleum exploration permit; three exploration wells were drilled during 2011.
Clearing	0% cleared
Vegetation type	Predominantly (89%) jarrah forest, 6% jarrah woodland, 4% softwood plantation, 1% shrub, herb and sedge land. 10% Old growth.
Geomorphology	Low to moderate relief; undulating plateau at low elevation, lateritic soils over Phanerozoic sedimentary rocks.
Harvest history	Large areas harvested at low intensity in the ‘60s (55%) and ‘70s (54%), harvested at low intensity in the ‘80s, 13% harvested in the ‘90s at a range of intensities (8% L, 2% M, 3% H) and 9% harvested in the ‘00s at low and moderate intensities.
Fire history	No recent wildfires, 37% autumn burnt 1997, 20% spring burnt 2007
Dieback	~60% of the catchment interpreted for dieback. 66% of this infested.
Flow trends	No statistically significant trends observed. Categorised as ‘climate pattern dominant – no overall streamflow trend’.
Salinity data	Av. TSS to 1982 was 220 mg/L (WRB 1984b). Data reliability code: 5 (Mostly continuous measurements with very large estimated gaps (>3 months) or fewer than 6 discrete samples per year or data estimated from flow).


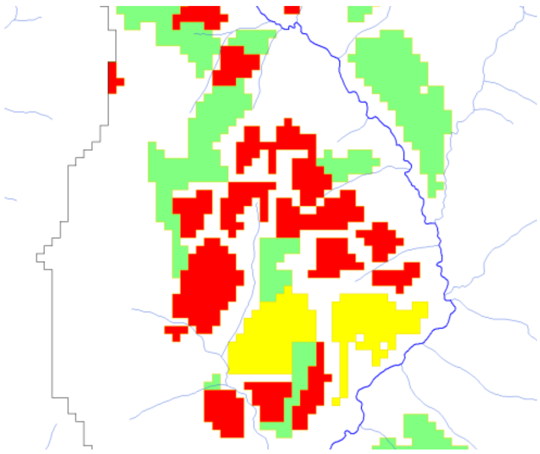

Figure A21 Crouch Road catchment views. L: Aerial photograph. R: Areas harvested in the 90s at high (red), medium (yellow) and low (green) intensity. The area harvested at high intensity is approximately 2% of the catchment.

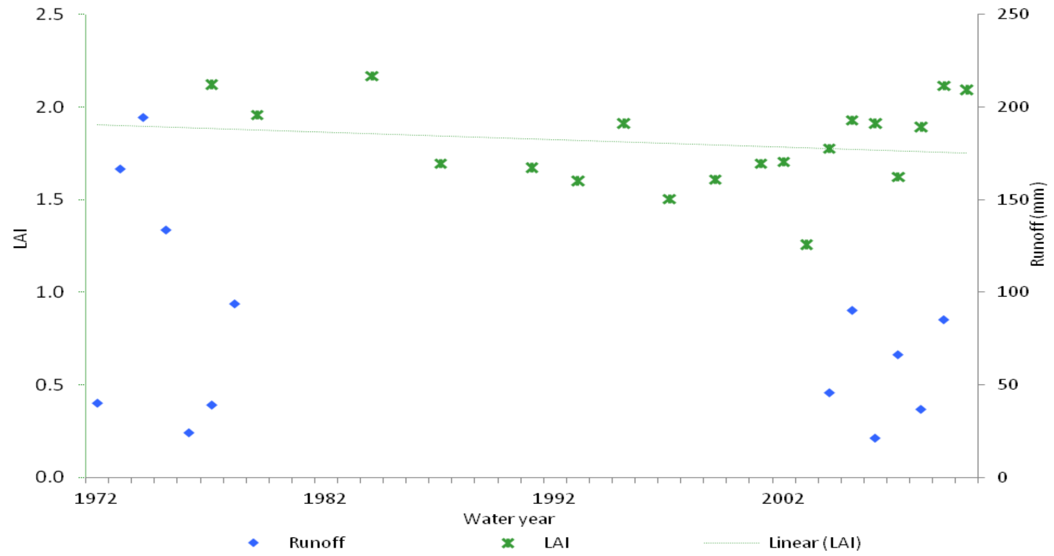

Figure A22 Annual streamflow, moving average, and leaf area index for Crouch Road

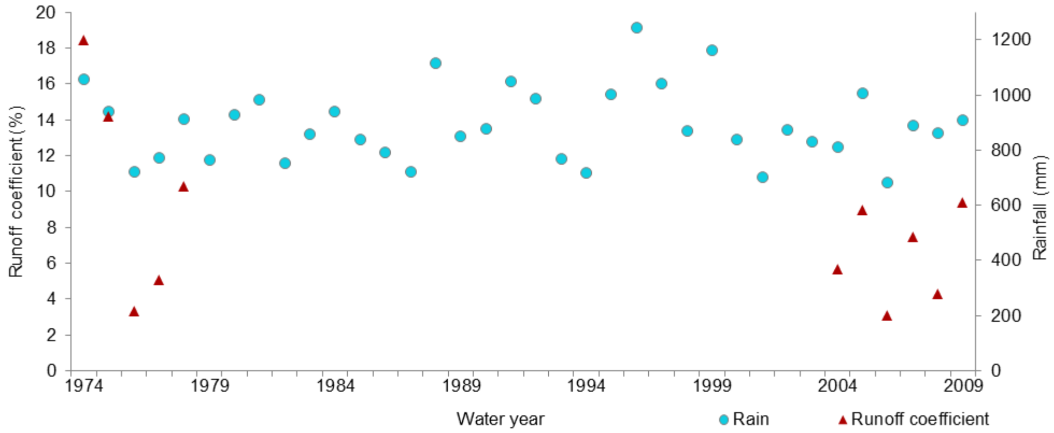

Figure A23 Annual rainfall and runoff coefficient for Crouch Road catchment

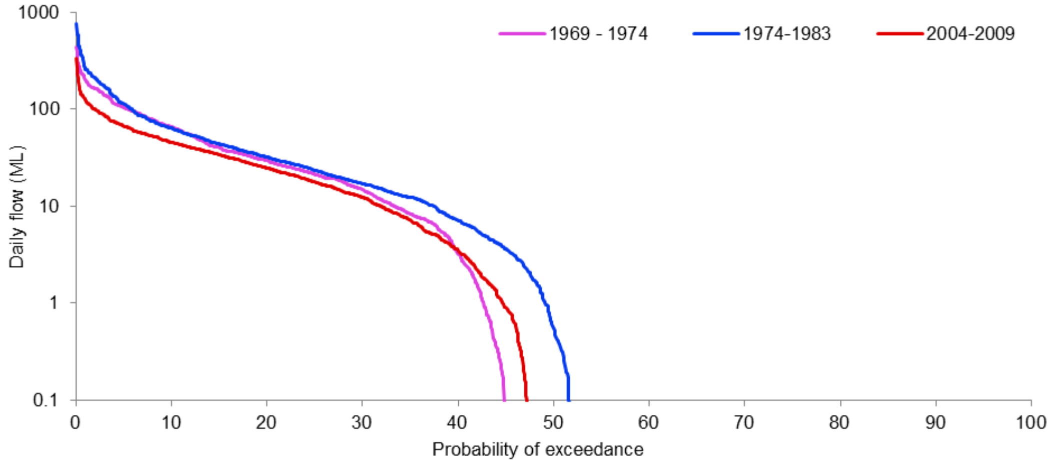

Figure A24 Flow duration curves for Crouch Road catchment

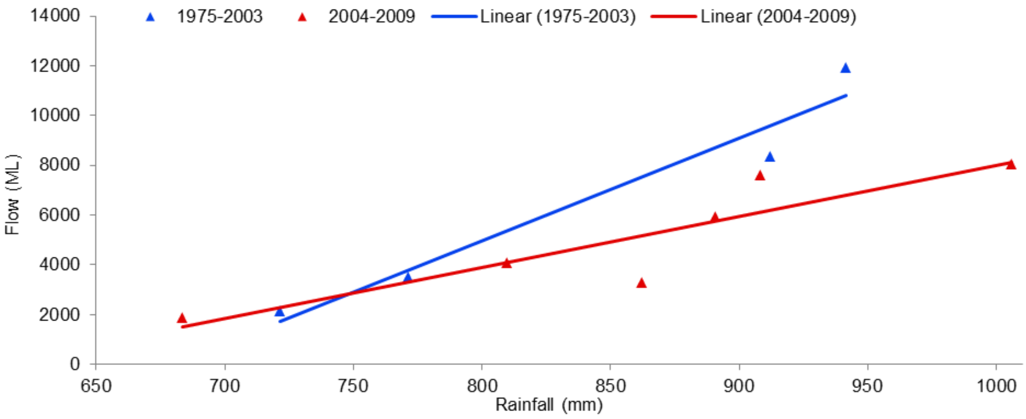

Figure A25 Annual runoff plotted by annual streamflow for Crouch Road.

Dee Tee 59 Falls Brook (Harvey) 613008

PDWSA Priority 1. Historically perennial stream but flows have been decreasing while vegetation coverage has increased, most likely as regrowth forest recovers from earlier logging in the absence of harvesting in the 80s and 90s. Some recent low intensity harvests have stabilised LAI but not reduced it to the levels of the 1960s. Stopped flowing for the first time on record in February 2007, and for the second time in February 2010.

Assessment	Primary catchment
Size & location	29 km^2 (medium); 33.04°S, 116.00°E
Av. rainfall	1064 mm/a
Tenure	80% State forest, 20% Nature reserve
Clearing	1% cleared
Vegetation type	84% jarrah forest, 11% Jarrah woodland, 2% swamps, 1% shrub, herb & sedge land
Geomorphology	Moderate relief; dissected plateau, lateritic soils over Archaean granitic and metamorphic rocks (WRB 1984b).
Timber harvest	94% harvested pre 1920s, 6% in 40s, 4% in the 50s, 92% in the 60s, 36% in the 1970s and 18% in the 2000s at low intensity. No timber harvesting in 1980s & 90s. No old growth.
Fire history	Very little burning occurred from 1961 to 1998. Spring burning of 23% in 2000, 45% in 2008, 4% in 2009. 5% autumn burnt in 2010. No recent wildfire history. Burn freq. post 89/90 4% once burnt, 72% twice burnt, 23% three times burnt.
Dieback	Almost two thirds of the catchment interpreted, 99% of this is infected.
Flow trends	Significant decreasing trend since 1975; average runoff of current FMP is significantly lower than 1975–2003 mean runoff. Progressive decline in flow regime observed in flow duration curve. Categorised as ‘climate pattern present, streamflow decline exacerbated by increasing vegetation cover’.
Salinity data	Average TSS to 1982 was 190mg/L (WRB 1984b). Data reliability code for current report: 6 (No or very little data).

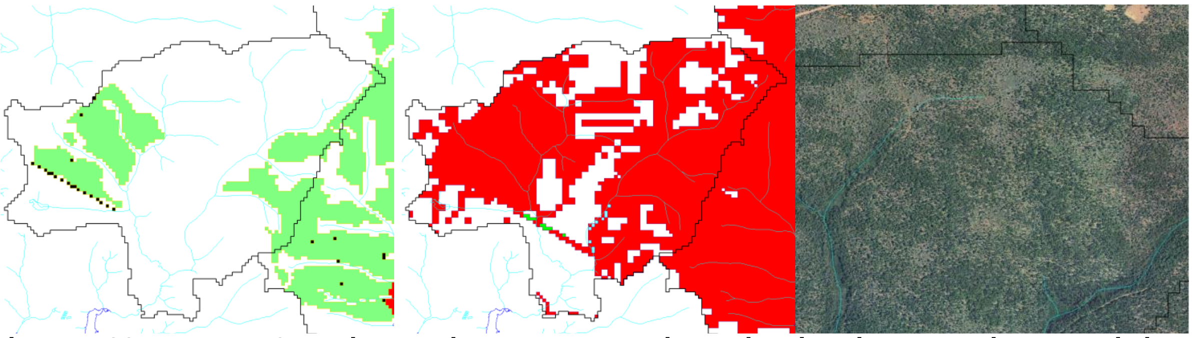

Figure A26 Dee Tee 59 catchment views. L: Harvest intensity showing areas harvested since the 1970s (green) at low intensity and cleared (black). M – Dieback status showing the majority of the catchment surveyed as infected. R: Aerial photograph showing considerable variation in vegetation coverage in the catchment.

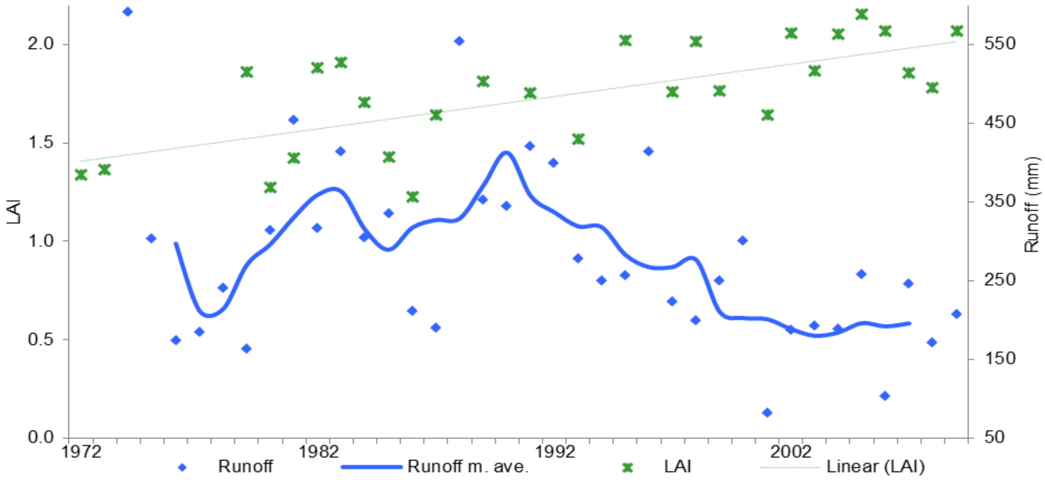

Figure A27 Annual streamflow, moving average, and leaf area index for Dee Tee 59 catchment

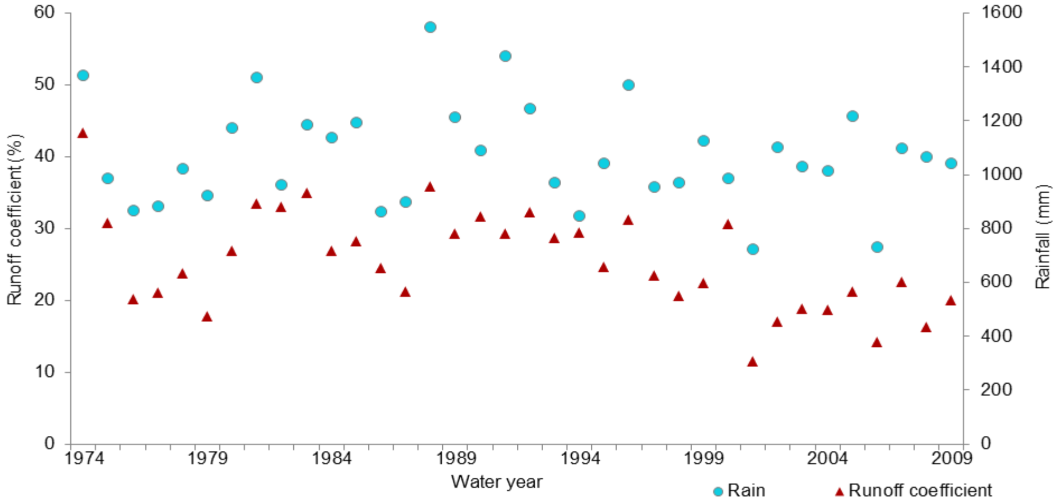

Figure A28 Annual rainfall and runoff coefficient for Dee Tee 59 catchment

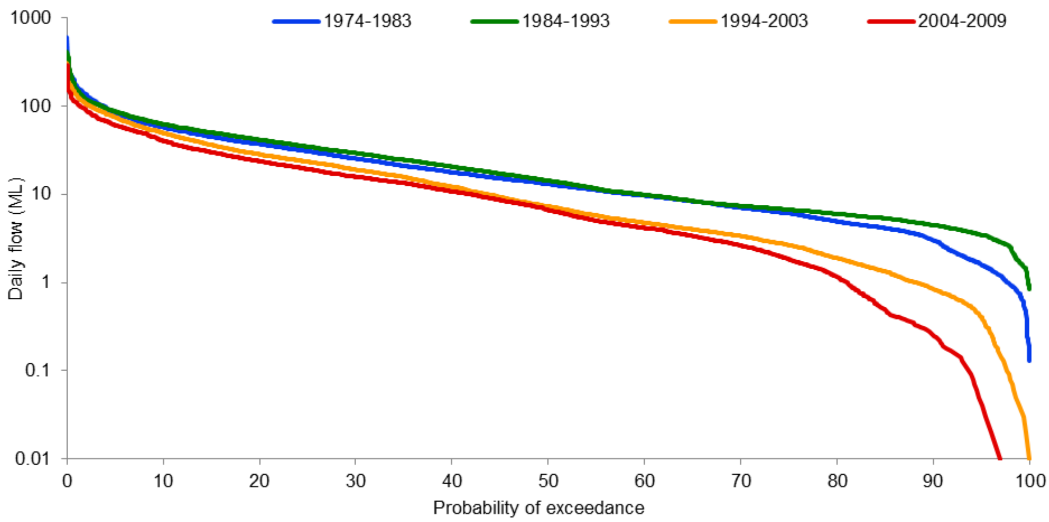

Figure A29 Flow duration curves for Dee Tee 59 catchment showing a transition from perennial to intermittent flows.

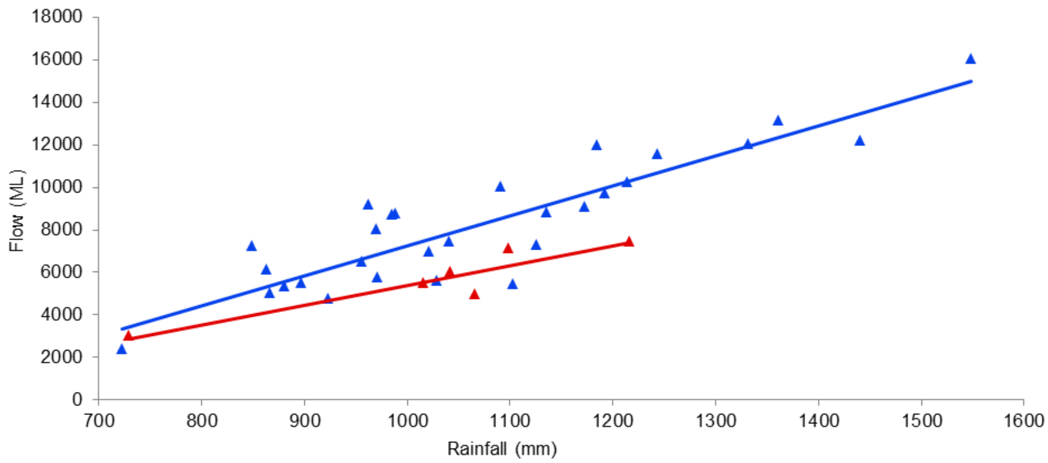

Figure A30 Annual runoff plotted by annual streamflow for Dee Tee 59, showing a decline in the rainfall-runoff relationship in recent years.

Del Park South Dandalup tribuitary, Murray River basin 614007

PDWSA Priority 1. Iconic research catchment. Intermittent stream since 1993, mixed perennial and intermittent history prior to this. LAI has increased, particularly in the unmined parts of the catchment.

Approximately 20% of the catchment was mined and revegetated between 1974–79. The revegetated understorey was thinned in 1985 (Ruprecht et al. 1990). Groundwater levels increased after mining, up to peak of 3.1 m compared to control, and peak increases in flow 98 mm/yr – 49% of flow were observed. Groundwater levels returned to within 1 m of the control eight years after mining. A further 11% was mined in 1986-89. Comparison with control shows the runoff coefficient increased a maximum of 9% in response to mining. When rehabilitation completed in 1989, water yield returned to the pre-mining level (Bari & Ruprecht 2003).

Hughes et al. (2012) found high linear correlation between the annual change in the groundwater level and annual rainfall, for 1975–2009. Groundwater levels decreased by an average of 1.4 mm per 1 mm of rainfall below the catchment threshold, indicating that the response is greater than the cause. They found that the threshold required for groundwater levels to rise in this catchment is 1242 mm. Croton (2004) compared Del Park with Waterfall Gully streamflows, using equation Del Park = 0.7 x Waterfall Gully. Recent data review of the interception experiment in this catchment shows 13% of annual rainfall is lost though interception alone (Croton & Norton 1998; quoted in Bari & Ruprecht 2003). Others measured annual tree water use of jarrah stands at the Del Park and Hansen catchments. Av. annual tree water uptake was 485 mm, approx. 34% of annual rainfall. The ventilated chamber technique was used to measure evapotranspiration from the middle storey and ground layer in this catchment. The middle-storey trees evaporated 16% and ground layer 37% of rainfall respectively (Bari & Ruprecht 2003). Grigg (2009) suggested immediate experimental thinning in this catchment.

Assessment	Supplementary catchment
Size & location	1.4 km^2 (small), 32.67°S, 116.04°E
Av. rain	1147 mm/a for 1975-2008
Clearing	0% cleared
Timber harvest	0% old growth. 40% non-forest type or last harvested prior to 1920. 50% last harvested in 70s, 10% last harvested in the 80s.
Av. rainfall	1147 mm (nearest met stations 509249 & 509237)
Dieback	39% of the catchment interpreted for dieback; of this 61% was infested.
Flow trends	Highly significant declines in streamflow. Progressive, dramatic decline in flow regime (flow days) since 1970s. Categorised as 'climate pattern present, streamflow decline exacerbated by increasing vegetation cover'.
Salinity data	Data reliability code: 3 (Mostly continuous measurements with small estimated gaps. some discrete data available too. Between 1976 and 2000 the annual salinity was stable, varied 100–150 mg/L TDS.

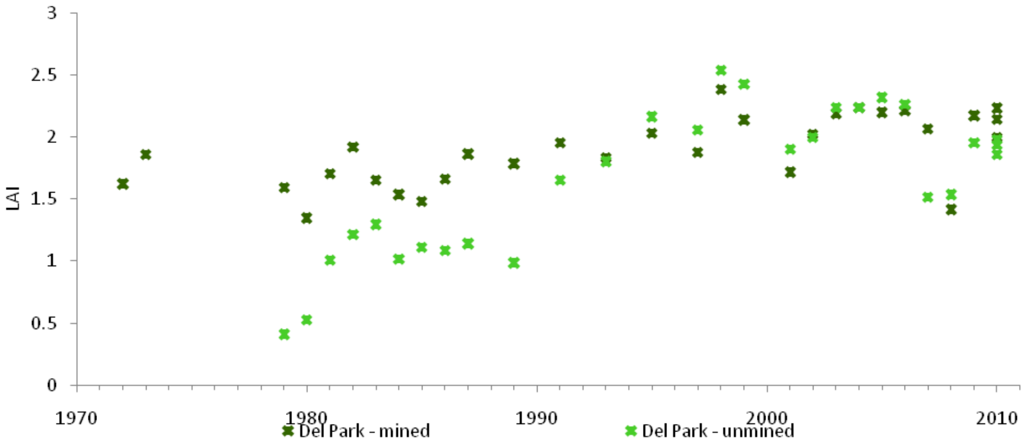

Figure A31 Leaf area index data shown separately for mined and unmined parts of Del Park catchment

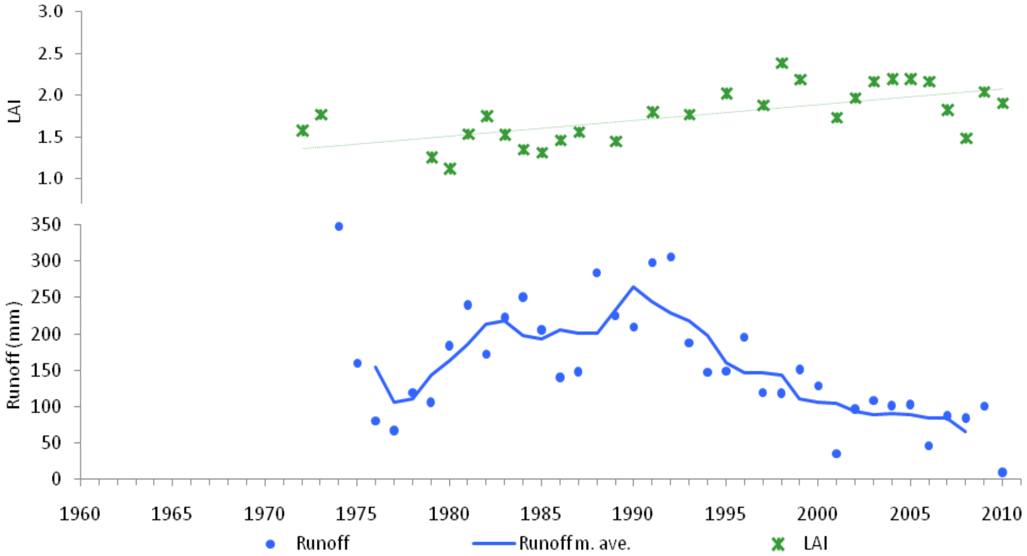

Figure A32 Annual streamflow, moving average, and leaf area index for Del Park catchment

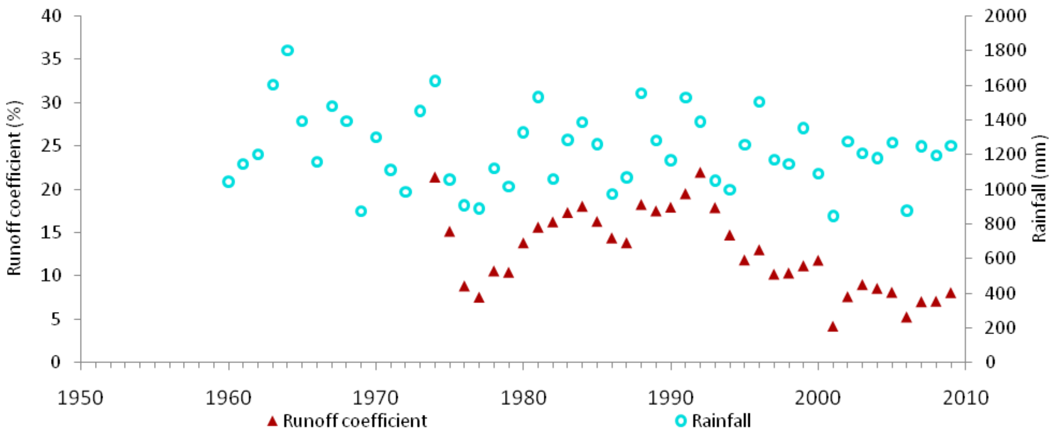

Figure A33 Annual rainfall and runoff coefficient for Del Park catchment

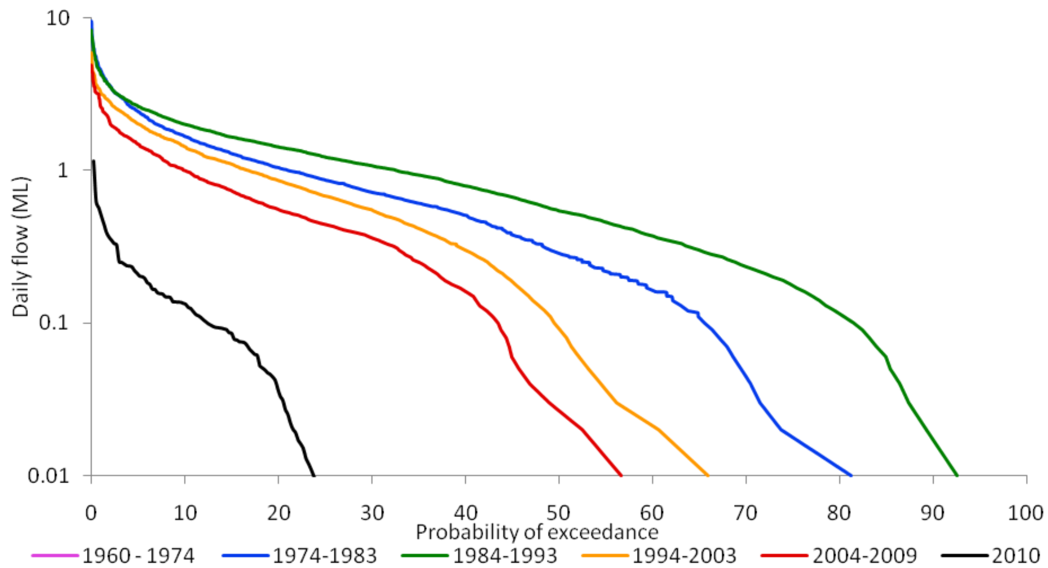

Figure A34 Flow duration curves for Del Park catchment showing shift from perennial to intermittent flow, and progressive declines in flows throughout the year, except for an increase in flows in 1984-93 following mining

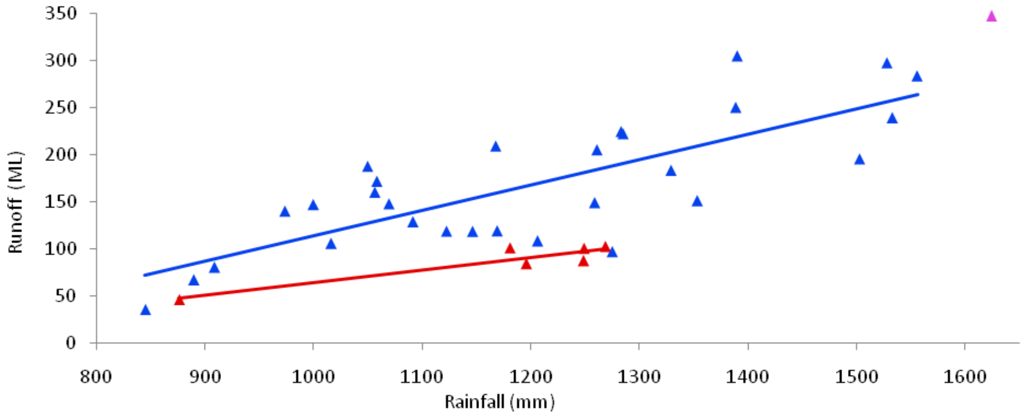

Figure A35 Annual runoff plotted by annual streamflow for Del Park, showing a decline in the rainfall-runoff relationship in recent years.

Dingo Road Harvey River (Harvey River Basin) 613002

PDWSA Priority 1. Historically perennial stream but flows stopped for around a month at a time during early 2002 and 2004. Extensive harvest history, with smaller, less intense recent harvesting that may be associated with increases in vegetation coverage in regrowth forest following large 1970s harvests. Extensive dieback infestation, impact of wildfires visible in LAI data, with fast recovery. Progressive declines in coefficient show a changing relationship between rainfall and runoff, with a large decrease also observed in estimated groundwater storage. Hughes (pers. comm..) calculated the threshold annual rainfall, below which groundwater declines, is 1051 mm.

Assessment Primary catchment

Size & location	147.2 km^2 (large). 33.01°S, 116.09°E
Geomorphology	Low to moderate relief; undulating plateau – moderate dissection, lateritic soils over Archaean granitic and gneissic rocks.
Av. rainfall	1070 mm/a for 1975-2008
Tenure	100% State forest
Clearing	1% cleared
Vegetation type	86% jarrah forest, 11% jarrah woodland, 2% shrub, herb and sedge land.
Timber harvest	3% old growth. 38% harvested pre 1920s; 28% in 1920s–30s, 39% in 1940s, 24% in 1960s, 45% in 1970s 13% in 1980s, and 19% in 2000s
Fire history	Very little burning occurred from 1961 to 2007. Spring burning of 11% in 2007 and 15% in 2008. 54% impacted by wildfire in 2009/10.
Dieback	70% of the catchment has been interpreted, 94% is infected with dieback.
Flow trends	Significant decline in streamflow observed, along with shift from perennial to intermittent flow regime, and progressive declines in rainfall-runoff relationship. Categorised as 'climate pattern present, streamflow decline possibly exacerbated by increasing vegetation cover'.
Salinity data	Insufficient data for analysis. Data reliability code: 5 (Mostly continuous measurements with very large estimated gaps (>3 months). Average salinity 1982-2002 approx. 120 mg/L (WRB 1984b).

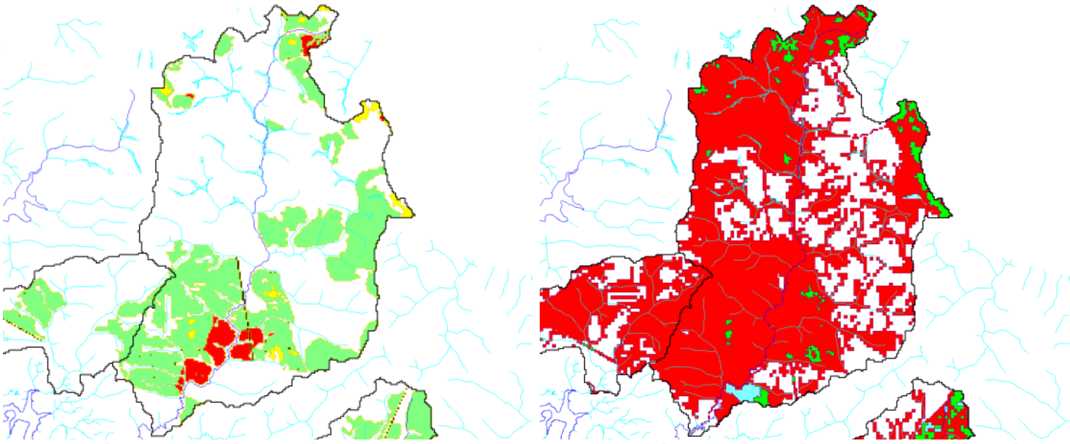

Figure A36 Dingo road catchment views. L: Harvest intensity since 1990 showing areas cleared (black) and harvested at high (red), medium (yellow) and low (green) intensity. R – Map of dieback status showing the majority of areas interpreted are infected.

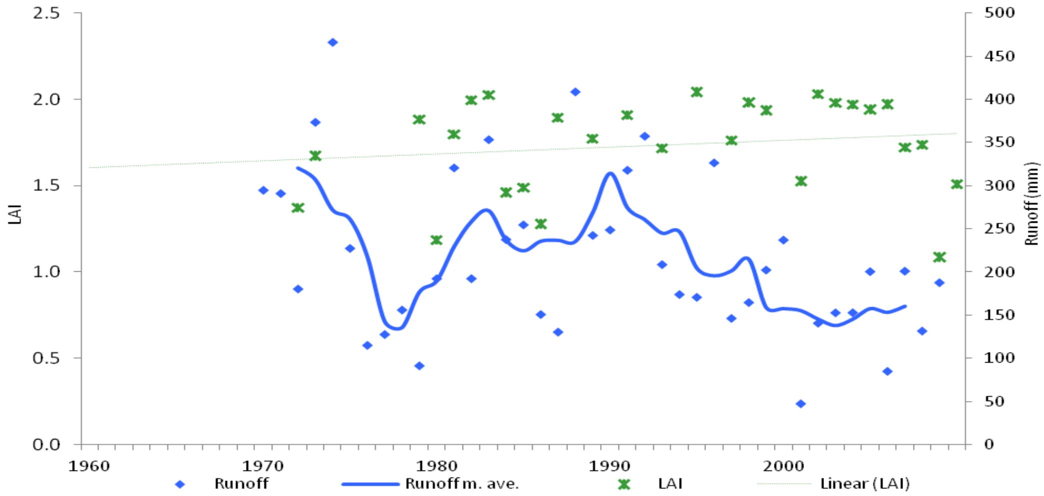

Figure A37 Annual streamflow, moving average, and leaf area index for Dingo Road catchment

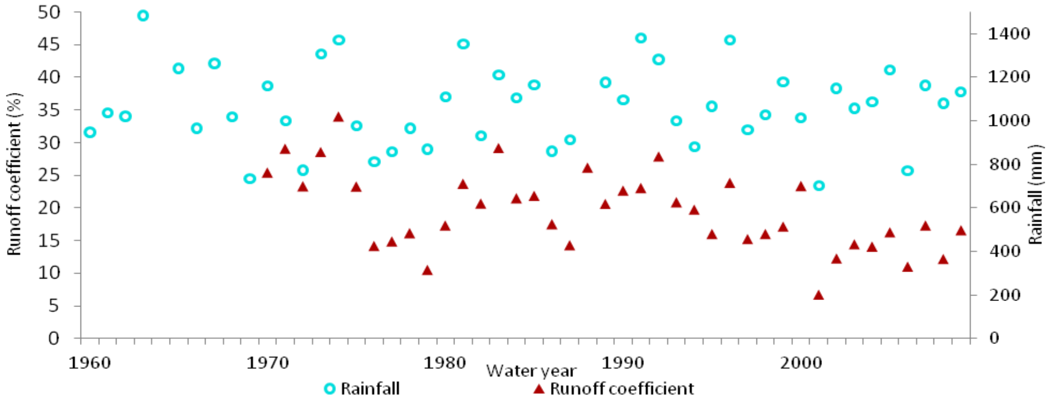

Figure A38 Annual rainfall and runoff coefficient for Dingo Road catchment

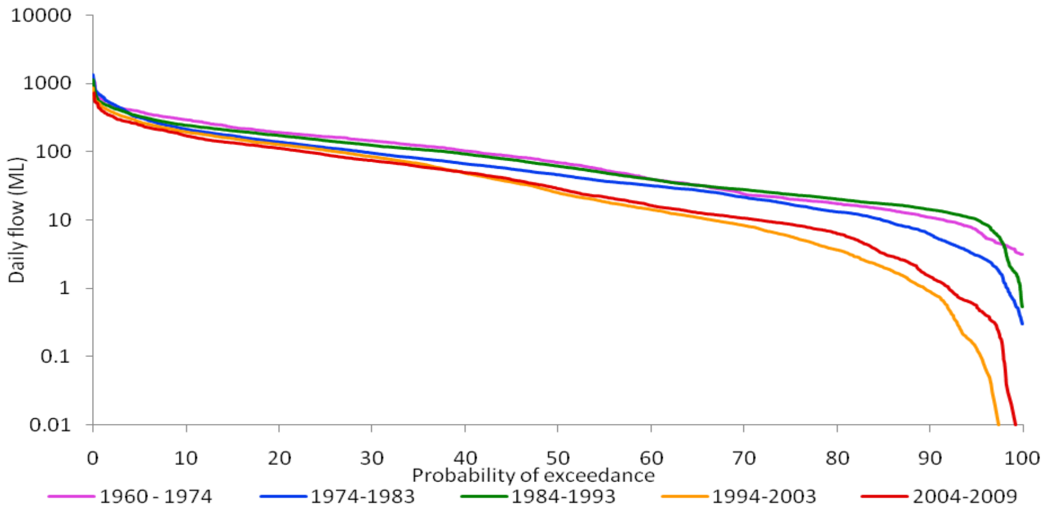

Figure A39 Flow duration curves for Bates catchment showing shift from perennial to intermittent flow, and progressive declines in flows throughout the year.

