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

Surface water hydrology of the lower Collie catchment

Supporting information for the lower Collie surface water allocation plan

Looking after all our water needs

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Department of Water

Surface water hydrology series

Report no. HY35

April 2011

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April 2011

ISSN 1836-9626 (print)
ISSN 1836-9634 (online)

ISBN 978-1-921789-73-1 (print)
ISBN 978-1-921789-74-8 (online)

Acknowledgements

The Department of Water would like to thank the following for their contribution to this publication. Michael Braccia (technical work and author), Jacqueline Durrant (technical work and author), Ian Loh (technical advice) and Mark Pearcey (technical advice).

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Summary

This report discusses the surface water hydrology of the lower Collie catchment area and has been used to assist with the development of a surface water allocation plan. It includes work specifically requested by the Water Allocation Planning Branch for the development of their plan. The area covered by the plan has been divided into 24 resource areas at a scale suitable for water allocation purposes. Estimates of streamflow and sustainable yields have been determined for these areas.

Observed and modelled annual streamflows from 1975 to 2007 for a number of gauging stations within the lower Collie area are used to characterise the streamflow. Mean annual flow and minimum annual flow figures for the 1975 to 2007 period have been estimated for each of the resource areas.

Estimates of the average annual irrigation return were made for each gauging station and resource area that was influenced by the addition of irrigation return water from the Collie River irrigation channel into the river.

Plantations are currently a small proportion of the overall land use. The analysis shows that the current level of plantations does not have a significant impact on the surface water resources.

Sustainable diversion volumes are provided for the resource areas. These are a regional, hydrologic estimate of the sustainable yield. The volume of water able to be diverted in the minimum flow year is also shown.

Future climate scenarios centred on 2020 and 2030 were developed to quantify the possible future surface water resources of the lower Collie given the risk of a non-stationary climate to runoff and water availability. The analysis shows that the effect of all the future climate scenarios is towards reduced river flows with the percentage reduction in the minimum annual streamflow greater than the percentage reduction in the mean annual streamflow. The reduced flows result in less availability of surface water and the implications of this for streamflow and sustainable diversion volumes are also discussed.

1 Introduction

1.1 Structure of this report

The aim of this report is to present the hydrologic data needed to set allocation limits in the lower Collie surface water allocation plan area. The data is in the form of 'sustainable diversion volumes' providing 80% reliability of supply.

Two sets of figures have been produced, one based on the current climatic situation (Table 7) and the other based on future climate projections (Table 15). These tables have been combined in Table 16.

The structure of the report is described below.

Section 1	provides background information about the area under study.
Section 2	looks at the streamflow gauging network and analyses the data available from it.
Section 3	estimates sustainable diversion volumes based on the current climatic situation. The results are presented in Table 7.
Section 4	estimates sustainable diversion volumes based on projected future climatic situations. The results are presented in Table 15.
Section 5	summarises the overall results of the hydrologic study in a form that is suitable to be used in allocation planning. It contains Table 16.

1.2 Catchment description

The lower Collie catchment is located approximately 200 km south of Perth, and just north of Bunbury, and covers the western half of the Collie River Basin (Figure 1). The lower Collie catchment includes the catchments of the Wellesley and Brunswick rivers, as well as the Collie River catchment downstream of Wellington Dam. The watercourses within these catchments discharge via the Collie River into the Leschenault Estuary (Figure 2).

The watercourses within the Preston River catchment, including the Preston and Ferguson rivers, also discharge into the Leschenault Estuary but are outside the bounds of the lower Collie allocation planning area and so are not discussed here.

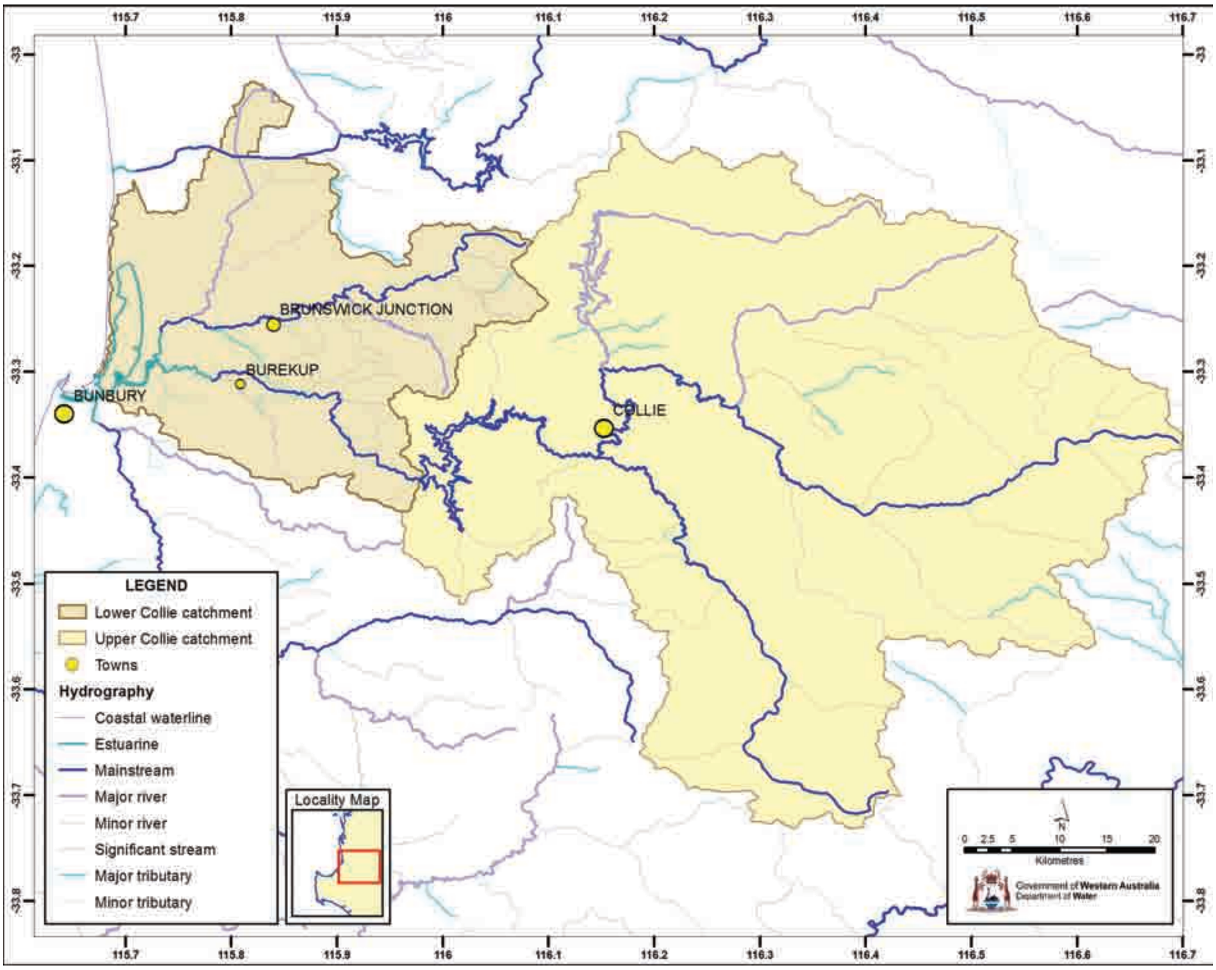


Figure 1 Location of the lower Collie catchment

Topography, geology and soils

About one-half of the lower Collie area lies on the Darling Scarp. There is a change in the geology where the Darling Scarp meets the Swan Coastal Plain with the South Western Highway corresponding with the location of the fault line. Elevations on the plain range from approximately 0 to 30 m AHD, increase to about 80 m AHD up the scarp and then gradually increase from west to east to around 400 m AHD.

The western half of the Swan Coastal Plain is characterised by sets of dune systems that are parallel to the coastline and correspond to different soil types (Weaving 1998). Lakes and wetlands commonly occur in the low-lying depressions between the dunes. The eastern half of the Swan Coastal Plain is flat alluvial plain which is typically poorly drained. As a result, a large portion of the watercourses, particularly the Wellesley River, have been heavily modified as part of an artificial drainage system to drain the Swan Coastal Plain, enabling its use for dairy farming and other forms of agriculture. These areas were previously palusplain wetlands, sumplands or floodplain areas.

The Darling Range is a lateritic plateau characterised by steep slopes and deeply incised valleys. These become broader to the east with the area consisting of lateritic, sandy soils to loamy, gravel soils with deep sand (Weaving 1998).

Water harvesting, land use and water quality

In the upper part of the catchments, the terrain is suitable for surface water storages. The Wellington Reservoir, Worsley Reservoir and Beela Dam are the main storages. There are also self-supply dams built directly on streams. As the topography and soil changes from the scarp to the plain, the suitability of the terrain for dam construction reduces and there is a greater reliance on abstraction from groundwater, direct pumping of surface water and the Harvey Water Irrigation Cooperative (Harvey Water) irrigation channel to obtain water.

Native vegetation occupies about 44% of the catchment and is mainly located in the upper reaches of the catchment on the Darling Plateau. Plantations currently occupy only 3% of the catchment. Worsley Alumina is located in the upper part of the Augustus River catchment, a tributary of the Brunswick River. Land use on the coastal plain includes cattle raising for beef and dairy, horticulture and viticulture. Kemerton industrial park is located on the coastal plain west of the Wellesley River. The town of Australind is located towards the coast and the town of Brunswick Junction is located at the base of the Darling Scarp.

Nutrient monitoring in the lower Collie catchment shows high levels of total nitrogen and total phosphorus, particularly in the lower Brunswick and Wellesley rivers. The poor water quality has led to eutrophication of the waterways and the occurrence of algal blooms and fish kills in the lower Collie and Brunswick rivers (Kelsey and Hall 2009, see Section 1.5).

Due to the low topography on the plain, the lower reaches of the Brunswick and Collie rivers are tidally influenced which causes saltwater intrusion in summer. The saltwater wedge can extend past the Australind Bypass bridge crossing the Brunswick River.

Water resources

The lower Collie River is regulated by Wellington Dam, which was constructed in 1933 to provide summer irrigation water to farm lands between Collie and Bunbury. Wellington Dam was last raised in 1961 to provide a total storage capacity of 186 GL. Outflow from Wellington Reservoir currently includes scour, spills and irrigation releases. The tributaries of Falcon Brook and Stones Brook contribute to the natural catchment downstream of Wellington Dam to Burekup Weir. Burekup Weir is about 10.5 km downstream of Wellington Dam and is the diversion point for the Collie River irrigation district.

The Harvey Water Irrigation Cooperative obtain irrigation water from the Wellington, Stirling and Harvey dams (Collie River and Harvey irrigation district). The Harvey irrigation district is piped and the southern end delivers water to part of the Wellesley catchment. The Collie River irrigation district supplies water to the remainder of the eastern coastal plain in the lower Collie area. Water is delivered via open concrete lined channels but piped under or over major watercourses. Historically, water has been released from the irrigation network into the Brunswick River, Henty Brook and Ferguson River.

Flaherty Brook, Henty Brook, Millars Creek and some minor tributaries contribute to the Collie River downstream of Burekup Weir. The catchment area of Collie River downstream of Wellington dam is 293 km^2 and the river discharges into the Leschenault Estuary at the town of Australind.

The Brunswick River has its headwaters in the scarp and receives contributions from several tributaries including the Ernest River, Lunenburgh River, Augustus River, Eluira Gully and Wellesley River before discharging into the Collie River. Beela Dam was constructed in 1938 and is a small water supply dam located in the centre of the catchment with a storage capacity of 0.02 GL. Beela Dam was decommissioned by the Water Corporation in 2004. Worsley Reservoir was constructed in 1982 on the Augustus River and has a capacity of 5.8 GL. The Brunswick River catchment, excluding the Wellesley River, has an area of 286 km^2.

The Wellesley River has a catchment area of 239 km^2 and joins with the Brunswick River about 1 km upstream of where the Australind Bypass Road crosses the Brunswick River. The Wellesley River is contained on the Swan Coastal Plain and as a result is heavily modified with irrigation supply and artificial drainage channels. Contributions are made to the Wellesley River from the Mangosteen Drain, Bear Drain, Wellesley River diversion and Mornington Creek.

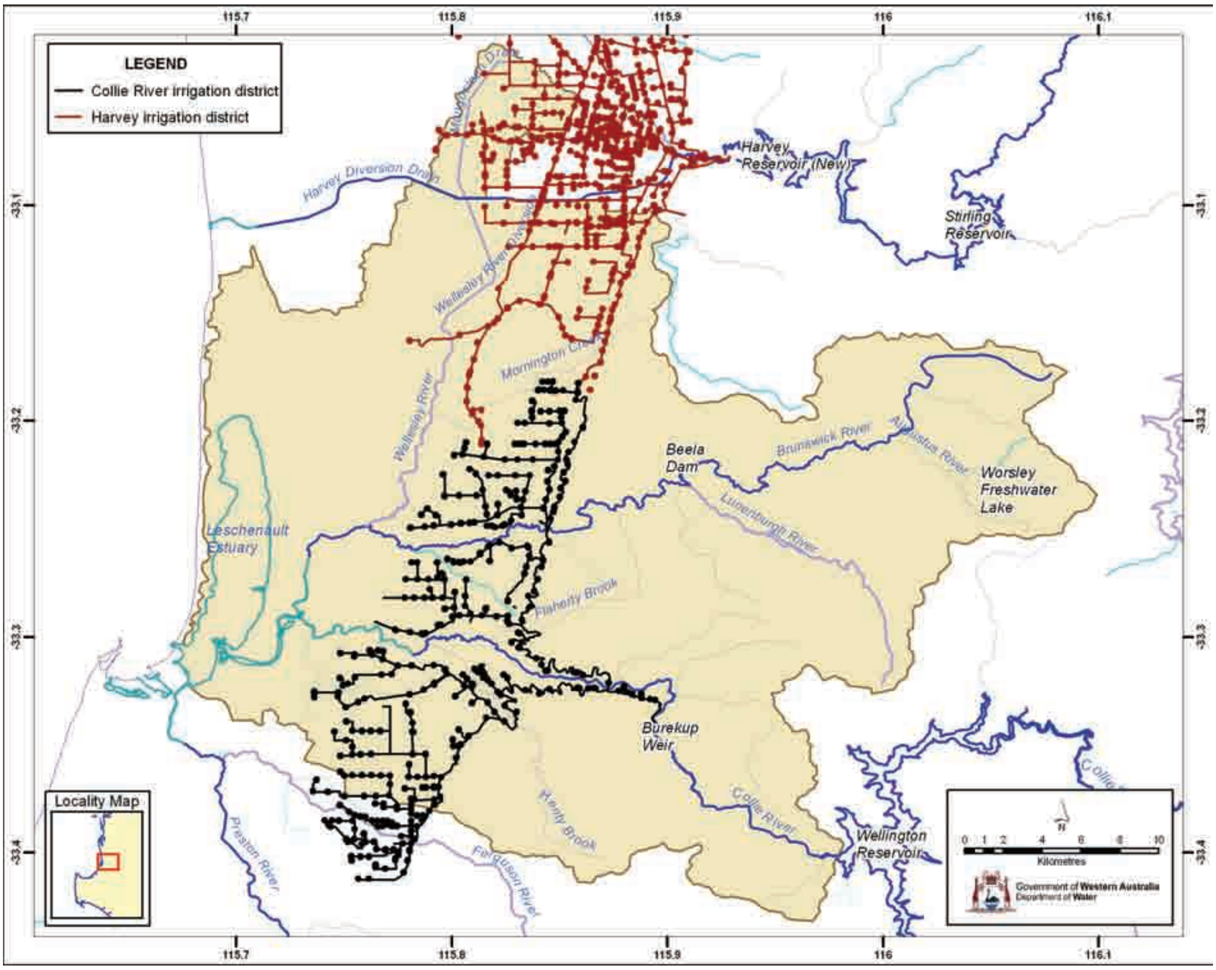


Figure 2 Water resources of the lower Collie catchment, including the Collie River and Harvey irrigation network

1.3 Subcatchment delineation

Sustainable diversion limits (SDLs) have been developed for the south-west of Western Australia (see Section 3). As part of the SDL project, catchments were defined on a hydrologic basis using the location of streamflow gauging stations, and then at a finer spatial scale that is practical for management (SKM 2008b). For the purpose of this report, these catchments have been called 'resource areas'.

There are 26 resource areas in the lower Collie catchment (Figure 3, Table 1). The area covered by the lower Collie surface water allocation plan excludes the Leschenault Estuary (two resource areas). This report outlines the regionalisation of estimates of mean annual flow, minimum annual flow and sustainable diversion limits to the 24 resource areas covered by the plan.

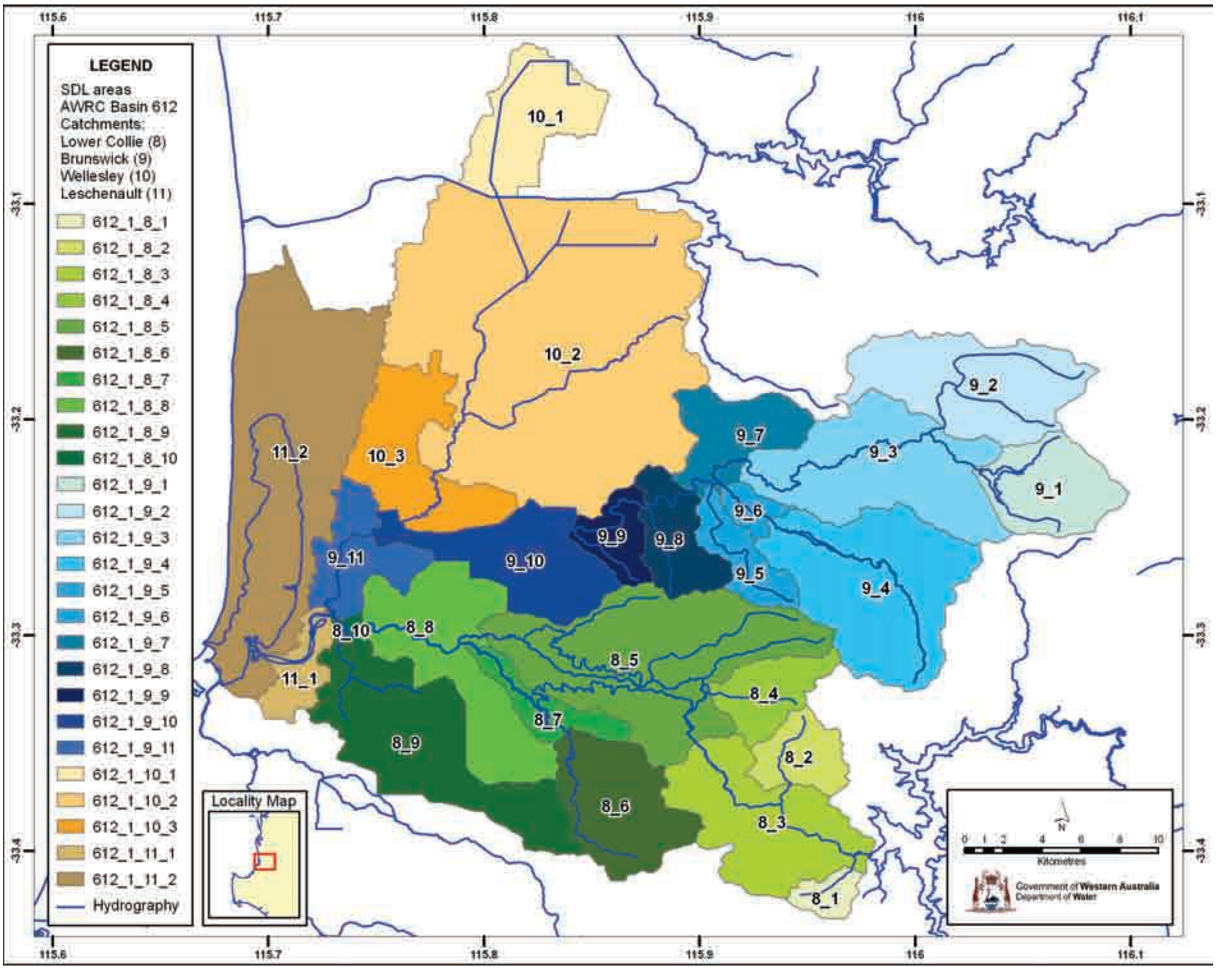


Figure 3 Resource areas in the lower Collie catchment

Table 1 Summary details of resource areas in the lower Collie catchment

Catchment	Resource area	Gauging station	Area km^2	Native vegetation %
Collie River	612_1_8_1	612012	5.5	100
	612_1_8_2	612005	13	100
	612_1_8_3	612006	41	99
	612_1_8_4		15	88
	612_1_8_5	612043	72	39
	612_1_8_6		30	54
	612_1_8_7		11	25
	612_1_8_8		43	7
	612_1_8_9		51	10
	612_1_8_10		1.4	16
Brunswick River	612_1_9_1	612024	23	33
	612_1_9_2		42	94
	612_1_9_3	612022	51	83
	612_1_9_4	612023	56	79
	612_1_9_5		12	22
	612_1_9_6		4.8	28
	612_1_9_7	612047	20	35
	612_1_9_8	612152	16	38
	612_1_9_9		11	34
	612_1_9_10	612032	32	13
	612_1_9_11		19	27
Wellesley River	612_1_10_1		28	11
	612_1_10_2	612039	178	25
	612_1_10_3		33	47
Leschenault Estuary	612_1_11_1		11	
	612_1_11_2		97	

1.4 Current climate

The lower Collie catchment has a temperate climate, with warm dry summers and cool wet winters (Bureau of Meteorology 2010) and is located in a high rainfall zone. Rainfall isohyets from 1975 to 2003 indicate that the average annual rainfall ranges from 750 mm, increasing to 970 mm, and then decreasing to 900 mm from west to east across the catchment. The area of increased rainfall is due to the orographic effect of the Darling Ranges approximately 15 km from the coast.

Rainfall in the catchment is typically derived from rain bearing low pressure systems and cold fronts crossing the coast in winter. However, high intensity summer storms do occur as a result of thunderstorms or rain from ex-tropical cyclones. For example, in January 1982 Tropical Cyclone Bruno decayed into a rain bearing depression and produced the second highest daily rainfall total, since records began in 1909, of 117 mm at Brunswick Junction.

Rainfall and evaporation records at three Bureau of Meteorology stations within the lower Collie catchment have been used to summarise the climate and rainfall data within the region. The stations are Wokalup (009642) located in the upper part of the Wellesley catchment, Brunswick Junction (009513) located at the Brunswick Junction town site and Roelands (009657) located along the Collie River (Figure 4).

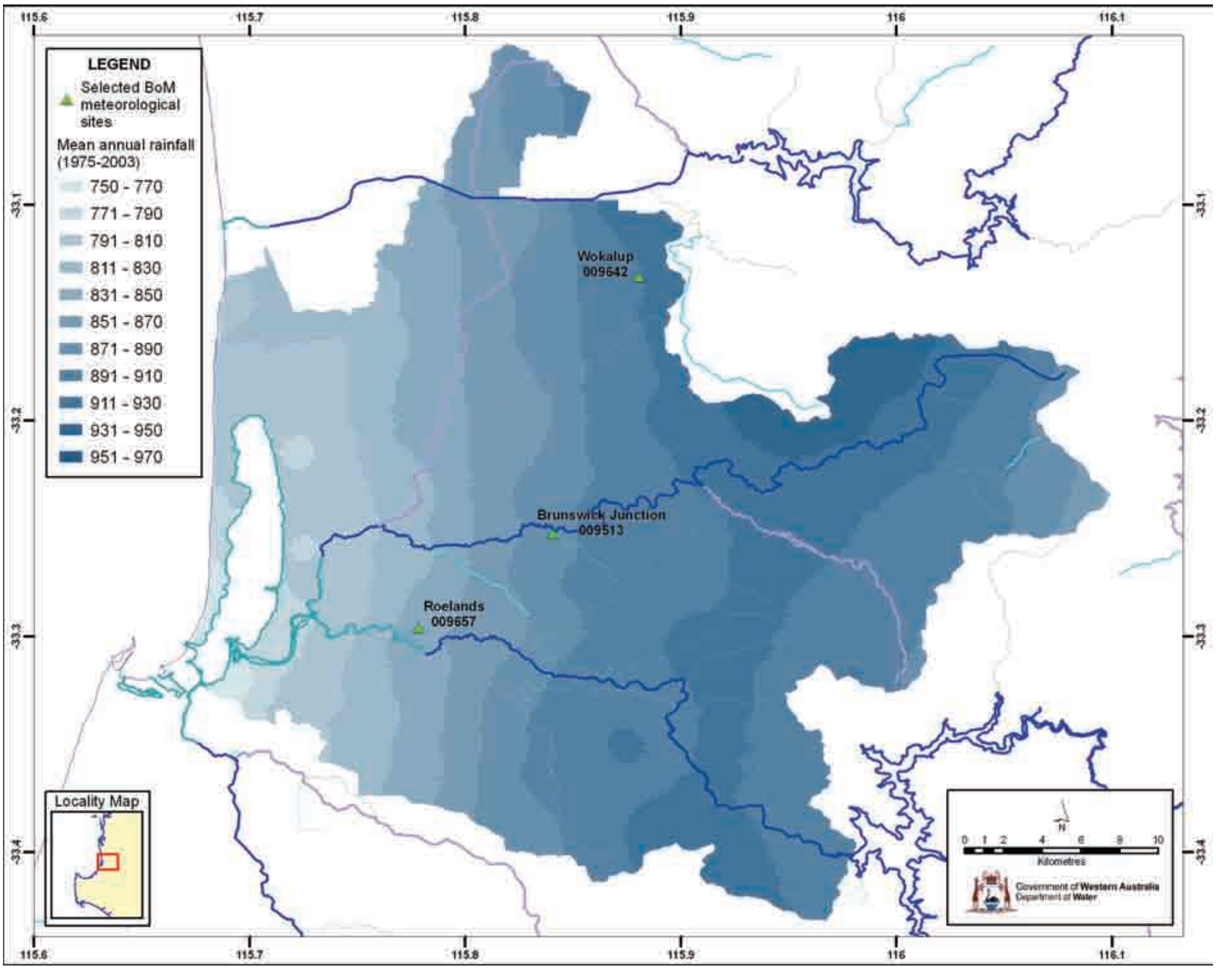
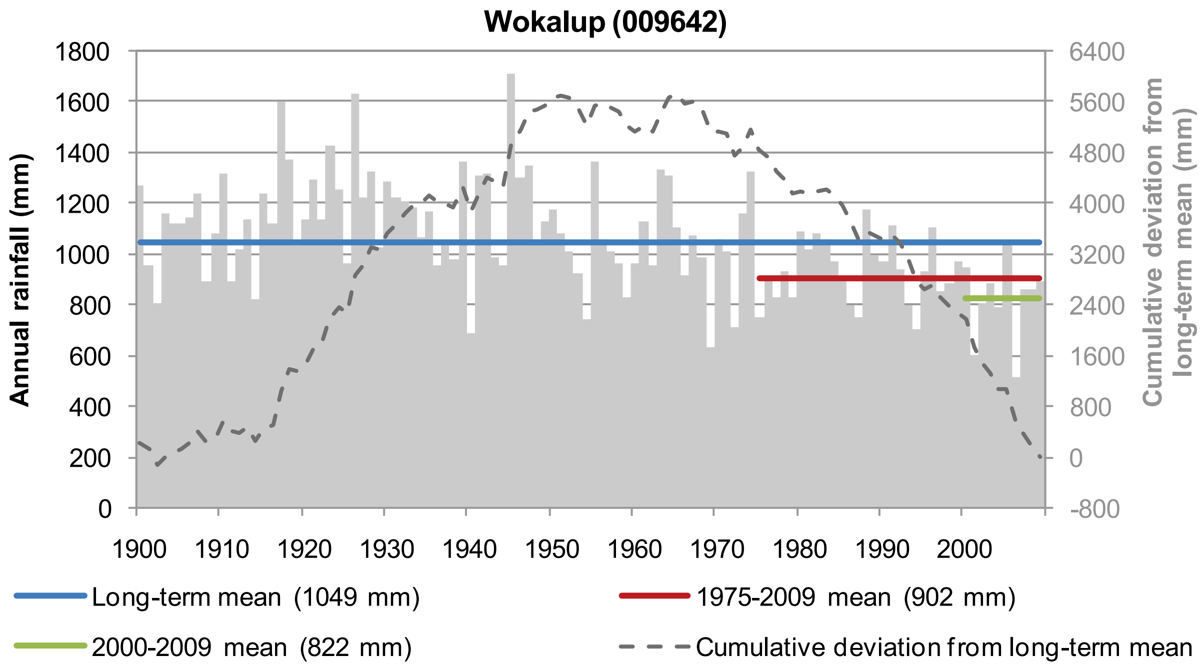
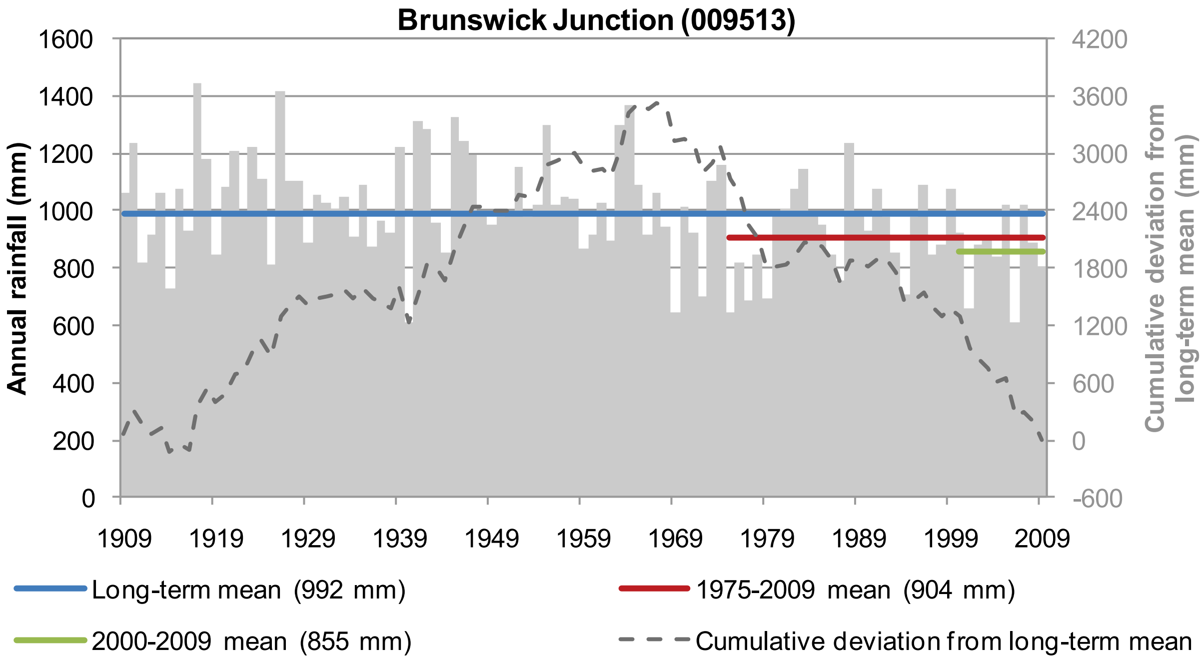