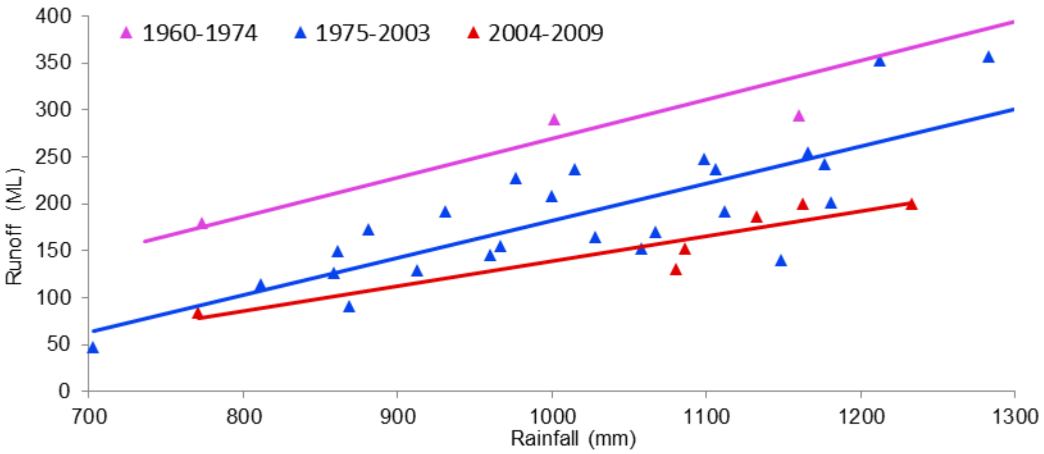

Figure A40 Annual runoff plotted by annual streamflow for Dingo Road, showing a progressive decline in the runoff observed per unit rainfall received

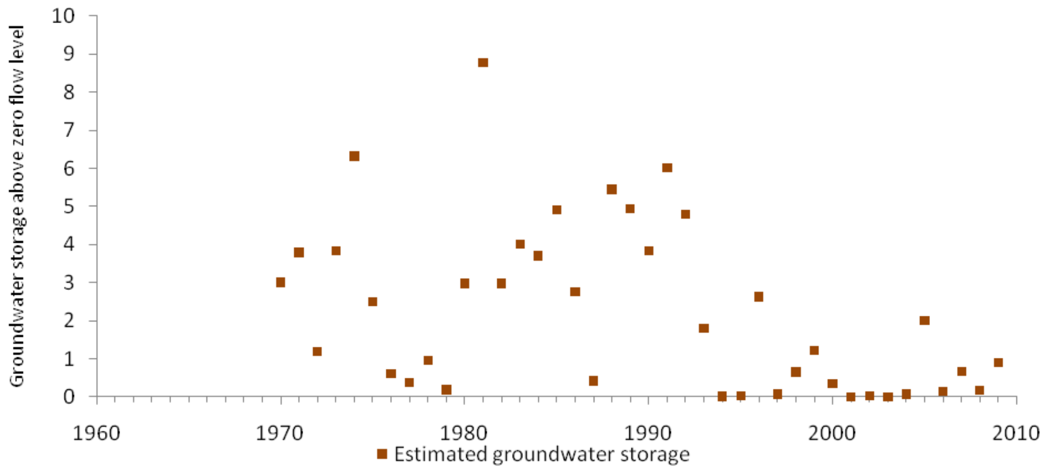

Figure A41 Estimated groundwater storage for Dingo Road catchment

Ernies Bingham River Trib (Collie River Basin) 612008

PDWSA. Intermittent stream. Uncleared control in paired study to understand the groundwater and streamflow responses to clearing native forest in low rainfall areas. Paired with Lemon and Dons catchments. Runoff coefficient has stayed relatively stable over this time (Silberstein et al. 2003). Av. TSS 90 mg/L to 1982 (WRB 1984a).

Assessment	Supplementary catchment
Size & location	2.66 km^2 (small); 33.30°S, 116.46°E
Av. rainfall	711 mm/a for 1975-2008
Geomorphology	Low relief; undulating plateau, bauxitic laterite soils over Archaean granitic rocks (WRB 1984a).
Vegetation type	87% jarrah forest, 4% jarrah woodland, 7% wandoo forest, 2% shrub, herb and sedgeland.
Timber harvest	0% clear. 0% old growth. 48% logged pre-1920s. 32% logged in 30s, 24% in

	40s, 96% in 60s, and 3% between 1990 and 2010.
Fire history	29% burnt 2002; 71% burnt 2003.
Dieback	39% interpreted for dieback presence; none identified.
Flow trends	Non-significant streamflow declines observed. Stark decrease in average flow days in recent years. Categorised as 'climate pattern dominant – streamflow decline observed'.
Salinity data	Discrete data available. Data reliability code 3 (Mostly continuous measurements with small estimated gaps (<10 days or more than 30 discrete samples per year)

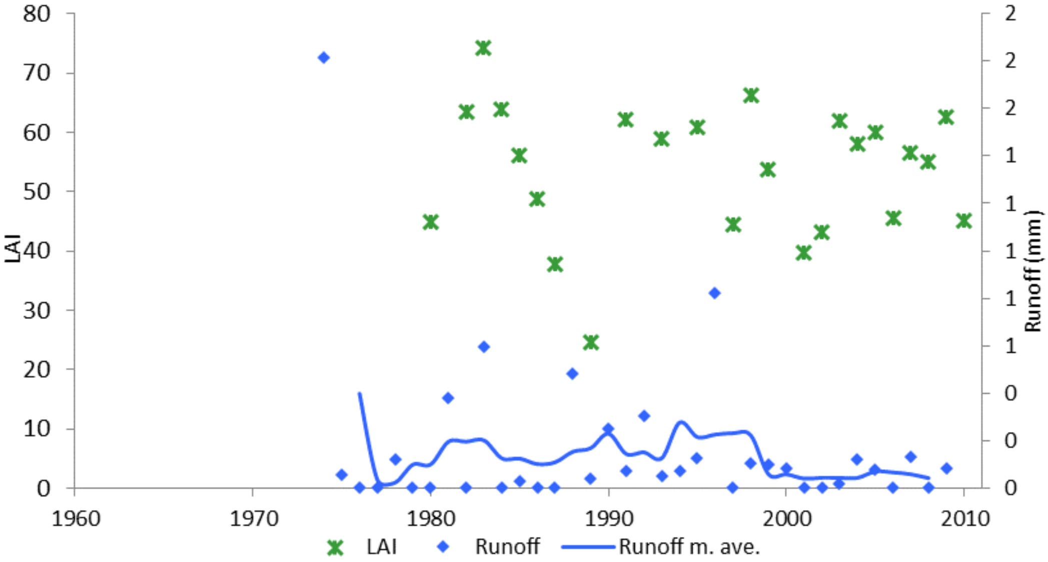

Figure A42 Annual streamflow, moving average, and leaf area index for Ernies catchment

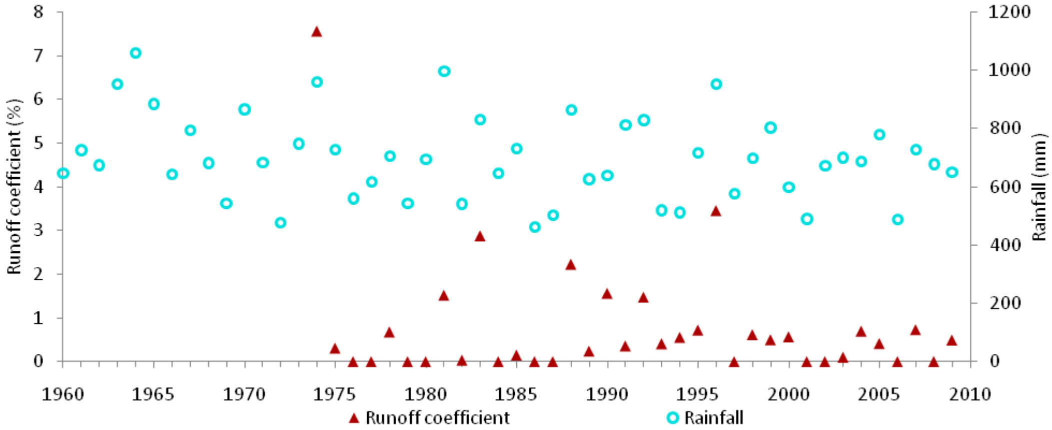

Figure A43 Annual rainfall and runoff coefficient for Ernies catchment

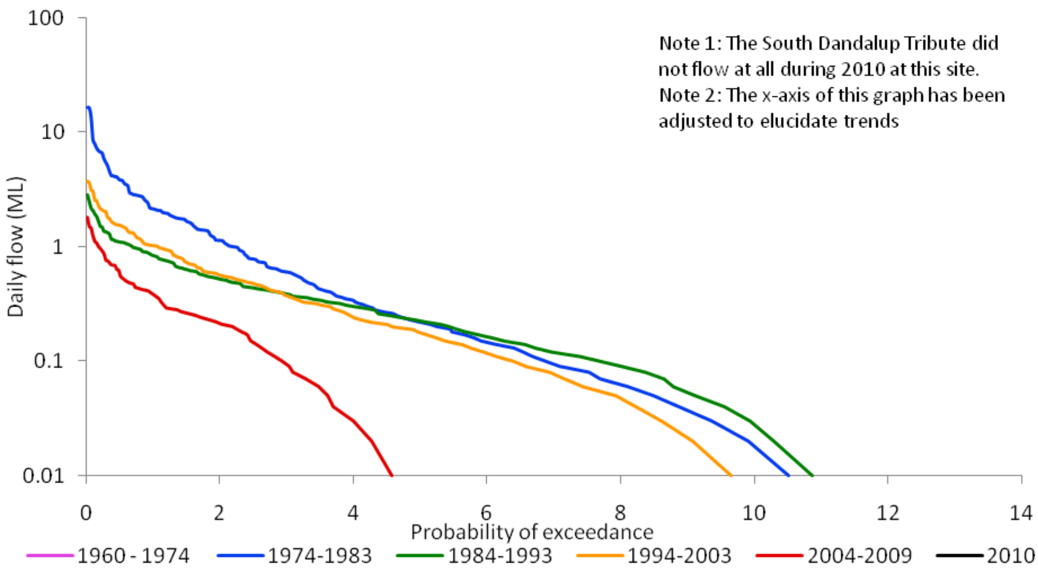

Figure A44 Flow duration curves for Ernies catchment

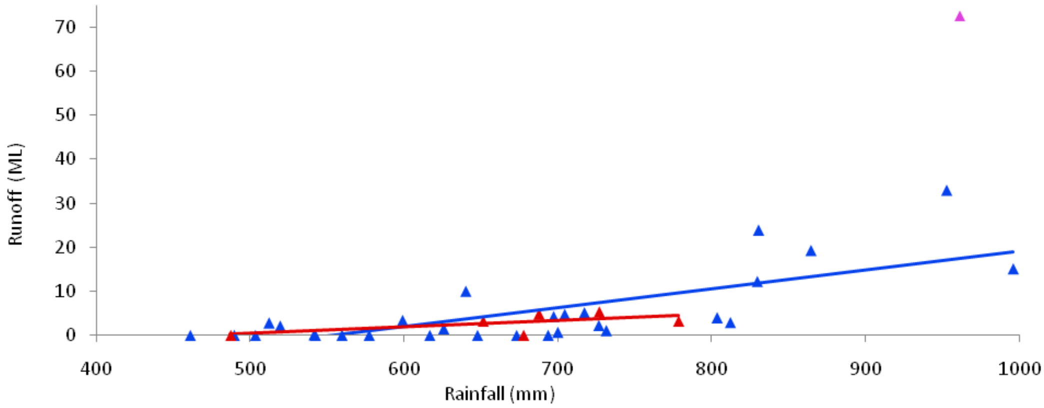

Figure A45 Annual runoff plotted by annual streamflow for Ernies catchment

Gordon South Dandalup R. Trib (Murray River Basin) 614060

PDWSA Priority 1. Intermittent stream.

Used as a control catchment in Trial Mining Project and Yarragil thinning experiment. Groundwater levels >20 m below stream zone, and completely disconnected from streams. Steady decline in groundwater levels observed since 1995 (Hughes et al 2012). Runoff coefficients are low (<3%) and correlation between groundwater and runoff are low.

Assessment	Supplementary catchment
Size & location	2.1 km^2 (small). 32.63°S, 116.25°E
Av. Rainfall	959 mm/a for 1975-2008
Vegetation type	100% jarrah forest. (79% open forest and 21% medium woodland)
Timber harvest	0% cleared. 0% old growth. This catchment was entirely harvested prior to 1920, and 93% of it was harvested again in the 1920s. A further 82% and 17% were harvested during the 1960s and 80s respectively. Much of the catchment is therefore likely to be in an intermediate stage of forest growth, a claim supported by the observed increases in LAI.

Dieback	The whole catchment has been interpreted for dieback. 4% is infested.
Flow trends	Decreasing trend since 1975; average runoff of current FMP is significantly lower than 1975–2003 mean runoff. Progressive decline in flow regime observed in flow duration curve. Categorised as 'climate pattern present, streamflow decline exacerbated by increasing vegetation cover'.
Salinity data	Discrete data available. Data reliability code: 4 – fewer than 30 samples per year.
Salinity trends	Salinity is low (average 81 mg/L) and appears to be declining (statistically significant step decline observed for 1975-2003 versus 2004–09).

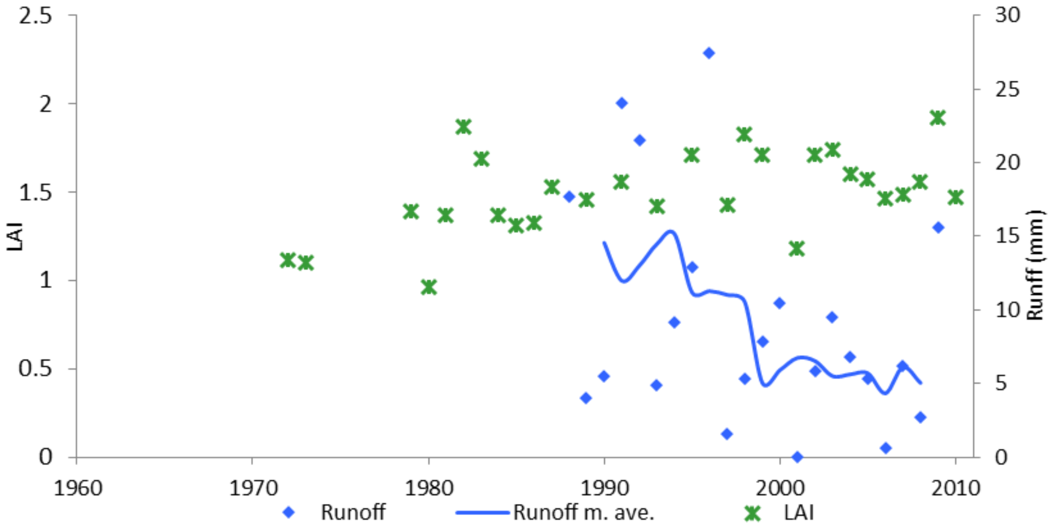

Figure A46 Annual streamflow, moving average, and leaf area index for Gordon catchment

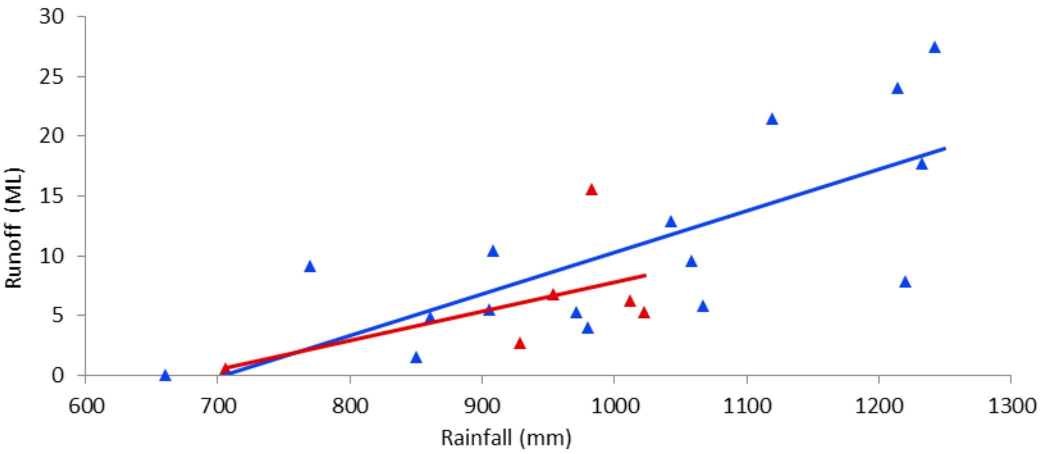

Figure A47 Annual runoff plotted by annual streamflow for Gordon, showing a decline in the rainfall-runoff relationship in recent years.

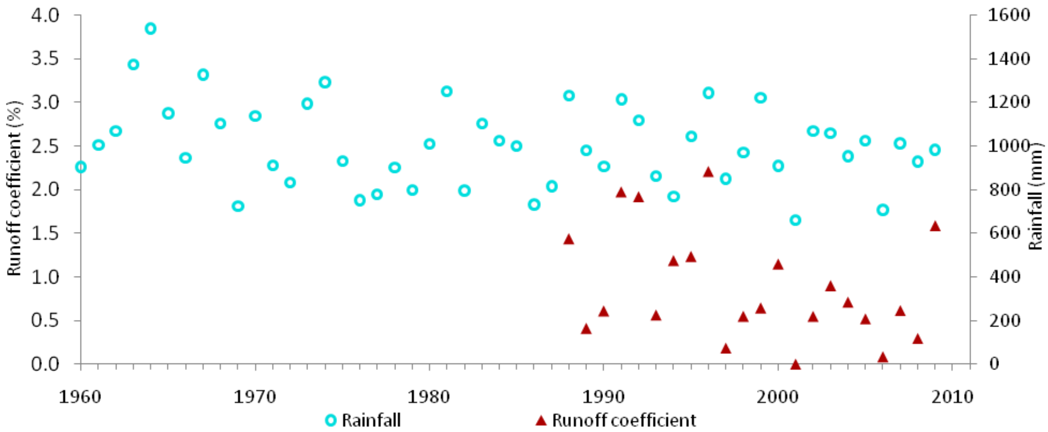

Figure A48 Annual rainfall and runoff coefficient for Gordon catchment

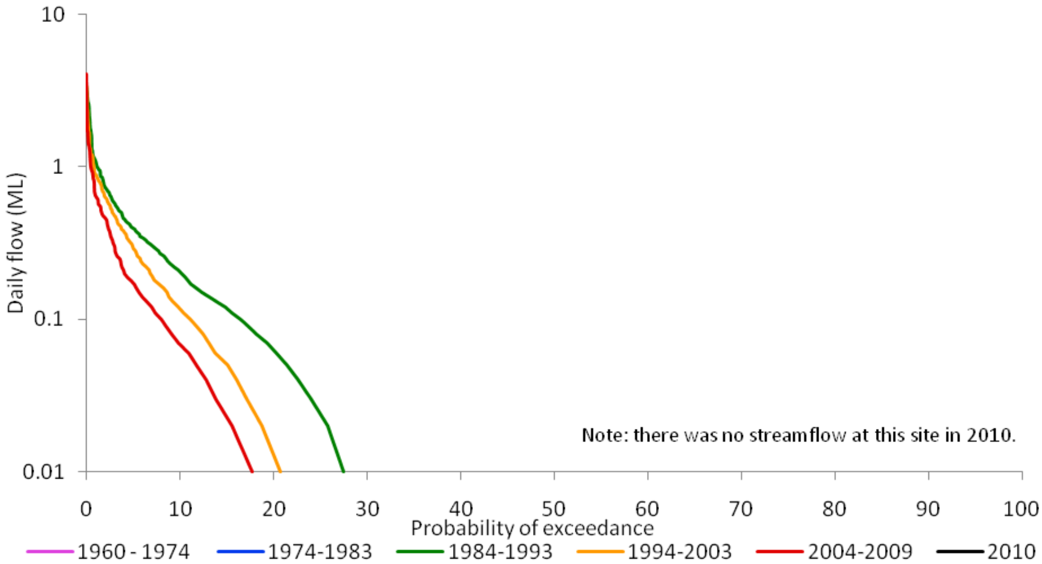

Figure A49 Flow duration curves for Beigpiegup catchment

Hairpin Bend Road Little Darkin River (Swan River Basin) 616010

PDWSA Priority 1. Intermittent stream. Extensive harvest history prior to 1940, then no harvest till 1990s, when 39% was harvested at mainly moderate and high intensities. Average vegetation cover has generally declined since 1970s, but rebounded in 2000, possibly following moderate and high intensity harvesting in the 90s.

Although declines in streamflow and rainfall coefficient have been observed (particularly in comparing pre and post 1975 periods), these were not found to be significant within the post 1975 period and when comparing 1975–2003 and 2004–09 flows. The average number of no-flow days increased by 6% between these periods.

In the 1960–74 period this stream flowed for an average of 45% of the year, but in 2010 it flowed for just three days.

There was a large drop in LAI due to a wildfire that burnt 65% of the catchment in 2005, and water yield was 2.2 times that which would have been expected based on historical comparisons (Batini & Barrett 2007).

Assessment	Primary catchment
Size & location	37.8 km^2 (medium). 32.07°S, 116.25°E
Av. rainfall	956 mm/a for 1975-2008
Geomorphology	Moderate relief; dissected plateau, lateritic soils over Archaean granitic and metamorphic rocks (WRB 1984b).
Tenure	90% State forest, 10% National Park
Clearing	0% cleared
Vegetation type	86% Jarrah forest, 6% wandoo, 5% rocky outcrops. 3% Jarrah woodland
Timber harvest	2% old growth. 69% harvested pre 1920s, 29% in the 1920s, 34% in the 1930s, 39% in the 1990s
Fire history	27% spring burnt in 2004. 85% impacted by wildfire in Jan 2005, causing sedimentation issues..
Dieback	89% of the catchment interpreted; only 3% found to be infested.
Flow trends	No statistically significant trends observed. Categorised as 'climate pattern dominant – no overall streamflow trend'. Wildfire in 2005 caused temporary spike in flows with 120% increase in flows.
Salinity data	Insufficient data available for analysis. Data reliability code for current report: 6 (No or very little data). Average to 1982 was 390 mg/L

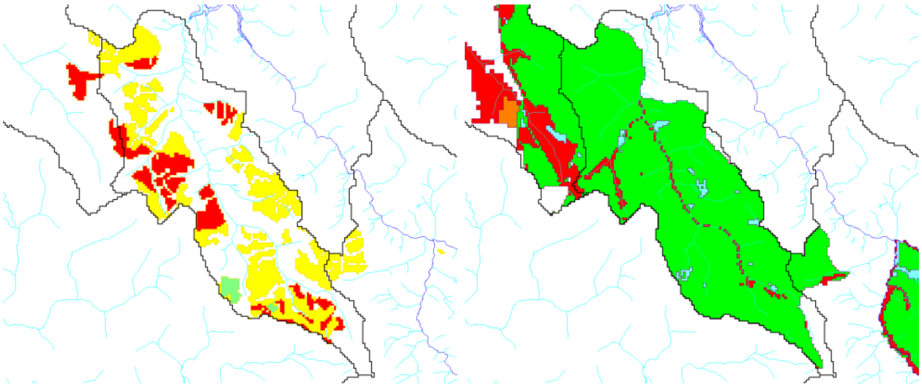

Figure A50 Hairpin Bend Road catchment views. L: Harvest intensity since 1990 showing low (green), medium (yellow) and high (red) intensity R: Dieback status showing the majority of the catchment that has been interpreted is not infected.

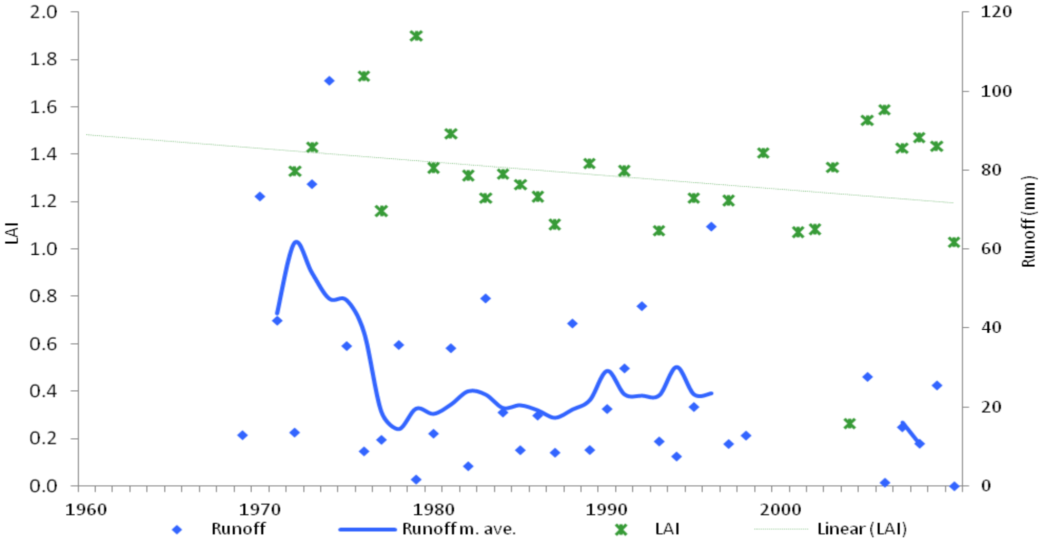

Figure A51 Annual streamflow, moving average, and leaf area index for Hairpin Bend Road

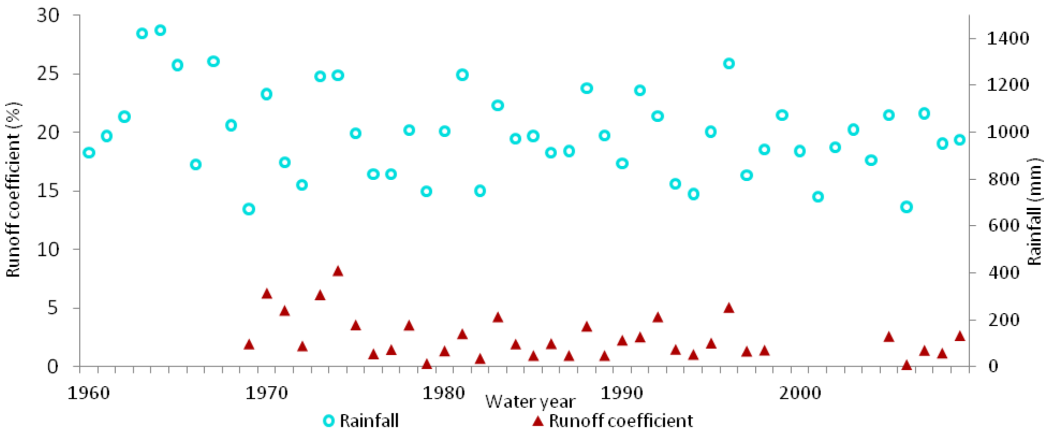

Figure A52 Annual rainfall and runoff coefficient for Hairpin Bend Road catchment

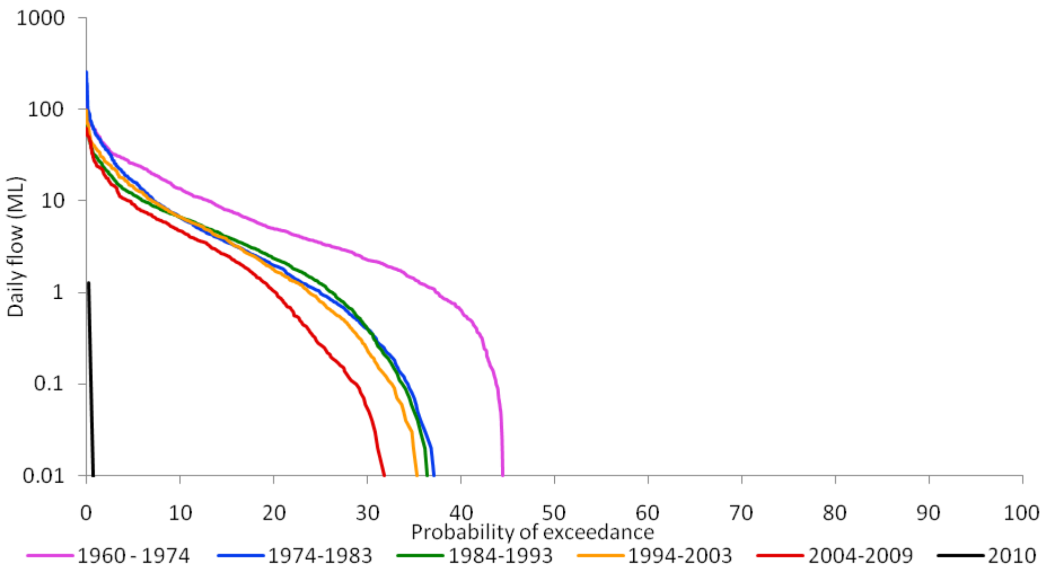

Figure A53 Flow duration curves for Hairpin Bend Road catchment

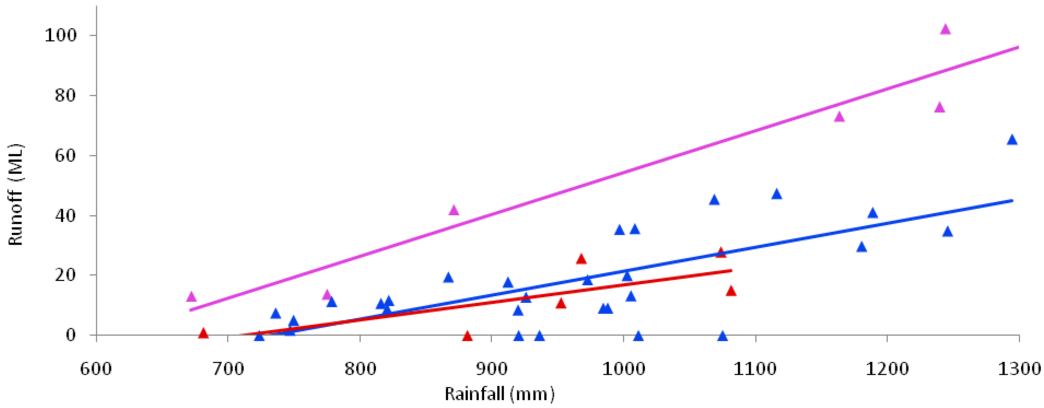

Figure A54 Annual runoff plotted by annual streamflow for Hairpin Bend Road

Hansens Little Dandalup Tribuitary (Murray River Basin) 614019

This catchment was uniformly thinned in the 1985/1986 summer, reducing basal area by 80% and reducing LAI to 0.6. This was followed by large increases in runoff and groundwater levels; the flow regime shifted from intermittent to perennial and has remained this way, with groundwater connected to streams. Largely dieback infected jarrah forest. Mining 63% of the catchment began in late 1990s, with rehabilitation commencing in 2003.

Assessment	Supplementary catchment
Size & location	0.7 km^2 (small). 32.59°S, 116.05°E
Av. rainfall	1140 mm/a for 1975-2008 (nearby met stations 509347, 509346, 509349)
Geomorphology	Low to moderate relief, dissected plateau, lateritic soils over Archaean granitic and gneissic rocks.
Tenure	100 % State forest
Clearing	0% cleared
Vegetation type	91% jarrah forest, 9% jarrah woodland

Timber harvest	0% old growth. 100% harvested pre-1920 then again in 1930s, and 1980s. 59% was harvested again in the 2000s, with jarrah regeneration implemented.
Fire history	61% last burnt spring 1989, 39% last burnt spring 2007.
Dieback	100% of the catchment has been interpreted; 77% is infested.
Flow trends	Significant increases in flows observed, associated with bauxite mining in the catchment. Categorised as 'climate pattern present, clearing and/or intensive thinning have stabilised or increased streamflows'.
Salinity data	Insufficient data for analysis. Data reliability code: 5 (Mostly continuous measurements with very large estimated gaps (>3 months) or fewer than 6 discrete samples per year or data estimated from flow). Bari and Ruprecht (2003) remained about 110–120 mg/L.

Figure A55 Hansens catchment views. L: Area cleared shown in black. R – Aerial photo showing area cleared for mining (black line shows gridded catchment boundary).

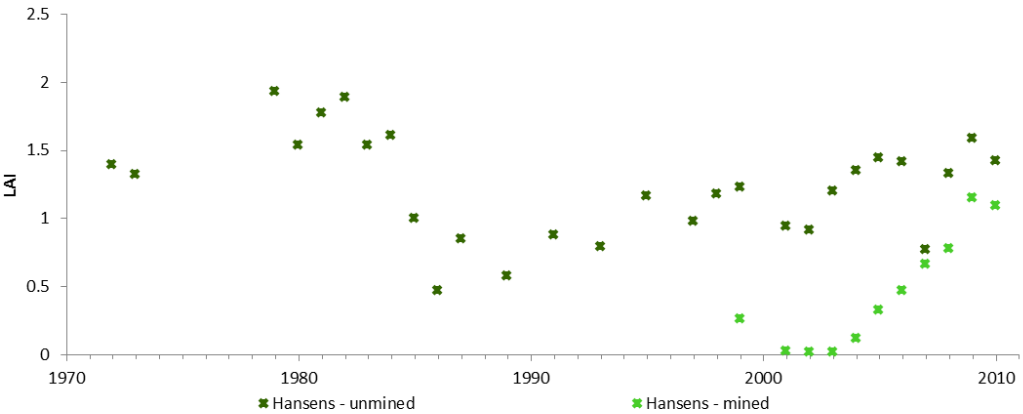

Figure A56 Leaf area indices shown for mined and unmined parts of Hansens catchment

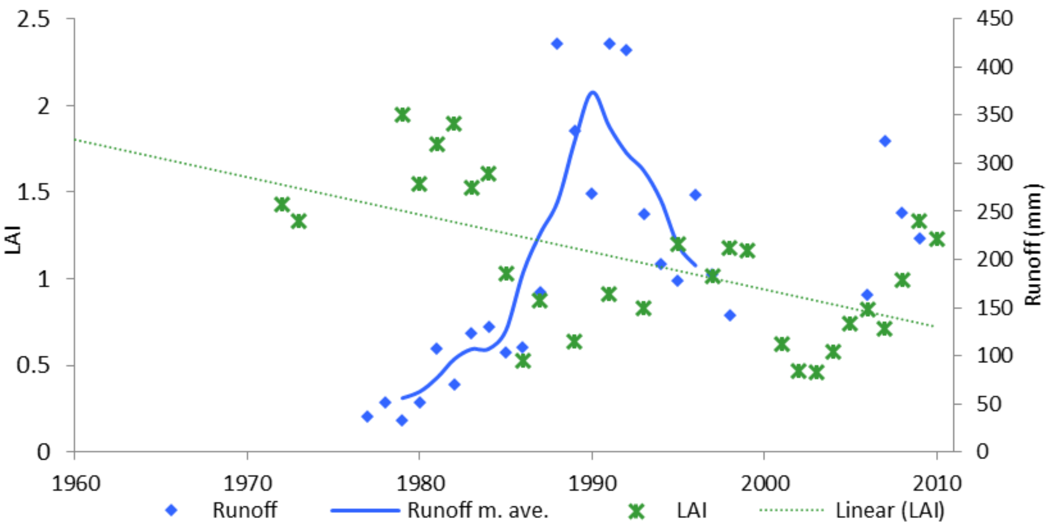

Figure A57 Hansens annual streamflow and catchment average leaf area index

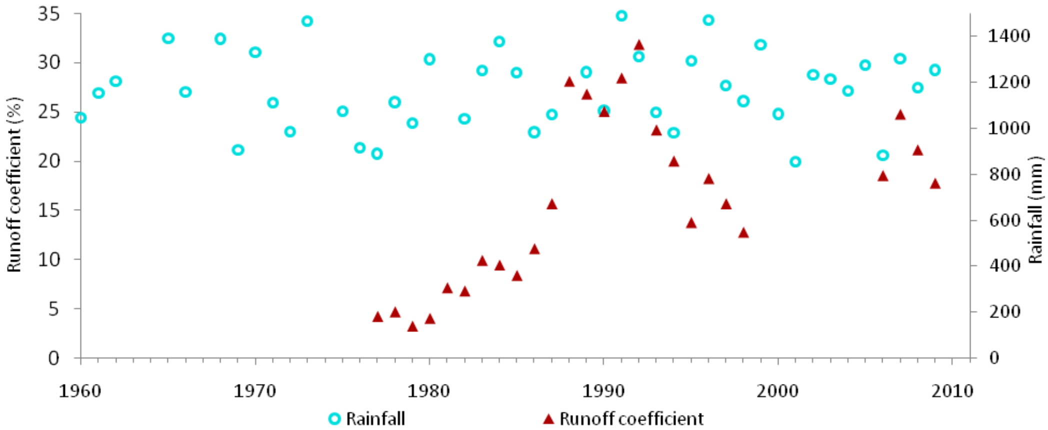

Figure A58 Annual rainfall and runoff coefficient for Hansens catchment

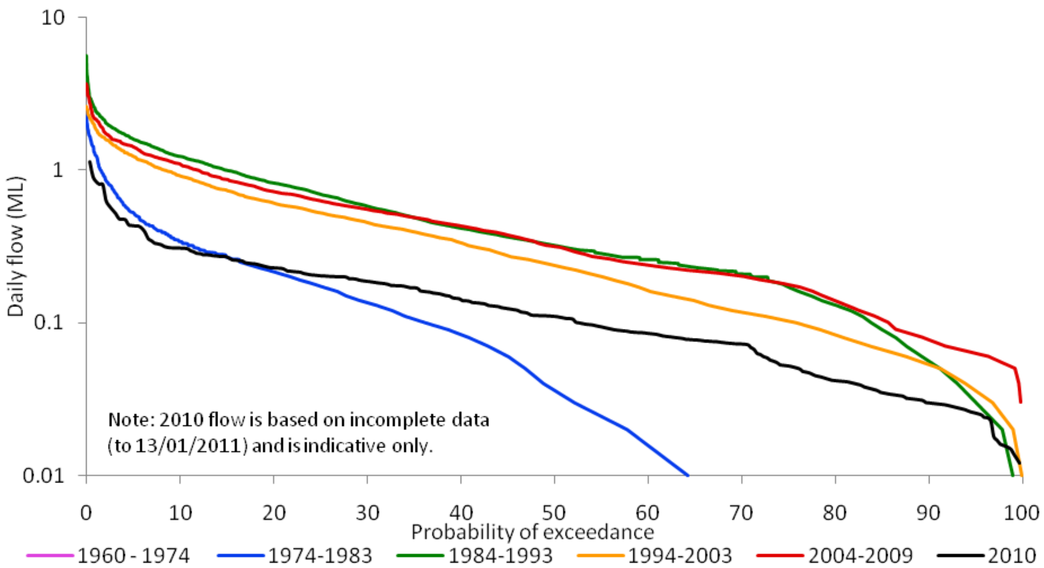

Figure A59 Flow duration curves for Hansens catchment

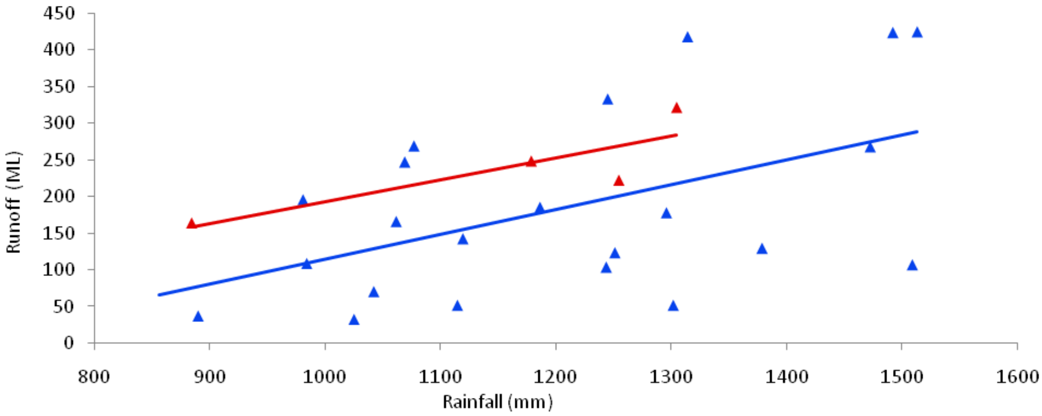

Figure A60 Annual runoff plotted by annual streamflow for Hansens, showing an increase in the amount of runoff per unit of rain in recent years.

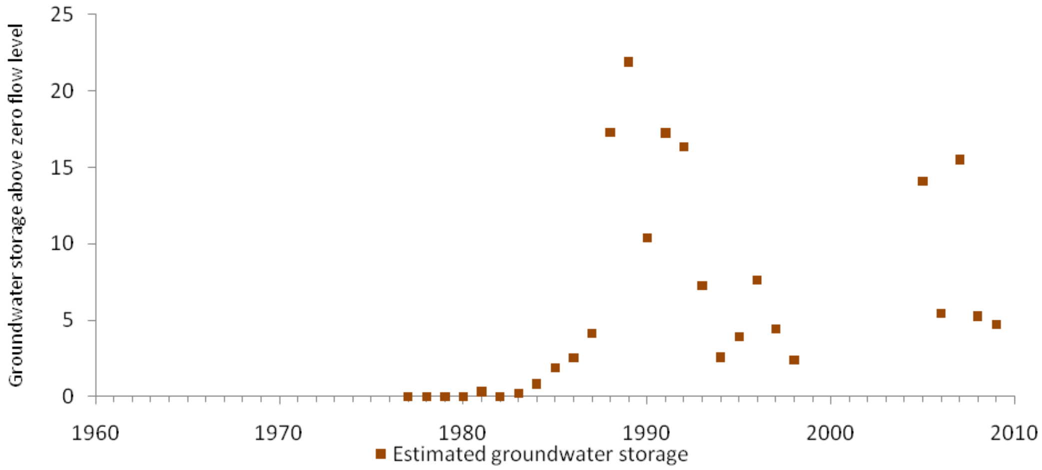

Figure A61 Estimated groundwater storage for Hansens catchment

Jayrup Big Brook (Serpentine – Murray River Basin) 614093

PDWSA Priority 1. Intermittent stream. Trial mining and rehabilitation for the Joint Intermediate Rainfall Zone Research Program occurred between 2005 and 2012. 6.15 km^2 (14%) cleared for mining (data from Mauger – using Landsat; Croton et al. 2011). LAI increased from the early 1970s to the 1990s, and has decreased since.

Climate pattern dominated streamflow pattern, no overall decline observed, likely due to mining in catchment.

Assessment	Supplementary catchment
Size & location	45.5 km^2 (medium). 32.59°S, 116.23°E
Av. rainfall	972 mm/a for 1975-2008
Vegetation type	84% Jarrah forest, 9% jarrah woodland, 3% shrub, herb and sedgeland
Timber harvest	0% old growth. 51% harvested pre-1920s, 96% in 30s, 12% in 60s, 49% in 90s, 26% in 00s.
Mining	Areas cleared for mining and not yet rehabilitated, by year are: 2004: 1%, 2005: 3%, 2006: 6%, 2007: 8%, 2008: 9%, 2009: 6%, 2010: 6% 2011: 6%, 2012:1%, 2013: 1%.

Av. rainfall	972 mm (nearby met station 509569)
Clearing	5% cleared
Dieback	100% interpreted for dieback, 20% infested.
Flow trends	No statistically significant trends observed. Categorised as 'climate pattern dominant – no overall streamflow trend'.
Salinity data	High quality continuous salinity data since 1995. Data reliability code: 1 (mostly continuous measurements).
Salinity trends	No trends apparent, average salinity is ~76 mg/L.

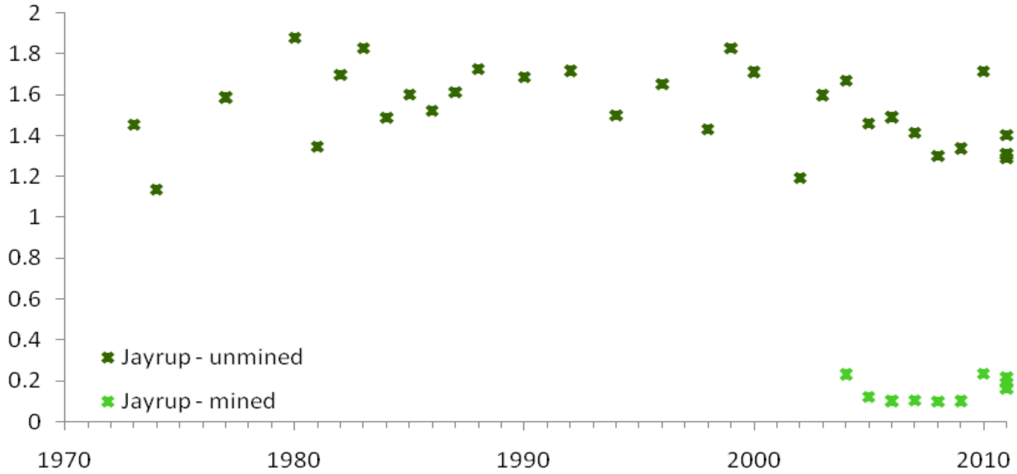

Figure A62 Leaf area index data shown separately for mined and unmined parts of Jayrup catchment

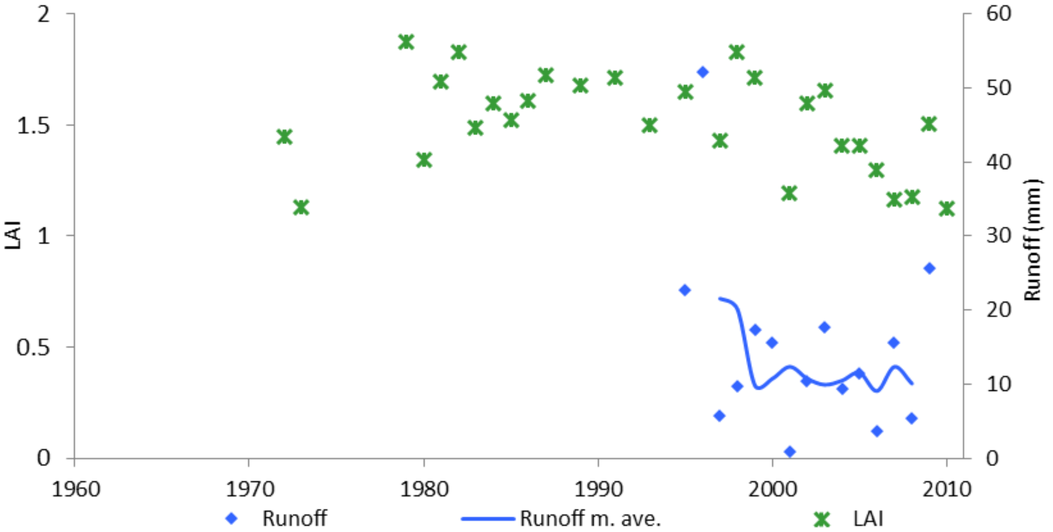

Figure A63 Annual streamflow and average catchment leaf area index for Jayrup catchment

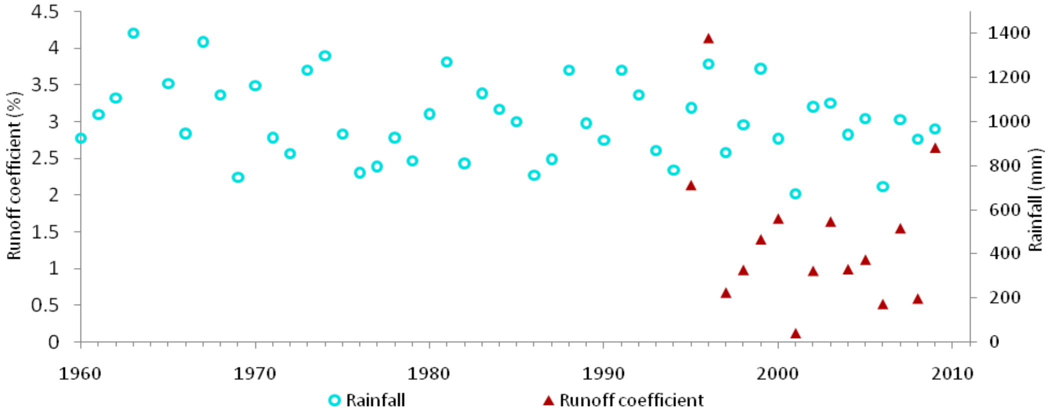

Figure A64 Annual rainfall and runoff coefficient for Jayrup catchment

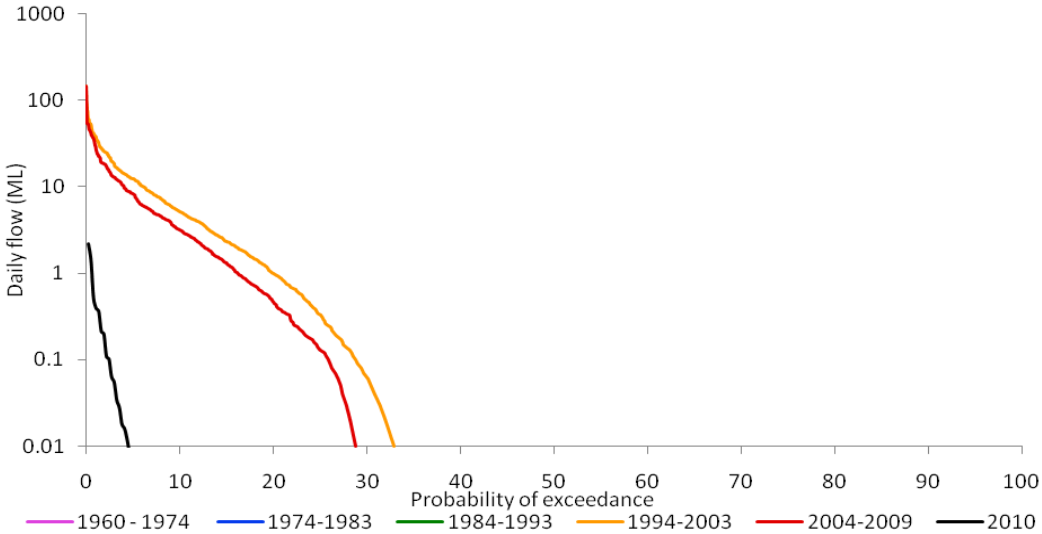

Figure A65 Flow duration curves for Jayrup catchment

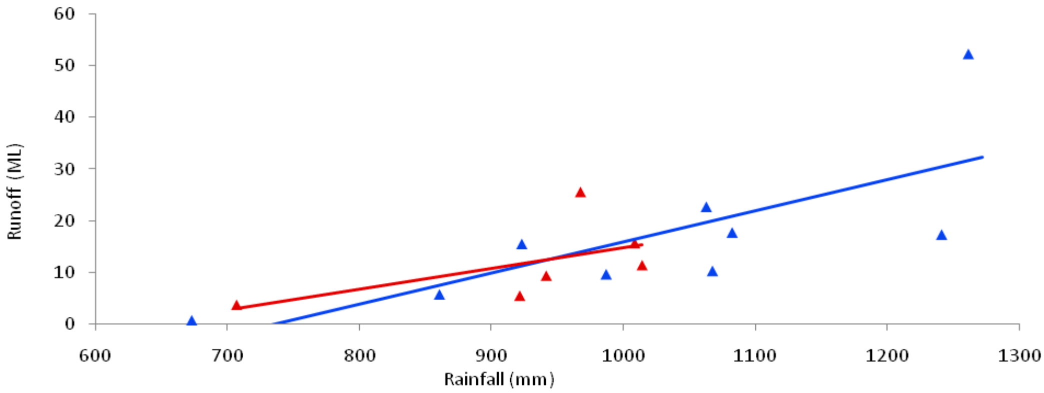

Figure A66 Annual runoff plotted by annual streamflow for Jayrup catchment

Lewis North Dandalup tributary (Murray River Basin) 614021

PDWSA Priority 1. Perennial from mid 1980s till 2005, and intermittent prior to and since this time. Prior to the 90s, Lewis was the control in the paired catchment study of thinning that involved Hansens.

51% of this catchment was mined between1996 and 2000, with rehabilitation established between 1998 and early 2003. Streamflow responded positively to mining with peak increase in flow 163 mm/yr, 135% of flow (Croton & Reed 2007). Groundwater levels peaked in 2000 and have declined steadily since, while LAI has increased, particularly in mined areas. Groundwater levels found to be negatively correlated with streamflow (Hughes et al 2012), but has since declined. There is a government and industry call for immediate thinning in this catchment (e.g. Grigg 2009).

Increase in streamflow in late 80s was likely climate-related, whereas increase in late 90s was most likely cause by mining in the catchment. Sharp decrease in 2000s is probably due to a combination of both rainfall decline and the effects of vegetation regeneration.

Assessment	Supplementary catchment
Size & location	1.94 km^2 (small). 32.57°S, 116.07°E
Av. rainfall	1123 mm/a for 1975-2008 (Lewis met station by gauging station)
Geomorphology	Low relief; undulating plateau, laterite soils over Archaean granitic and gneissic rocks (WRB 1984b).
Vegetation type	93% jarrah forest, 1% jarrah woodland, 6% shrub, herb and sedgeland.
Timber harvest	0% old growth. 100% harvested prior to 1920. 63% in 1940s, 61% in 60s, 11% in 80s, 50% in 90s, 5% in 00s, with regeneration implemented.
Clearing	0% cleared.
Fire history	Devastating fire in 1961 led to large streamflow increases.
Dieback	100% interpreted for dieback, 57% infested.
Flow trends	Significant increases in flows observed, associated with bauxite mining in the catchment. Categorised as 'climate pattern present, clearing and/or intensive thinning have stabilised or increased streamflows'. Flows since 2004 have, however, been lower than previous.
Salinity data	Continuous and discrete data available. Data reliability code 4 (Mostly continuous measurements with large estimated gaps (<1 month) or fewer than 30 discrete samples per year)
Salinity trends	Salinity is fresh at approx. 109 mg/L but is significantly increasing.

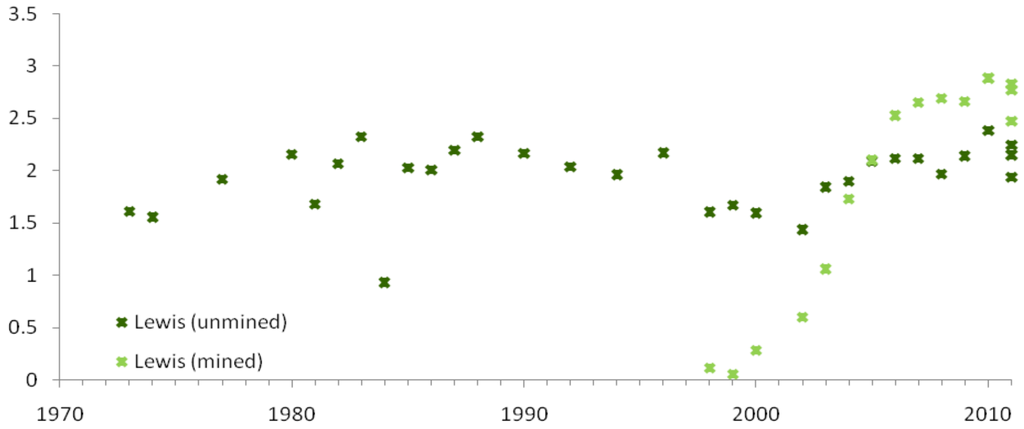

Figure A67 Leaf area index data shown separately for mined and unmined parts of Lewis

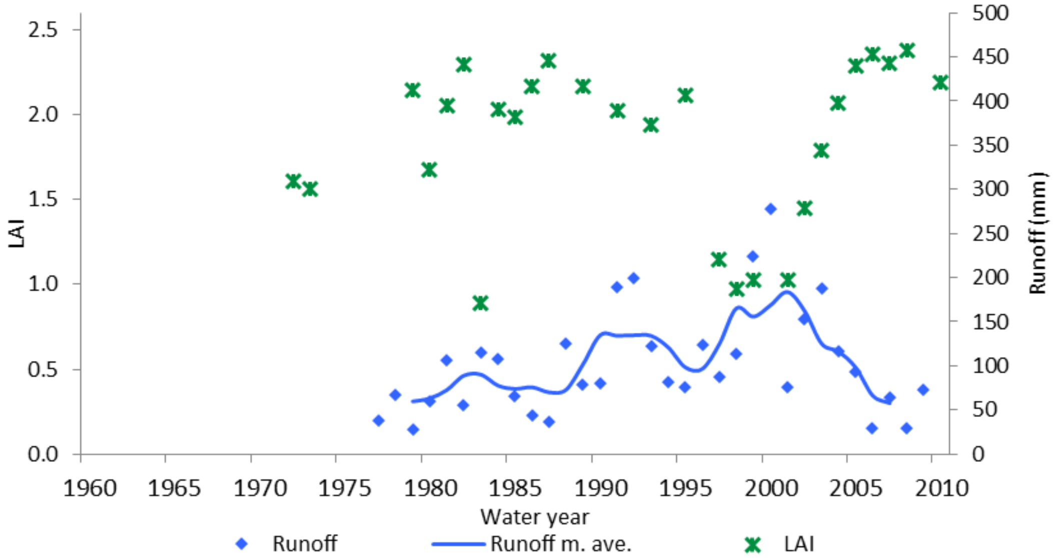

Figure A68 Annual streamflow, moving average, and catchment average leaf area index for Lewis catchment

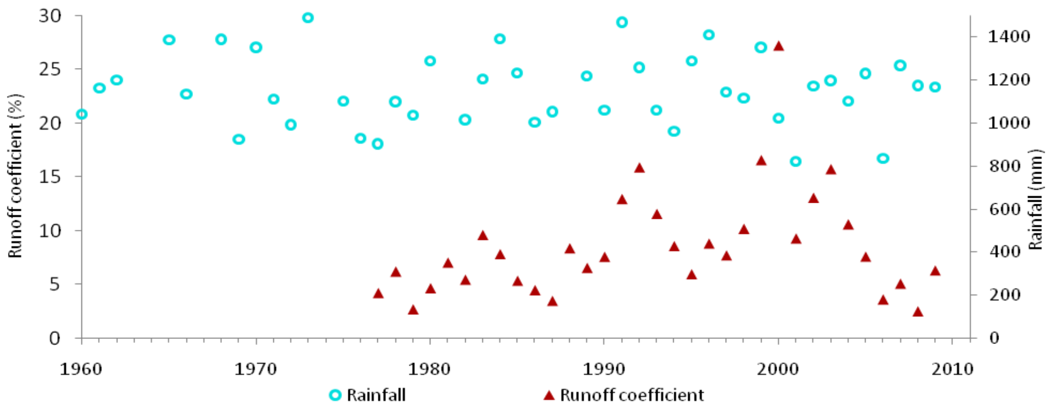

Figure A69 Annual rainfall and runoff coefficient for Lewis catchment

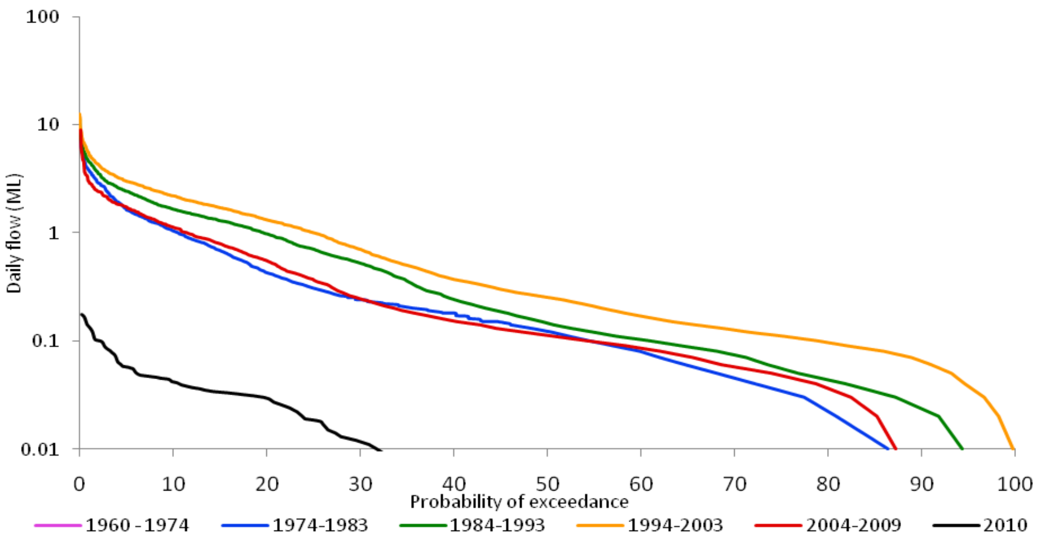

Figure A70 Flow duration curves for Lewis catchment

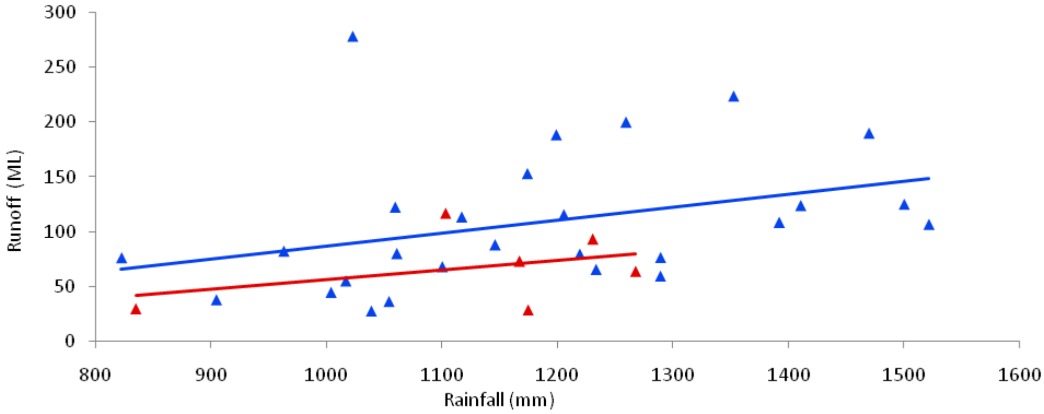

Figure A71 Annual runoff plotted by annual streamflow for Lewis, showing a decline in the rainfall-runoff relationship in recent years.

More Seldom Seen Creek Ceriani Farm (Canning - Swan basin) 616022

PDWSA. Historically a perennial stream transitioned to intermittent in 1998. 60% of this catchment was mined and rehabilitated between 1969 and 1994, with restoration beginning in 1971 and much of the earlier restorationconsisting of eastern-states eucalypts. Aerial photographs and DPaW records indicate forest cover was thin due to logging and dieback prior to mining. Flow increased by up to 90 mm/yr; 31% of flow and peaked in 1981, although elevated streamflows lasted 20 years (Croton et al. 2005). Streamflow trends inversely mirror LAI trends, with increasing vegetation coverage (especially in mine rehabilitation) since the early 1980s and drastic declines in streamflow.

Modelling in this catchment indicated young post-mine revegetation has higher evapotranspiration rate than unmined forest, reducing streamflow. Streamflow reductions in 2002 were estimated to be 55 mm/yr for More Seldom Seen, 42% of flow (Croton et al. 2005). Croton et al. (2005) indicated soil water storages still decreasing with further streamflow reductions to be expected, and suggested that the LAI for the unmined forest increased during the study period, additionally reducing streamflow. There is a government and industry call for immediate thinning in this catchment (e.g. Grigg 2009).

Salinity increased 20–30 mg/L during mining period with no signs of returning to pre-mining conditions in 1995 (Davies et al. 1995). Bari and Ruprecht reported stable salinities to 2000. Average TSS 150 mg/L to 1982 (WRB 1984b).

Assessment	Supplementary catchment
Size & location	3.4 km^2 (small). 32.26°S, 116.08°E
Av. rainfall	1083 mm/a for 1975-2008
Geomorphology	Low relief; undulating plateau, lateritic soils over Archaean granitic and metamorphic rocks (WRB 1984b).
Vegetation type	46% exotic hardwood plantations (16% red mahogany and 15% spotted gum; Davies et al 1995). 34% jarrah forest, 16% jarrah woodland, 4% wandoo.
Timber harvest	100% harvested pre-1920, then again in 40s. 78% harvested in 70s, and 28% in 80s. Most harvesting was by clearcutting. No old growth.
Clearing	3% cleared (some orchards)
Fire history	78% spring burn in 2005 and 16% in 2008.
Dieback	58% of the catchment has been interpreted; 67% of this is infested.
Flow trends	Highly significant declines in streamflow. Progressive, dramatic decline in flow regime (flow days) since 1970s, including stark transition from perennial to intermittent flows. Categorised as ‘climate pattern present, streamflow decline exacerbated by increasing vegetation cover’.
Salinity data	Insufficient data for analysis. Data reliability code: 5 (fewer than 6 discrete samples per year or data estimated from flow).

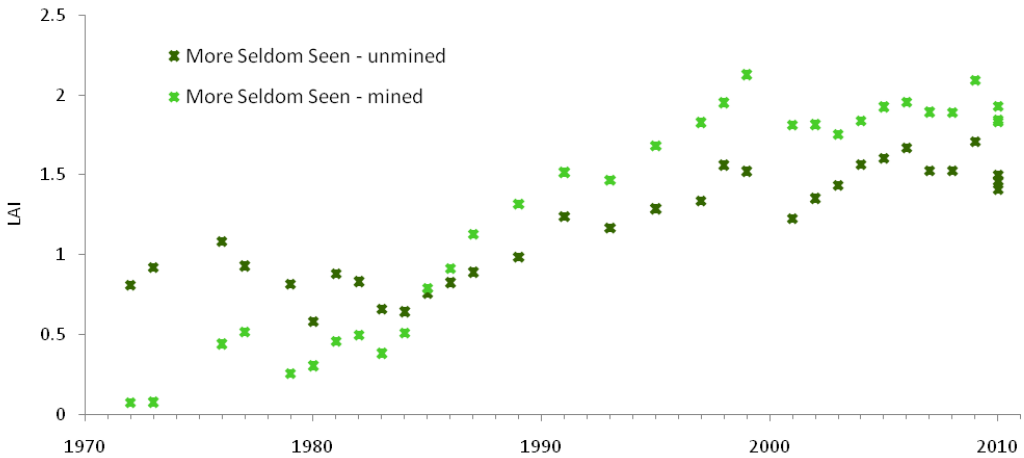

Figure A72 Leaf area index data shown separately for mined and unmined parts of More Seldom Seen (Ceriani Farm) catchment

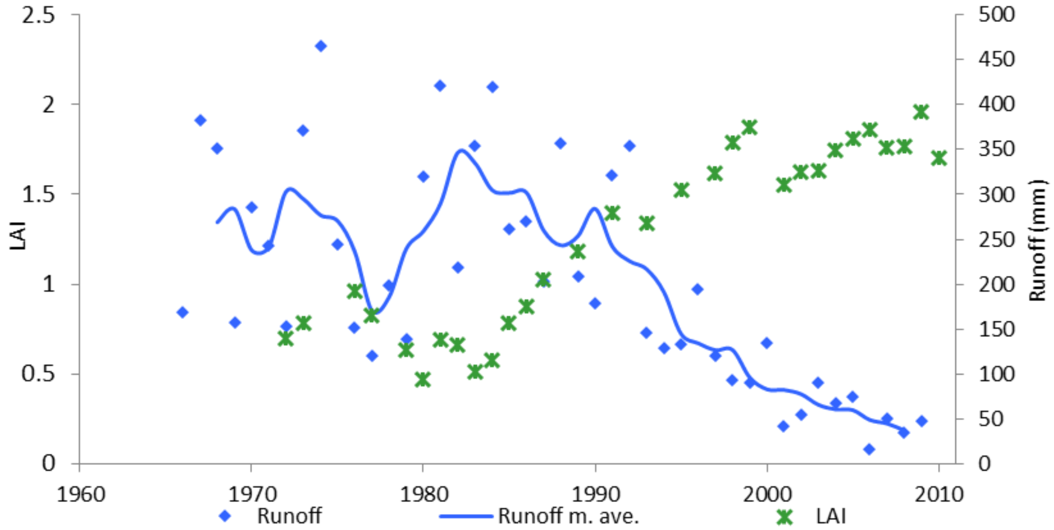

Figure A73 Annual streamflow, moving average, and catchment average leaf area index for More Seldom Seen catchment

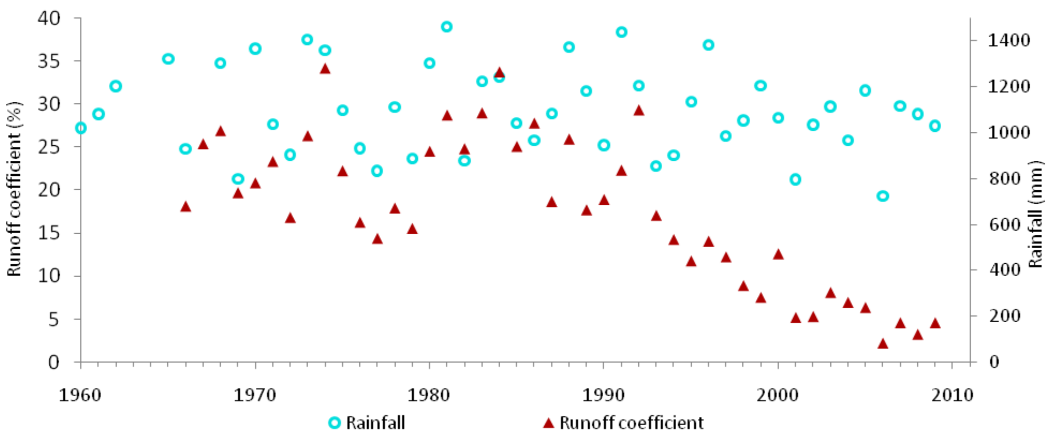

Figure A74 Annual rainfall and runoff coefficient for More Seldom Seen catchment

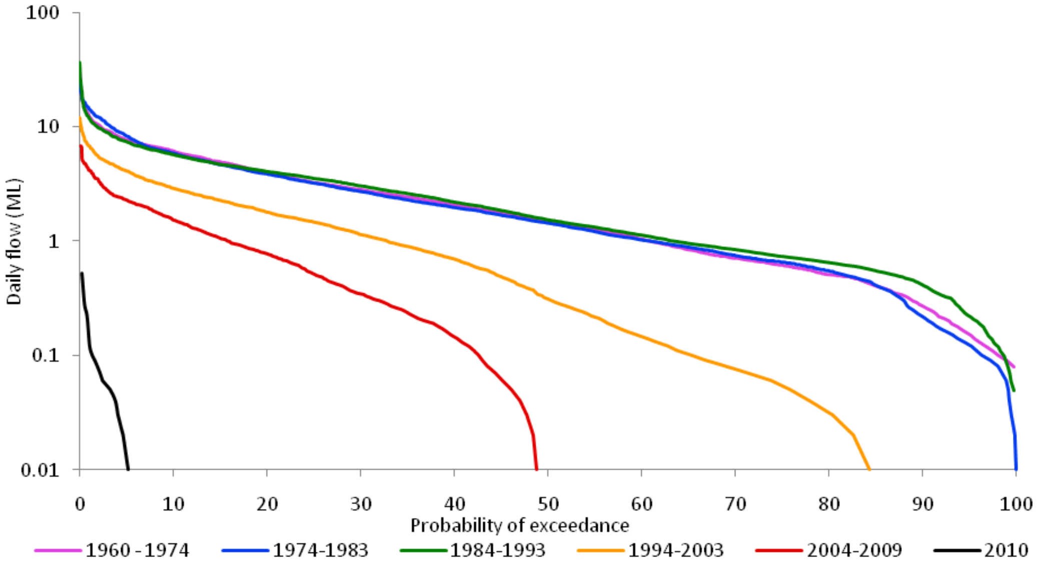

Figure A75 Flow duration curves for More Seldom Seen catchment showing a shift from perennial to intermittent flows and stark reductions in flow days.

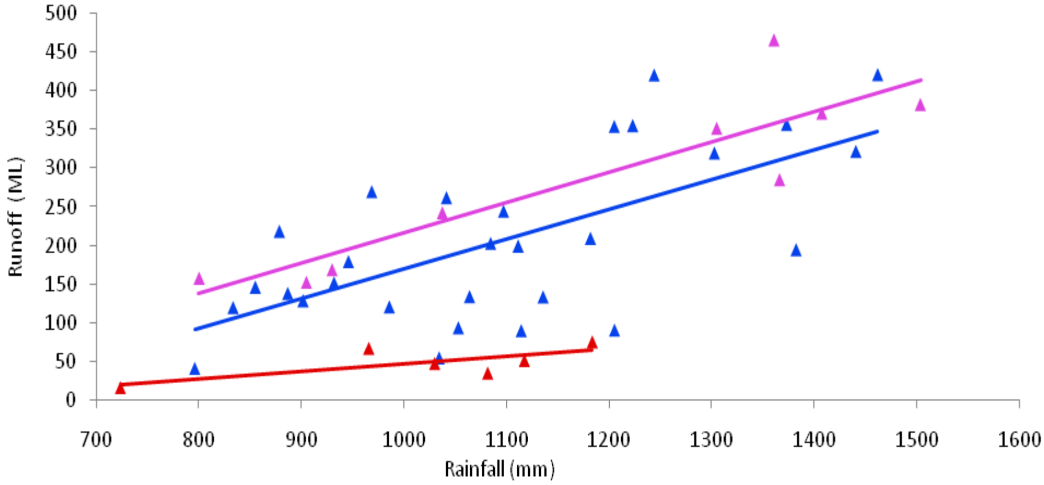

Figure A76 Annual runoff plotted by annual streamflow for More Seldom Seen catchment, showing a progressive decline in the runoff observed per unit rainfall received

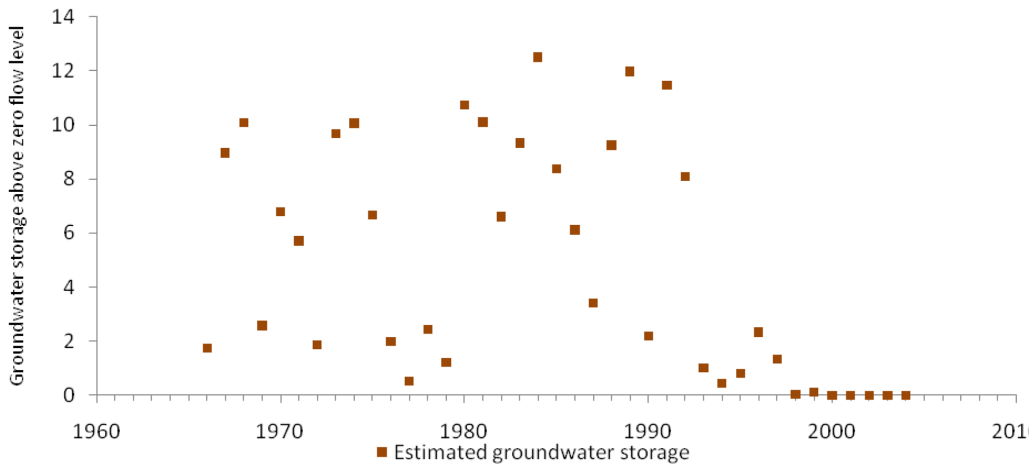

Figure A77 Estimated groundwater storage for More Seldom Seen catchment at Ceriani Farm

Ngangaguringuring Helena River (Swan Coastal basin) 616013

PDWSA Priority 1. Predominantly a perennial stream, with some intermittent flows prior to 1975. The hydrology of this catchment is dominated by the effects of clearing 6% of the catchment for agriculture in 1967, with estimated groundwater levels rising, peaking in 2000, then declining. Shifts in rainfall-runoff relationships show a reduction in the catchment's responsiveness to rainfall. The flow duration curve shows the historical variation in flow regime; note that in 2010 high flows are heavily reduced while low flows remain similar to the historical regime.

Part outside FMP tenure. Saline groundwater discharge due to nearby clearing over sedimentary aquifer. Brackish. Av. salinity 1983–92: 2200 mg/L; 1993–2002: 2000 mg/L. During same period av. flow increased 1.5 to 1.9 GL. Salt input lower than output – catchment appears to be leaching salt (Mayer et al. 2005). Roughly 8% permanently cleared, some replanting with pines. Mainly state forest reserve, cleared areas under pasture – sheep and cattle grazing. Some small farm dams on minor waterways. Brackish – TSS av. 1270 mg/L to 1982 (WRB 1984b). Removed from primary analysis list due to 6% clearing and 30% outside of DEC tenure.

Assessment	Supplementary catchment
Size & location	328 km^2 (large), 31.94°S, 116.51°E
Av. rainfall	652 mm/a for 1975-2008.
Geomorphology	Generally low relief; undulating plateau with minor dissections, lateritic soils over Archaean granitic and metamorphic rocks (WRB 1984b).
Tenure	50% National Park, 20% State forest, 30% Other (non-FMP tenure)
Clearing	6% cleared off FMP tenure for agriculture (grazing) in 1967 (Smith et al. 2007); none of this is within FMP Tenure
Vegetation type	59% wandoo, 12% jarrah forest, 8% jarrah woodland, 3% shrub, herb and sedge, 1% rocky outcrop.
Timber harvest	3% harvested pre 1920s, 21% in the 1950s, 59% in the 1960s, 5% in the 1970s, no timber harvesting post 1970s. 3% old growth.
Fire history	Minimal burning 1960–2000, 3% spring burnt in 1996, 5% autumn burnt 2003, 9% spring burnt 2004, 13% autumn burnt 2005, 13% autumn burnt 2006, 10% autumn burnt 2007, 4% spring burnt 2008, 6% spring burnt 2009, 3% autumn burnt 2010. 3% impacted by wildfire in 2001/2.
Burn freq.	Post 89/90: 22% not burnt, 39% once burnt, 37% twice burnt, 3% three times burnt
Dieback	No dieback information is available for this catchment.
Flow trends	Significant increases in flows observed since 1975, associated with some clearing in the catchment. Categorised as 'climate pattern present, clearing and/or intensive thinning have stabilised or increased streamflows'. Flows since 2004 have, however, still been lower than previous.
Salinity data	Continuous and discrete salinity data available for this catchment. Data reliability code: 1 (mostly continuous measurements). Average salinity 1993 to 2002: 2000 mg/L. Salt input is lower than output; catchment appears to be leaching salt (Mayer et al. 2005).
Salinity trends	Brackish stream; saline groundwater discharge due to nearby clearing over

sedimentary aquifer.