Figure 4 Rainfall isohyets and selected rainfall stations in the lower Collie catchment

Annual rainfall

Annual rainfall over the catchment is fairly consistent with the long-term mean annual total ranging from 1049 mm at Wokalup to 921 mm at Roelands (Figure 5). The coefficient of variation of annual rainfall for the three stations is 0.2 or less, indicating a low variability in annual rainfall. While the variability in annual totals is low there is an observed decreasing trend in the annual rainfall record. The long-term (1900–2009) and short-term (1975–2009) means are significantly different with the short-term mean ranging from 9 to 13% lower than the long-term average. The cumulative deviation from the mean indicates that lower than average rainfall totals are occurring more frequently after the 1960s. Furthermore the decline in rainfall has continued with the mean annual rainfall from 2000 to 2009 decreasing by a further 9% compared to the short-term averages.





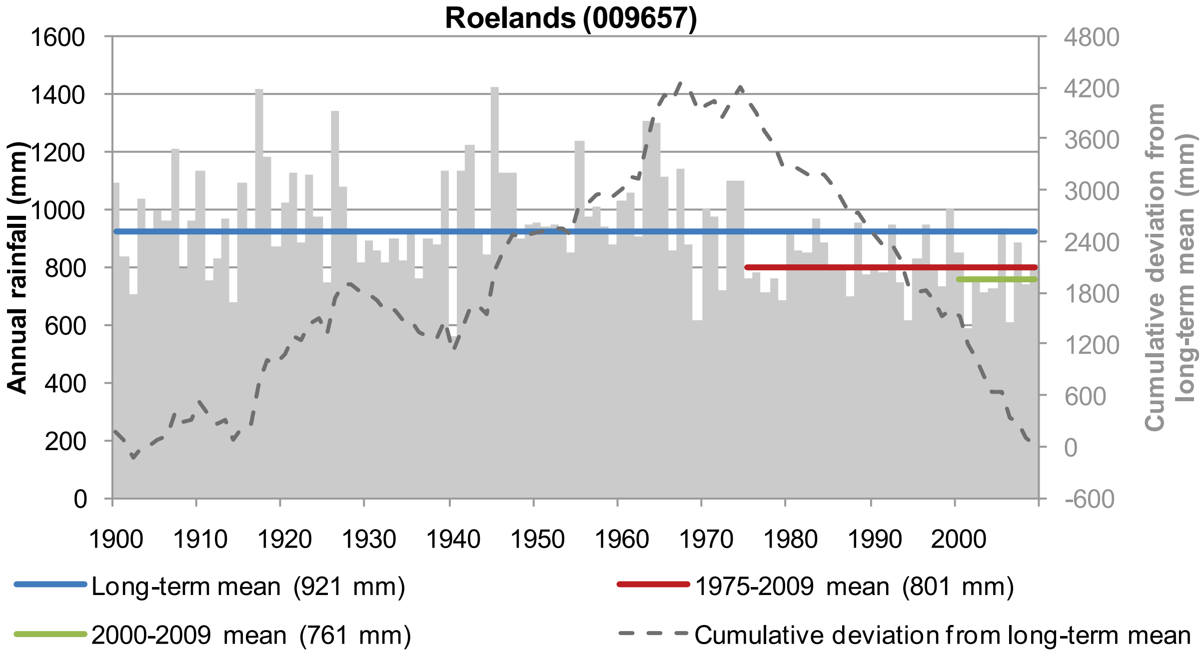


Figure 5 Annual rainfall at selected rainfall stations

Monthly rainfall

The mean monthly rainfall totals show a water limited period from October to April, when the mean monthly evaporation exceeds the rainfall (Figure 6). For all rainfall stations the water excess from May to September is large, indicating the highly seasonal rainfall distribution in the lower Collie catchment, with 79% of the annual rainfall occurring between May and September inclusive at all three stations. The long-term peak rainfall month is June and Figure 6 shows there is a shift in the recent record to a peak rainfall month of July. Evaporation is consistent over the catchment, whereas rainfall increases over the eastern parts of the catchment.

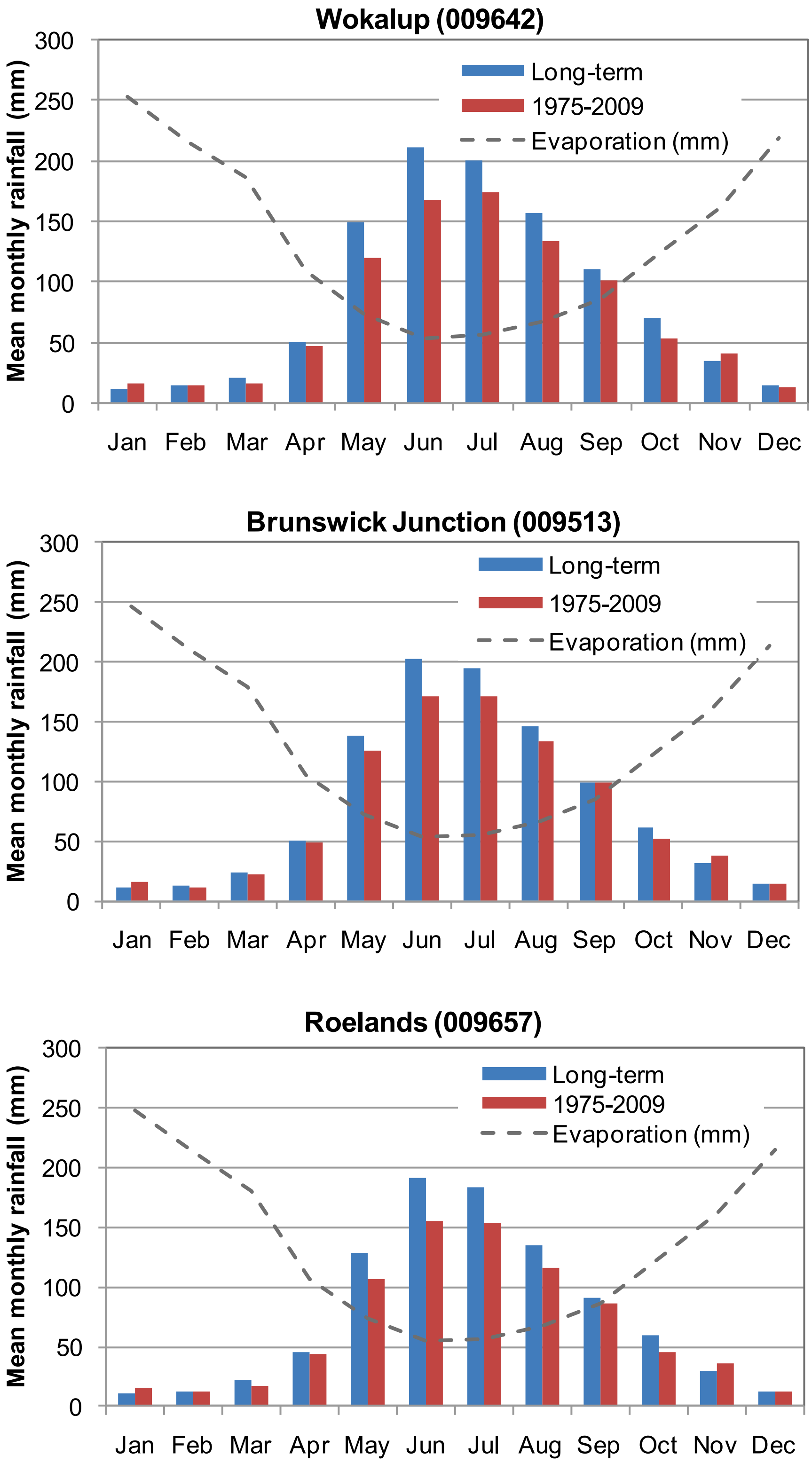


Figure 6 Mean monthly rainfall at selected rainfall stations

1.5 Previous hydrology work

Listed below is a summary of previous studies which incorporate all, or part of, the lower Collie catchment area and are considered relevant to this study.

***Brunswick River hydrology summary* (DoW, unpublished)**

A detailed study of the surface water hydrology of Brunswick River has been completed for the period 1975 to 2003. Streamflow was assessed at Cross Farm (612032) and Olive Hill (612152). Streamflow was found to be highly seasonal with the majority of flow occurring between June and October. The river flowed on an average of 85 to100% of days each year, with continuous flow from June to December. Irrigation returns were evident during summer at the downstream gauging station. This report and the streamflow modelling undertaken were used to determine the ecological water requirements of the Brunswick River (Donohue et al. 2009).

***A comparison of techniques for investigating groundwater–surface water interactions along the Brunswick River, Western Australia* (Annan 2006)**

This study identified reaches of hydraulic connection between surface water and groundwater along the Brunswick River. The majority of the river was identified as gaining or strongly gaining (where groundwater discharges into surface water). Only one reach, on the coastal plain, was identified as losing (where surface water recharges the groundwater stores). It was also noted that the flow in the lower Brunswick is affected by irrigation returns during summer.

***South West groundwater areas allocation plan* (DoW 2009a)**

This plan covers the coastal plain area of the lower Collie catchment and outlines the development of allocation limits for the groundwater areas (with the exception of the Kemerton subareas). Of importance to this study is that groundwater abstraction is to be managed to avoid causing any impact on the groundwater–surface water interaction of the Brunswick River.

***Kemerton water study phase 2* (Aquaterra 2002)**

A groundwater model was developed to form an understanding of the interactions between the significant values of the surface water, groundwater and dependent ecological systems for the area surrounding the Kemerton industrial park. The industrial park is bounded to the east and south-east by the Wellesley River and further to the south the area is drained by the Collie and Brunswick rivers. The modelling showed that the interaction between leakage from and to the rivers and aquifer outflow to drains is a minor component of the overall water balance. This work, along with other studies, contributed to the development of allocation limits for the Kemerton groundwater subareas (DoW 2007).

***Water balance modelling of the Leschenault catchment* (Marillier et al. 2009)**

Monthly water balance modelling was undertaken for the period 1998 to 2007 for major rivers in the Leschenault catchment which includes the catchments of the Wellesley, Brunswick, Ferguson and Preston rivers, as well as the Collie River downstream of Wellington Reservoir. The model incorporated the modified drainage on the coastal plain and irrigation supply in summer. Results from this study have been used directly in Section 2.6 of this report.