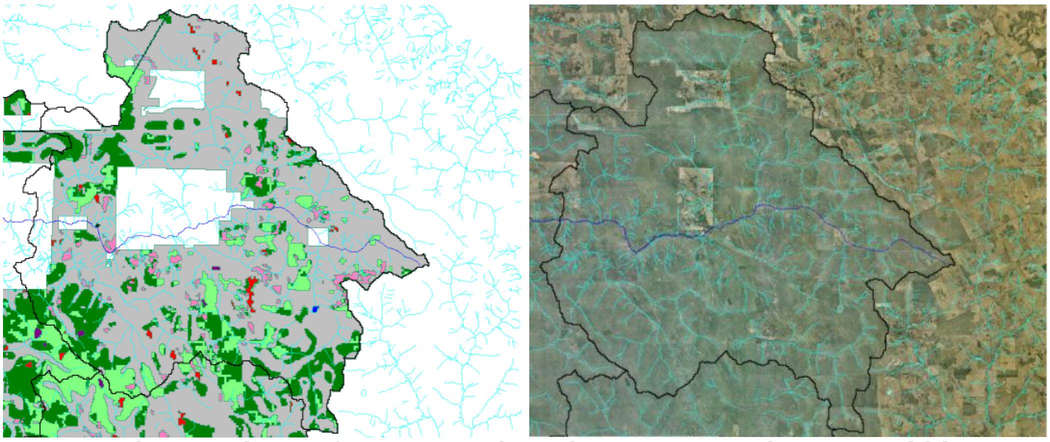

Figure A78 Catchment views of Ngangaguringuring. L: Vegetation type within FMP tenure showing jarrah forest (dark green), jarrah woodland (light green), wandoo (grey), shrub, herb and sedgeland (pink), and rocky outcrops (red). R: aerial image.

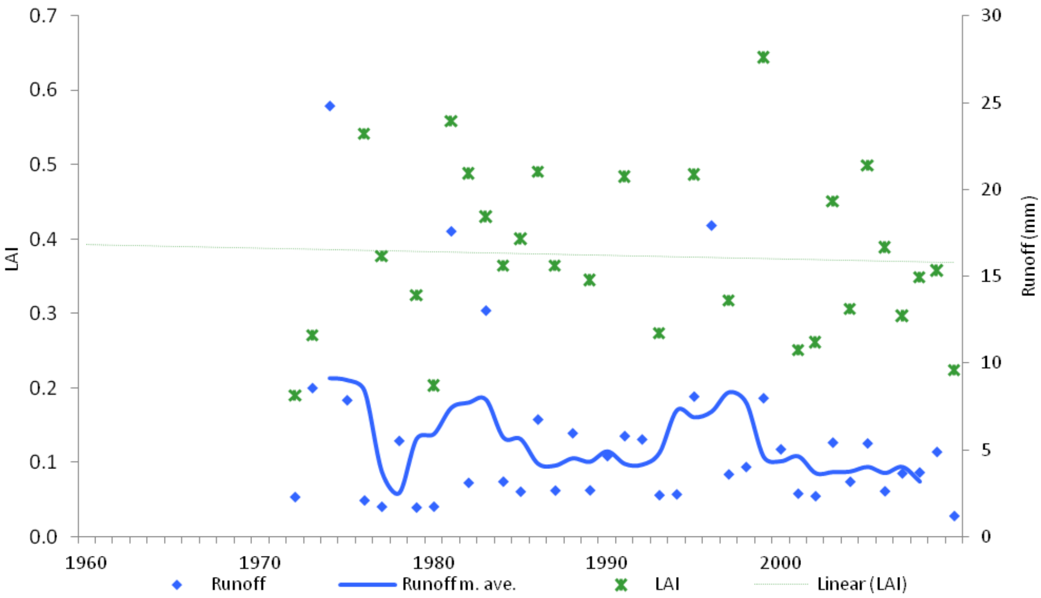

Figure A79 Annual streamflow, moving average, and leaf area index for Ngangaguringuring

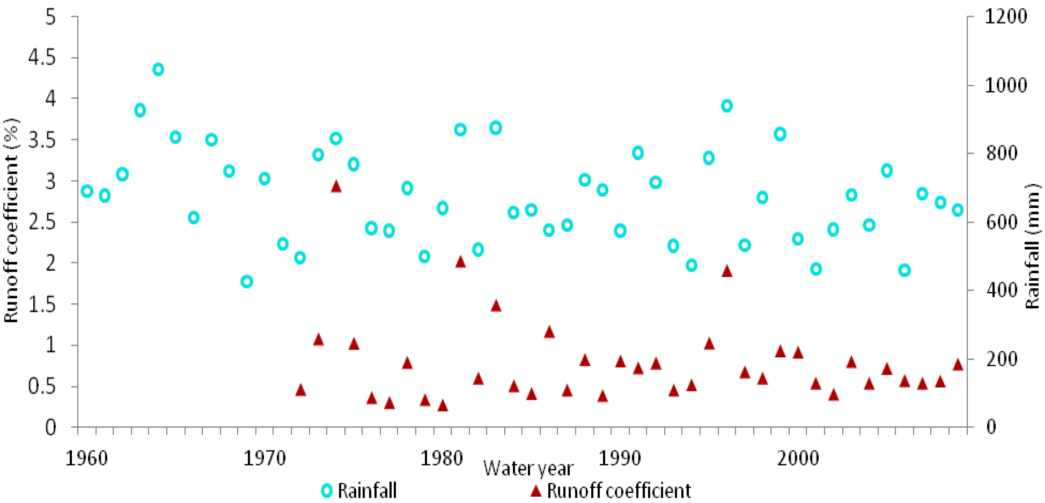

Figure A80 Annual rainfall and runoff coefficient for Ngangaguringuring catchment

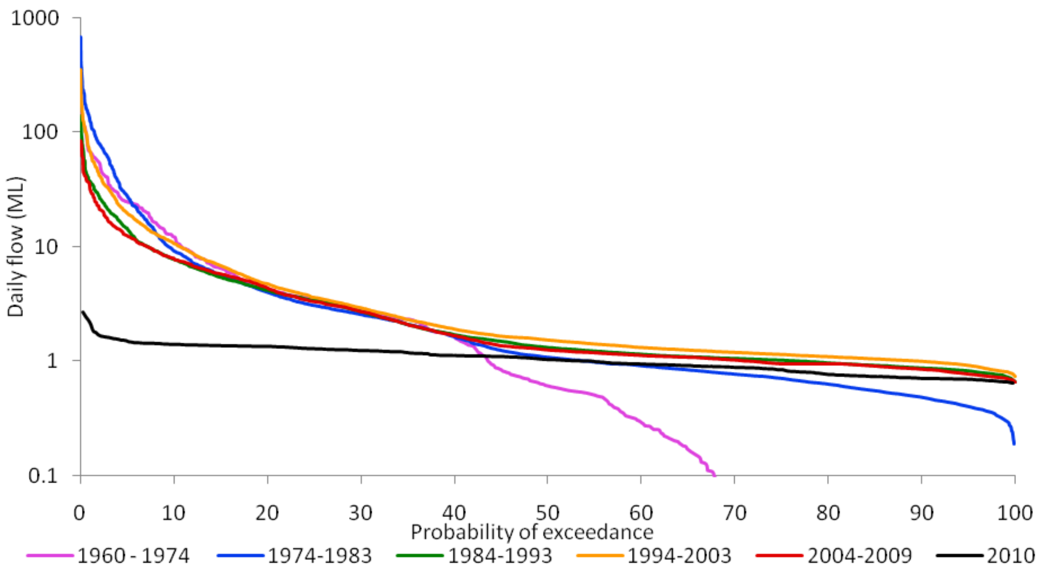

Figure A81 Flow duration curves for Ngangaguringuring catchment showing a historical shift from intermittent to perennial flows

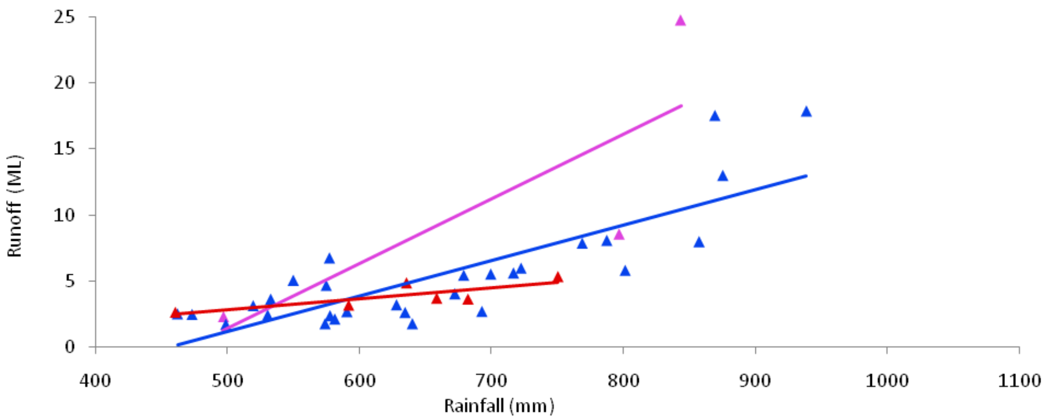

Figure A82 Annual runoff plotted by annual streamflow for Ngangaguringuring

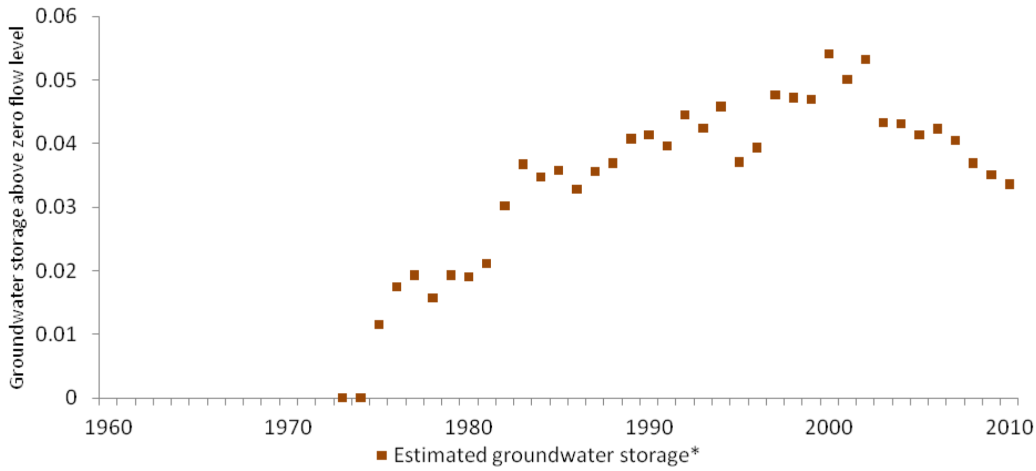

Figure A83 Estimated groundwater storage for Ngangaguringuring showing a clear response to clearing

O'Neil Road Big Brook (Serpentine – Murray river basin) 614037

PDWSA Priority 1. Intermittent stream. Catchment includes Jayrup subcatchment. 15% of the catchment was mined between 2004 and 2010 as part of Alcoa's Trial Mining Project in the intermediate rainfall zone (Croton et al. 2011).

Assessment	Supplementary catchment
Av. rainfall	975 mm/a for 1975-2008
Size & location	22.5 km^2 (medium); 32.55°S, 116.24°E
Av. rainfall	975 mm/a for 1975-2008
Geomorphology	Granitoid rock; monzogranite dominant
Tenure	Dwellingup State Forest.
Clearing	0% clear
Vegetation type	86% jarrah forest, 11% jarrah woodland, 2% shrub, herb and sedgeland.
Timber harvest	40% harvested pre-1920s; 13% harvested in 1920s, 51% in 30s, 35% in 40s, 20% in 60s, 20% in 70s, 26% in 90s and 36% in 00s. <1% old growth.
Fire history	83% of the catchment was burnt in 1995 and a further 7% in 1999.
Dieback	94% of the catchment has been interpreted for dieback; 30% was found to be infected.
Flow trends	No statistically significant trends observed. Categorised as 'climate pattern present, clearing and/or intensive thinning have stabilised or increased streamflows'. Flows since 2004 have, however, been lower than previous.
Salinity data	Continuous and discrete salinity data available for this catchment. Data reliability code: 1 (mostly continuous measurements). Average salinity 1993 to 2002: 2000 mg/L. Av. salinity 1993–2002: 120. Salt input much higher than output – catchment appears to be accumulating salt (Mayer et al. 2005).
Salinity trends	Statistically significant declines in salinity have been observed in this catchment (see Chapter 5 salinity trends).

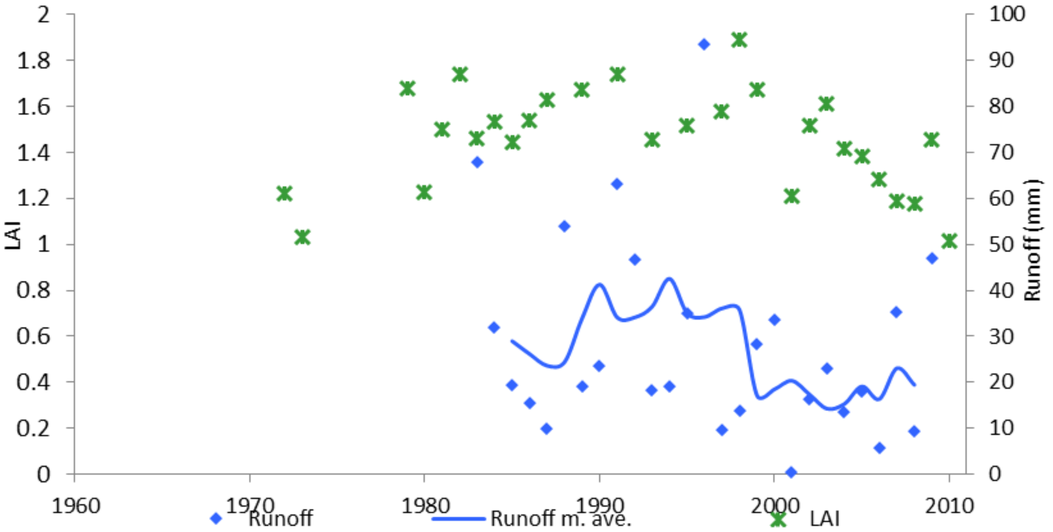

Figure A84 Annual streamflow, moving average, and leaf area index for O'Neil Road

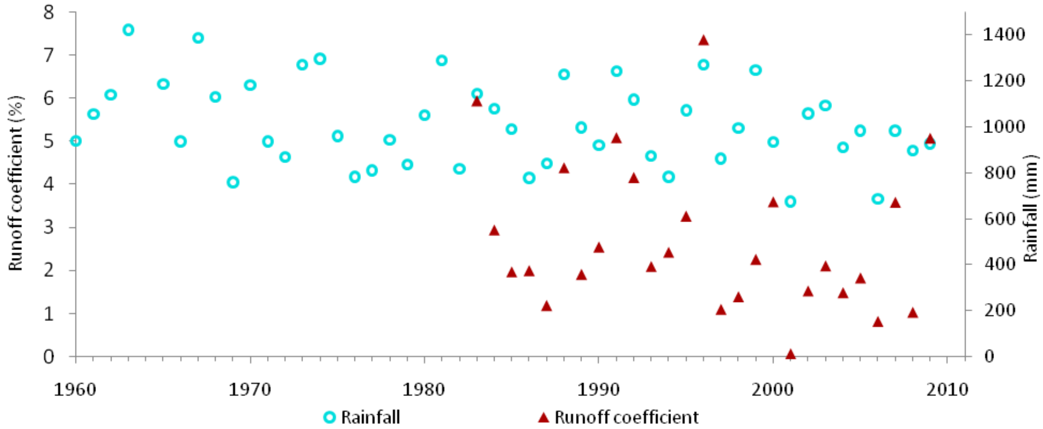

Figure A85 Annual rainfall and runoff coefficient for O'Neil Road catchment

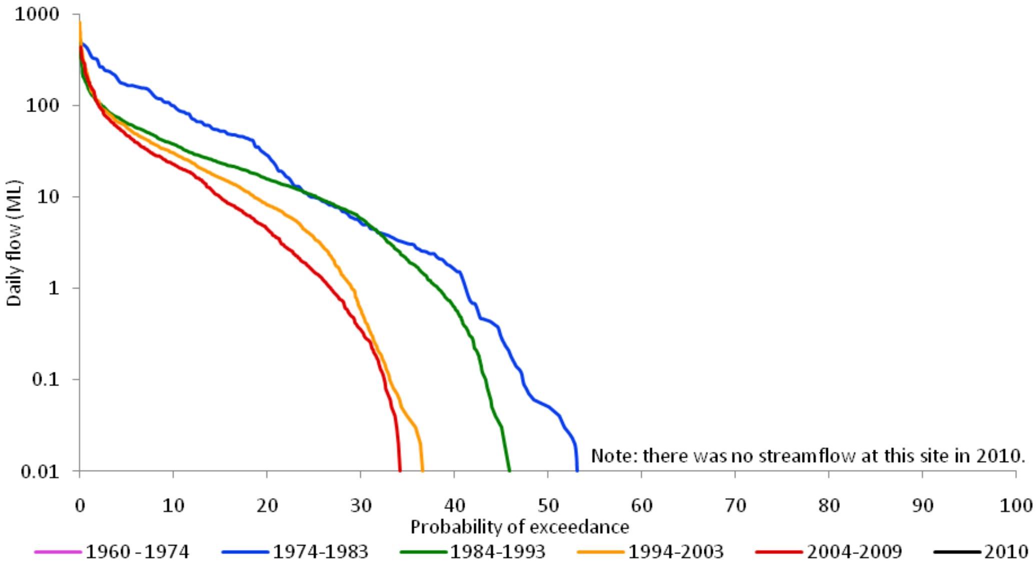

Figure A86 Flow duration curves for O'Neil Road catchment

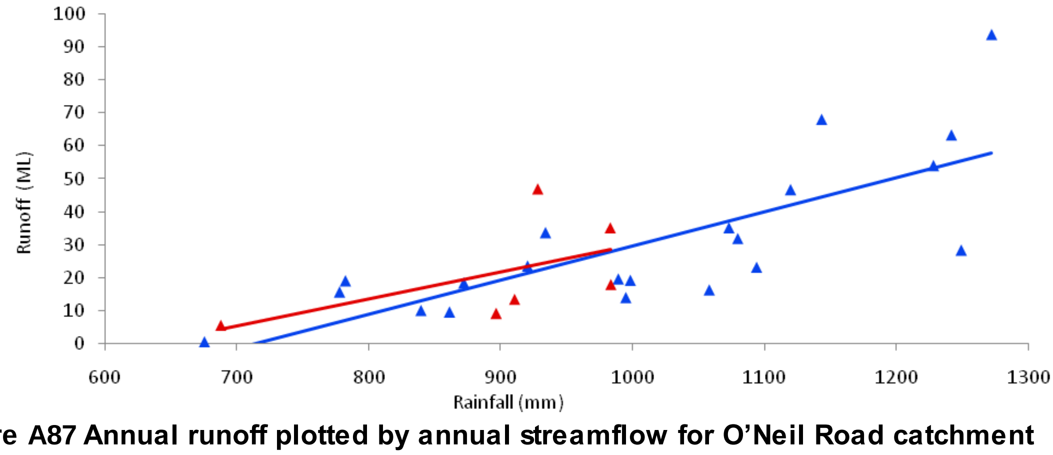

Figure A87 Annual runoff plotted by annual streamflow for O'Neil Road catchment

Ordnance Road Crossing Weld River (Nornalup – Shannon basin) 606195

PDWSA. Predominantly intermittent stream. LAI decreased over the period 1972–93, then subsequently increased, possibly reflecting the harvest history.

Observed declines in flow and runoff coefficients were observed over the period of record, with the current FMP period having the lowest volume of streamflow per unit rainfall, but no significant declines were found for the period since 1975. Flow durations have declined a bit, but were substantially lower in 2010.

Assessment	Supplementary catchment
Size & location	250 km^2 (large); 34.72°S, 116.51°E (south coast region)
Av. rainfall	1033 mm/a for 1975-2008
Geomorphology	Moderate relief, undulating plateau with incised mainstream valley. Proterozoic origins. Granitoid gneiss, migmatite, quartzo-feldspathic gneisses in some places porphyritic, minor metamorphic rock and quarzite, generally weathered to clay or clayey sand, often with a clay subsurface. Local aquifers with some quaternary alluvium.
Clearing	1% cleared
Vegetation type	38% karri, 40% jarrah, 21% shrub, herb and sedge land
Timber harvest	No harvesting prior to 1950s. Around 10% harvested in each of the 1960s, 70s, 80s; around 5% in each of the 1990s and 2000s. 35% old growth.
Fire history	8% of the catchment burnt in a wildfire in 2001-02. 26%, and 20% of the catchment were burnt by prescribed burns in the 2003–04 and 2005-06 summers, respectively.
Dieback	54% of the catchment has been interpreted for dieback; 37% was found to be infected.
Flow trends	Significant decline in streamflow observed. Progressive decline in rainfall-runoff relationship and flow regime over recent decades. Catchment categorised as 'climate pattern present, streamflow decline observed'.
Salinity data	Insufficient data for analysis. Data reliability code: 5 (fewer than 6 discrete samples per year or data estimated from flow). Av. salinity 1983–92: 160 mg/L; 1993–2002: 210 mg/L. Salt input lower than output – catchment appears to be leaching salt (Mayer et al. 2005).

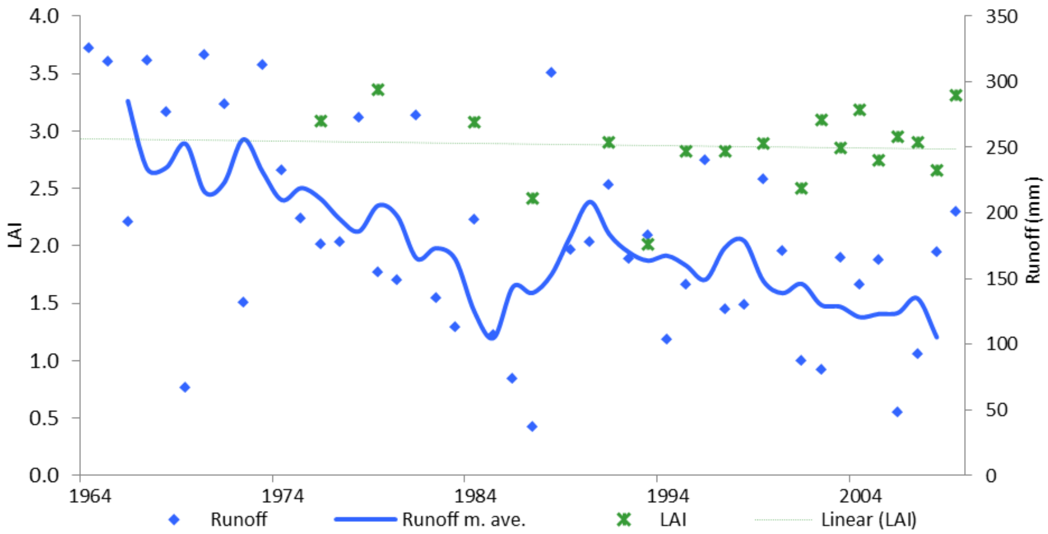

Figure A88 Annual streamflow, moving average, and leaf area index for Ordnance Road

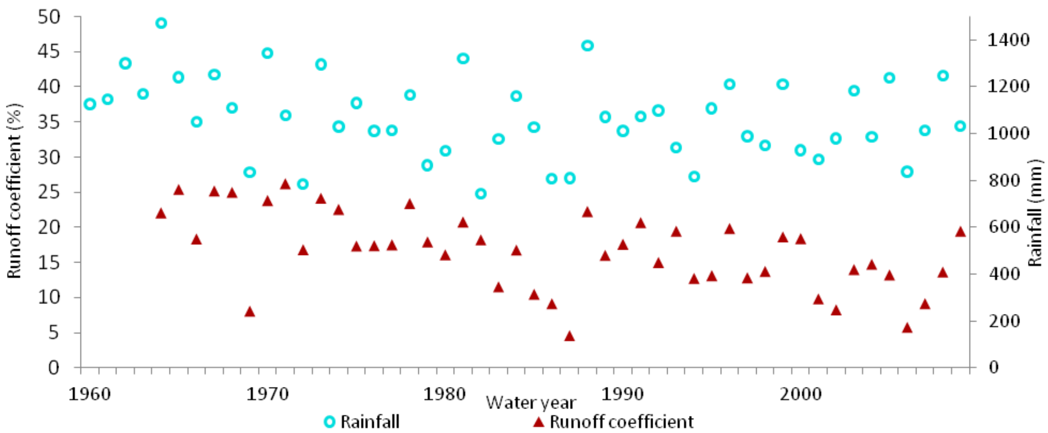

Figure A89 Annual rainfall and runoff coefficient for Ordnance Road catchment

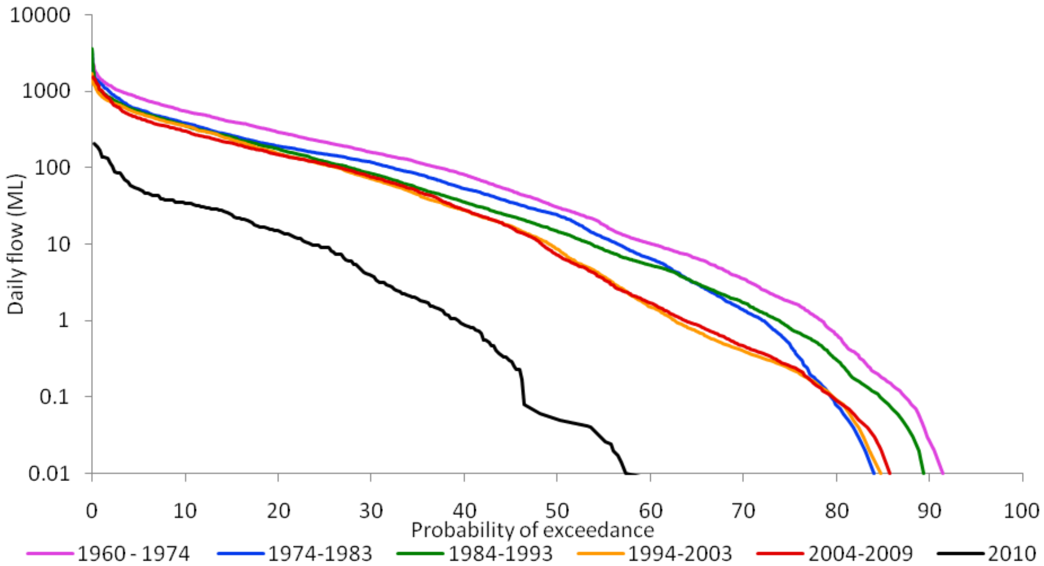

Figure A90 Flow duration curves for Ordnance Road catchment

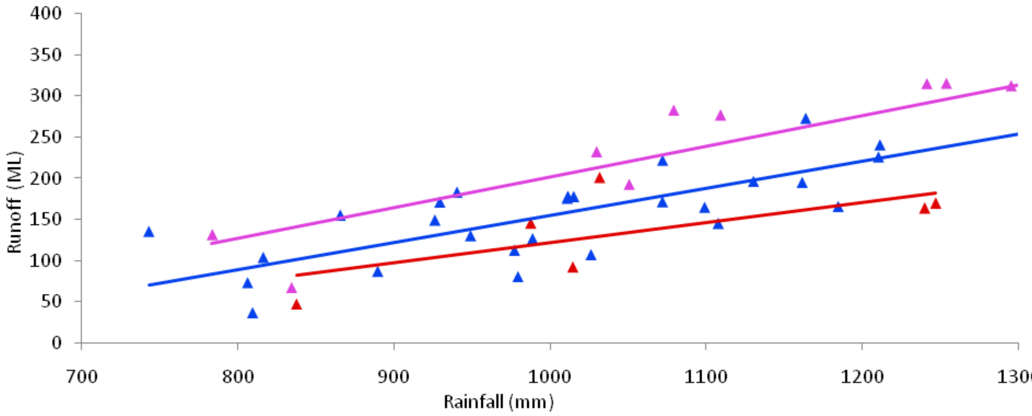

Figure A91 Annual runoff plotted by annual streamflow for Ordnance Road, showing a progressive decline in the runoff observed per unit rainfall received

Palmer Bingham River (Collie River basin) 612014

PDWSA. Intermittent stream. Rainfall runoff relationships have changed little except for a reduction in the responsiveness of streamflow to rainfall during the current FMP compared to the historical data. For earlier flows from essentially the same gauged catchment see nearby station 612037 (WRB 1984a).

Assessment	Supplementary catchment
Size & location	363 km^2 (large); 33.23°S, 116.51°E
Av. rainfall	694 mm/a for 1975-2008
Geomorphology	Low relief, undulating plateau with lateritic soils over Archaean granitic rocks (WRB 1984a).
Tenure	Lane Poole reserve and Muja State Forest, 15% freehold land.
Clearing	5% cleared (most of this is on land outside of FMP tenure)
Vegetation type	70% jarrah forest, 11% wandoo, 5% shrub, herb and sedgeland, 2% jarrah woodland and 1% exotic species.
Timber harvest	8% harvested prior to 1920s, 18% harvested in 1930s, 29% in 40s, 32% in 50s, 11% in 60s, 10% in 70s, 10% in 90s and 11% in 00s. 15% old growth.
Fire history	10% of the catchment was burnt in 2002, 24% in 2004, 21% in 2007
Dieback	32% of the catchment has been interpreted for dieback presence; 2% has been found to be infested
Flow trends	No statistically significant trends observed. Categorised as 'climate pattern present, clearing and/or intensive thinning have stabilised or increased streamflows'. Flows since 2004 have, however, been lower than previous.
Salinity data	Continuous and discrete salinity data available for this catchment since 1991. Data reliability code: 1 (mostly continuous measurements). Av. salinity 1983–92: 360 mg/L; 1993–2002: 320. During same period average flow down from 7.1 to 5.3 GL. Salt input much higher than output – catchment appears to be accumulating salt (Mayer et al. 2005).
Salinity trends	Statistically significant declines in salinity have been observed in this catchment (see Chapter 5 salinity trends).

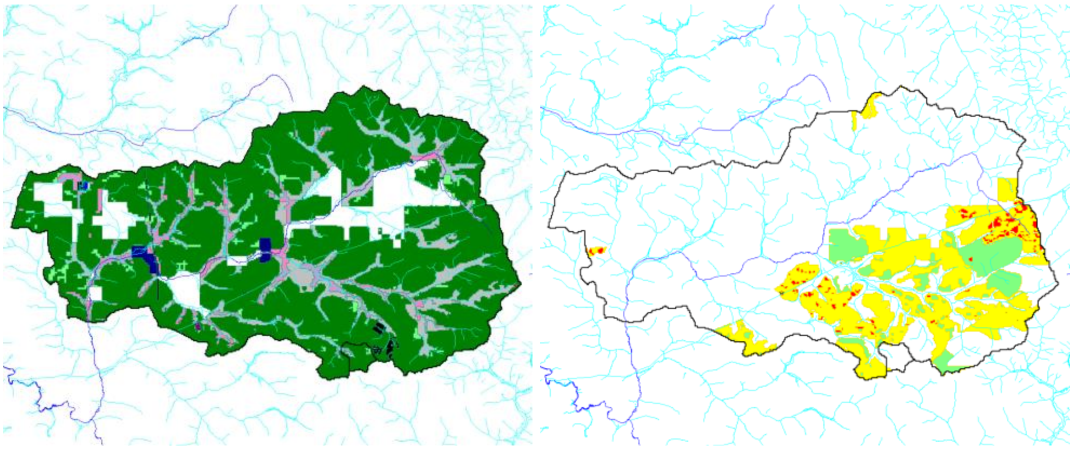

Figure A92 Palmer catchment views. L: vegetation type within FMP tenure showing areas of jarrah forest (dark green), shrub, herb and sedgeland (pink), and streams (light blue). R: Harvest intensity since 1990 showing areas cleared (black) and harvested at high (red), medium (yellow) and low (green) intensity

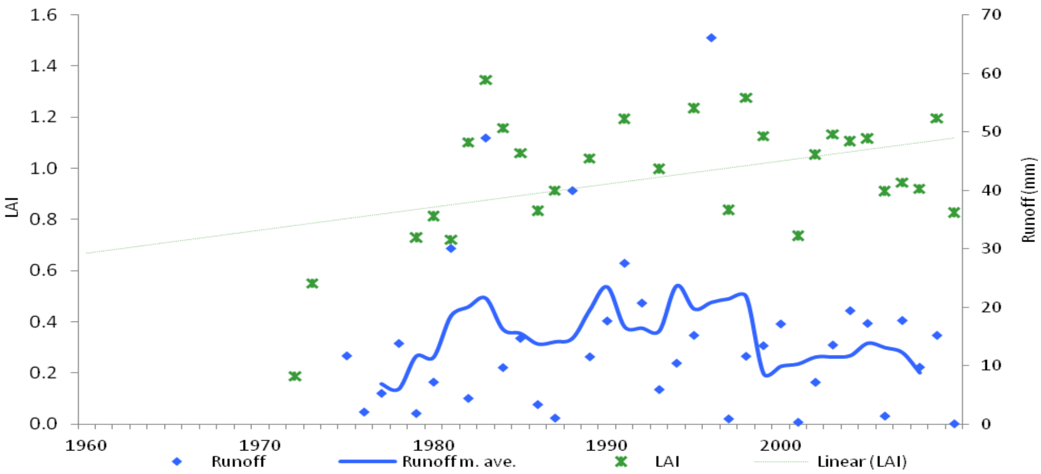

Figure A93 Annual streamflow, moving average, and catchment average leaf area index for Palmer catchment

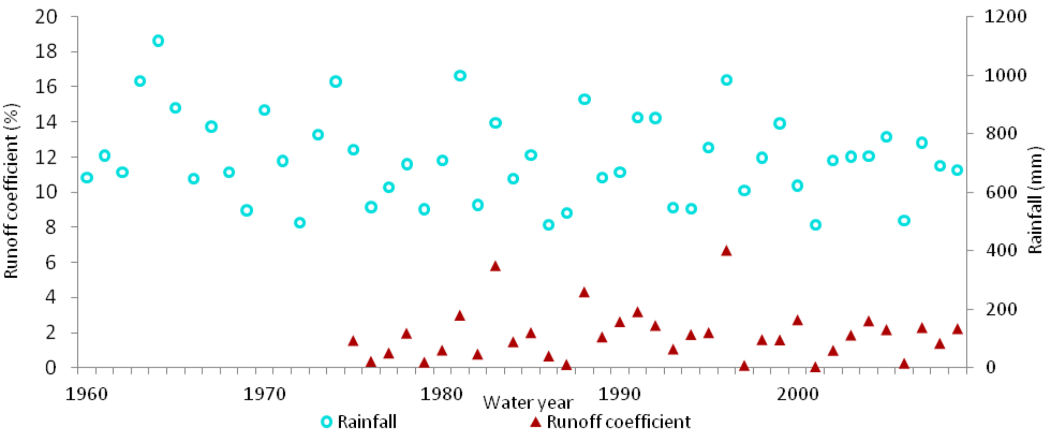

Figure A94 Annual rainfall and runoff coefficient for Palmer catchment

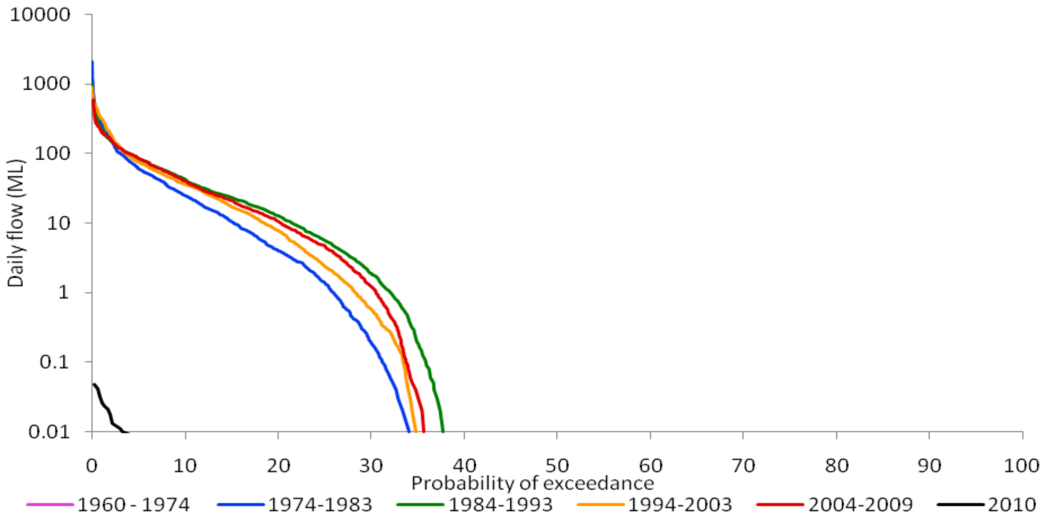

Figure A95 Flow duration curves for Palmer catchment

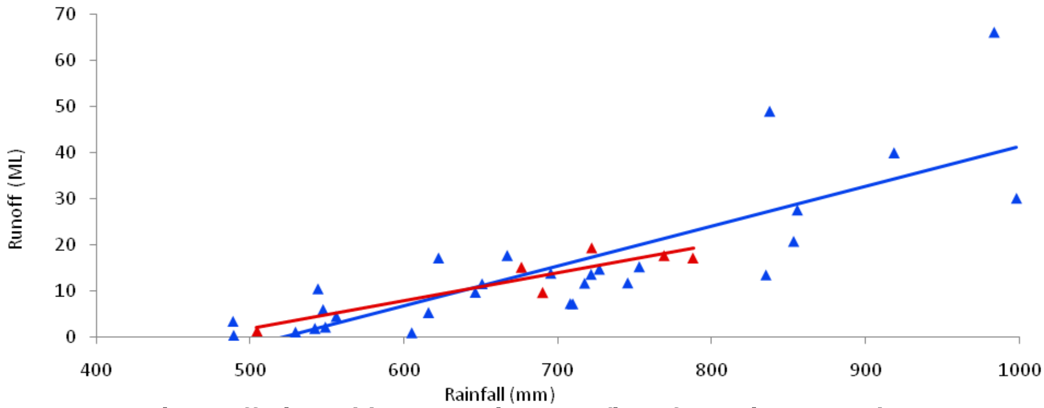

Figure A96 Annual runoff plotted by annual streamflow for Palmer catchment

Pine Plantation Darkin River (Helena-Swan coastal basin) 616002

PDWSA Priority 1. Intermittent stream. Part outside FMP tenure. Croton and Dalton (1999) found an exponential regression relationship between rainfall and streamflow.

Assessment	Primary catchment
Size & location	665.3 km^2 (large); 32.14°S, 116.46°E
Av. rainfall	1021 mm/a for 1975-2008
Geomorphology	Low to moderate relief, undulating plateau with minor dissection, lateritic soils over Archeaen granitic and metamorphic rocks (WRB 1984b).
Tenure	Helena National Park, Mundaring State Forest, Wandoo National Park, Jarrahdale State Forest. Approximately 6% cleared freehold or other non-FMP tenure.
Clearing	5% cleared along the stream zone in the upper catchment (private farms)
Vegetation type	43% jarrah forest, 38% wandoo woodland, 8% jarrah woodland, 3% shrub, herb and sedgeland, 2% rocky outcrops, 1% exotic species (pine plantations)
Timber harvest	7% old growth. 17% was harvested prior to 1920, 11% harvested in 30s, 5% in 40s, 21% in 50s, 41% in 60s, 28% in 70s, <5% per decade since.
Fire history	6% burnt in 2002, 15% burnt in 2004–5, 11% burnt in 2005–6, 8% in 2006–7,

	6% in 2008, 5% in 2009–10.
Dieback	16% of the catchment has been interpreted for dieback; 4% has been found to be infected.
Flow trends	No statistically significant annual flow trends observed, however there has been a progressive decline in flow days since the 1960s, and flows since 2004 have been lower than previously.
Salinity data	Continuous and discrete salinity data available for this catchment since 2000. Data reliability code: 1 (mostly continuous measurements). Av. salinity 1983–92: 180 mg/L; 1993–2002: 240 mg/L. During same period av. flow decreased 4.3 to 3.3 GL. Average salinity for 1975-2009 was 228 mg/L. Salt input much higher than output – catchment appears to be accumulating salt (Mayer et al. 2005).
Salinity trends	Statistically significant declines in salinity have been observed in this catchment (see Chapter 5 salinity trends).

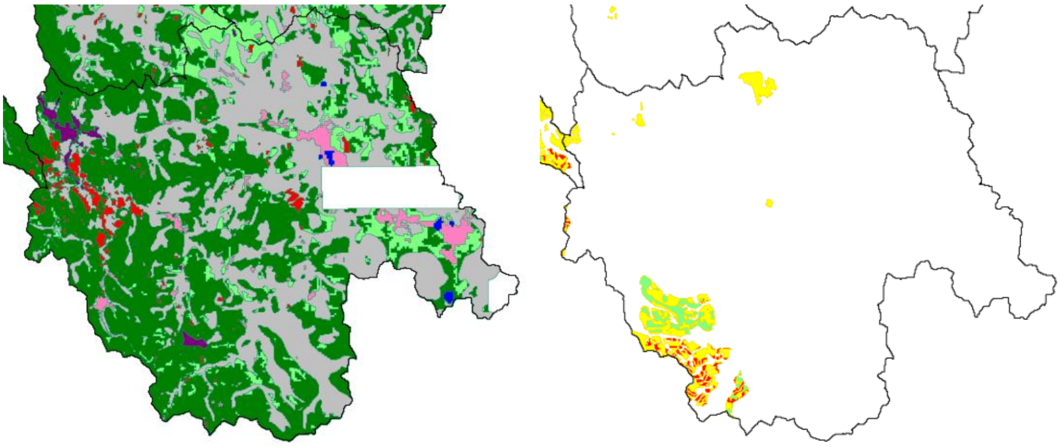

Figure 97 Pine Plantation catchment views. L: vegetation type within FMP tenure showing areas of jarrah forest (dark green), woodland (grey) shrub, herb and sedgeland (pink), and rocky outcrops (red). R: Harvest intensity since 1990 showing areas cleared (black) and harvested at high (red), medium (yellow) and low (green) intensity

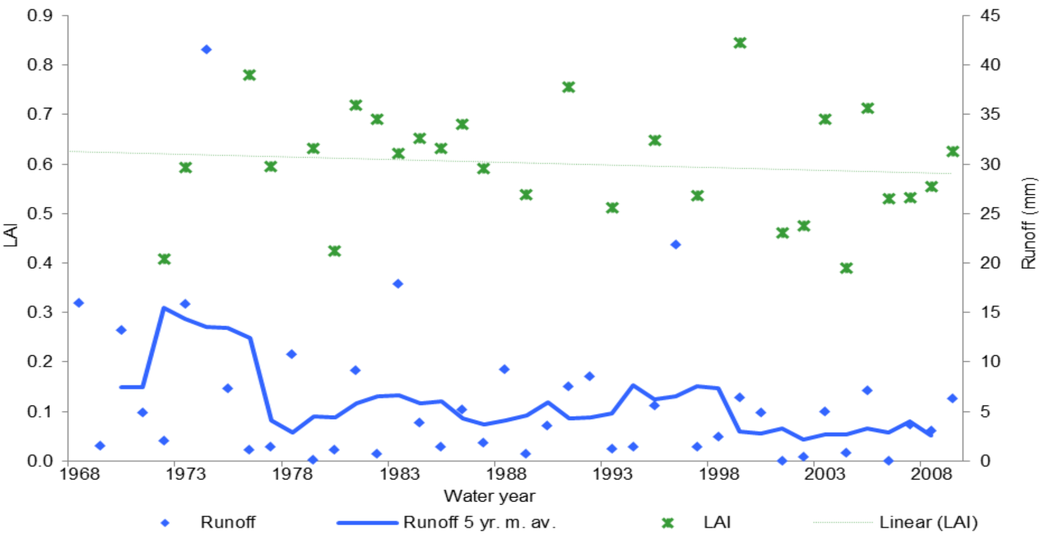

Figure A98 Annual streamflow, moving average, and leaf area index for Pine Plantation

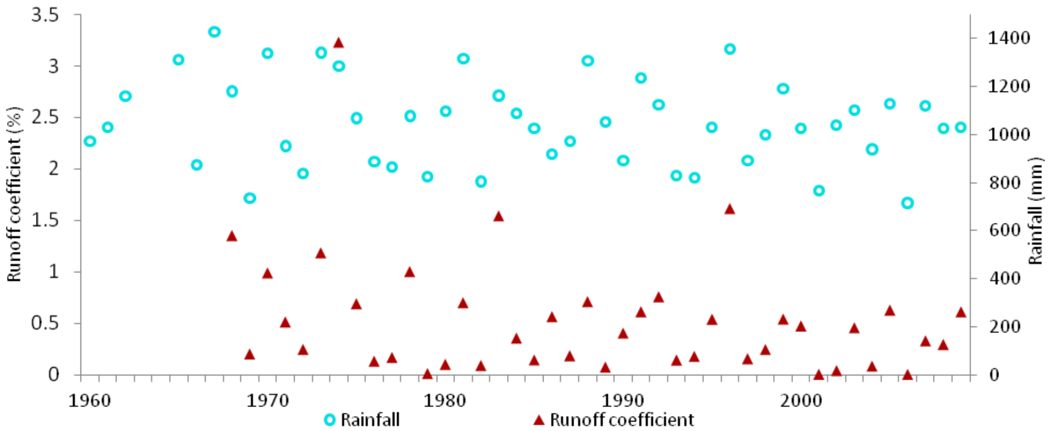

Figure A99 Annual rainfall and runoff coefficient for Pine Plantation catchment

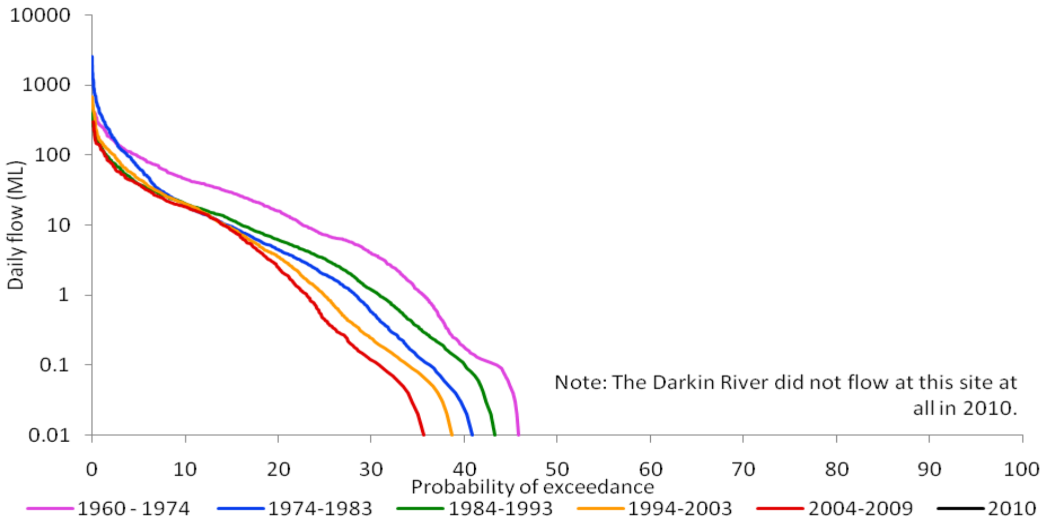

Figure A100 Flow duration curves for Pine Plantation catchment showing a progressive decline in flow days and flows throughout the year

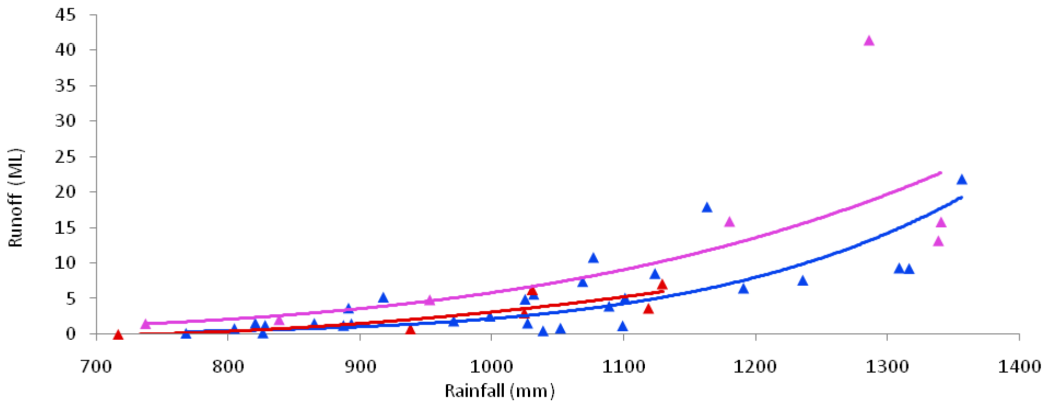

Figure A101 Annual runoff plotted by annual streamflow for Pine Plantation

Poison Lease Helena River (Swan Coastal river basin) 616216

PDWSA. Brackish, intermittent stream.

Virtually all the native forest was harvested during 1950–75 to provide firewood for the Wundowie charcoal-iron plant and wandoo for industrial extracts (Croton & Dalton 1999). Roughly 10% cleared in 1984, although part was being reforested at the time, with a few small farms grazing livestock (WRB 1984b).

Assessment	Supplementary catchment
Size & location	592.9 km^2 (large); 31.96°S, 116.35°E
Av. rainfall	785 mm/a for 1975-2008
Geomorphology	Low to moderate relief; undulating plateau with moderate dissection, lateritic soils over Archaean granitic and metamorphic rocks (WRB 1984b).
Tenure	26% outside FMP tenure.
Clearing	6% cleared
Vegetation type	37% jarrah forest. 25% wandoo. 6% jarrah woodland, 2% exotics, 2% exotic species, 1% rocky outcrops and 1% shrub, herb and sedgeland.
Timber harvest	3% old growth forest. 57% harvested pre-1920s. 22% in 1950s; 39% in 60s, 7% in 70s; 2% in 90s.
Fire history	6% burnt in 2001/02, 9% in 2003/4, 12% in 2004/5, 24% in 2005/6, 6% in 20067, 7% in 2008/9, 10% in 2009/10.
Dieback	<1% of the catchment has been interpreted for dieback; 56% of this was found to be infested.
Flow trends	No statistically significant trends observed. Categorised as 'climate pattern present, clearing and/or intensive thinning have stabilised or increased streamflows'. Flows since 2004 have, however, been lower than previous.
Salinity data	Continuous salinity data exists for this catchment. Data reliability code: 5 (fewer than 6 discrete samples per year or data estimated from flow). Brackish. Av. salinity 1983–92: 1400 mg/L; 1993–2002: 1300 mg/L (WRB1984b). Average salinity for 1975–2009 was 1140 mg/L. Salt input somewhat lower than output – catchment appears to be leaching salt (Mayer et al. 2005).
Salinity trends	Statistically significant declines in salinity have been observed in this catchment (see Chapter 5 salinity trends).

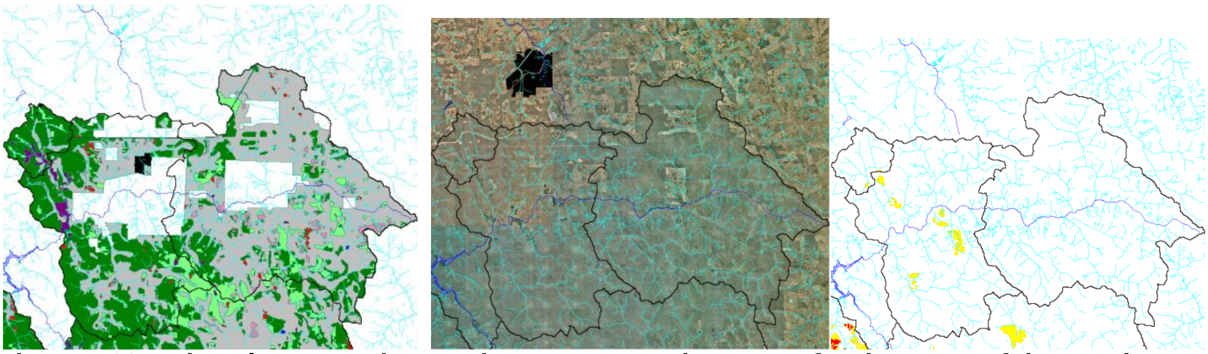

Figure 102 Poison lease catchment views. L: vegetation types for the parts of the catchment within FMP tenure, showing jarrah forest (dark green), jarrah woodland (light green), wandoo (grey), shrub, herb and sedgeland (pink), and plantations (purple). M: aerial image of catchment. R: Harvest intensity since 1990 showing areas harvested at high intensity (red) and medium intensity (yellow).

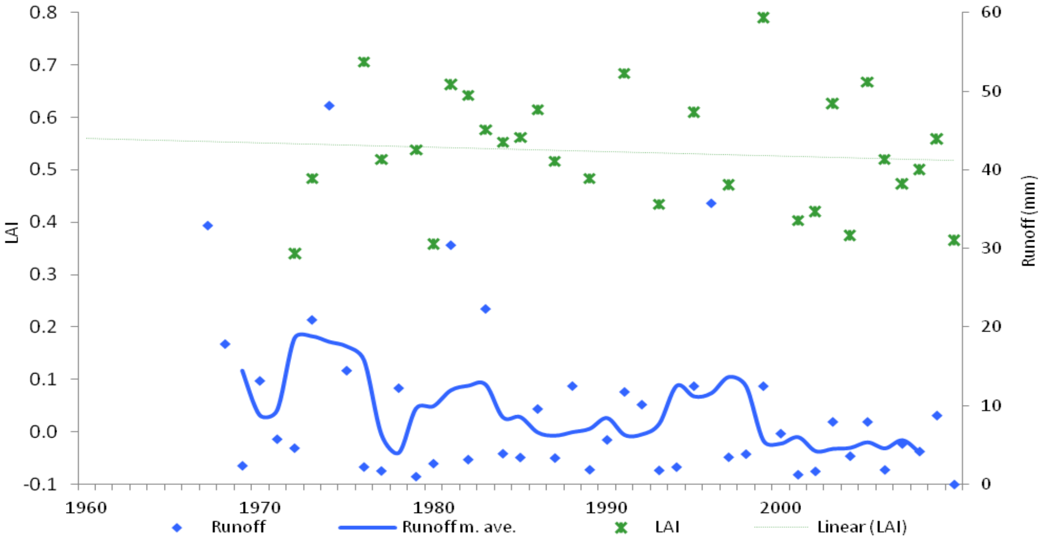

Figure A103 Annual streamflow, moving average, and leaf area index for Poison Lease

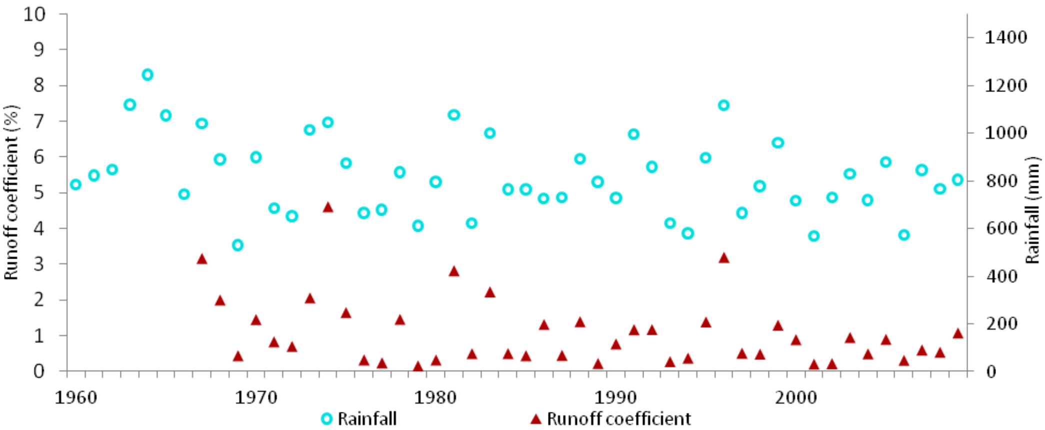

Figure A104 Annual rainfall and runoff coefficient for Poison Lease catchment

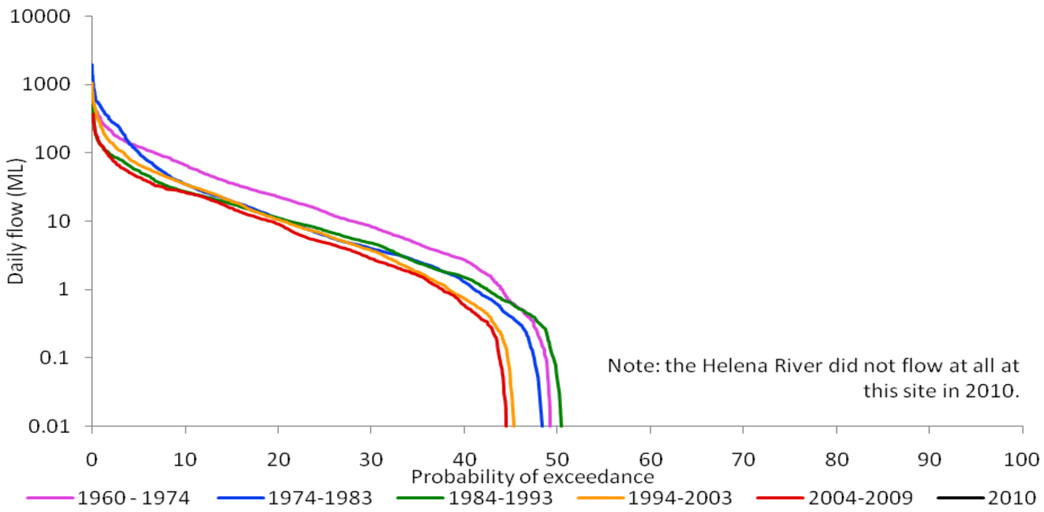

Figure A105 Flow duration curves for Poison Lease catchment

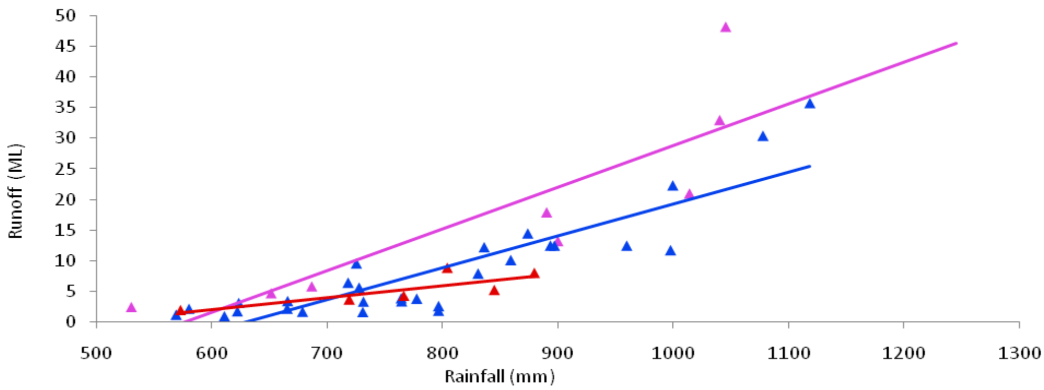

Figure A106 Annual runoff plotted by annual streamflow for Poison Lease

Seldom Seen Creek - Travellers Arms (Canning-Swan coastal basin) 616021

PDWSA. Historically perennial stream, intermittent since 2006.

Note: The AWRC name for this gauging station is Travellers Arms, but in this report the catchment is referred to by its stream name (Seldom Seen Creek), for consistency with the literature and practitioner use.

A total of 32% of the catchment was cleared, mined, and rehabilitated. Mining began in 1967/68. Rehabilitation was completed in 2001; most rehabilitation consisted of eastern states eucalypts. Aerial photographs and Department of CALM FMIS database records indicate that forest cover was already thin from logging and dieback, prior to clearing for mining.

Pre-mining streamflows were perennial (Croton et al. 2005). Cleared area within the catchment peaked in 1977, but the peak streamflow response was observed in 1981, indicating a lag. At this time, runoff coefficient was estimated to be 23% greater than a no-mining scenario, with Waterfall Gully used as a control. By 1981, 27% had been mined and 17% rehabilitated, with av. rehabilitation stand age 5–6 yr. Flow had almost returned to pre-mining levels by 1994. Salinity increased by 20–30 mg/L during the mining period, and showed no signs of returning to pre-mining conditions (Davies et al. 1995).

Grigg (2009) suggests that this catchment (amongst others) is a strong candidate for immediate thinning treatment, to minimise the adverse effects of densely stocked rehabilitation on stream yields. Modelling indicated that the higher evapotranspiration rates of mine revegetation led to an estimated 12 mm/yr reduction in runoff (13% of flow) in 2002 (Croton et al. 2005). Croton et al. (2005) indicated that soil water storages were still decreasing at time of publication and that further reductions in streamflow could be expected. In addition, Croton et al. (2005) estimated that the leaf area for the unmined forest increased during the study period, creating reductions in streamflow beyond those due to mine revegetation.

Assessment	Supplementary catchment
Size & location	7.2 km^2 (small); 32.27°S, 116.10°E
Av. rainfall	1083 mm/a for 1975-2008
Tenure	100% crown reserve (Jarrahdale State Forest)
Clearing	2% cleared.
Vegetation type	66% jarrah forest, 15% jarrah woodland, 18% exotic species.
Timber harvest	0% old growth. 1005 harvested pre-1920s, 100% harvested in 1940s, 23% in 1960s, 76% in 1970s, 6% in 1980s, 2% in 1990s.
Fire history	94% burnt in 2005-06.
Dieback	65% of the catchment has been interpreted for dieback; 66% of this was found to be infested. 36.4% of the catchment treated for dieback in 1985.
Flow trends	Significant decline in streamflow observed, along with shift from perennial to intermittent flow regime, dramatic reduction in average flow days and progressive declines in rainfall-runoff relationship. Categorised as ‘climate pattern present, streamflow decline exacerbated by increasing vegetation cover’.

Salinity data	Average TSS to 1982 was 140 mg/L (WRB 1984b). Good quality discrete data records are available for this catchment. Data reliability code: 4.
Salinity trends	Bari and Ruprecht reported stable salinities up to 2000. Over the years 1975–2009, statistically significant reductions in salinity were observed (see Section 5), although the change was small (~15 mg/L).

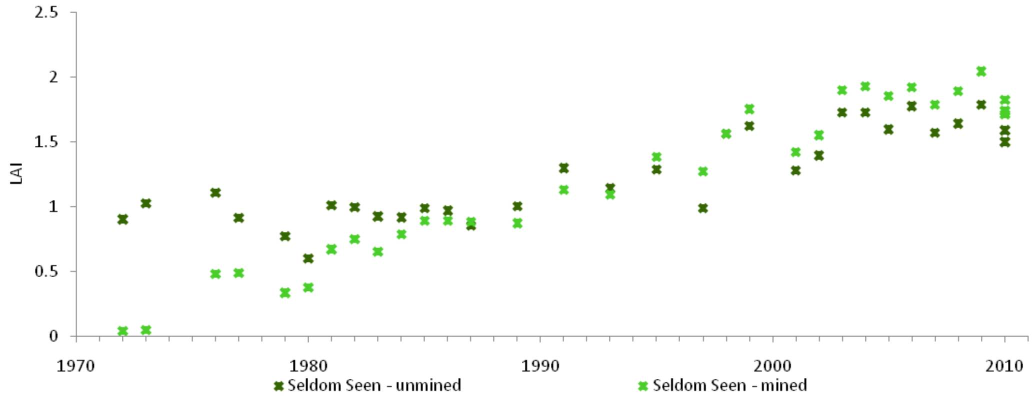

Figure A107 Leaf area index data shown separately for mined and unmined parts of More Seldom Seen (Ceriani Farm) catchment

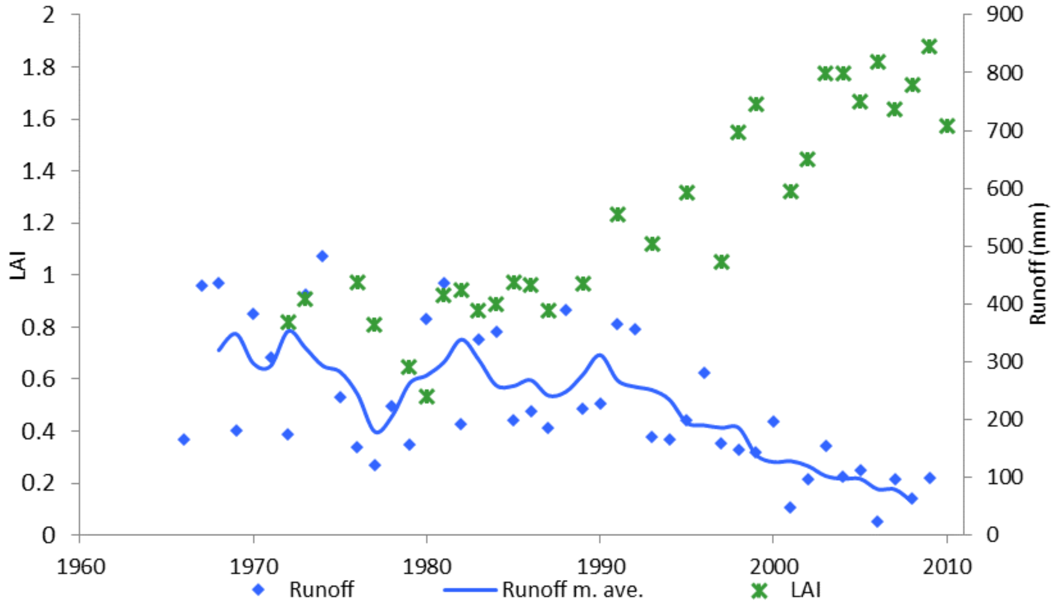

Figure A108 Annual streamflow, moving average, and leaf area index for Seldom Seen

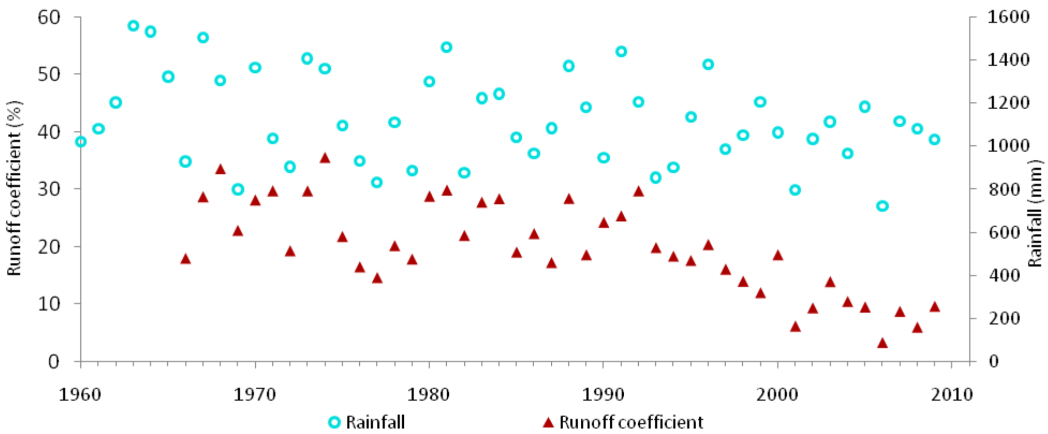

Figure A109 Annual rainfall and runoff coefficient for Seldom Seen catchment

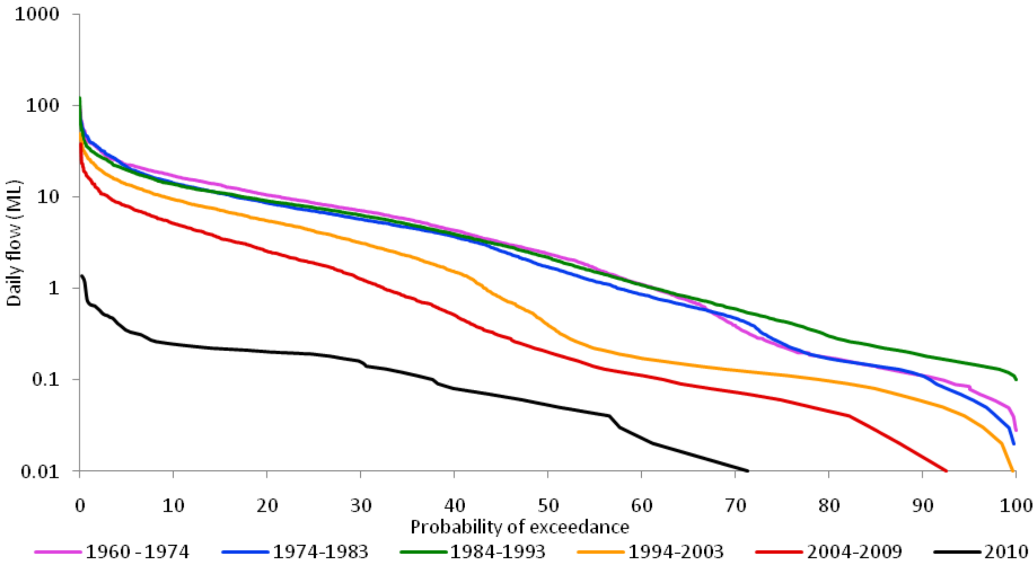

Figure A110 Flow duration curves for Seldom Seen catchment showing a shift from perennial to intermittent flows and stark reductions in flow days.

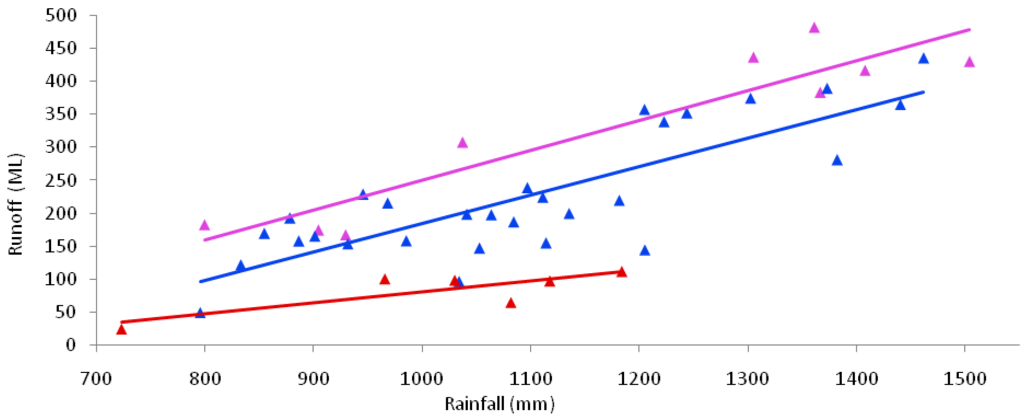

Figure A111 Annual runoff plotted by annual streamflow for Seldom Seen catchment, showing a progressive decline in the runoff observed per unit rainfall received

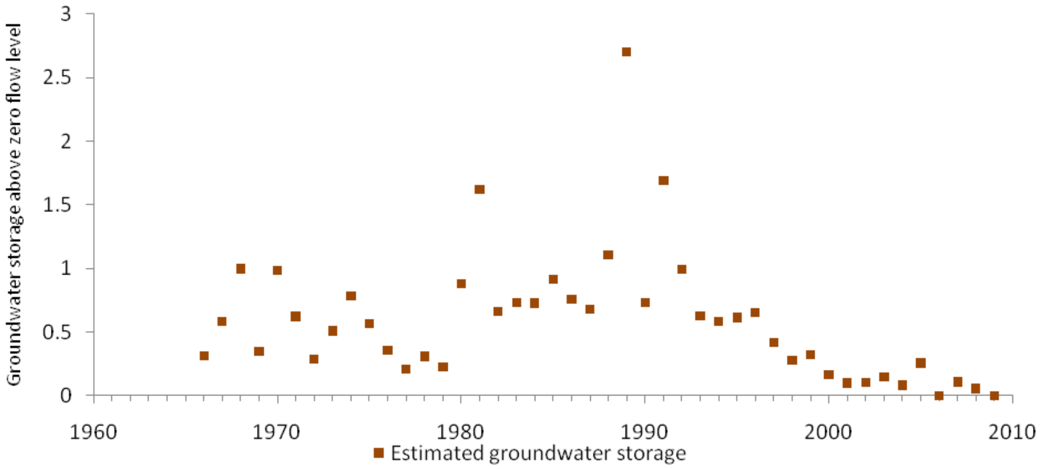

Figure A112 Estimated groundwater storage for Seldom Seen catchment at Travellers Arms

Slavery Lane Pickering Brook (Swan coastal basin) 616009

PDWSA Priority 1. Intermittent stream. Streamflow data for 1999–2004 missing. Steady decline in streamflow, runoff coefficient and flow duration observed, with a statistically significant step decline observed. In the period of the current FMP the stream has the lowest average volume of streamflow per unit rainfall recorded, and the shortest average flow duration. This stream had minimal flows in 2006 and 2010.

This catchment has an extensive timber harvest history but no harvesting in the 1990s, which may explain the increase in vegetation coverage around this time and in the following decade, as previously harvested vegetation recovered. The effects of large fires on vegetation coverage are apparent.

Assessment	Primary catchment
Size & location	29 km^2 (medium size); 32.03°S, 116.19°E
Av. rainfall	1018 mm/a for 1975-2008
Geomorphology	Low to moderate relief; undulating to dissected plateau, lateritic soils over Archaean granitic and metamorphic rocks (WRB 1984b).
Tenure	95% State forest, 5% National Park
Clearing	2% cleared
Vegetation type	86% jarrah forest, 11% jarrah woodland, 2% shrub, herb and sedge land
Timber harvest	38% harvested pre 1920, 10% in 1920s, 18% in 1930s, 39% in 1940s, 24% in 1960s, 45% in 1970s, 13% in 1980s, and 19% in 2000s
Fire history	Very little burning occurred from 1961 to 2007. Spring burning of 11% in 2007 and 15% in 2008. 54% impacted by wildfire in 2009/10.
Burn freq.	Post 89/90: 8% once burnt, 39% twice burnt, 48% three times burnt, 3% four times burnt, 2% five times burnt. NOTE: these figures don't match the fire history
Dieback	54% of the catchment has been interpreted for dieback presence; approximately half of this is infected.
Flow trends	Significant decreasing trend since 1975; average runoff of current FMP is significantly lower than 1975–2003 mean runoff. Progressive decline in flow

	regime observed in flow duration curve. Categorised as 'climate pattern present, streamflow decline exacerbated by increasing vegetation cover'.
Salinity data	TSS 250 mg/L to 1982. Data reliability code for current report: 6 (No or very little data)

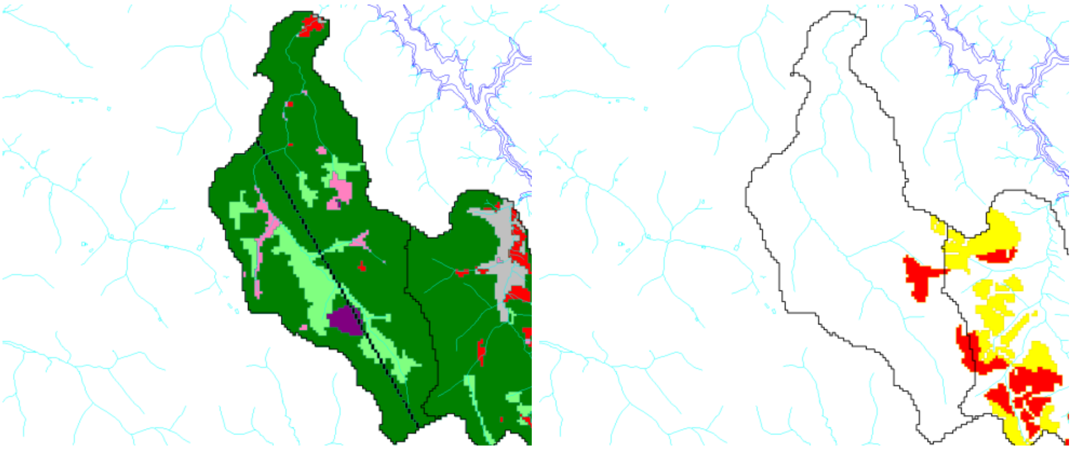

Figure 113 Slavery Lane catchment views. L: Vegetation type, showing jarrah forest (dark green), woodland (light green), shrub, herb, and sedge land (pink), plantations (purple) and rocky outcrops (red). R: harvest intensity since 1990 showing areas cleared (black) and harvested at high (red) and medium (yellow) intensity.