***Nutrient loads, status and trends in the Leschenault catchment* (Kelsey & Hall 2009)**

Total nitrogen and total phosphorus monitoring for the period 2006 to 2008 showed good water quality at sampling sites on the Darling Plateau while poor water quality was observed for sites on the coastal plain. The Wellesley catchment had the worst water quality due to intensive, irrigated land uses.

***Nutrient export modelling of the Leschenault catchment* (Kelsey 2010)**

Information from the previous two studies was used to model nutrient export to the Leschenault Inlet. Scenario modelling of management options was also undertaken. This study will be used to inform the *Leschenault water quality improvement plan* (DoW in prep).

***South-west sustainable yields project* (CSIRO 2009)**

The CSIRO south-west Western Australia sustainable yields project produced reports examining the likely water yield of surface water and groundwater catchments in the south-west of Western Australia as a result of future climate changes and land management changes. Results from this study have been used directly in Section 5 of this report.

***Wellington Dam yield estimation* (DoW 2003a)**

This internal department memorandum outlines the development of a semi-empirical, two-layer Wellington Reservoir daily water and salt balance model (TwoRes). The model is used to assess the impact of catchment management options on yield reliabilities and water quality and simulates releases, including scour, spills and irrigation releases, from the reservoir, that contribute to the lower Collie River.

***Review of quantities released from Wellington Reservoir and diverted at Burekup Weir from 1997 to 2001* (DoW 2003b) and *Review of quantities released from Wellington Reservoir and diverted at Burekup Weir from 2004 to 2008* (DoW 2009b)**

The two internal department memorandums outline the diversion efficiency (and associated losses) from irrigation releases from Wellington Reservoir and diversions at Burekup Weir. The diversion efficiency was estimated to be 90%.

2 Surface water hydrology

2.1 Streamflow gauging

A number of streamflow gauging stations have operated periodically on rivers in the lower Collie catchment area (Figure 7, Figure 8).

Streamflow data was used from gauging stations that had a record of at least 10 years, post-1975. Only data post-1975 was used as south-west Western Australia has experienced reduced rainfall, and subsequently reduced runoff, since this time.

The following streamflow gauges were used to assess water quantity and variability in this study:

- Wellesley River, Juegenup Wellesley (612039)
- Lunenburgh River, Silver Springs (612023)
- Brunswick River, Sandalwood (612022)
- Brunswick River, Cross Farm (612032)
- Falcon Brook, Falcon Road (612012)
- Stones Brook, Mast View (612005)
- Collie River, Rose Road (612043)

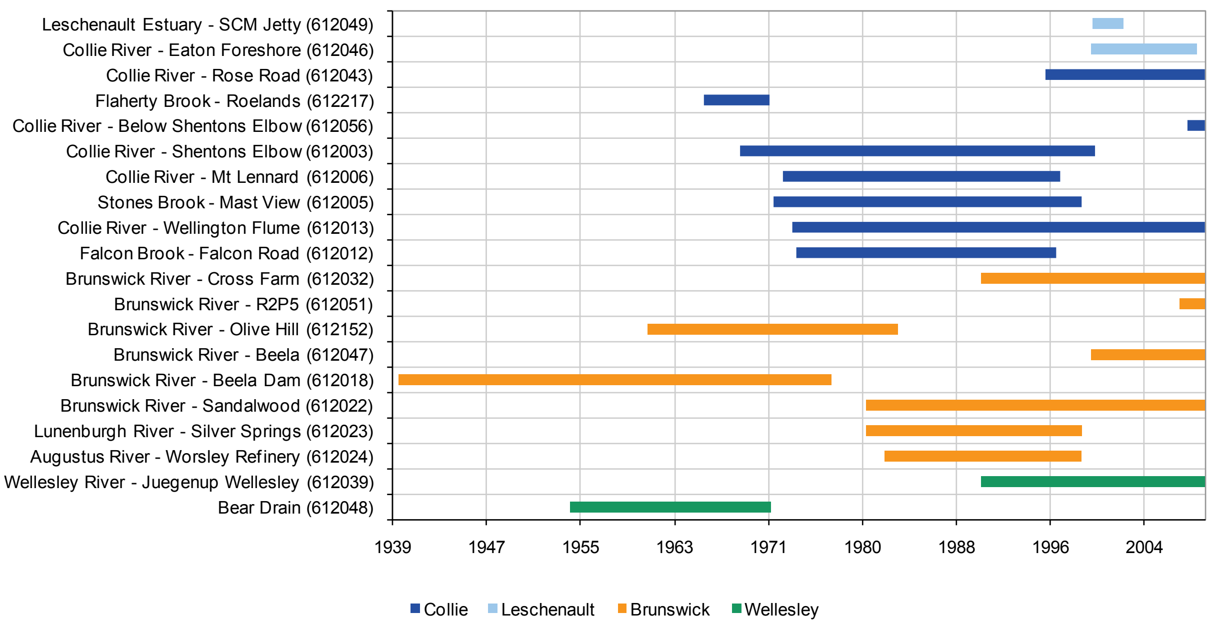


Figure 7 Period of record of streamflow gauging stations in the lower Collie catchment

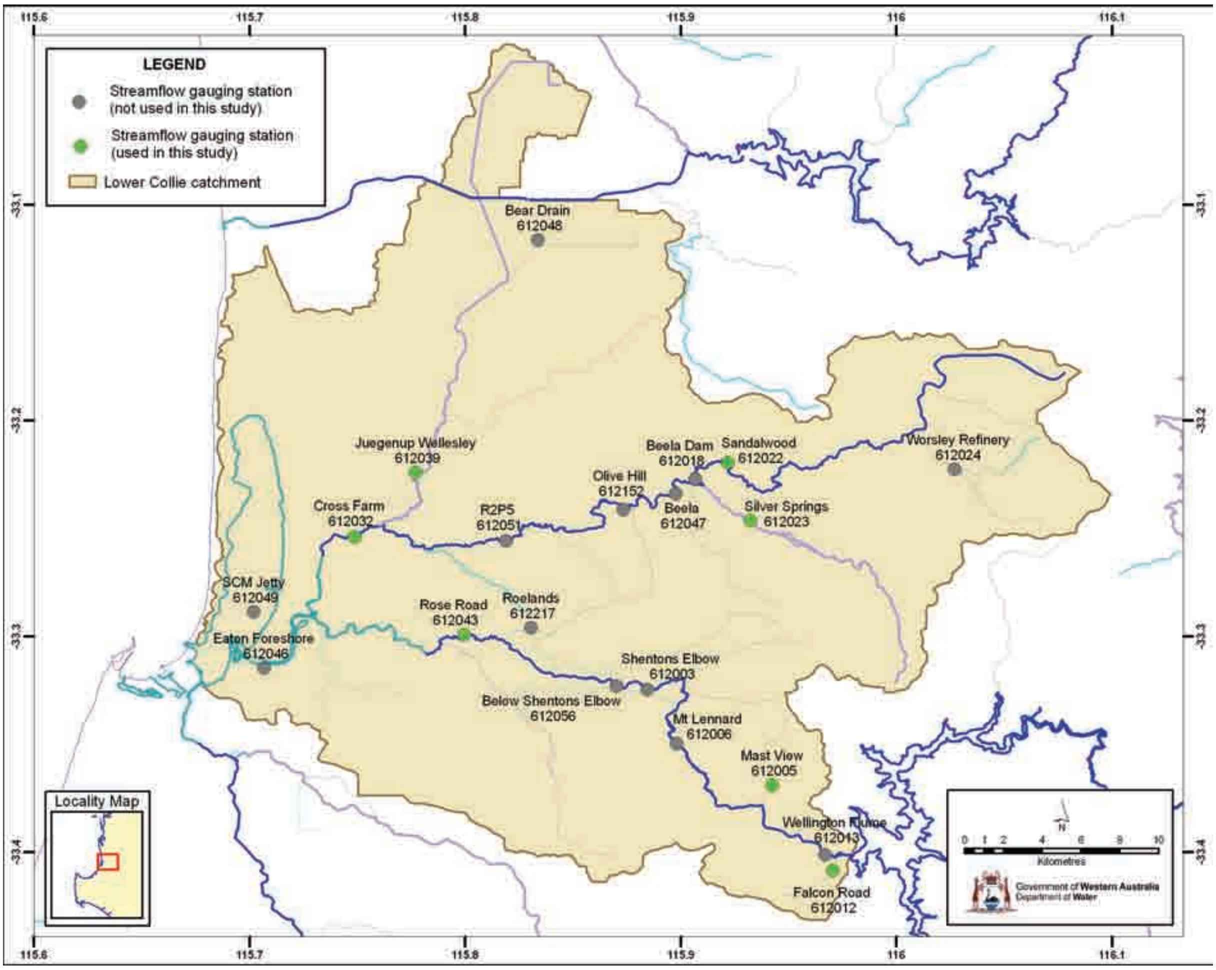


Figure 8 Location of streamflow gauging stations in the lower Collie catchment

The following gauges were not analysed in this study.

Leschenault

The two gauging stations listed for the Leschenault Estuary (SCM Jetty (612049) and Collie River, Eaton Foreshore (612046)) are used for monitoring tide level in the estuary so have not been used in this study.

Collie River

The installation at Collie River, Below Shentons Elbow (612056) is a water level monitoring probe and logger (not a complete streamflow gauging station) and was installed for a project specific purpose (environmental water requirement study). These sites typically run for around two years, long enough to obtain a good correlation between the data recorded at the probe and a long-term streamflow gauging station, before they are removed. The water level record produced at this site is not useful in this study due to the short period of record.

For use in resource assessment, the streamflow record needs to be free from the effects of major reservoirs. Therefore the records at Mt Lennard (612006) and Shentons Elbow (612003) were not used. However, they were used to prepare streamflow time-series for use in environmental water requirements studies. The Wellington Flume on the Collie River (612013) is operated by the Water Corporation and records all releases, including scour, spills and irrigation releases, from Wellington Reservoir. The information from the flume was used to calibrate the Wellington Reservoir model (DoW 2003a).

The gauge at Roelands on Flaherty Brook (612217) did not have sufficient record post-1975 for use in this study.

Brunswick River

The installation at Brunswick River, R2P5 (612051) was a water level monitoring probe and logger (not a complete streamflow gauging station) and was installed for a project specific purpose (environmental water requirement study). This site operated from 18 October 2007 to 22 December 2008. The water level record produced at this site is not useful in this study due to the short period of record.

The streamflow gauging station at Brunswick River, Beela (612047) ceased operation during the time of this study but had not recorded streamflow since September 2009. The initial purpose of the gauging station was for flood warning. Information from the Regional Management and Water Information division showed that the gauging station was not operating within required standards. The data was confirmed as erroneous on comparison with the streamflow gauging station record upstream at Sandalwood (612022) and downstream at Olive Hill (612152). Because of this, the data from this site is not suitable for resource assessment.

For use in resource assessment, the streamflow record needs to be free from the effects of major reservoirs. Therefore the record on the Augustus River at the Worsley Refinery (612024) was not used.

Two gauges on the Brunswick River did not have sufficient record post-1975 for use in this study; Olive Hill (612152) and Beela Dam (612018). The streamflow recorded at Olive Hill has a three-year overlapping period with the upstream gauging station at Sandalwood (612022) and a good correlation exists between these sites. This indicates that the gauge at Sandalwood is sufficient for resource assessment of this part of the Brunswick River.

Wellesley River

For use in resource assessment, the streamflow record needs to be free from the effects of major drainage systems. The gauging station at Bear Drain (612048) was not used in this study as it recorded modified streamflow. In addition the gauge has not operated post-1975.

2.2 Preparation of streamflow data

To assess the surface water resources in the lower Collie area, the observed streamflow records needed to be extended to cover from 1975. This is typically achieved through:

- correlation techniques to fill in gaps in the flow data with the long-term records from a nearby hydrologically similar catchment
- daily rainfall runoff models to extend the streamflow record based on rainfall and evaporation inputs.

The streamflow records for this study were extended to cover the period from 1975 to 2007 and were obtained from the CSIRO south-west Western Australia sustainable yields project (CSIRO 2009). Climate and streamflow data for future climate scenarios were also obtained from the CSIRO (2009) project (see Section 4.1).

The CSIRO (2009) project produced reports examining the likely water yield of surface water and groundwater catchments in the south-west of Western Australia as a result of future climate changes and land management changes. As part of this project, Sacramento (Burnash et al. 1973) and IHACRES (Littlewood et al. 1997) lumped conceptual daily rainfall–runoff models were created across south-west Western Australia and streamflow was simulated at a number of locations.

Climate data generated on 0.05° x 0.05° (approximately 5 km x 5 km) grid cells were used as model inputs. Historical gridded daily climate data, interpolated from point measurements made by the Bureau of Meteorology, was obtained from 1 January 1975 to 31 December 2007 from the SILO ‘data drill’ of the Queensland Government Department of Environment and Resource Management (<http://www.longpaddock.qld.gov.au/silo>).

The rainfall–runoff models were run on the 0.05° x 0.05° grid cells and the results were aggregated to report at a catchment scale. The models were calibrated against the available observed streamflow data between 1975 and 2007. CSIRO (2009) shows that the calibrations produced a good fit to the observed data when assessed using the Nash–Sutcliffe efficiency measure. Further information on the modelling and calibration, including statistical assessments of the goodness-of-fit, can be found in CSIRO (2009).

As of mid July 2010, the gridded climate and streamflow data used by CSIRO (2009) is not publicly available. However the Department of Water has access to the modelled runoff series at selected gauging stations used for model calibration and at additional streamflow reporting nodes. Streamflow reporting nodes are locations for where climate and runoff time series were produced but where calibration was not undertaken, even though they may coincide with a gauging station location. If a gauging station is located at a reporting node, calibration did not occur due to insufficient data record at the site.

2.3 Streamflow characteristics

Appendix A contains hydrologic summary sheets for the streamflow gauging stations in the catchment. These contain a description of the catchment characteristics, and summary plots and statistics of the observed and modelled streamflow. The following section provides a collation of the streamflow characteristics.