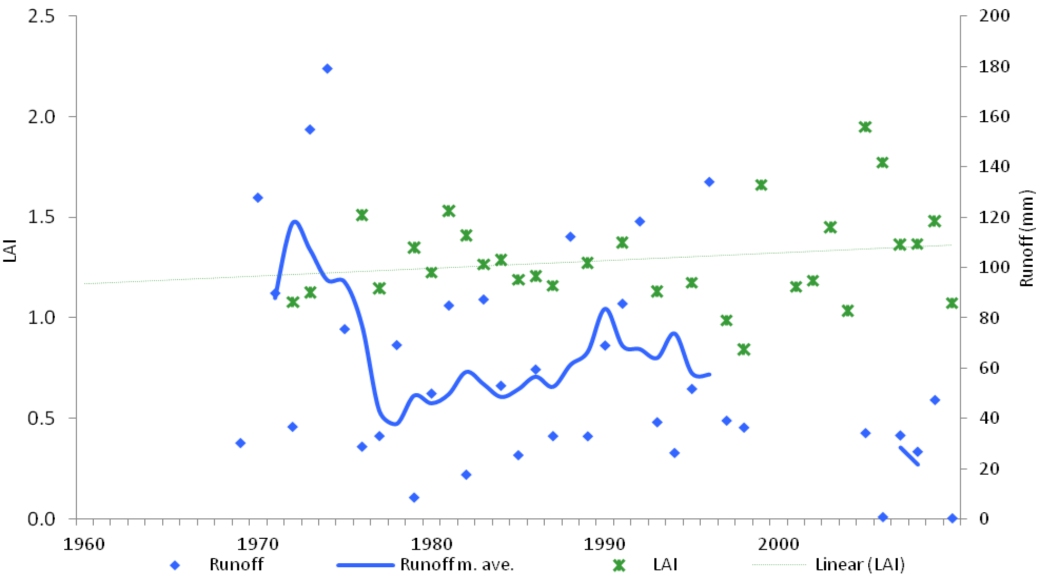

Figure A114 Annual streamflow, moving average, and leaf area index for Slavery Lane

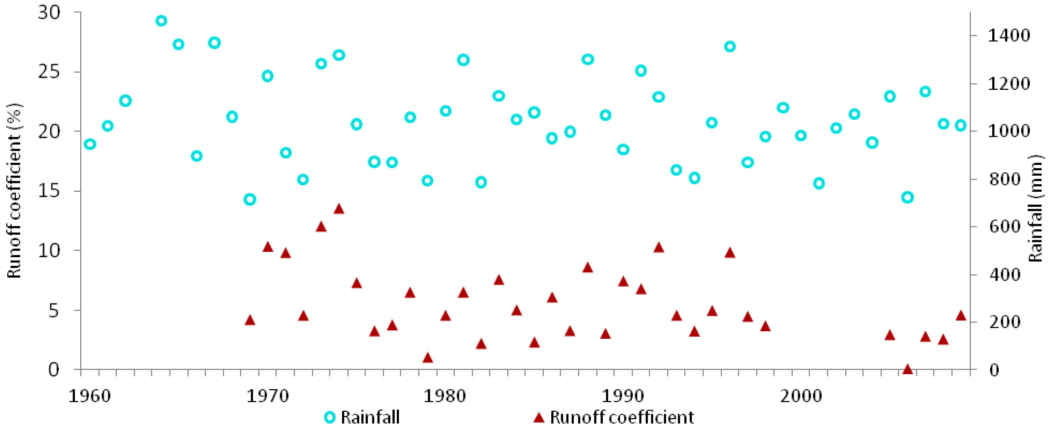

Figure A115 Annual rainfall and runoff coefficient for Slavery Lane catchment

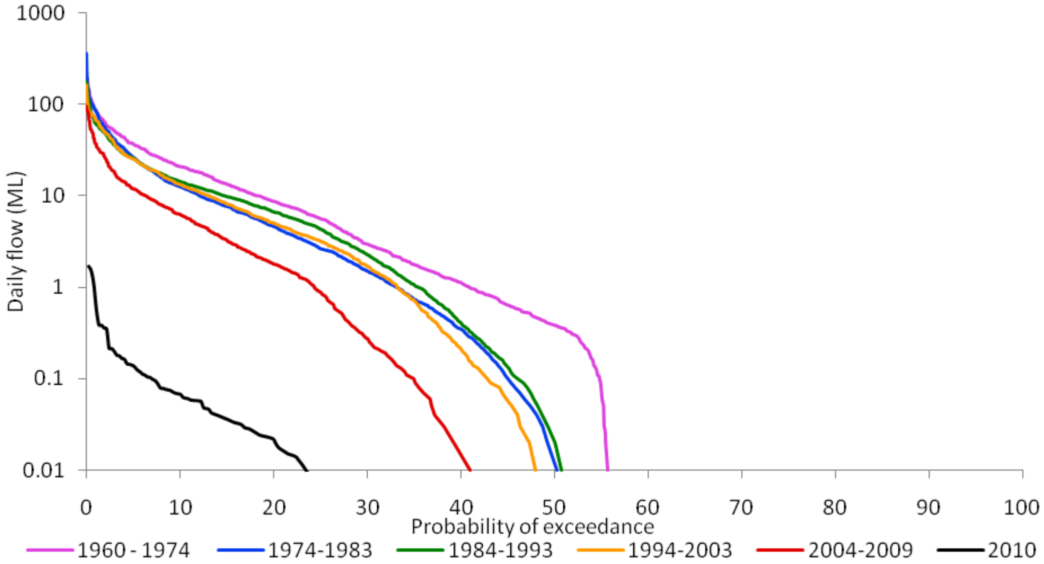

Figure A116 Flow duration curves for Slavery Lane catchment

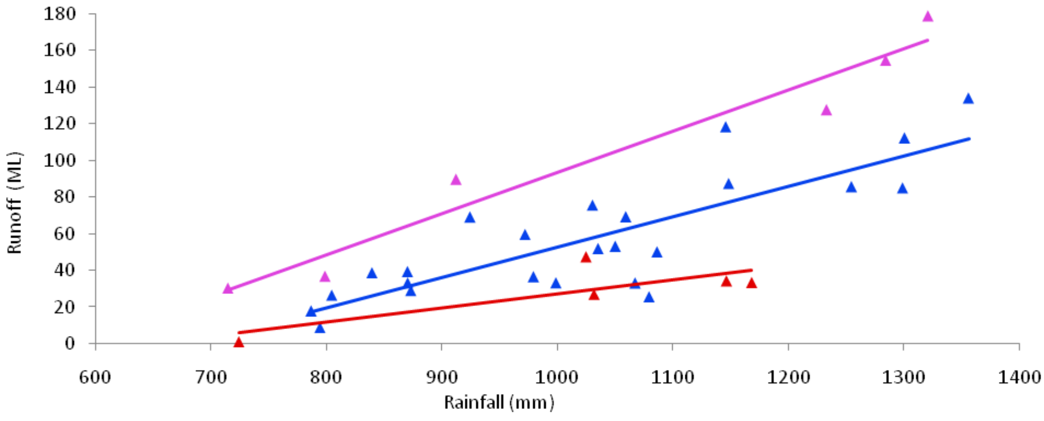

Figure A117 Annual runoff plotted by annual streamflow for Slavery Lane catchment, showing a progressive decline in the runoff observed per unit rainfall received

Staircase Road Carey Brook (Donnelly River basin) 608002

Perennial stream. Majority old growth karri and jarrah forest; minimal harvest history.

Runoff and runoff coefficients have decreased, in particular since 2000, although vegetation coverage has a slight, but insignificant, decreasing trend; it appears that this trend may be explained by climate factors alone. Trends in runoff are not statistically significant.

Assessment	Primary catchment
Size & location	30.3 km^2 (medium size); 34.36°S, 115.89°E
Av. rainfall	1182 mm/a for 1975-2008
Geomorphology	Archaean granitoid gneiss, foliated, minor migmatitie, schist and amphibolite: subsurface weathered to clay. Moderate relief, undulating plateau with incised valleys, bauxite laterite soils over Archaean granitic and metamorphic rocks.
Tenure	99.6% National Park, 0.4% State forest
Clearing	1% cleared
Vegetation type	61% karri, 27% jarrah forest, 2% shrub, herb and sedge land.
Timber harvest	Minimal harvesting; 29% in 1930s, 2% in 1980s, 3% in 1990s, small areas harvested since 1980s have been at high intensity. 66% old growth.
Fire history	12% spring burnt in 1986, summer burnt in 1991/2 (3%), 2004/5 (69%) and 2005/6 (8%). No recent wildfire history.
Dieback	12% of the catchment has been interpreted for the presence of dieback; 29% was found to be infested.
Flow trends	Significant declines in streamflow observed. Catchment categorised as 'climate pattern present, streamflow decline observed'.
Salinity data	Data reliability code: 4 – fewer than 30 samples per year, although continuous salinity monitoring did occur between 1993 and 2001. Average TSS of 116 mg/L to 1982 (WSB 1984a); 1983–92: 120 mg/L; 1993–2002: 110. Salt input somewhat lower than output – catchment appears to be leaching salt (Mayer et al. 2005).

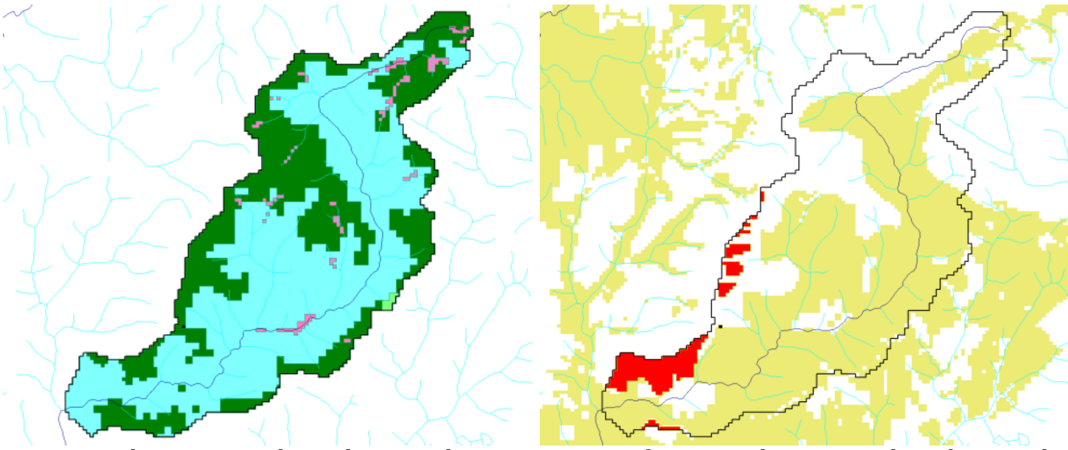

Figure 118 Staircase Road catchment views. L: Map of vegetation type showing majority of catchment is karri (blue) with jarrah forest around catchment divide (green) and small areas of shrub, herb and sedge land (pink). R: Map of timber harvesting history showing recent high intensity harvest since '80s (red) and areas classified by DEC as old growth (pale yellow). Most of the remaining area was harvested in the 1930s.

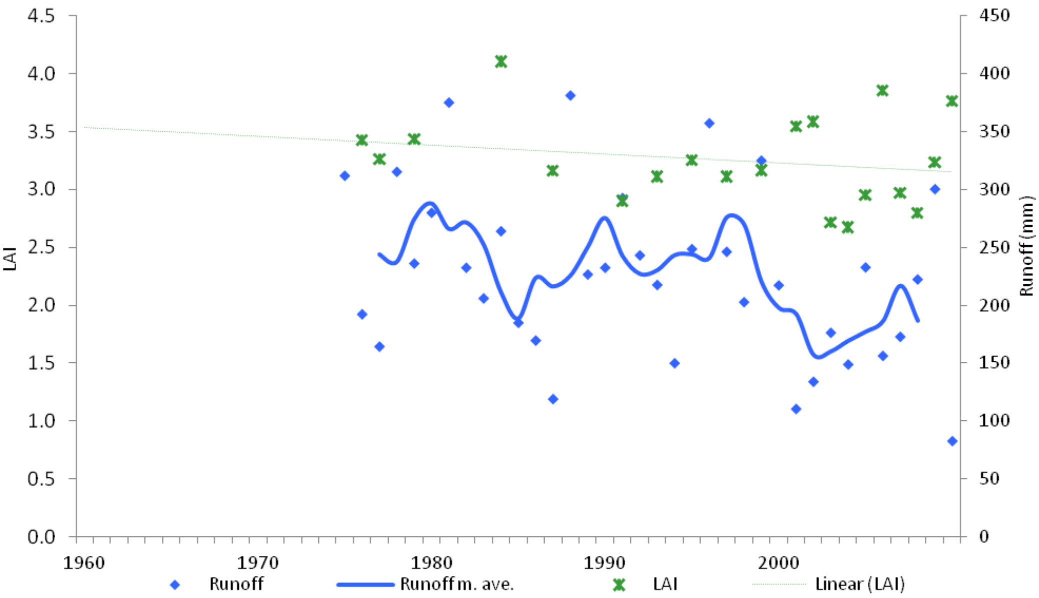

Figure A119 Annual streamflow, moving average, and leaf area index for Staircase Road

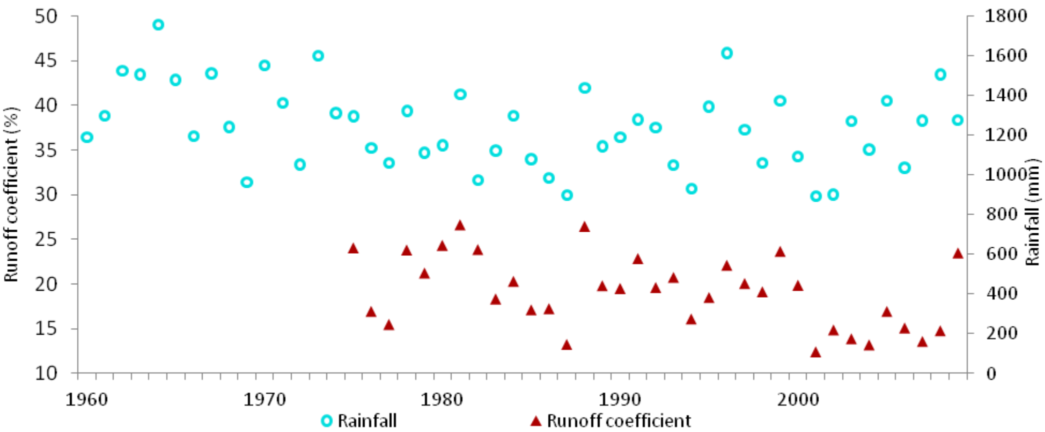

Figure A120 Annual rainfall and runoff coefficient for Staircase Road catchment

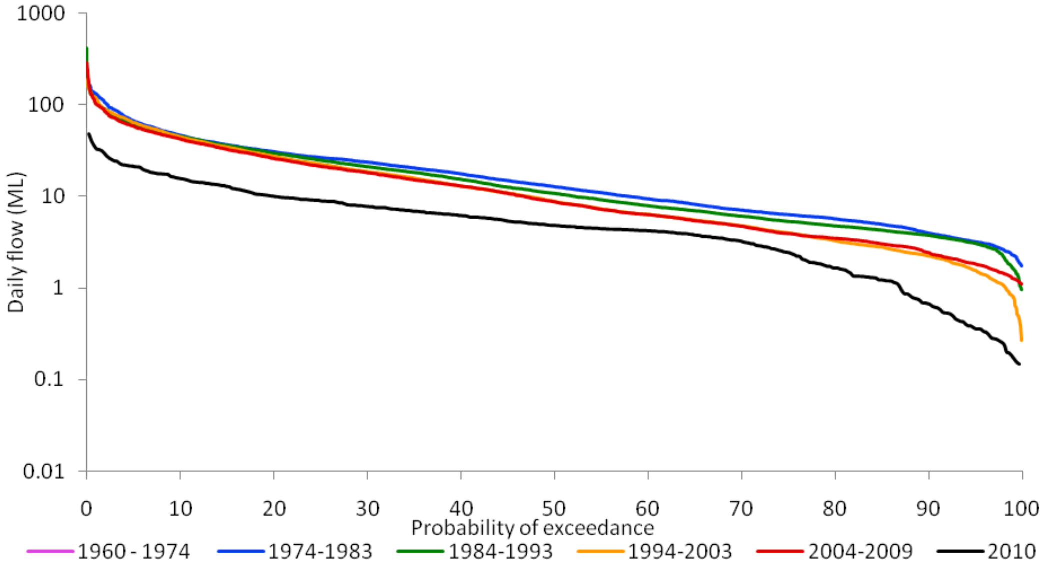

Figure A121 Flow duration curves for Staircase Road catchment

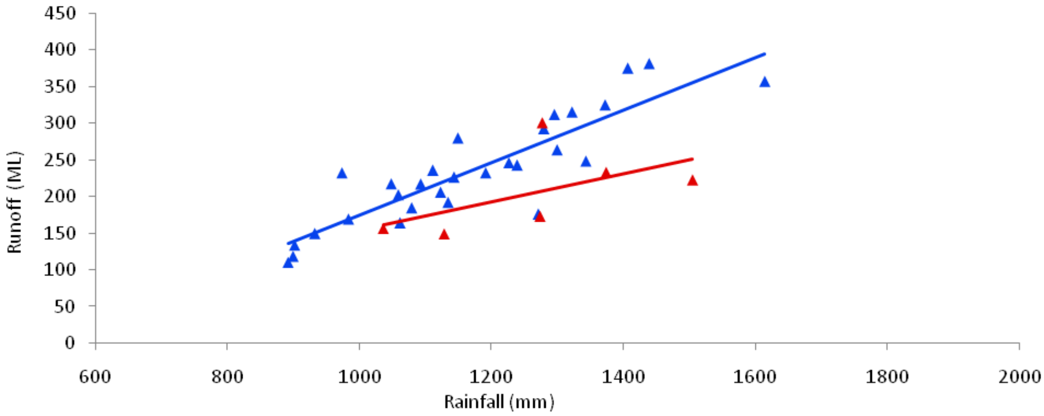

Figure A122 Annual runoff plotted by annual streamflow for Staircase Road, showing a progressive decline in the runoff observed per unit rainfall received

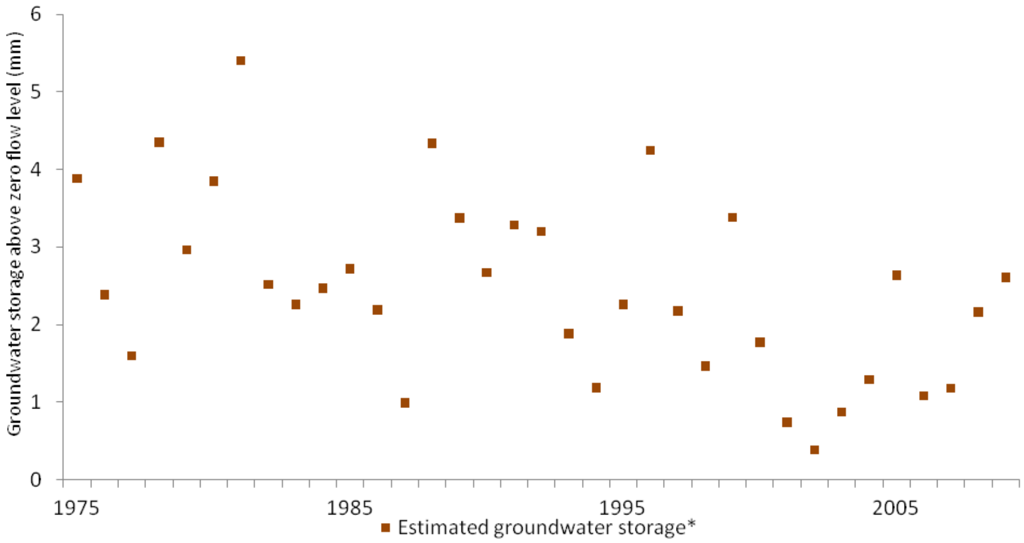

Figure A123 Estimated groundwater storage for Staircase Road

Ted's Pool Deep River (Shannon River basin) 606001

PDWSA. Intermittent stream. 40% of the catchment is old growth, with extensive harvesting history in the reminder of the catchment – although only 2% was harvested in the recent decade. Vegetation coverage is high, declined in the 1970–80s and has since increased.

Lake Muir basin occasionally overflows into the Deep River, but is not included in this catchment. Water highly coloured (WRB 1984a).

Assessment	Primary catchment
Size & location	467.8 km^2 (large). 34.61°S, 116.61°E
Av. rainfall	878 mm/a for 1975-2008
Geomorphology	Proterozoic origins. Granitoid gneiss, migmatite, quartzo-feldspathic gneisses in some places porphyritic and even-grained, minor metamorphic rock and quarzite, generally weathered to clay or clayey sand, often with a clay subsurface. Minor to major, local aquifers. With some alluvium. Low to moderate relief, undulating plateau with incised mainstream valleys, bauxitic laterite soils over Archaean granitic and metamorphic rocks. Swampy flats (WRB 1984a).
Tenure	54.5% National Park, 44.5% State forest, 0.8% Section 52, 0.2% other
Clearing	0% cleared
Vegetation type	63% jarrah forest, 20% karri (lower slopes), 13% shrub, herb & sedge land, 4% jarrah woodland.
Timber harvest	7% harvested in 1950s, 18% in 1960s, 12% in 1970s, 7% in 1980s, 11% in 1990s and 2% in 2000s. Approximately 40% is old growth.
Fire history	Since the 1960s, numerous small burns of up to 5% (mostly < 1%) have been conducted in association with the regeneration of harvested areas. 11% summer burnt in 2005/6, 12% spring burnt in 2009, 7% impacted by wildfire in 2009/10.
Flow trends	Non-significant declines in streamflow observed. Catchment categorised as 'climate pattern present, streamflow decline observed'.
Dieback	51% of the catchment interpreted for dieback; 27% of this is infested.
Salinity data	Insufficient data for analysis. Data reliability code: 5 (fewer than 6 discrete samples per year or data estimated from flow). Av. salinity in 1982: 180 mg/L; 1983–92: 200 mg/L; 1993–2002: 220. During same period av. flow 39 to 35 GL. Salt input lower than output – catchment appears to be leaching salt (Mayer et al. 2005).

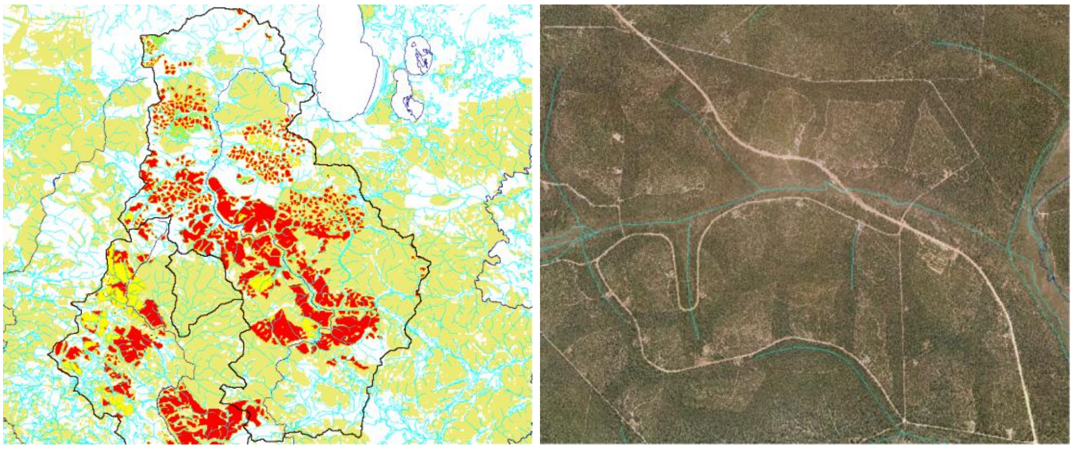

Figure A124 Catchment views for Ted's Pool. L: Timber harvesting history showing intensity of areas harvested since the 1970s (red = high, yellow = medium, green = low) Pale yellow areas are classified by DEC as old growth. R: Aerial photo showing mosaic of regenerating forest following high intensity harvest

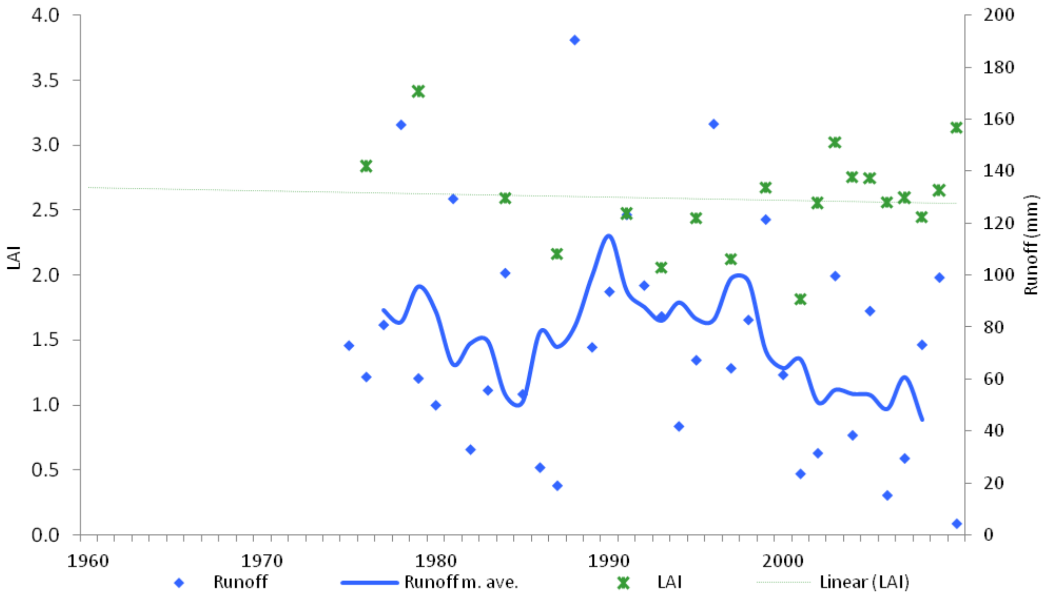

Figure A125 Annual streamflow, moving average, and leaf area index for Ted's Pool

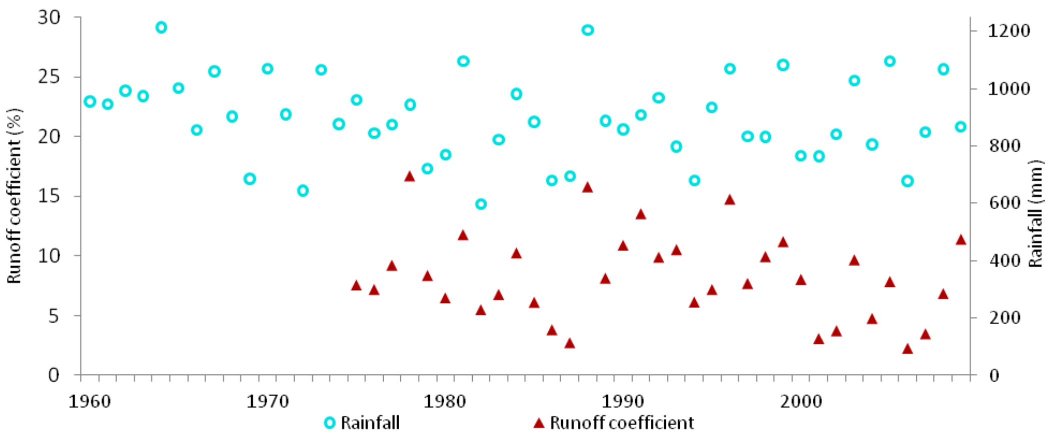

Figure A126 Annual rainfall and runoff coefficient for Ted's Pool catchment

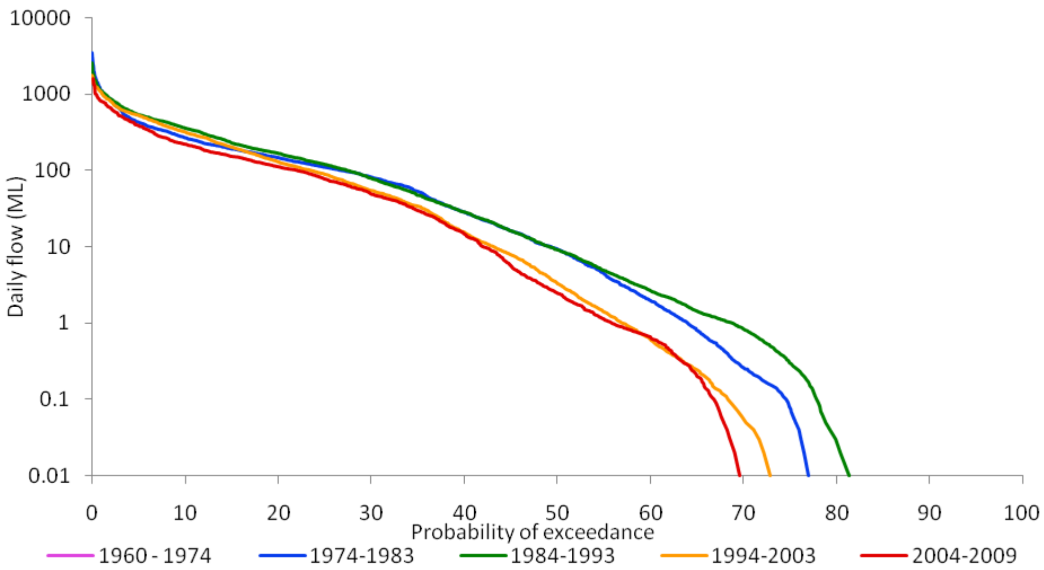

Figure A127 Flow duration curves for Ted's Pool catchment

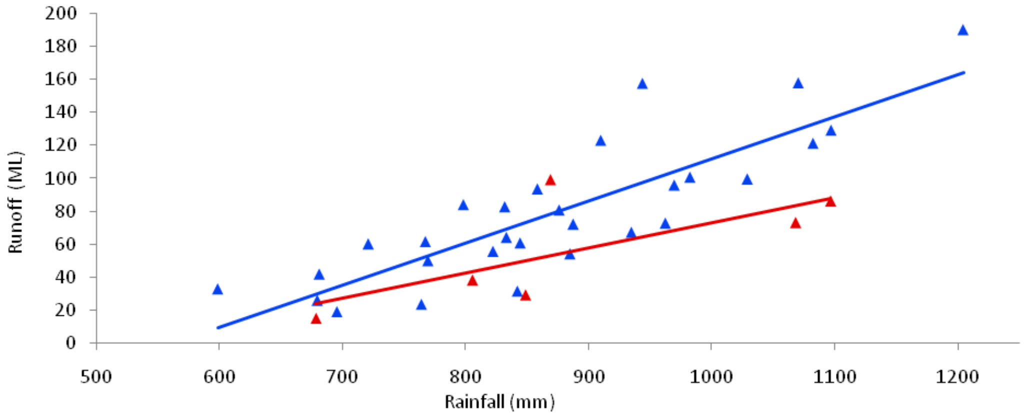

Figure A128 Annual runoff plotted by annual streamflow for Ted's Pool

Trew Road Helena Brook (Swan River basin) 616012

PDWSA Priority 1. Intermittent stream. Flowed for only two days in 2010. Long, extensive harvest history, but very little harvesting since 1970s.

Monitoring of this catchment was almost discontinued during recent gauging station reviews.. Removed from list of primary catchments due to extent of clearing and 11% outside of DEC tenure. Reached a peak cleared area fraction of 17.2% in 1968, reduced to 2.6 within FMP tenure by 1980.

Assessment	Supplementary catchment
Size & location	26 km^2 (medium); 31.89°S, 116.27°E
Av. rainfall	854 mm/a for 1975-2008
Geomorphology	Low to moderate relief; undulating to dissected plateau, lateritic soils over Archaean granitic and metamorphic rocks (WRB 1984b).
Tenure	89% State forest, 11% other (including highway)
Clearing	Area cleared within the catchment fluctuates due to pine plantation cycles; as at 2011 it was approximately 7%. Estimates from DPaW have stated 2%

	(within FMP tenure) plus ~7% (DoW land): 10% clear.
Vegetation type	69% jarrah forest, 12% wandoo, 7% jarrah woodland, 7% softwood (pine) plantation, 1% rocky outcrops.
Timber harvest	80% harvested pre 1920, 1% in 40s, 27% in 50s, 20% in 60s, 9% in 70s & 1% in 90s.
Fire history	Spring burnt in 1971 (9%), 1987 (12%), 2001 (7%, 2004 (9%) 2007 (6%), and 2009 (8%). Winter burnt in 2005 (9%). Autumn burnt in 2006 (17%) and 2007 (7%).
Dieback	Limited dieback interpretation has been conducted in this catchment.
Flow trends	Non-significant declines in streamflow observed. Catchment categorised as 'climate pattern present, streamflow decline observed'.
Salinity data	Data reliability code for current report: 6 (No or very little data). Marginal water quality – av. TSS 850 mg/L to 1982 (WRB 1984b).

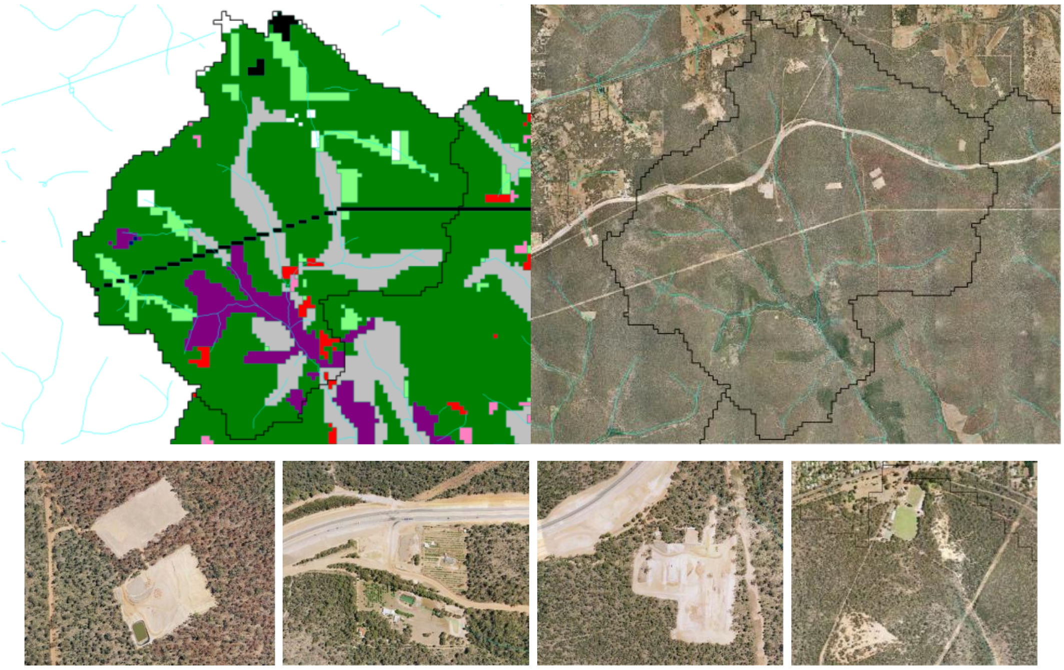

Figure A129 Catchment views of Trew Road. L: vegetation types showing jarrah forest (dark green), jarrah woodland (light green), wandoo (grey), plantations (purple), rocky outcrops (red) and cleared areas (black). R and lower row: aerial image of catchment and cleared areas

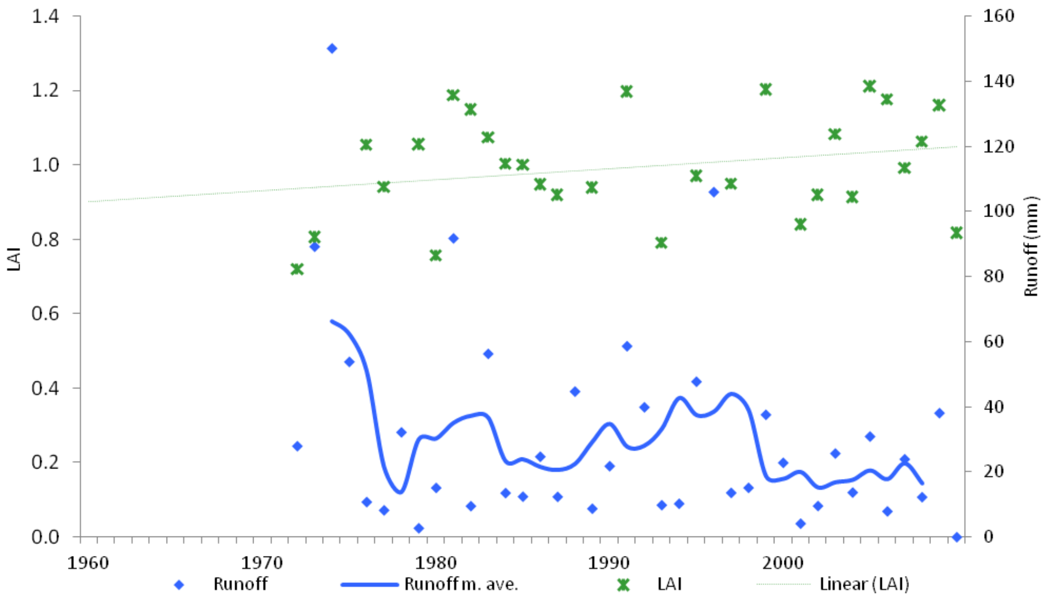

Figure A130 Annual streamflow, moving average, and leaf area index for Trew Road

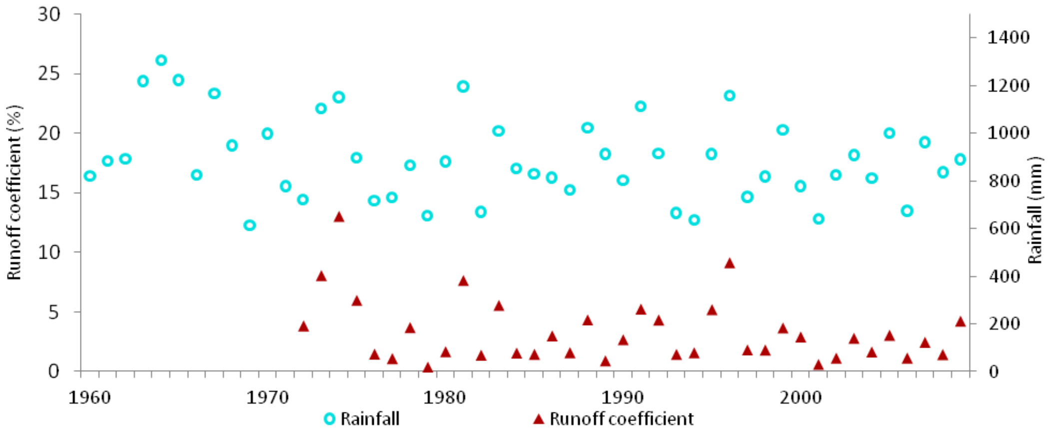

Figure A131 Annual rainfall and runoff coefficient for Trew Road catchment

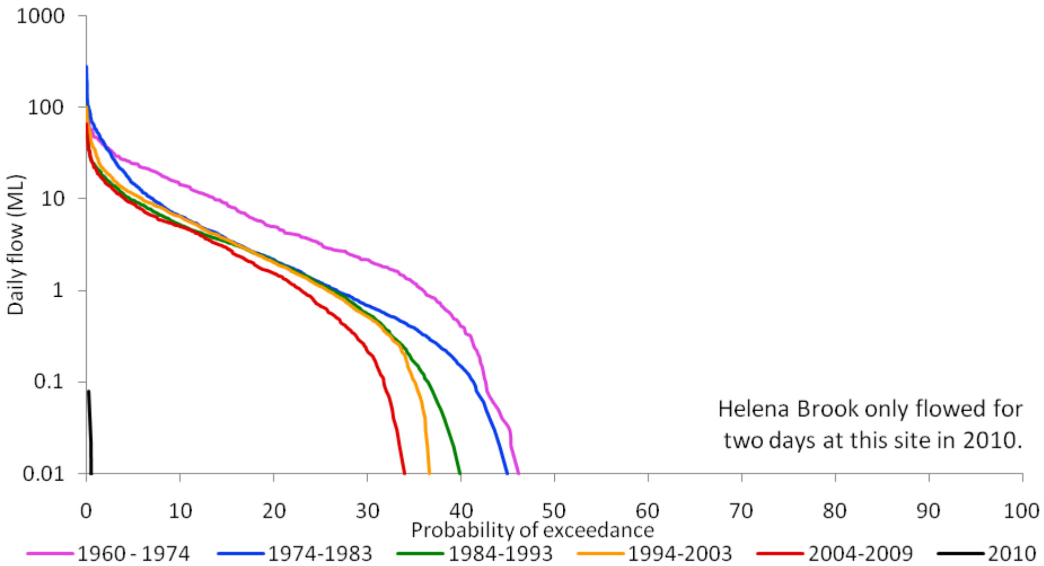

Figure A132 Flow duration curves for Trew Road catchment

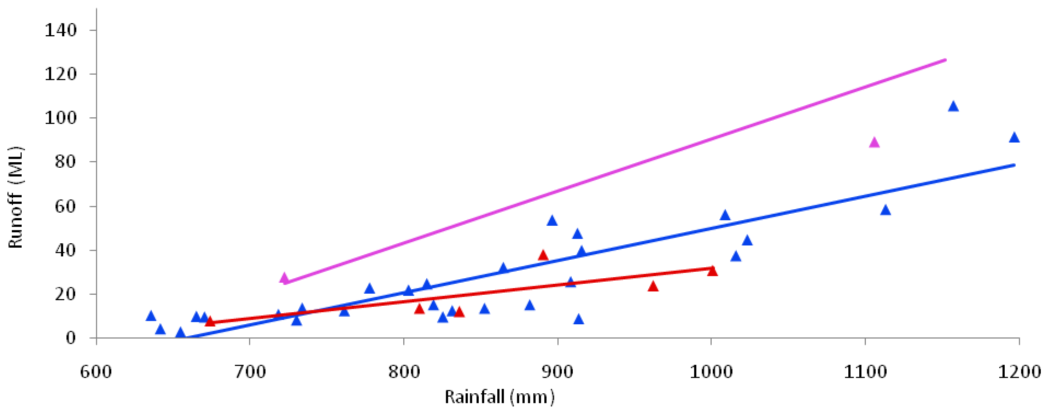

Figure A133 Annual runoff plotted by annual streamflow for Trew Road

Vardi Road Wungong Brook (Canning- Swan coastal) 616041

PDWSA. Historically perennial stream. Stopped flowing for the first time in history for several days in early 2005, intermittent since. Mostly dieback infected jarrah forest, with an extensive harvesting and mining history. ¼ mined between 1967 and 1998, regeneration (with both exotic species and jarrah forest) primarily since early 1980s, continued to 2001; some areas of revegetation are very dense. LAI increasing since early 1990s, streamflows show significant declines.

Contains nested catchments Cobiac and Chandler Road, where there has been thinning.

Assessment	Supplementary catchment
Size & location	80 km^2 (medium); 32.29°S, 116.16°E
Av. rainfall	1090 mm/a for 1975-2008
Geomorphology	Mainly Archaean granitoid rock; monzogranite dominant. Some granulite and migmatite; high-grade metamorphic rock.
Tenure	94% State forest, 4% National Park, 2% Other
Clearing	0% cleared
Vegetation type	70% jarrah forest, 15% jarrah woodland (incl. rehab), 6% exotic hardwood, 5% exotic softwood, 2% rocky outcrops, 1% wandoo
Timber harvest	Extensive history of timber harvest including 83% pre 1920, 23% in ‘30s, 60% in ‘40s, 46% in ‘70s, 18% in ‘80s, 12% in ‘90s and 7% in 2000s. Around ¼ cleared for mining and subsequently regenerated from 1967 onwards.
Fire history	Numerous small parcels generally less than 10% of catchment area spring or autumn burnt from the 1960s onwards. No recent wildfire history.
Dieback	97% of the catchment has been interpreted for dieback; 56% was found infected.
Flow trends	Statistically significant declining trends and step-changes observed. Catchment classified as ‘climate pattern present; streamflow decline exacerbated by increasing vegetation cover’.
Salinity data	Insufficient recent data to include in current analysis. Data reliability code: 5 (Mostly continuous measurements with very large estimated gaps (>3 months).

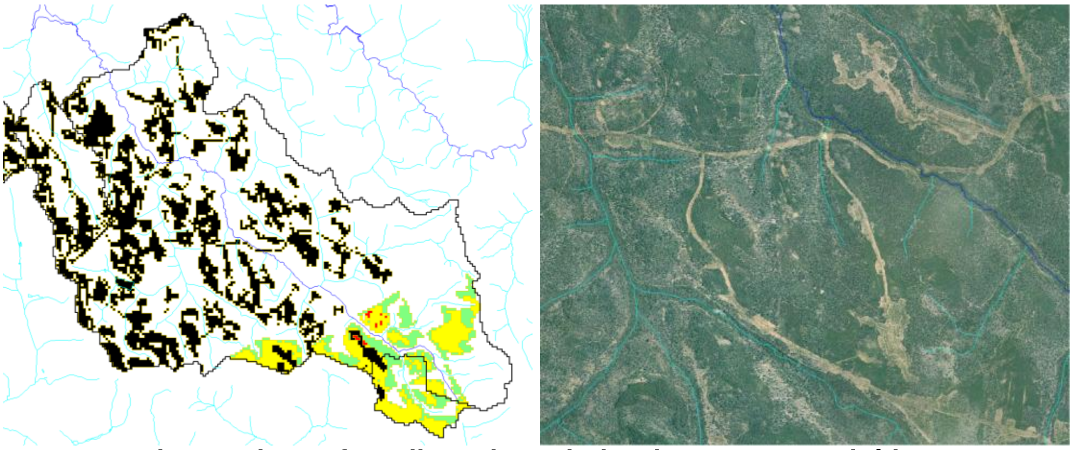

Figure A134 Catchment views of Vardi Road. L: Timber harvest. R: aerial image. Intensity of harvest (black = cleared, mined and replanted, red = High, yellow = Medium, Green = Low). R: Aerial image showing mosaic of mined and rehabilitated areas – age of regeneration 0–40 years

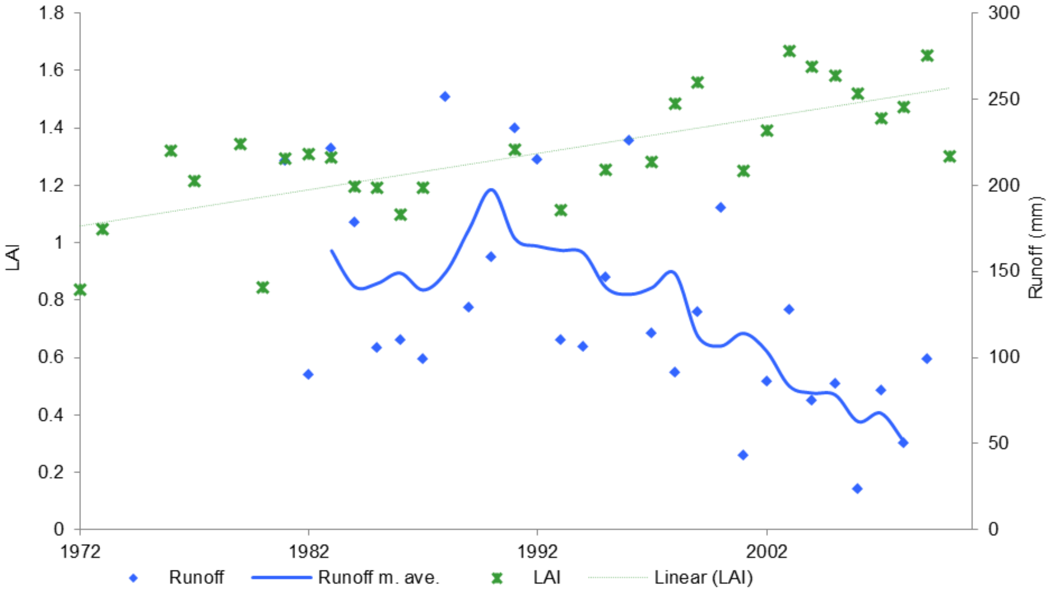

Figure A135 Annual streamflow, moving average, and leaf area index for Vardi Road

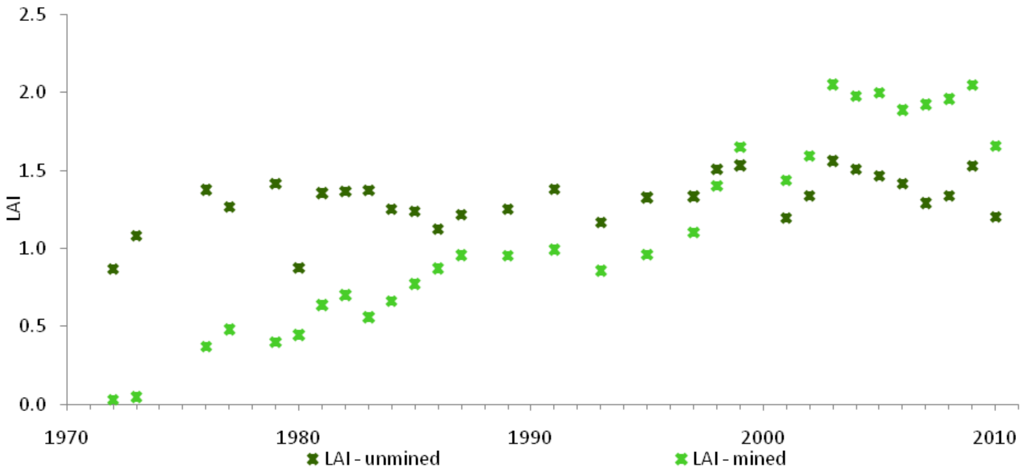

Figure A136 Leaf area index data shown separately for mined and unmined parts of Vardi Road catchment

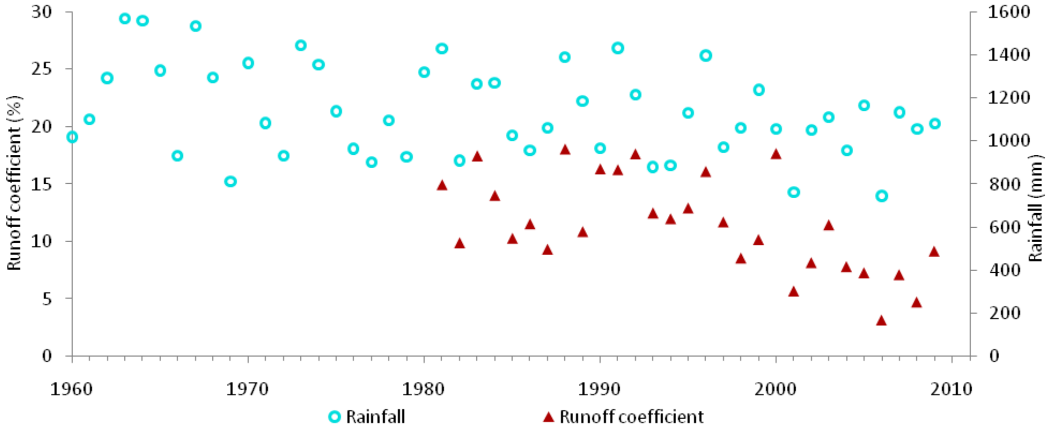

Figure A137 Annual rainfall and runoff coefficient for Vardi Road catchment

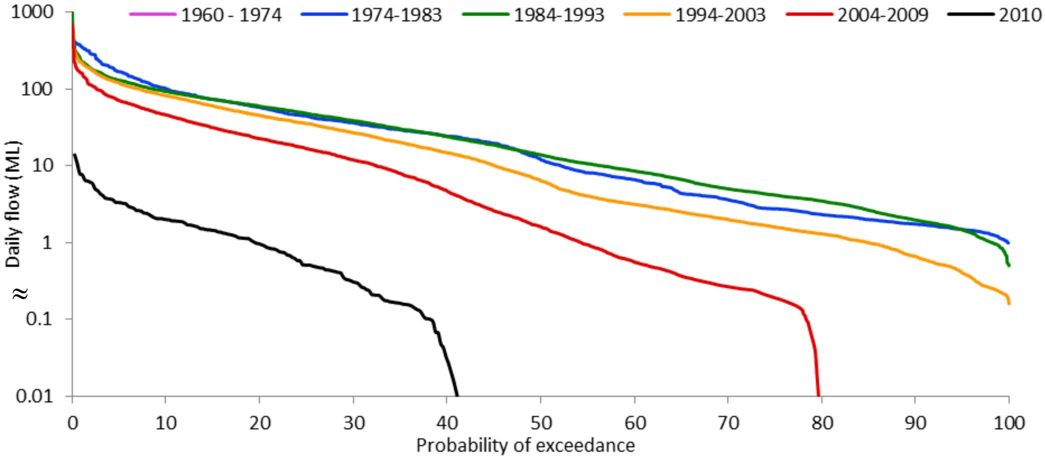

Figure A138 Flow duration curves for Vardi Road catchment showing shift from perennial to intermittent flow, and progressive declines in flows throughout the year.

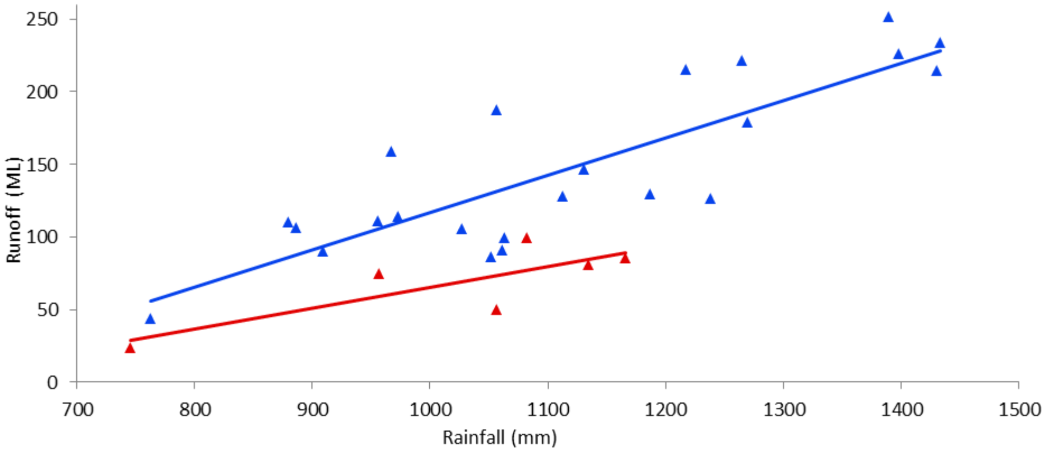

Figure A139 Annual runoff plotted by annual streamflow for Vardi Road, showing a progressive decline in the runoff observed per unit rainfall received

Waterfall Gully Mount Curtis (Canning – Swan River basin) 616023

PDWSA. Perennial stream. Trends in runoff coefficient mirror fluctuating and then declining trends in estimated groundwater storage, and the volume of streamflow per unit of rainfall has successively declined.

Flow duration curves show a decline in flow volumes across the year for the current FMP, and variations in flow volumes prior to that, reflecting climatic trends.

Unmined control catchment for Seldom Seen and More Seldom Seen bauxite mining and rehabilitation trial. Removed from primary catchments list due to clearing and 50% outside of DEC tenure.

Assessment	Supplementary catchment
Size & location	9 km^2 (small); 32.20°S, 116.10°E
Av. rainfall	1035 mm/a for 1975-2008
Geomorphology	Archaean granulite and migmatite; high-grade metamorphic rock.
Tenure	Approx. 50% Jarrahdale state forest, 35% DoW land, 12% Water Corporation Crown Reserve, 2% private freehold; 1% public roads.
Clearing	0% cleared within State forest, 1% cleared for agriculture in freehold.
Vegetation type	51% jarrah forest, 10% jarrah <30%, 2% shrub, herb and sedge land, 1% rocky outcrops
Timber harvest	96% harvested pre 1920s, 86% in the 1930s, 13% in the 1950s, 72% in the 1970s. No harvest activity since the 1970s
Fire history	98% spring burnt in 1999, no wildfire since 1995.
Dieback	Severely dieback-affected; this is likely to have increased streamflows (Davies et al. 1995; Bari & Ruprecht 2003). The majority of the catchment has been interpreted; it is mostly infected. 75% of the catchment has been interpreted for dieback and 84% of this was found to be infested.
Flow trends	Statistically significant declining trends and step-changes. Categorised as 'climate pattern present; streamflow decline observed'.
Salinity data	Discrete salinity data available. Data reliability code: 4 – fewer than 30 samples per year. Long-term salinity to 1982 140 mg/L, no significant trends (WRB 1984b).
Sallinity trends	During period 1966–94, stream salinity at mean flow decreased –may be associated with gradual fall of groundwater levels due to lower rainfall conditions in the last 20 years (Davies et al. 1995). In the current study, statistically significant declines and downward step-changes in flow-weighted mean salinity were observed, probably due to reduced groundwater discharge.

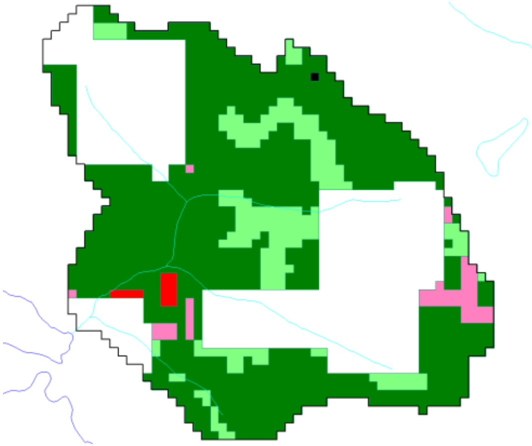

Figure A140 Waterfall Gully catchment views. L: Portions of the north-west of the catchment off FMP tenure have been cleared for development. R: Forest structure (within FMP tenure) indicates the majority of the catchment is jarrah forest (dark green), with areas of jarrah forest (light green), shrub, herb and sedge land (pink) and rocky outcrops (red).

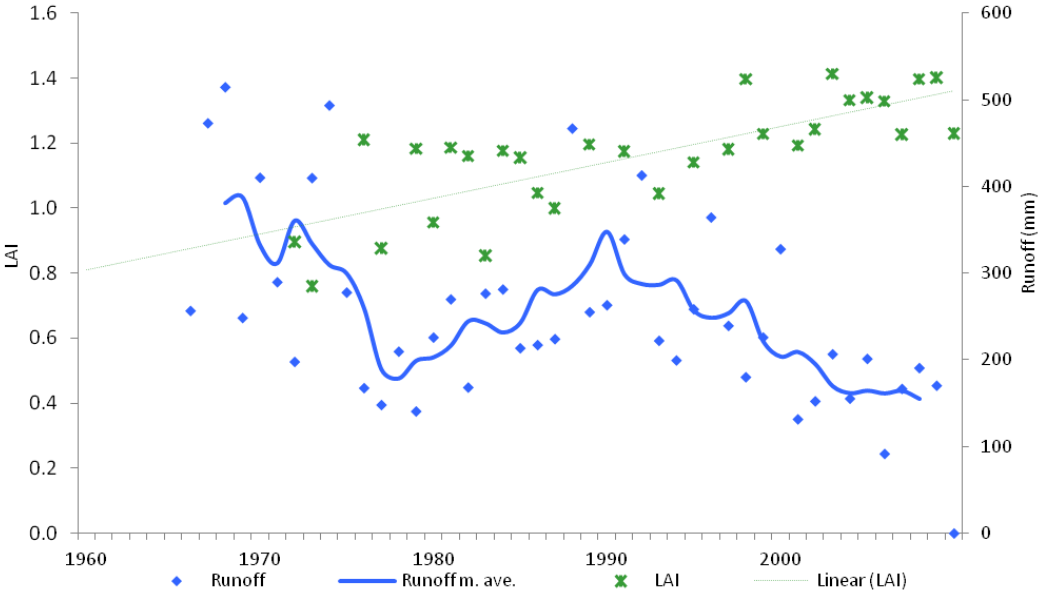

Figure A141 Annual streamflow, moving average, and leaf area index for Waterfall Gully

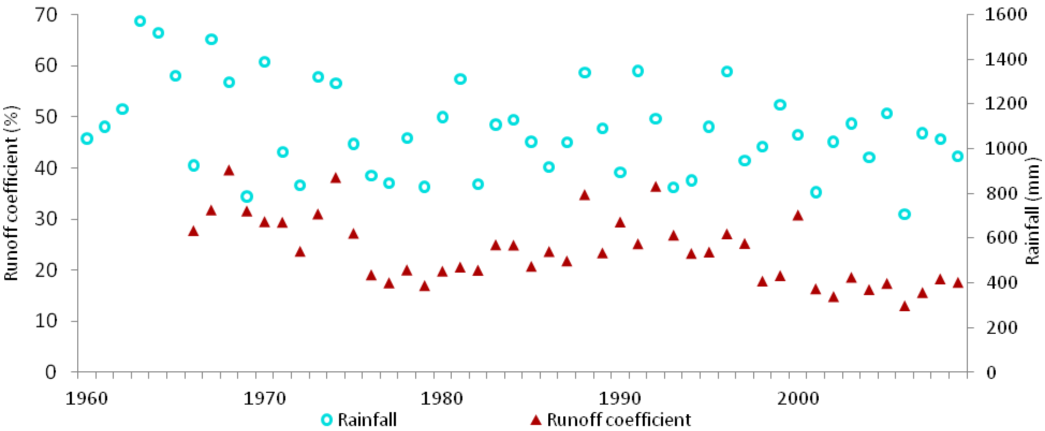

Figure A142 Annual rainfall and runoff coefficient for Waterfall Gully (Mt Curtis) catchment

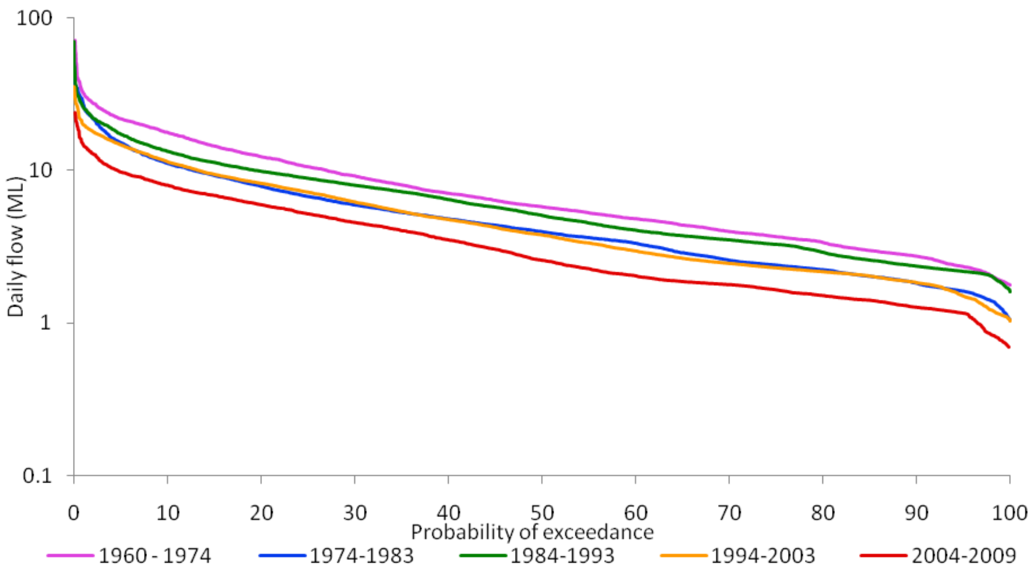

Figure A143 Flow duration curves for Waterfall Gully (Mt Curtis) catchment

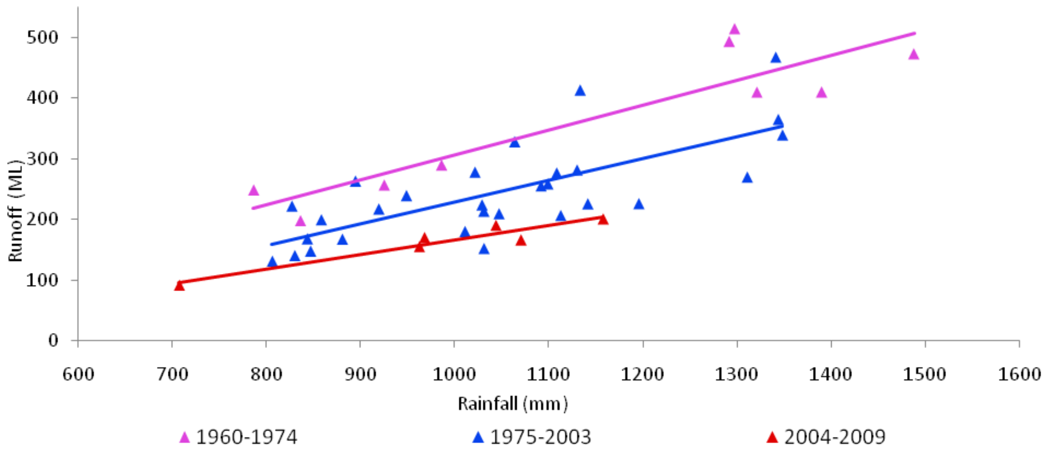

Figure A144 Annual runoff plotted by annual streamflow for Waterfall Gully, showing a progressive decline in the runoff observed per unit rainfall received

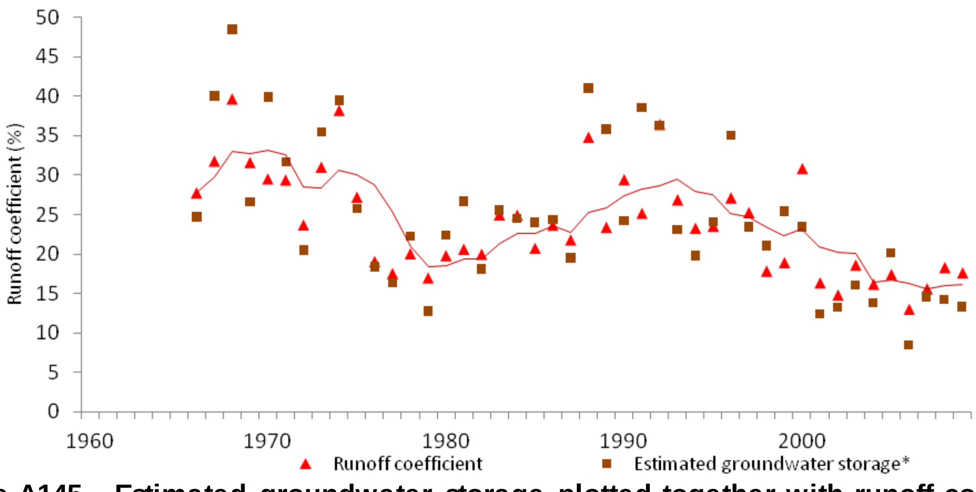

Figure A145 Estimated groundwater storage plotted together with runoff coefficient for Waterfall Gully

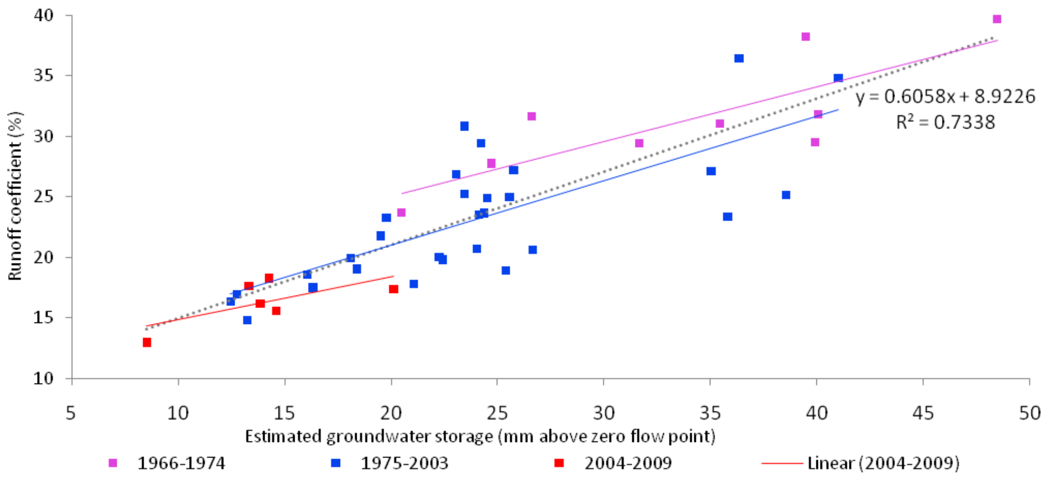

Figure A146 Scatter plot showing the relationship between estimated groundwater storage and runoff coefficient. The linear trends for the pre 1974, 1975–2003 and 2004–09 periods show a progressive decline in the runoff coefficient that exists for a given level of groundwater storage.

Wattle Block 606002 Weld River (Nornalup-Shannon River basin)

PDWSA. Intermittent stream. Predominantly old growth karri forest with high, and slightly increasing, LAI.

No significant trends in streamflow, slight decrease in runoff coefficient in recent decade. Flow regime shows little overall historical change, except a slight increase in medium to low flows during the late 80s and 90s.

80% tall Karri forest, long-term salinity 160 mg/L in 1982, with no discernible trends. Water very highly coloured (WRB 1984a).

Assessment	Primary catchment
Size & location	24 km^2 (medium); 34.66°S, 116.54°E
Av. rainfall	961 mm/a for 1975-2008
Geomorphology	Proterozoic origins. Granitoid gneiss, migmatite, quartzo-feldspathic gneisses in some places porphyritic and even-grained, minor metamorphic rock and quarzite, generally weathered to clay or clayey sand, often with a clay subsurface. Minor to major, local aquifers with some alluvium. Moderate relief, undulating plateau with incised mainstream valleys, bauxitic laterite soils over Archaean granitic and metamorphic rocks, swampy flats (WRB 1984a).
Tenure	98% Mount Frankland national park, 2% Lake Muir state forest
Clearing	<1% cleared
Vegetation type	60% karri, 32% jarrah forest, 4% shrub, herb and sedge land, 3% jarrah woodland
Timber harvest	4% harvested in 1960s, remainder old growth or non-forest.
Fire history	100% of catchment burnt in autumn 2004. No recent wildfire history.
Dieback	13% of this catchment has been interpreted for dieback presence; 18% of this was found to be infested.

Flow trends	Climate pattern dominant (i.e. streamflow reflects rainfall variations); no overall streamflow decline evident.
Salinity data	Insufficient recent data to include in current analysis. Data reliability code: 5 (Mostly continuous measurements with very large estimated gaps (>3 months) or fewer than 6 discrete samples per year or data estimated from flow)

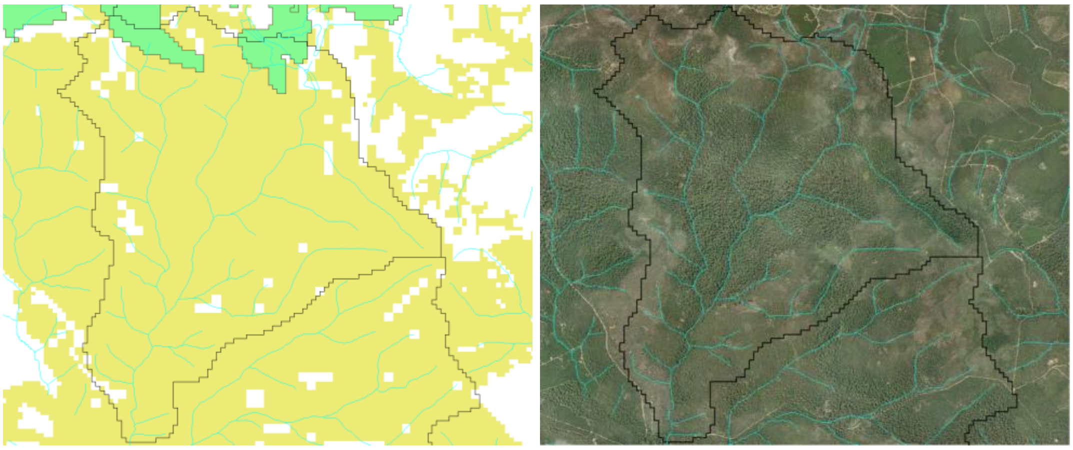

Figure A147 Wattle Block catchment views. L: Old growth areas shown in yellow, green area on northern divide harvested in '60s, white areas are rocky outcrop or shrub, herb and sedge land. R: Aerial photograph showing karri vegetation in valleys and jarrah around catchment divide.

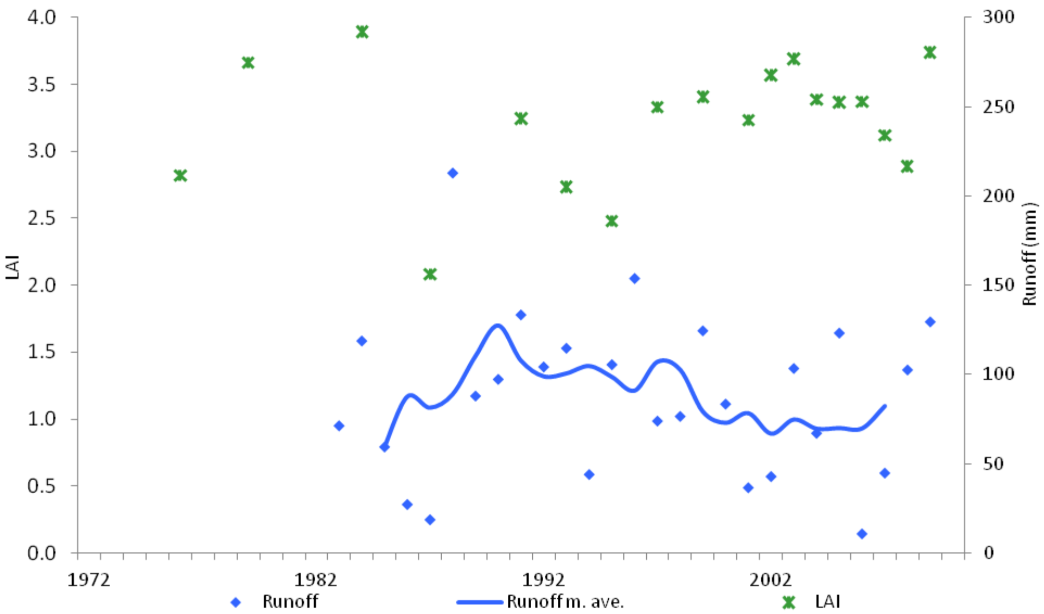

Figure A148 Annual streamflow, moving average, and leaf area index for Wattle Block

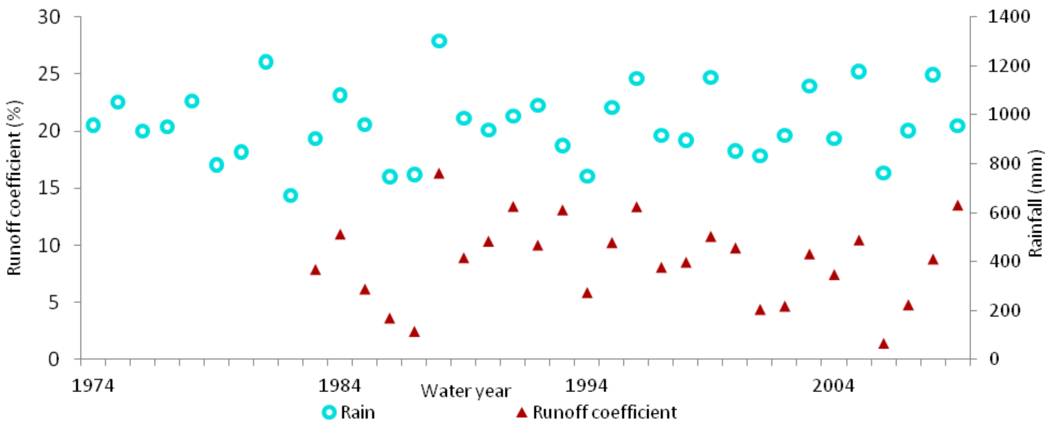

Figure A149 Annual rainfall and runoff coefficient for Wattle block catchment

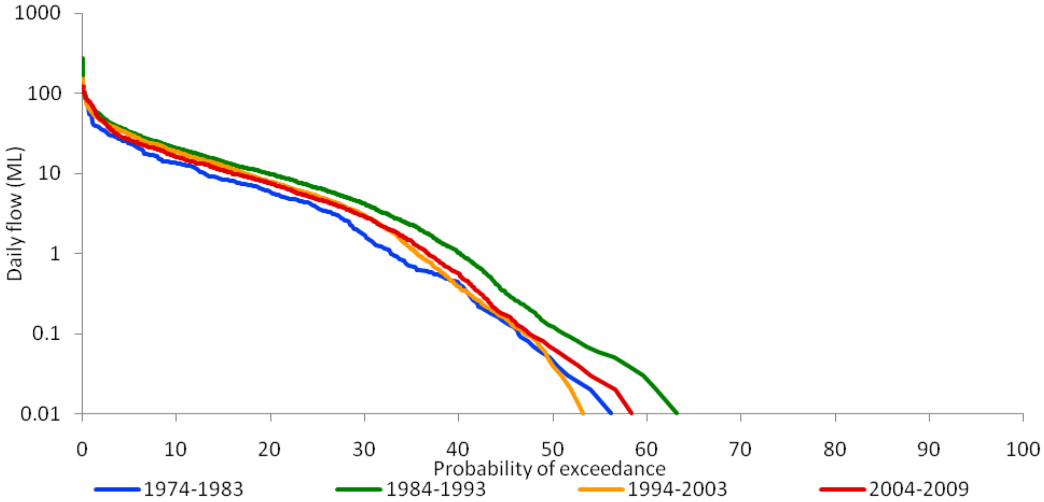

Figure A150 Flow duration curves for Wattle Block catchment

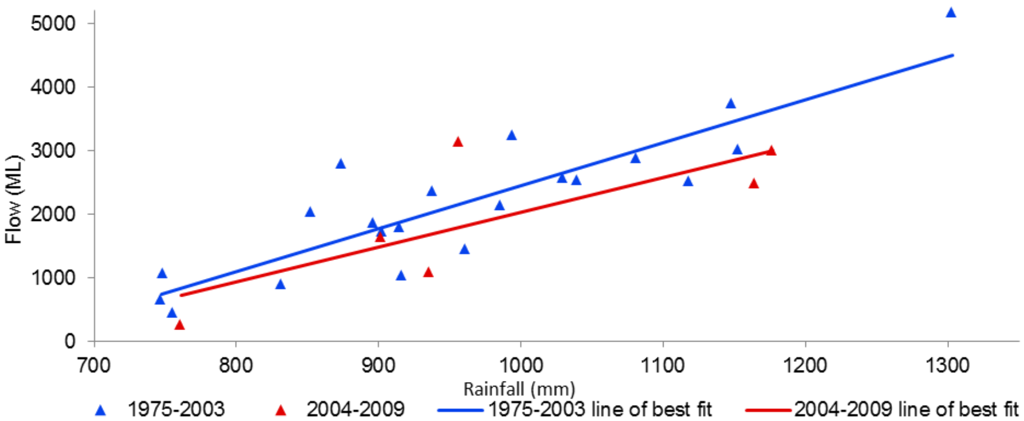

Figure A151 Annual runoff plotted by annual streamflow for Wattle Block

Whicher Range Margaret River Nth (Busselton Coast basin) 610008

PDWSA Priority 1. Intermittent stream. Predominantly jarrah forest. Extensive harvest history, but no harvests in the last 25 years. LAI values rebound quickly after harvest and major burns, and have increased over last 20 years. Prior to mid 1990s, drying climate may have been offset by forest harvesting, with 55% of the catchment harvested in the 1980s, and increasing runoff coefficients till 1999. There has been no harvesting since 1986, and the vegetation coverage has subsequently increased, followed by slight, insignificant, decreases in streamflow. Rainfall-runoff relationships have remained remarkably constant. 2010 was very dry.