As with rainfall, streamflow across the catchment is highly seasonal with 75 to 89% of the annual flow occurring from June to September inclusive for the Brunswick and Wellesley rivers and tributaries. The peak flow month is typically July or August. There is a lag between the rainfall starting in May and the corresponding runoff response starting in June and also between the peak rainfall month (June) and the peak flow month. This is generally characteristic of catchments with large soil storage capacities.

The majority of the Brunswick tributaries are intermittent streams. However, the Brunswick River is perennial. The Sandalwood gauging station is located in national park near the headwaters of the river and the mean annual runoff is 204 mm. The Lunenburg River flows into the Brunswick a few kilometres downstream of the Sandalwood gauge. The Lunenburg River has minor clearing in the upstream reaches and the recorded mean annual runoff is 206 mm. The mean annual runoff at the downstream section of the Brunswick River is 231 mm. Summer flows in the downstream reach of the Brunswick River are from groundwater contribution and irrigation return flows. Irrigation return flow is the irrigation water applied to a field that returns to the river.

The Wellesley River is heavily modified with artificial drainage channels that often intersect groundwater. Streamflow at the gauging station is perennial and the mean annual runoff at the Wellesley streamflow gauge is 293 mm. The response and variability in flows is fairly consistent across the Brunswick catchment but the influence on streamflow of the irrigation return flows can be seen in the gauged record. Wellesley River has the lowest coefficient of variation of annual flow (0.35) but the highest runoff (293 mm) and runoff coefficient (36%) within the lower Collie catchment. This is due to the consistency of flows during the summer months.

Three streamflow gauging stations are located in the Collie River catchment downstream of Wellington Dam, at Rose Road (Collie River), Mast View (Stones Brook) and Falcon Brook (Falcon Brook). The Stones and Falcon Brook tributaries are intermittent streams with high annual variability (coefficient of variation of annual flow is 0.65 and 0.64 respectively) and low runoff totals (119 mm and 89 mm respectively) and low runoff coefficients (12% and 9% respectively).

The Rose Road streamflow gauge located on the Collie River recorded higher summer flows compared to the other gauges, due to leakage from and spill over Burekup Weir from the irrigation releases from Wellington Reservoir. The majority of the streamflow is in winter with 66% of the annual streamflow occurring from June to September. Henty Brook, a tributary of the Collie River, has never been gauged even though there are a large number of surface water users within the catchment.

2.4 Annual streamflow

As allocation limits are set as the total volume of water that can be used every year, annual flows are needed in order to provide an indication of the quantity and variability of streamflow in the catchment. The mean annual flow and minimum annual flow are of particular interest for the purpose of allocation planning. Figure 9 to Figure 15 show the observed and modelled annual flows from 1975 to 2007 for the gauging stations used within the lower Collie area.

The mean, median, standard deviation and coefficient of variation (CV) are given for the whole period of record. The volume and year of occurrence of the minimum annual flow and the maximum annual flow are also identified.

A loess curve (locally weighted scatterplot smoothing fitted to the dataset) is also plotted on the time-series to aid in visually identifying any trend in the annual streamflow. The loess curve shows decreasing streamflow at all sites occurring from around the mid 90s.

Trend analysis also identified that the median and mean annual flows were statistically different between 1975 to 1996 and 1997 to 2007 at half of the sites. This only provides weak evidence of change due to the short period of record used (10 years post 1997) and insignificant results for alternative trend tests.

The annual time-series for Rose Road (612043) on the Collie River contains no observed streamflow as the CSIRO (2009) project did not simulate releases from Wellington Reservoir. The modelled annual flow is therefore a simulation of catchment flows downstream of the dam (Figure 15).

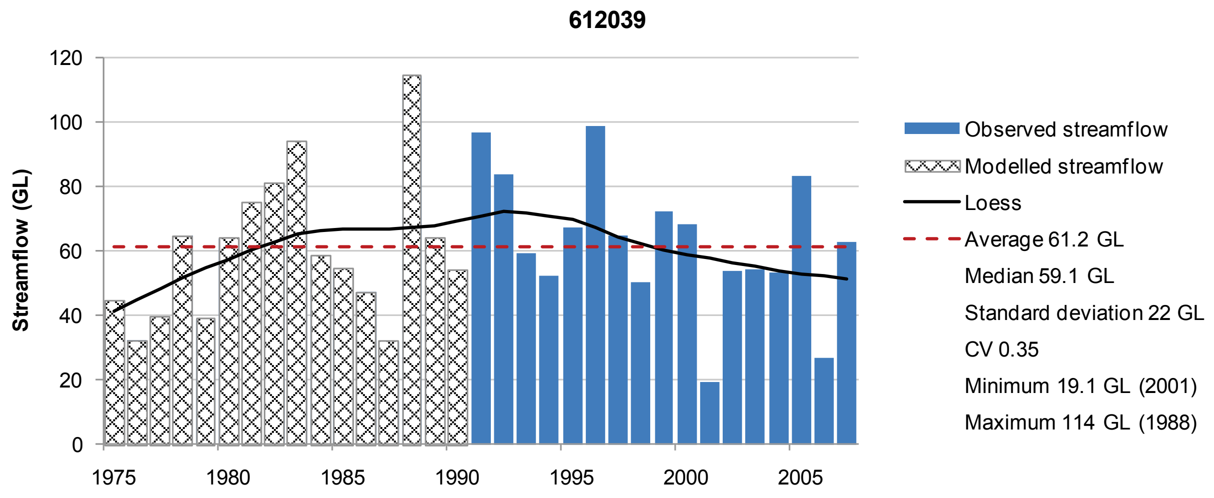


Figure 9 Annual flow series, including observed and estimated data, at Juegenup Wellesley (612039)

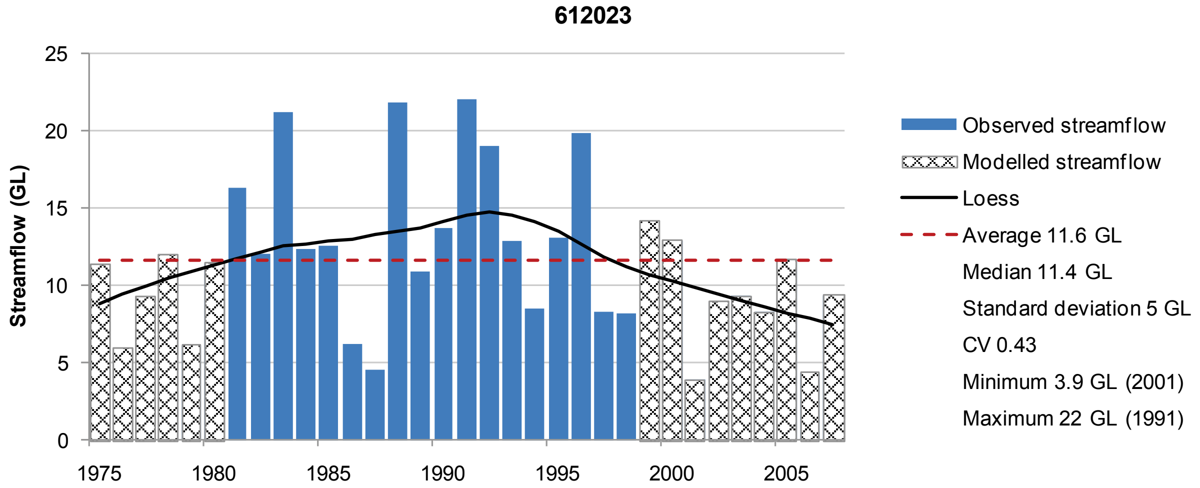


Figure 10 Annual flow series, including observed and estimated data, at Silver Springs (612023) on the Lunenburgh River

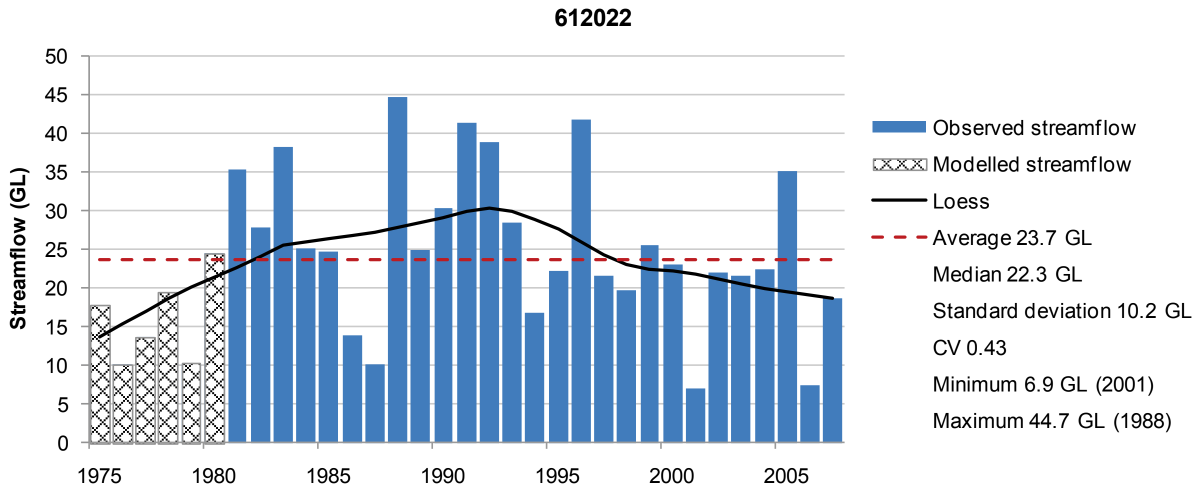


Figure 11 Annual flow series, including observed and estimated data, at Sandalwood (612022) on the Brunswick River

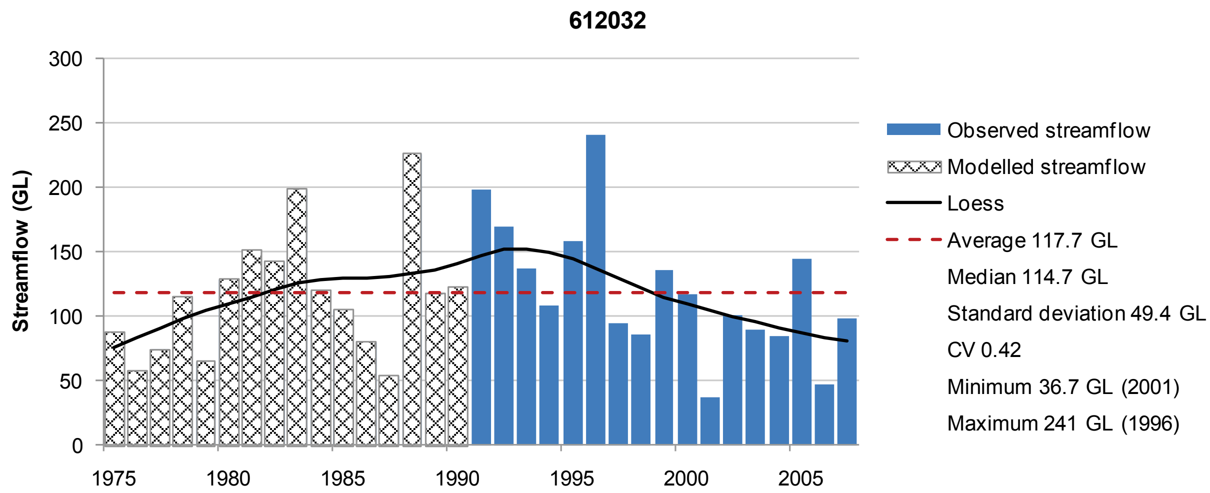


Figure 12 Annual flow series, including observed and estimated data, at Cross Farm (612032) on the Brunswick River

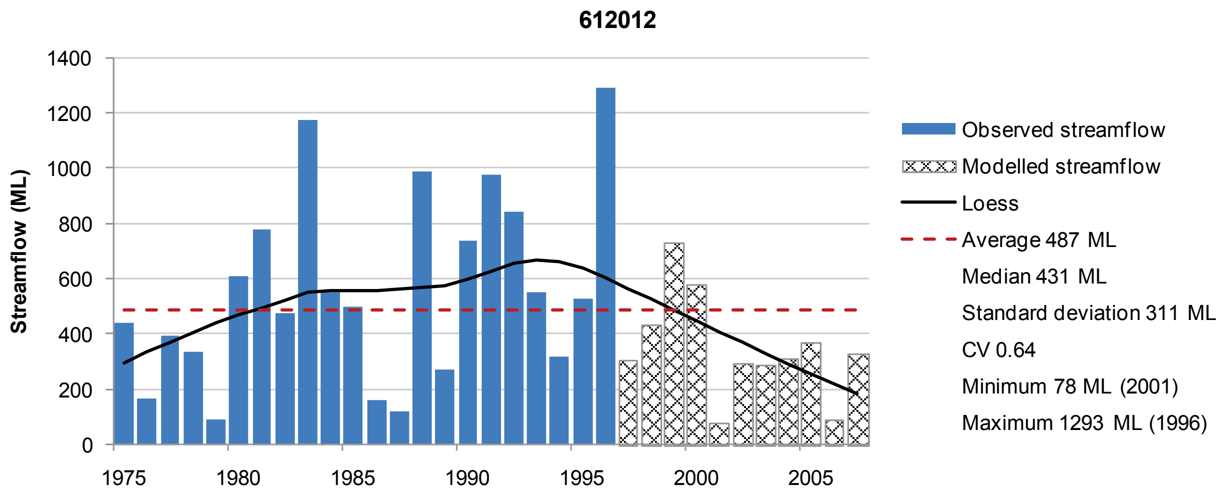


Figure 13 Annual flow series, including observed and estimated data, at Falcon Road (612012) on Falcon Brook