Data missing from 2000-2005 due to temporary station closure. Key water Management area, Yarragadee SW/GW interaction zone, wetlands affected by abstraction, regionally significant, strategic in consideration of Whicher Plan.

Assessment	Primary catchment
Size & location	15 km^2 (medium); 34.66°S, 116.54°E
Av. rainfall	878 mm/a for 1975-2008
Geomorphology	Cainozoic, quaternary and early Pleistocene laterite and associated quartz sand.
Tenure	91% Millbrook state forest (crown reserve), 9% Whicher national park
Clearing	0% cleared
Vegetation type	92% jarrah forest, 5% jarrah woodland, 3% pine plantations.
Timber harvest	84% harvested in 1940s, 32% in 1950s, 30% in 1960s, 55% in 1980s. Last sawlog harvests were at low intensity over 31% of catchment area in 1985 and 17% of catchment area in 1986.
Fire history	Spring burn in 1978 (4%), 2001 (7%) & 2005 (87%). 2% autumn burn in 1998. 80% burnt December 2005.
Dieback	All of the 32% of the catchment which has been interpreted is infested.
Flow trends	No trends or declines have been observed for this catchment. Unusual similarity in rainfall-runoff relationship over time in this catchment: more investigation would be required to understand why. Categorised as ‘further investigation required’.
Salinity data	Insufficient recent data to include in current analysis. Data reliability code: 5 (fewer than 6 discrete samples per year or data estimated from flow). Av. salinity 1977–82 201 mg/L (WRB 1984a); 1983–92: 160 mg/L; 1993–2002: 160mg/L. Salt input bit higher than output – catchment may be accumulating salt (Mayer et al. 2005).

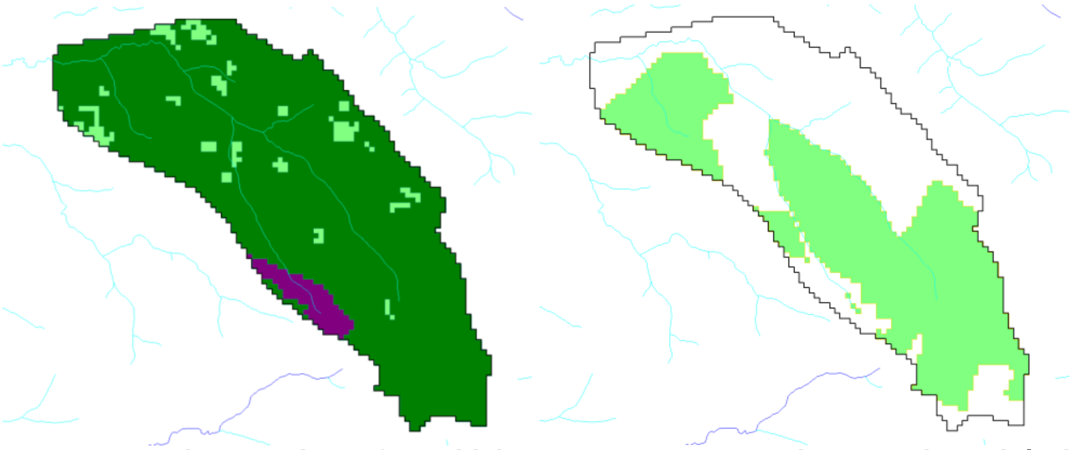

Figure A152 Catchment views for Whicher range. L: Vegetation type is mainly jarrah woodland (dark green), softwood plantation is purple and jarrah woodland (light green). R: Map showing intensity of harvest on areas harvested since 1980.

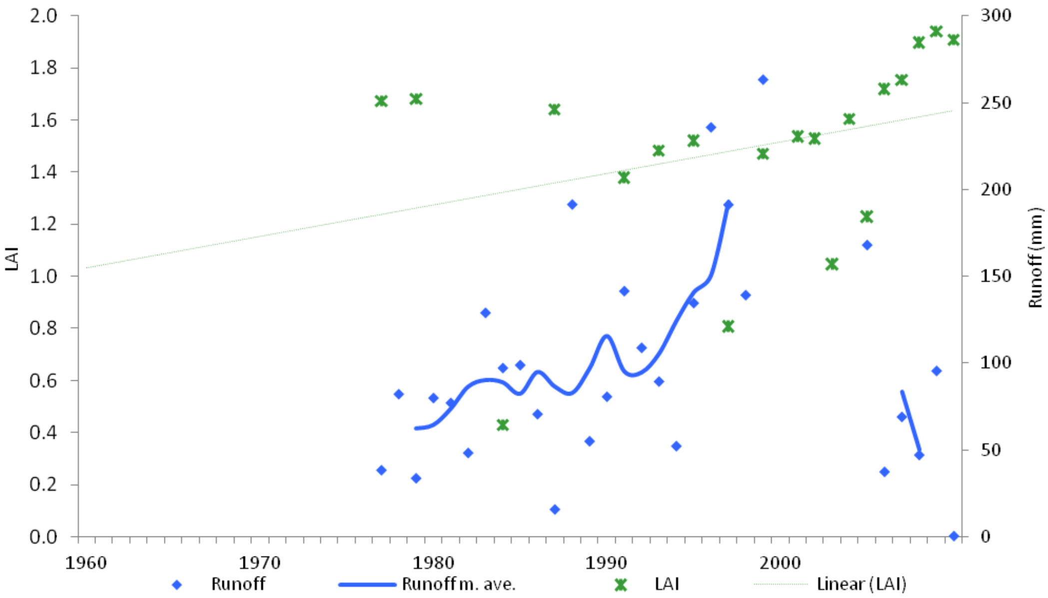

Figure A153 Annual streamflow, moving average, and leaf area index for Whicher Range

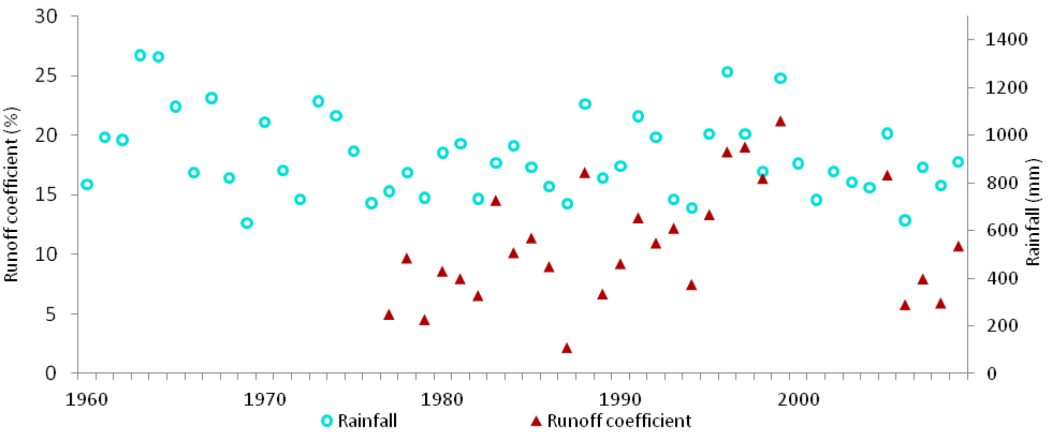

Figure A154 Annual rainfall and runoff coefficient for Which Range catchment

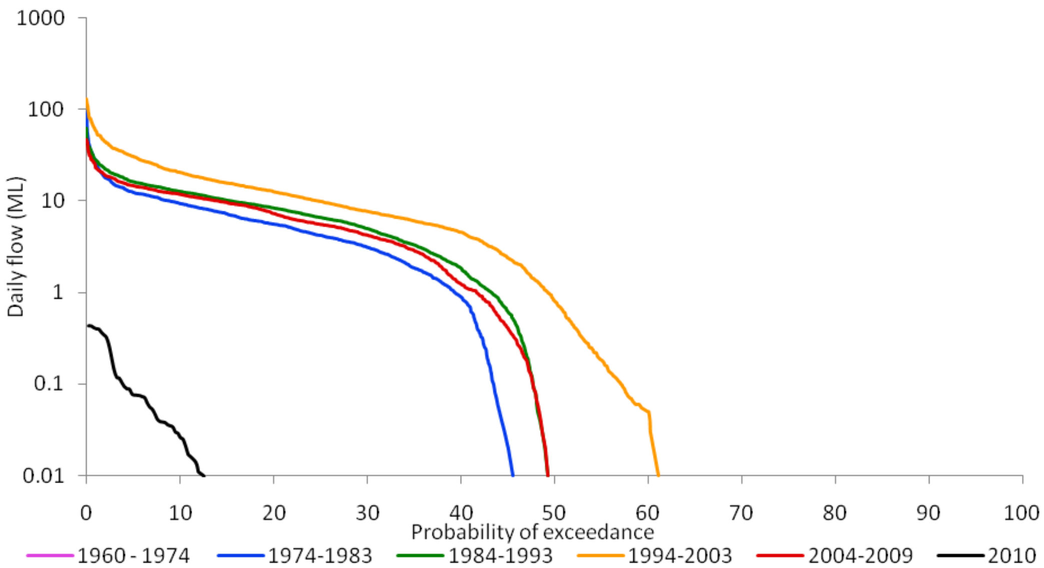

Figure A155 Flow duration curves for Whicher range catchment

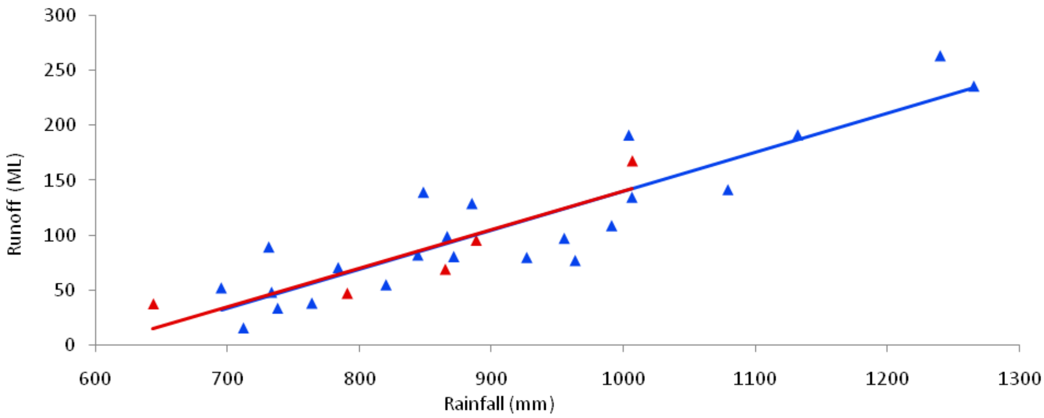

Figure A156 Annual runoff plotted by annual streamflow for Whicher Range, showing an unusually stability in the amount of runoff observed per unit of rain received

Worsley Hamilton River (Collie River basin) 612004

PDWSA. Predominantly intermittent stream, with some perennial flows in the 70s to early 90s.

Some softwood plantations, established as land-use research catchment (forest to pines experiment).

Assessment	Primary catchment
Size & location	32 km^2 (medium); 33.28°S, 116.06°E
Av. rainfall	972 mm/a for 1975-2008
Geomorphology	Low relief, undulating plateau, bauxitic lateritic soils over Archaean granitic rocks. Mixed geology: Colluvium, including valley-fill deposits, variably lateritized and podsolised; Laterite - chiefly massive, but includes overlying pisolithic gravel and minor lateritized sand; and old alluvial deposits, strongly lateritized in part;

	Conglomerate, sand and clay.
Tenure	88% State forest, 12% freehold
Clearing	2% on DPaW plus approx. 4.2% (140 ha) on private land = 6% cleared.
Vegetation type	81% jarrah >30% crown cover, 4% jarrah <30% crown cover, 1% exotic species, 1% shrub, herb and sedgeland.
Timber harvest	68% harvested in the 1930s, 15% in the 1940s, 4% in the 1950s, 3% in the 1960s, 31% in the 1970s, 56% in the 1980s. All harvesting in the 1980s was at low intensity. No harvesting since the 1980s.
Fire history	Minimal recorded burning from the 1960s to 1996. 30% spring burnt in 1996, 57% spring burnt in 2005.
Dieback	Interpretation has been conducted on a quarter of the catchment; 92% of the area interpreted was infected with dieback.
Flow trends	Non-significant streamflow declines observed. Classified as 'climate pattern dominant (i.e. streamflows follow rainfall variation), streamflow decline observed'.
Salinity data	Insufficient recent data to include in current analysis. Data reliability code: 5 (fewer than 6 discrete samples per year or data estimated from flow). Av. TSS to 1982 was 208 mg/L (WRB 1984a).

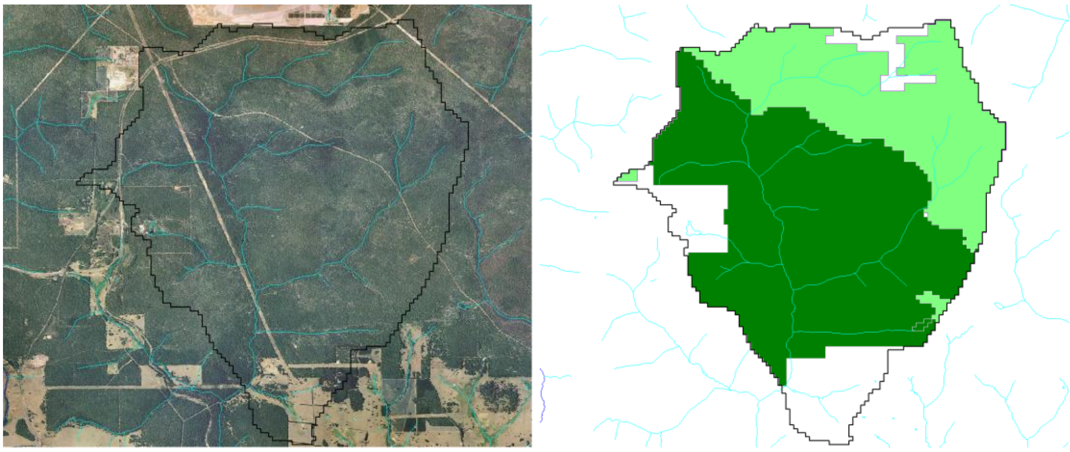

Figure A157 Catchment views for Worsley. L: Aerial photo showing cleared portion of private land to the south of the catchment. R: Map showing that almost all DPaW managed land within the catchment was harvested (at low intensity) in the 1970s (light green) or 1980s (dark green).

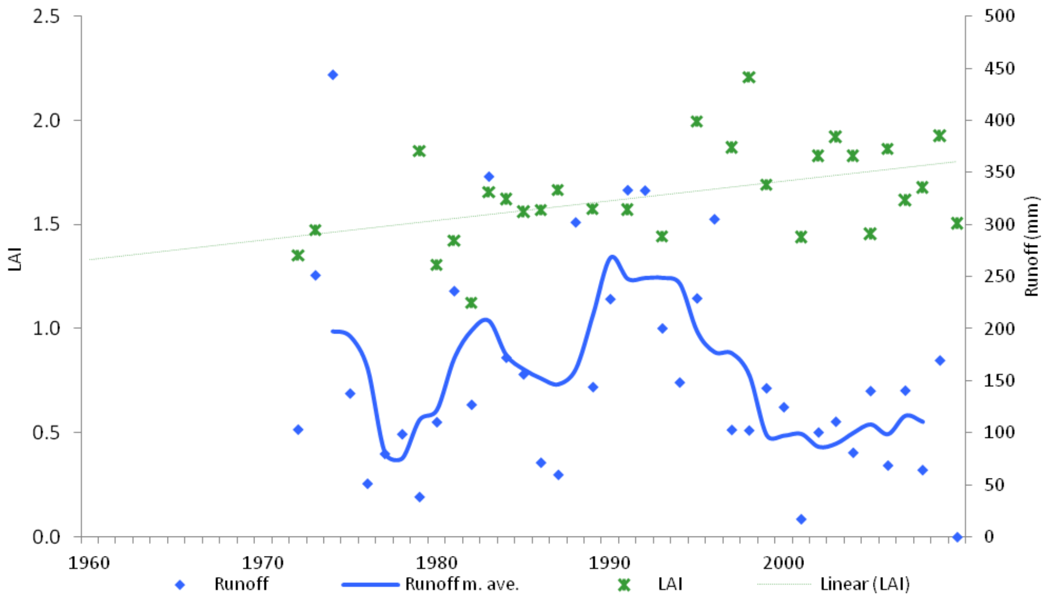

Figure A158 Annual streamflow, moving average, and leaf area index for Worsley catchment

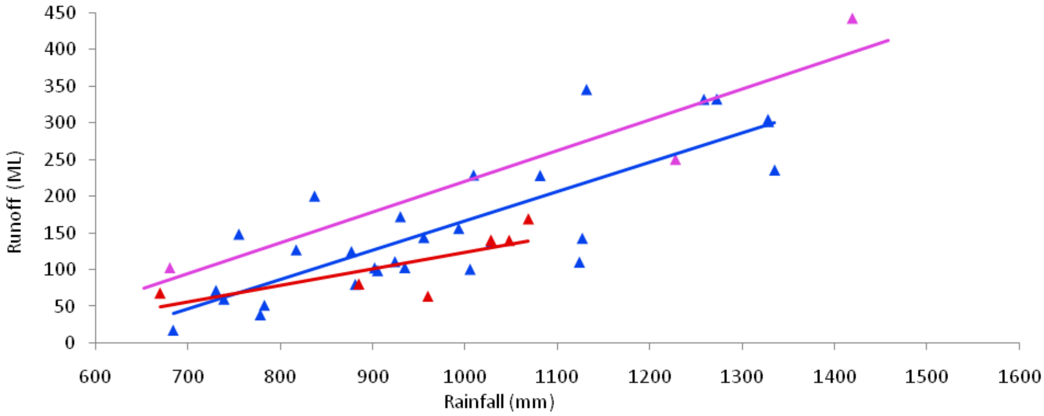

Figure A159 Annual runoff plotted by annual streamflow for Worsley catchment

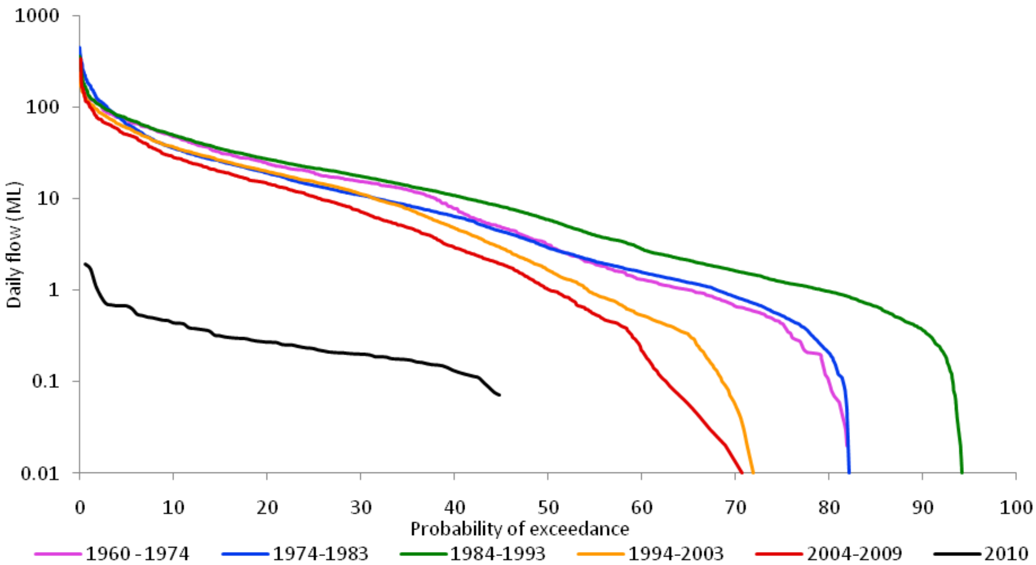

Figure A160 Flow duration curves for Worsley catchment

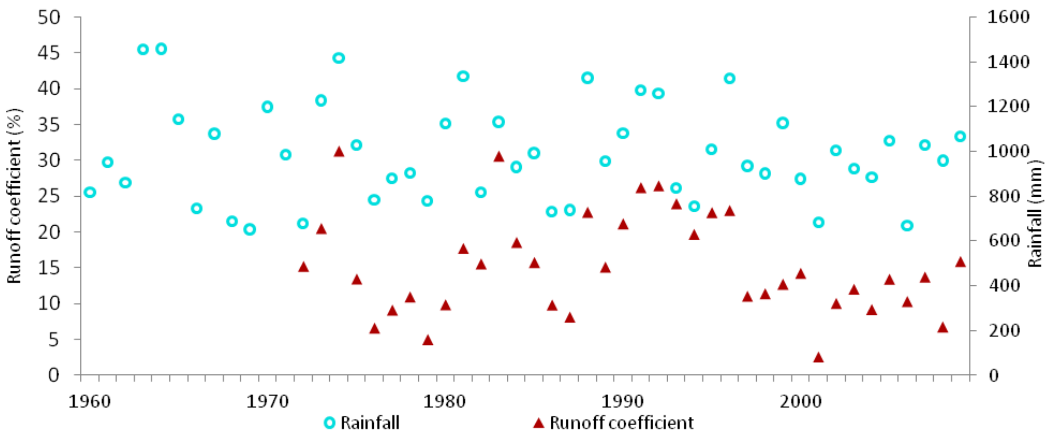

Figure A161 Annual runoff plotted by annual streamflow for Worsley catchment

Yarragil Formation Yarragil Brook (Murray River basin) 614044

Intermittent stream. Predominantly dieback-free jarrah forest with a regular harvest history; intensively harvested in 1990s and 2000s, with decreasing LAIs. Strong declines in streamflow, runoff coefficient, and flow duration, despite intensive silviculture. Groundwater declines described by Kinal and Stoneman (2011). Intermediate rainfall zone.

Contains nested experimental catchments for thinning trials:

- **4X:** Control in 1980s, standard thinning treatment (–30%) in early 2001; Kinal & Stoneman 2011
- **4L:** Thinned twice. First thinned in 1983 such that 20% of canopy cover was retained with basal area reduced from 35 to 11 m²/ha – a reduction of 60–70% (Stoneman & Schofield 1989; Moulds et al. 1994; Bari & Ruprecht 2003). Compared to the control 4X, groundwater levels at 4L rose by 4.4 m in the valley area. The av. pre-treatment streamflow for 4X was 3.8 mm and during the post-treatment period av. streamflow increase was more than 15-fold to 55 mm. The highest streamflow (95 mm or 11% of rainfall) was observed approx. nine years after treatment. The post-treatment annual streamflow was still elevated 15 years after treatment. These results emphasise the importance of ongoing management to sustain water yields (Bari & Ruprecht 2003).
- **6C:** Intensively thinned in 2001 (Kinal & Stoneman 2011).

Assessment	Primary catchment
Size & location	73.9 km² (medium); 32.82° S, 116.23°E
Av. rainfall	945 mm/a for 1975-2008
Geomorphology	Low to moderate relief; undulating to dissected plateau, lateritic soils over Archaean granitic and gneissic rocks.
Tenure	98% state forest, 2% conservation park
Clearing	1% cleared
Vegetation type	92% jarrah forest, 5% jarrah woodland, 2% exotic species (hardwood), 1% shrub, herb & sedge land, 1% cleared
Timber harvest	5% old growth. Regular history of timber harvest – 54% pre 1920s, 22% in

	1920s, 44% in 1930s, 18% in 1940s, 11% in 1950s, 39% in 1990s, 31% in 2000s.
Fire history	15% spring 1993, 8% spring 97, 18% spring 1999, 6% autumn 2000, 27% spring 2002, 9% autumn 2007. No recent wildfire history.
Dieback	The majority of the catchment is free of dieback.
Flow trends	Significant decreasing trend since 1975; average runoff of current FMP is significantly lower than 1975–2003 mean runoff. Decline in flow regime observed in flow duration curve. Categorised as 'climate pattern present, streamflow decline observed'.
Salinity data	Insufficient recent data to include in current analysis. Data reliability code: 5 (fewer than 6 discrete samples per year or data estimated from flow). Av. TSS 410 mg/L to 1982 (WRB 1984b).

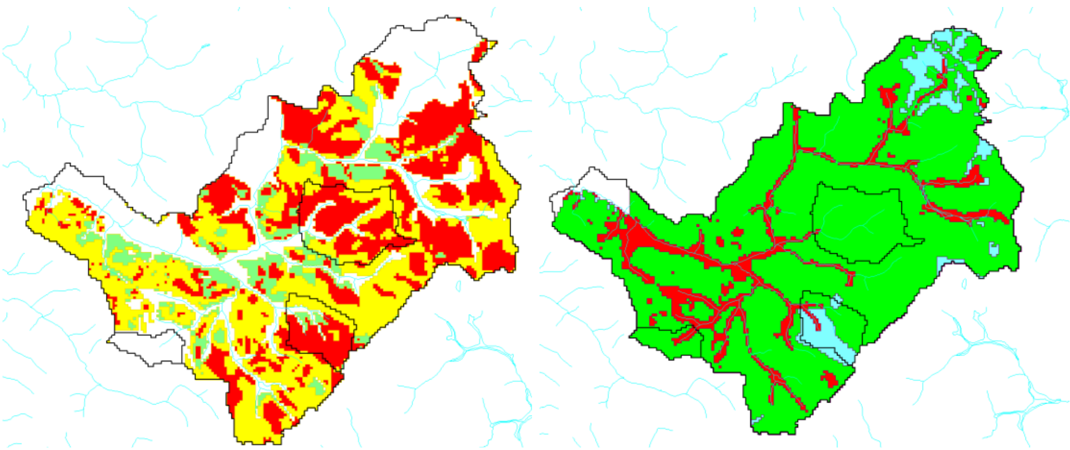

Figure A162 Yarragil catchment views. L – Intensity of harvest since 1990 showing a range of high (red), medium (yellow) and low (green) intensity. R – Dieback status showing mostly dieback free (green), although the streamlines are mostly infected (red = dieback present) and some areas (blue) are uninterpretable.

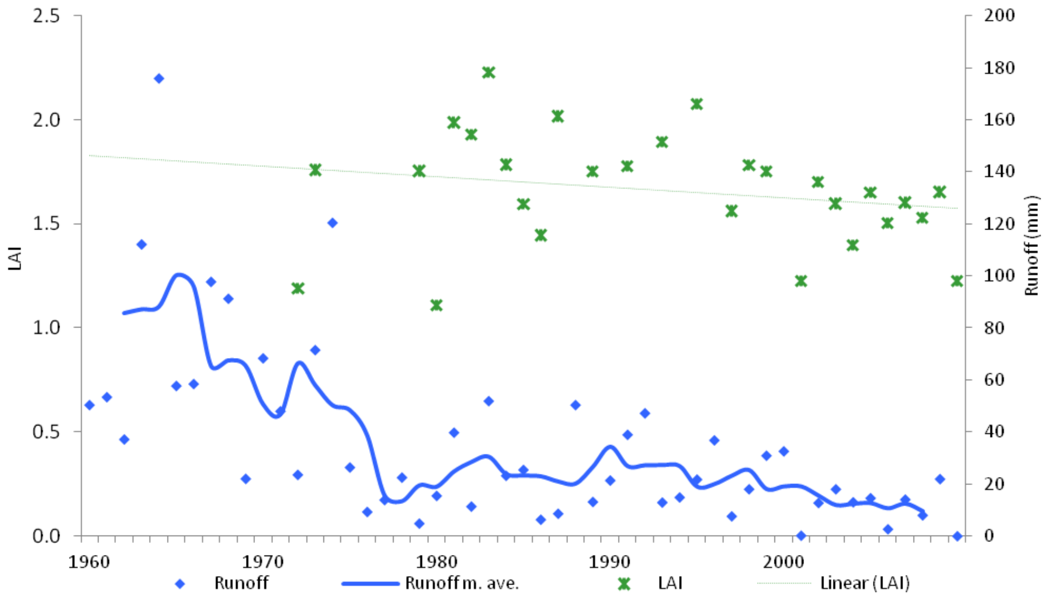

Figure A163 Annual streamflow, moving average, and leaf area index for Yarragil catchment

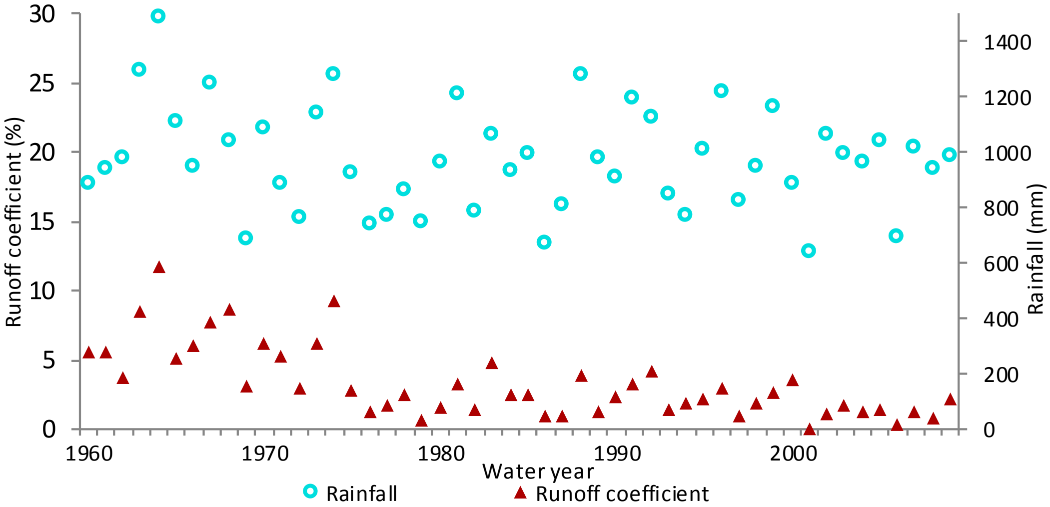

Figure A164 Annual rainfall and runoff coefficient for Yarragil catchment

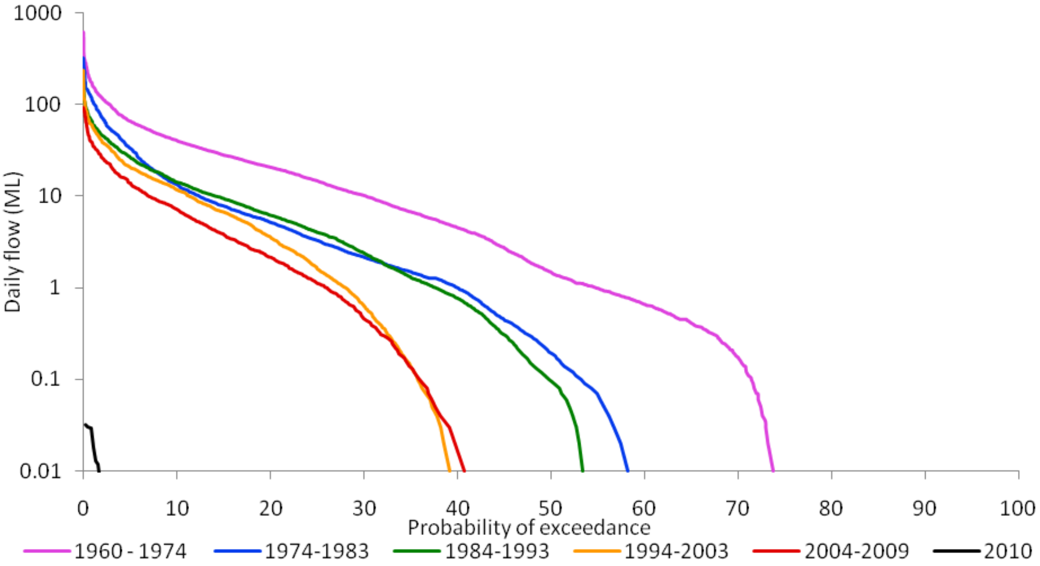

Figure A165 Flow duration curves for Yarragil catchment

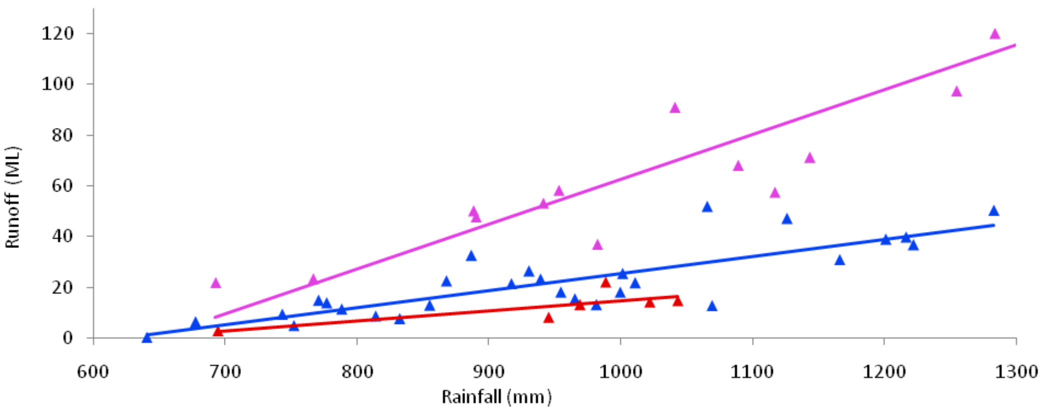

Figure A166 Annual runoff plotted by annual streamflow for Yarragil catchment

Appendix B South-west salinity rating relationship

Three linear relationships between salinity (total dissolved solids) and conductance have been derived for streams of the south-west of Western Australia, for three ranges of conductance. They are:

TDS = 5.0728EC+10 for conductances below 261.

TDS = 5.8893EC – 203.12 for conductances between 261 and 1707.

TDS = 7.82EC – 3498.7 for conductances greater than 1707.

This rating curve was generated by the Water Resources Section of the Public Works Department in the early 1980s. Information provided by Michael O'Malley, Water Information and Modelling, Department of Water 2009).

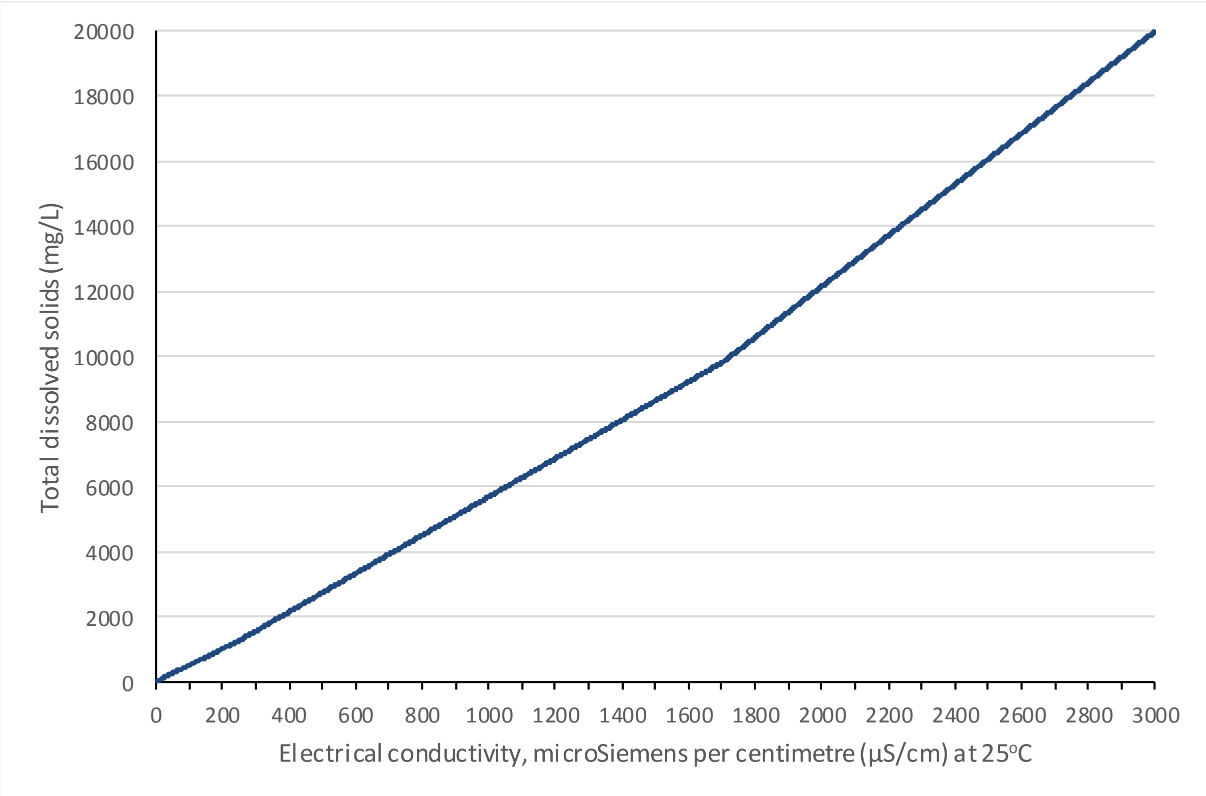

Figure B1 South-west salinity rating curve showing the relationship between electrical conductivity and salinity (expressed as total dissolved solids) used to calculate salinity for the salinity study catchments.