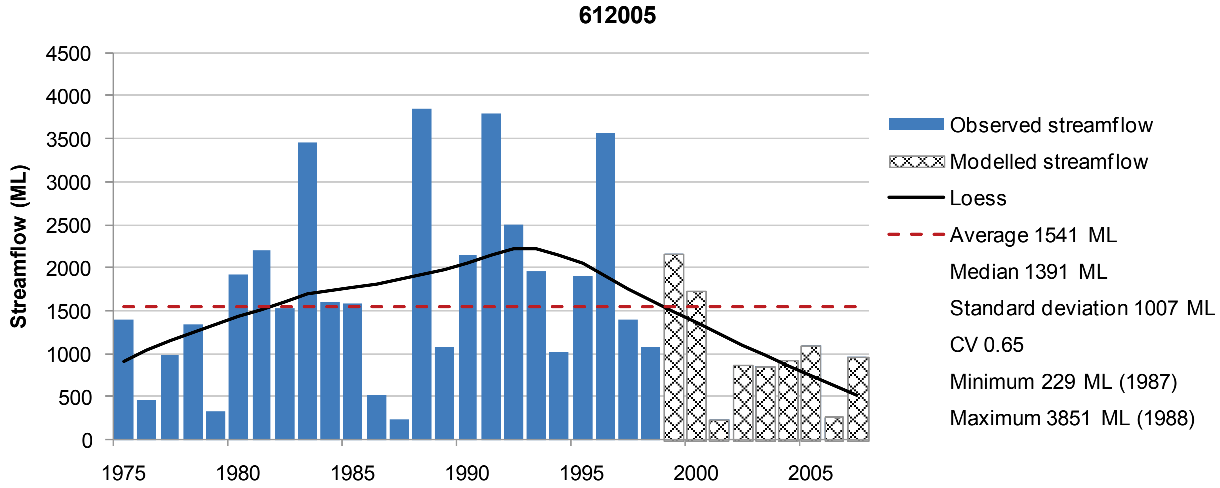


Figure 14 Annual flow series, including observed and estimated data, at Mast View (612005) on Stones Brook

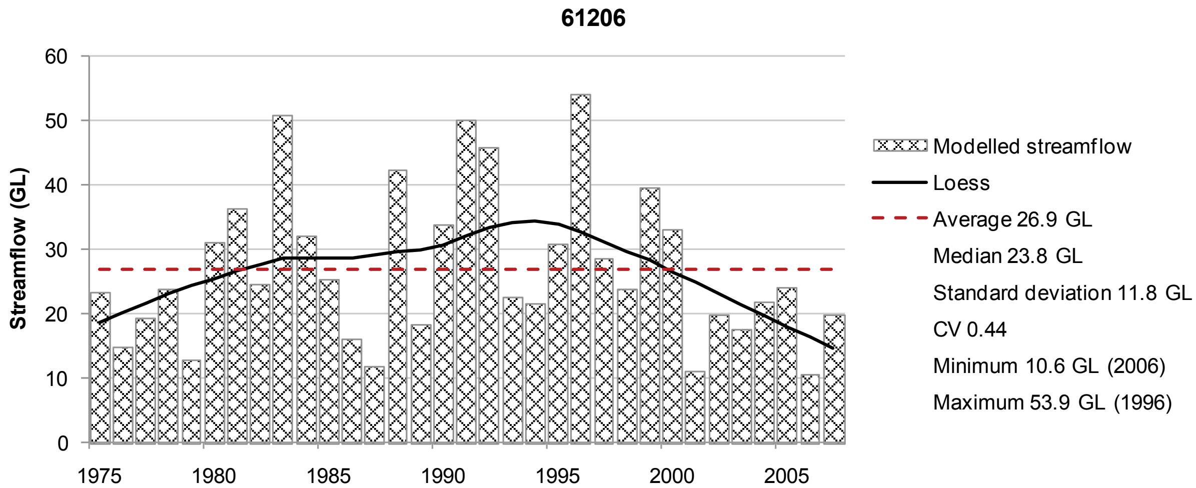


Figure 15 Modelled annual flow series at 61206 (Rose Road) on the Collie River

2.5 Regionalisation

For areas where gauged streamflow information was not available, regional relationships based on climatic and physiographic catchment characteristics were applied to provide an estimate of the mean annual flow and the minimum flow threshold (SKM 2008b). These two statistics were used in regionalising the gauged mean annual flow and minimum annual flow respectively to the 24 lower Collie resource areas.

As part of the sustainable diversion limits project, ‘indicator’ streamflow gauges for all resource areas were selected based on a combination of proximity and hydrologic similarity measures (SKM 2008b). The streamflow gauging stations shown in Figure 9 to Figure 15, as well as two gauges outside the lower Collie area, were identified as the hydrologically similar streamflow gauges for the lower Collie resource areas. Figure 16 and Figure 17 show the observed and modelled annual flows and statistics for the indicator gauging stations that are outside the lower Collie catchment.

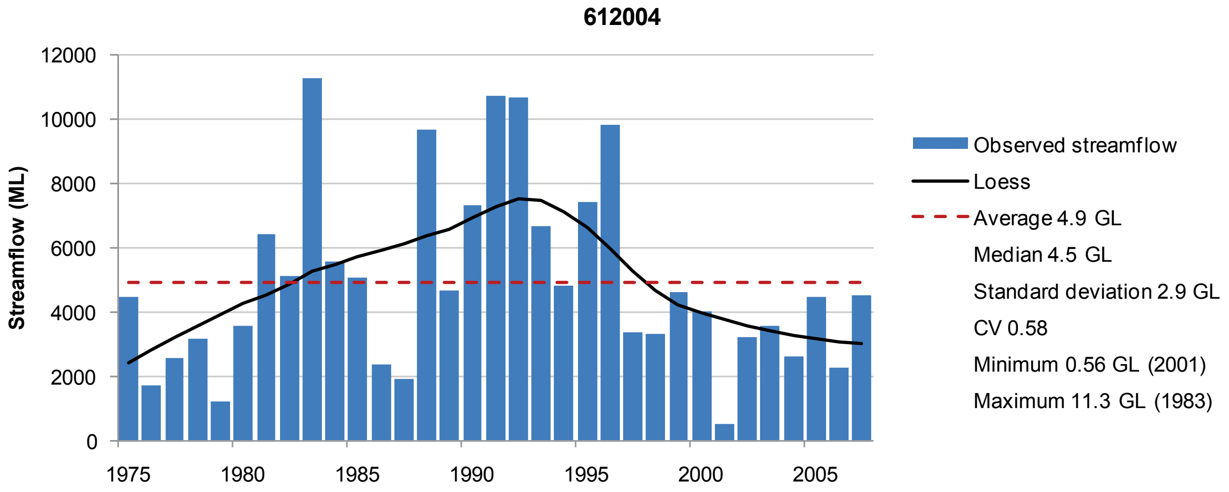


Figure 16 Annual flow series at Worsley (612004) on Hamilton River

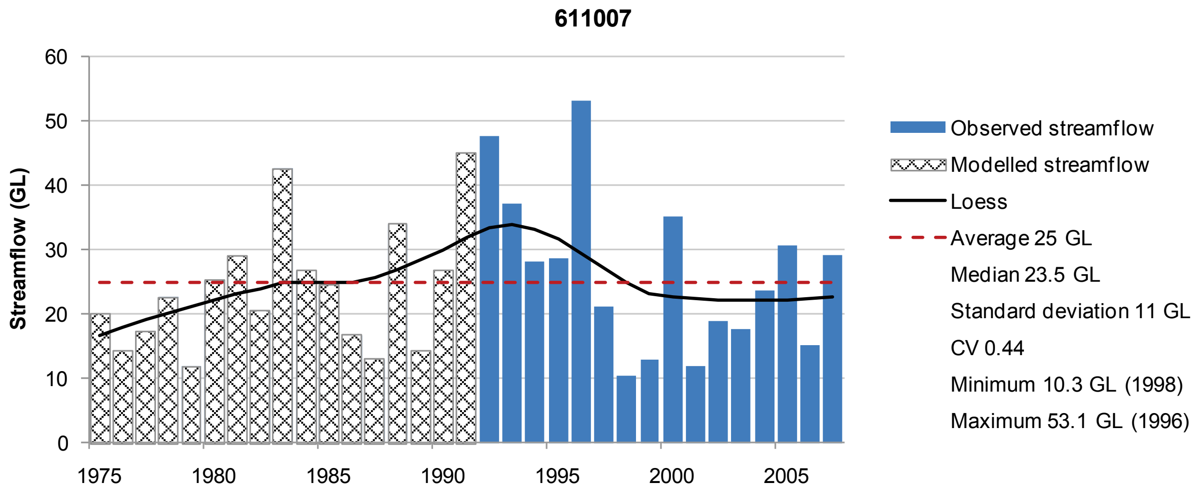


Figure 17 Annual flow series, including observed and estimated data, at South West Highway (611007) on Ferguson River

Estimates of the mean annual flow and minimum flow threshold for the SDL indicator gauges were calculated using the regional prediction equation (RPE). There was a small difference between the predictions of the RPE for *the indicator gauges* and the actual flows at those gauges, so the flows predicted by the RPE for *resource areas* were adjusted to take this into account. The equations below show how the final mean annual flows and minimum annual flows for the resource areas were calculated.

$$MAF_{\text{resource area}} = MAF_{\text{predicted for resource area by RPE}} \times \frac{MAF_{\text{actual at indicator gauge}}}{MAF_{\text{predicted at indicator gauge by RPE}}}$$

$$MinAF_{\text{resource area}} = MFT_{\text{predicted for resource area by RPE}} \times \frac{MinAF_{\text{actual at indicator gauge}}}{MFT_{\text{predicted at indicator gauge by RPE}}}$$

Where the terms have the following meanings:

$MAF_{\text{resource area}}$	estimate of mean annual flow for the resource area
$MAF_{\text{predicted for resource area by RPE}}$	Regional Prediction Equation estimate of mean annual flow for the resource area
$MAF_{\text{Actual at indicator gauge}}$	observed mean annual flow at the indicator gauging station
$MAF_{\text{Predicted at indicator gauge by RPE}}$	Regional Prediction Equation estimate of mean annual flow at the indicator gauging station
$MinAF_{\text{resource area}}$	estimate of minimum annual flow for the resource area
$MFT_{\text{predicted for resource area by RPE}}$	Regional Prediction Equation estimate of minimum flow threshold for the resource area
$MinAF_{\text{Actual at indicator gauge}}$	observed minimum annual flow at the indicator gauging station
$MFT_{\text{Predicted at indicator gauge by RPE}}$	Regional Prediction Equation estimate of minimum flow threshold at the indicator gauging station

The streamflow recorded at a number of the indicator gauging stations are influenced by irrigation return flows during summer and these were removed from the annual streamflow statistics before they were regionalised. The irrigation return was then calculated for each resource area and added back to the mean and minimum annual flows (see Section 2.6).

A manual check was made to ensure that the flows for the individual resource areas added up to the observed flow at known points (streamflow gauging stations). For nested catchments (a catchment that has an upstream gauged subcatchment), the observed upstream flow time-series was subtracted from the downstream flow time-series before the manual check was performed.

The resource areas, indicator gauges and regionalised mean and minimum annual flow estimates are shown in Table 2 and spatially in Figure 18 for mean annual flow and in Figure 19 for the minimum annual flow.

Table 2 Annual flow information (including irrigation return flows) for resource areas in the lower Collie catchment

Catchment	Resource area	Indicator gauging station	Mean annual flow ML/year	Minimum annual flow ML/year
Collie River	612_1_8_1	612005	602	92
	612_1_8_2	612005	1 541	229
	612_1_8_3	61206	3 055	1 474
	612_1_8_4	612005	4 851	516
	612_1_8_5	61206	16 819	8 263
	612_1_8_6	611007	11 664	3 601
	612_1_8_7	611007	4 745	1 468
	612_1_8_8	611007	8 029	1 895
	612_1_8_9	611007	9 323	4 555
	612_1_8_10	612032	113	57
Brunswick River	612_1_9_1	612004	5 636	1 175
	612_1_9_2	612022	7 294	2 202
	612_1_9_3	612022	10 790	3 557
	612_1_9_4	612023	11 572	3 865
	612_1_9_5	612004	4 408	1 200
	612_1_9_6	612004	1 849	376
	612_1_9_7	612022	4 012	1 492
	612_1_9_8	612022	3 794	1 762
	612_1_9_9	612022	3 777	1 085
	612_1_9_10	612032	2 577	412
	612_1_9_11	612032	1 013	386
Wellesley River	612_1_10_1	612039	7 067	3 629
	612_1_10_2	612039	54 174	15 505
	612_1_10_3	612039	738	422

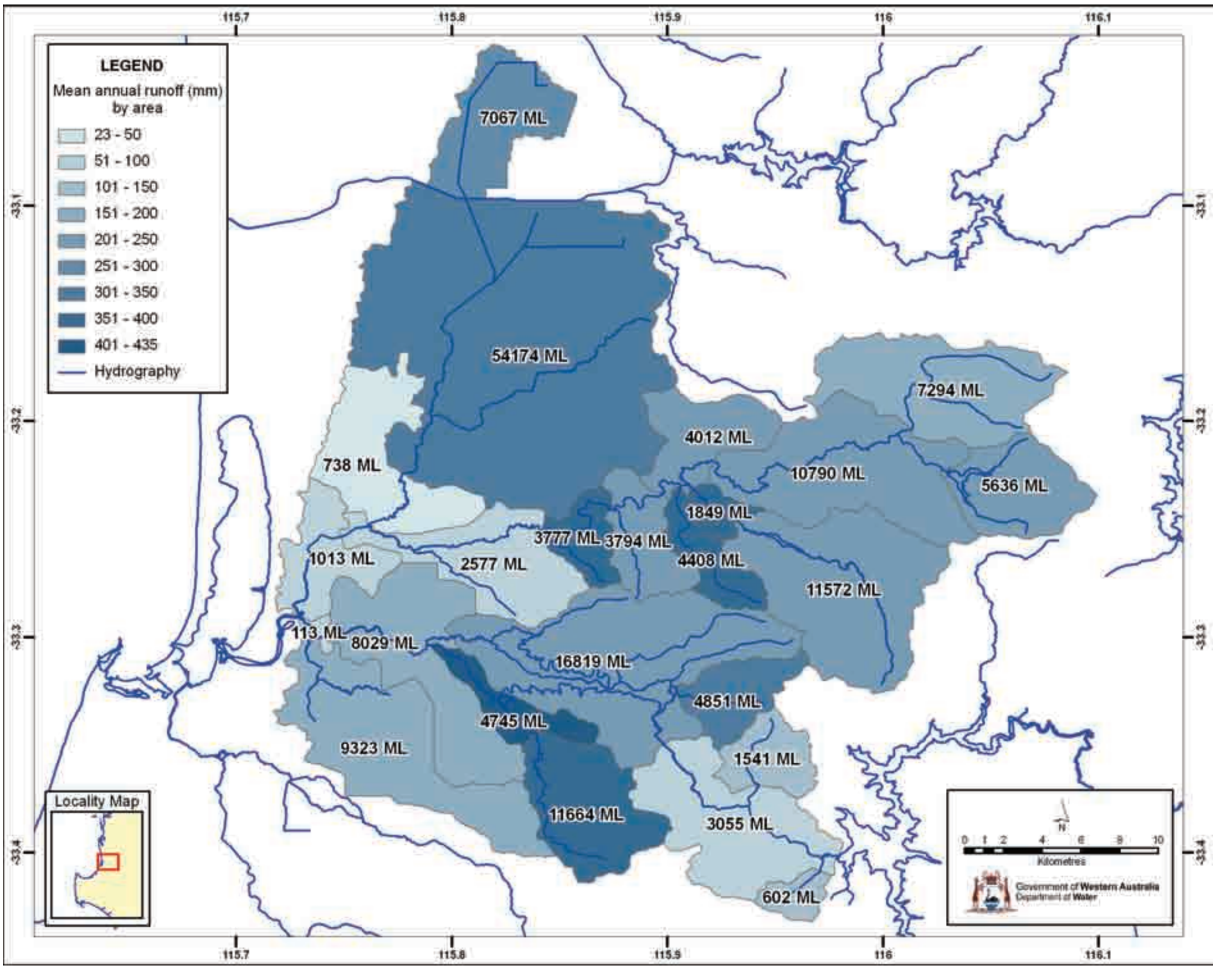


Figure 18 Mean annual runoff and flow in the lower Collie catchment

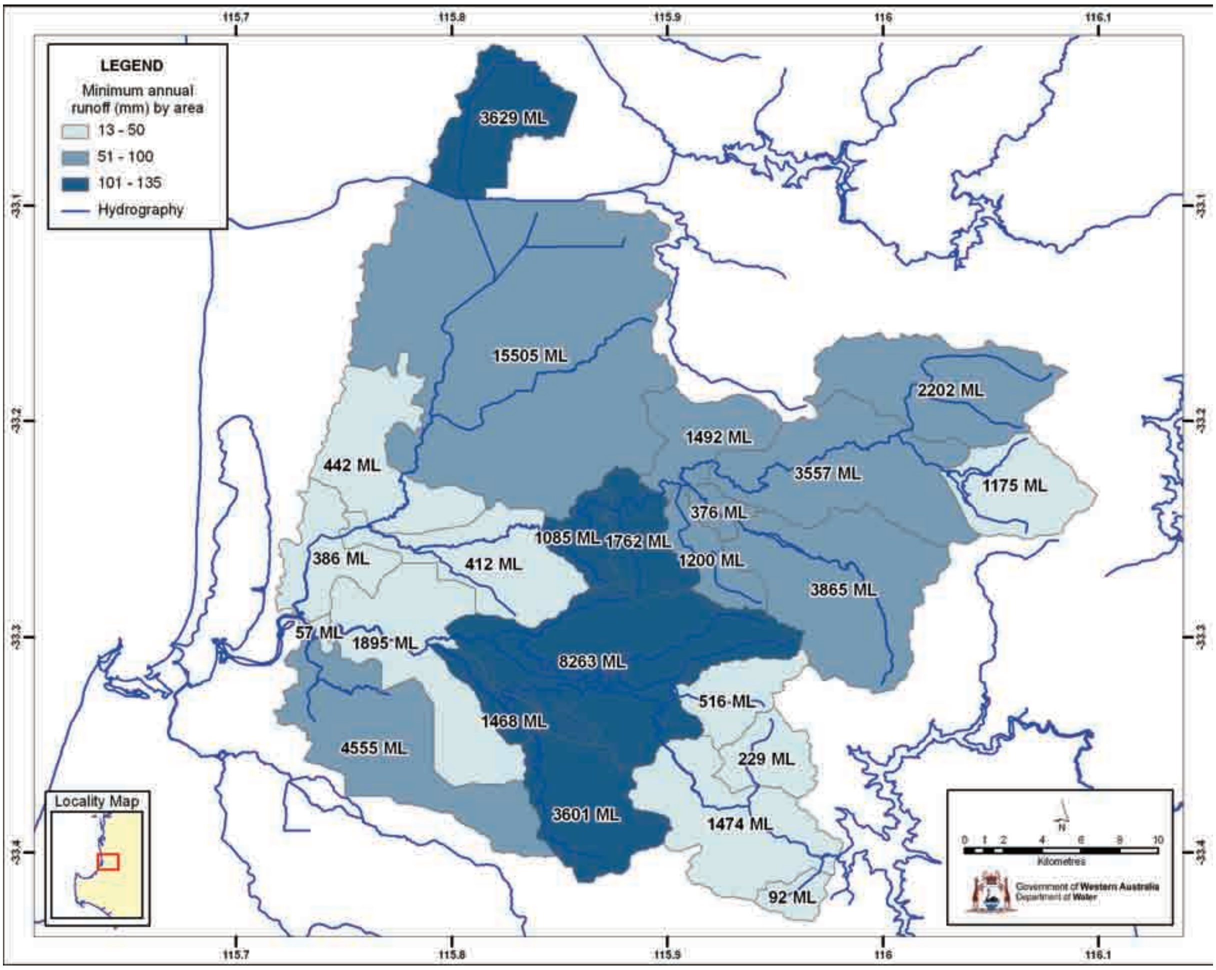


Figure 19 Minimum annual runoff and flow in the lower Collie catchment

Uncertainty in the regional prediction equations for mean annual flow and the minimum flow threshold

It is useful to have an understanding of the uncertainties associated with regionalisation of flow estimates. For gauged catchments, the uncertainties relate to measurement errors and the length of the record used to estimate the flow statistics due to climate variability. For catchments where flow is estimated from a regional relationship, an estimate of the prediction error can be made by applying the adopted multiple regression equation to the gauged catchments. This provides an indication of some of the uncertainty involved in the regionalisation of flow.

Mean annual flow

The regional relationship developed by SKM (2008b) for mean annual flow was based on 140 gauged catchments. For these catchments, the mean annual flow was calculated using the regional prediction equation and compared with the observed mean annual flow value. The plot of the prediction equation results against the mean annual flow calculated from observed data is presented in Figure 20. This shows a reasonably uniform distribution of residuals about the fitted regression equation.

The resulting error in the prediction equation was calculated as the ratio of the value from the equation to the observed value (Figure 21). The dashed black line in the plot shows the theoretical log-normal distribution of the error ratio. The actual error ratio closely approximates the dashed black line as per the standard assumption that errors in multiple linear regression analysis are normally distributed in the logarithmic domain.

In Figure 21 a ratio of one indicates that the prediction equation exactly matches the observed mean annual flow, larger than one indicates that the predicted is more than the observed and less than one that the prediction is less than the observed. From the theoretical distribution, for the middle 80% of catchments, the regression equation would produce an estimated mean annual flow of between −51% and +93% of the observed value. This is slightly greater than the level of error that is observed for the gauged catchments used to derive the regression equation.

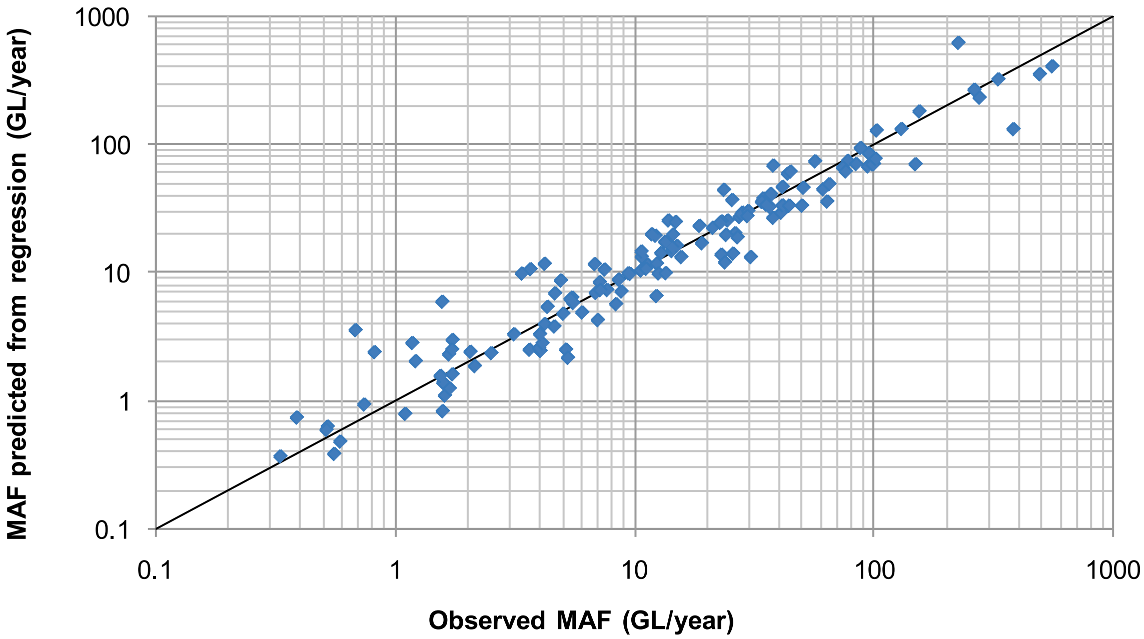


Figure 20 Comparison of mean annual flow predicted by SKM (2008b) regression equation and calculated from observed data for gauged catchments

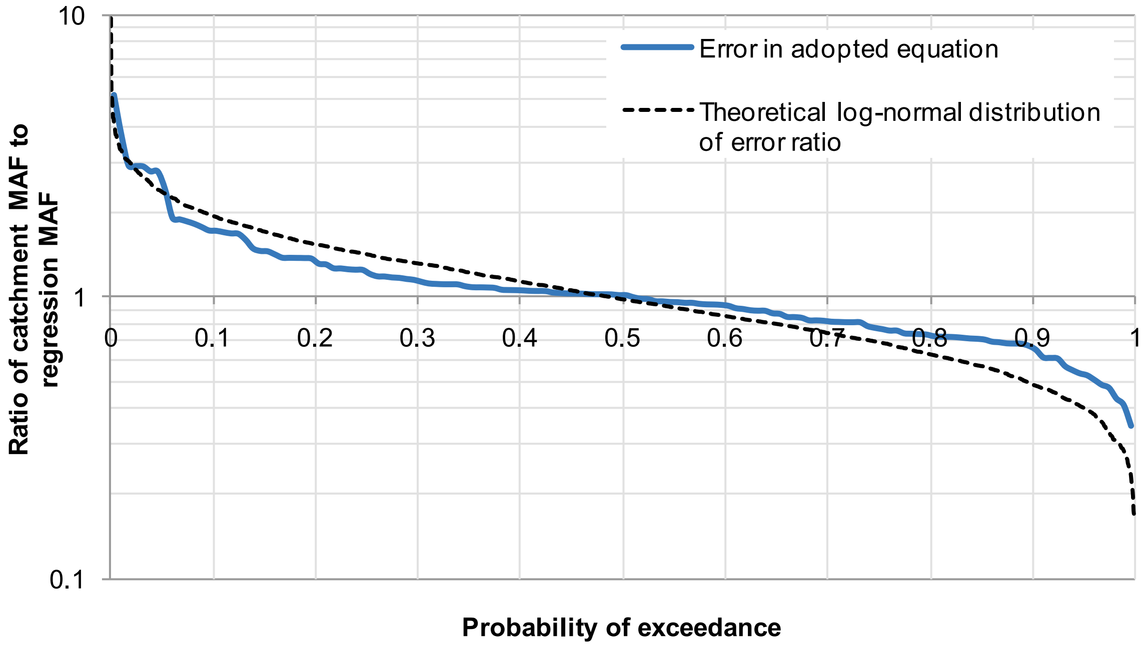


Figure 21 Ratio of mean annual flow estimated from the regression equation to the observed value for gauged catchments

Minimum flow threshold (minimum annual flow)

The minimum flow threshold prediction equation was used to regionalise the minimum annual flow. The same approach was used to quantify the error in the minimum flow threshold prediction equation to provide an indication of some of the uncertainty involved in the regionalisation of the minimum annual flow.

For the calibration catchments, the minimum flow threshold was calculated using the regional prediction equation and compared with the minimum flow threshold calculated from gauged data. The plot of the prediction equation results against the minimum flow threshold calculated from observed data is presented in Figure 22.

The resulting error in the prediction equation was calculated as the ratio of the value from the equation to the observed value (Figure 23). The dashed black line in the plot shows the theoretical log–normal distribution of the error ratio. The actual error ratio closely approximates the dashed black line with the exception of the tail of the data which indicates that in around 5% of the catchments, the prediction equation is less than the calculated value by more than would be expected from a normal distribution. These points can be clearly identified in Figure 22 with the remainder of the residuals showing a reasonably uniform distribution about the fitted regression equation.

From the theoretical distribution, for the middle 80% of catchments, the regression equation would produce an estimated minimum flow threshold of between −59% and +98% of the observed value. This is similar to the level of error that is observed for the gauged catchments used to derive the regression equation.

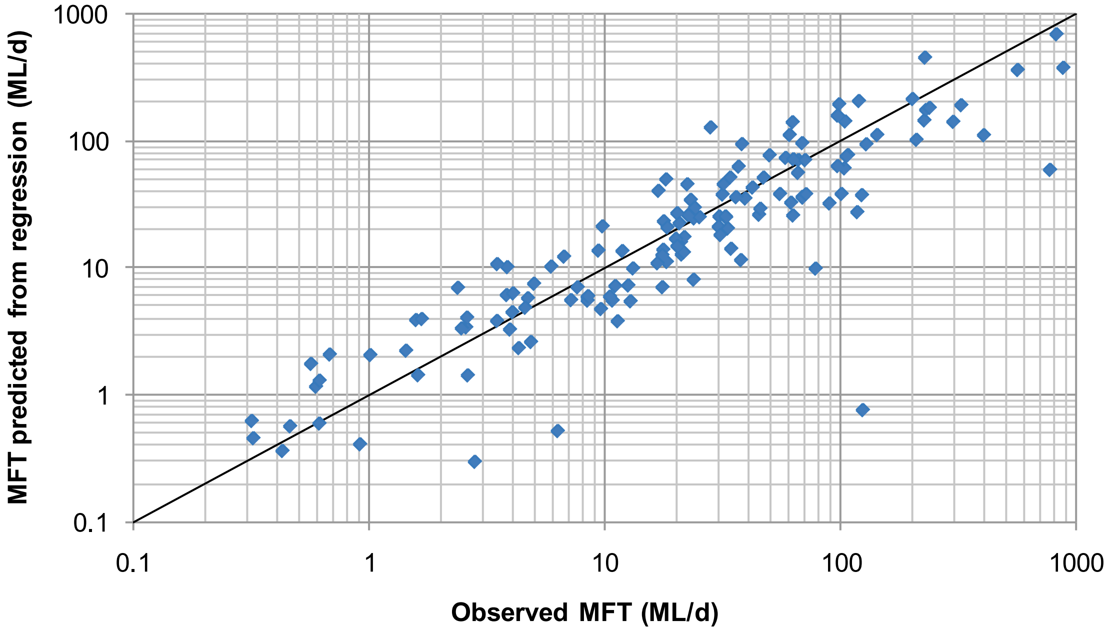


Figure 22 Comparison of the minimum flow threshold predicted by SKM (2008b) regression equation and calculated from observed data for gauged catchments

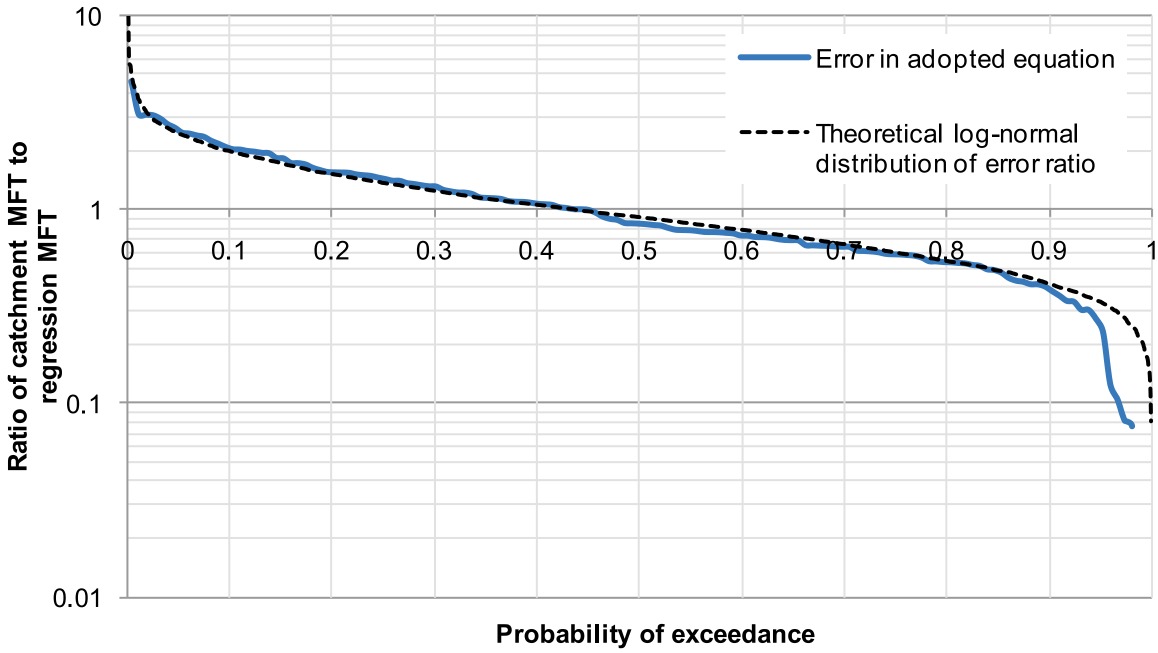


Figure 23 Ratio of the minimum flow threshold estimated from the regression equation to the observed value for gauged catchment

2.6 Irrigation

As mentioned in Section 2.5, streamflows recorded at a number of the gauging stations used as indicator gauges are influenced by the addition of irrigation return water and artificial inputs from the irrigation channel into the river. This also influences the regionalisation of streamflow to the resource areas. An estimate of the average annual irrigation return was made for each affected gauging station and resource area.

As part of the *Leschenault water quality improvement plan* (WQIP) (DoW, in preparation), monthly water balance modelling was undertaken for major rivers in the Leschenault catchment which includes the lower Collie area as well as the catchments of the Ferguson and Preston rivers (Marillier et al. 2009).

The water balance model was divided into 13 subcatchments, defined at streamflow gauging stations, and calibrated monthly for the period 1998 to 2007. Where applicable, an irrigation module was used over the summer months. Irrigation return flow was estimated as a proportion of direct irrigation return in addition to subsurface flow as a result of irrigation (Marillier et al. 2009).

The monthly irrigation data used in Marillier et al (2009) was obtained from Harvey Water and Preston Valley Irrigation Cooperative. It was assumed that the total monthly volume of water supplied for irrigation was distributed evenly across the catchment it was delivered to. From the calibrated model, irrigation return flow averaged around 24% of irrigation water applied for the lower Collie catchments (Marillier et al. 2009).

As the time period used for modelling in the Leschenault WQIP differs from the time period used in this study (post-1975), the proportion of average annual irrigation return to average annual flow from Marillier et al (2009) was applied to the average annual flow calculated in this study for the period 1975 to 2007 (Table 3). As the catchment area between the WQIP subcatchments and the resource areas also differed, the average annual flow was scaled by the catchment area. The volume of irrigation return was removed from the mean annual flow and minimum annual flow series shown in Figure 9 to Figure 17 before regionalising the flows to the resource areas.

Once the flows (minus the irrigation return) were regionalised to the resource areas, the irrigation return for the actual resource area was added back to the regionalised flow (as shown in Table 2). The irrigation return estimated for the resource areas affected by irrigation supply is shown in Table 4 and Figure 24.

Table 3 Irrigation information applied to streamflow records at gauging stations in the lower Collie catchment

WQIP modelling area*	Gauging station	Resource area that irrigation is applicable to	Average annual proportion of irrigation return to flow %*	Mean annual flow ML**	Irrigation return ML
Wellesley	612039	612_1_10_1 and 612_1_10_2	8	61 240	5 012
Mid Brunswick	612032	612_1_9_10 and 612_1_10_3	8	14 733	1 160
Upper Ferguson and Lower Ferguson	611007		3	24 953	743
Collie Lower 2	61206	612_1_8_5 (downstream of Burekup Weir)	0.2	15 201	34
Collie Lower 1		612_1_8_7, 612_1_8_8 and 612_1_8_9	8	22 097	1 662

** Marillier et al. 2009*

*** Mean annual flow is scaled to the catchment area that the irrigation is applicable to*

Table 4 Irrigation return information regionalised to resource areas affected by irrigation supply in the lower Collie catchment

Catchment	Resource area	Indicator gauging station	Catchment area km^2	Average irrigation return ML/year
Collie River	612_1_8_5	61206	72	30
	612_1_8_7	611007	11	174
	612_1_8_8	611007	43	679
	612_1_8_9	611007	51	809
Brunswick River	612_1_9_10	612032	32	569
Wellesley River	612_1_10_1	612039	28	669
	612_1_10_2	612039	178	4343
	612_1_10_3	612039	33	591

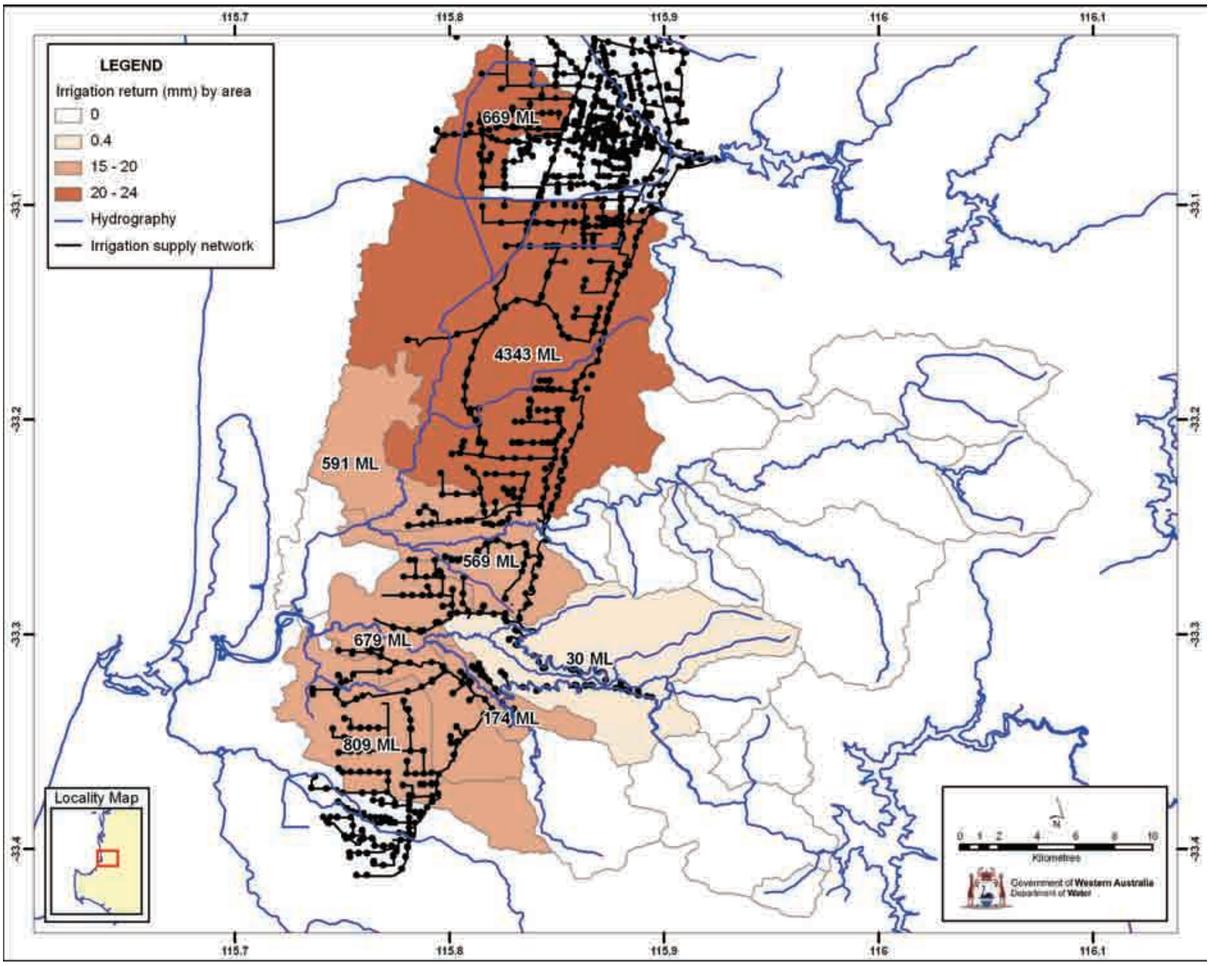


Figure 24 Irrigation return flows in the lower Collie catchment

2.7 Plantations

Plantations intercept surface runoff and subsurface flow that would otherwise flow into the rivers. Within the lower Collie catchment, the upper Brunswick and Wellesley catchments have the highest current, or potential, plantation developments. The Forest Cover Flow Change (FCFC) tool is used to examine the changes to streamflow caused by clearing the existing plantations or the development of future plantations (CRC-CH 2005).

Land-use mapping information was developed by Kelsey (2010) in partnership with the Department of Agriculture and Food using a combination of existing information, 2003 aerial photography and 2006 aerial photography in the urban areas.

Upper Brunswick catchment

Currently within the lower Collie catchment the largest proportion of plantations is within the upper part of the Brunswick River (resource areas 612_1_9_1, 612_1_9_2 and 612_1_9_3). According to a recent land-use survey plantations cover 6 km^2, approximately 5% of the total area (Table 5).

Observed streamflow from the Sandalwood gauge (612022) was interpreted through the FCFC tool with a 5% increase and decrease in plantations. The 5% decrease shows the changes to the flow regime if the current level of plantations are cleared and the 5% increase shows the effects of developing plantations to the maximum possible level.

Flow duration curves (FDCs) for the different land-use scenarios show the variation in flows caused by increasing or decreasing plantations (Figure 25). The FDC shows no variation in the distribution of flows at Sandalwood if current plantations (5% of the resource area) are cleared. This suggests that the current levels of plantations are too small to have any significant effect on streamflow (mean daily streamflow increases by 6% (4 ML) with clearing). For a 5% increase in plantations there is a change in the flow regime at Sandalwood. The FDC shows there is a reduction in low flows, most likely due to plantations reducing groundwater contributions. Furthermore, the 27-year flow record at Sandalwood showed that 14 days recorded zero flow whereas the FCFC modelled flow series showed 407 days of zero flow over the same period. This highlights that although the mean and high flows are similar for the current and the increased plantations scenario, the low flows are substantially reduced. This could have an effect on meeting any low-flow related environmental flow thresholds in the upper Brunswick catchment.

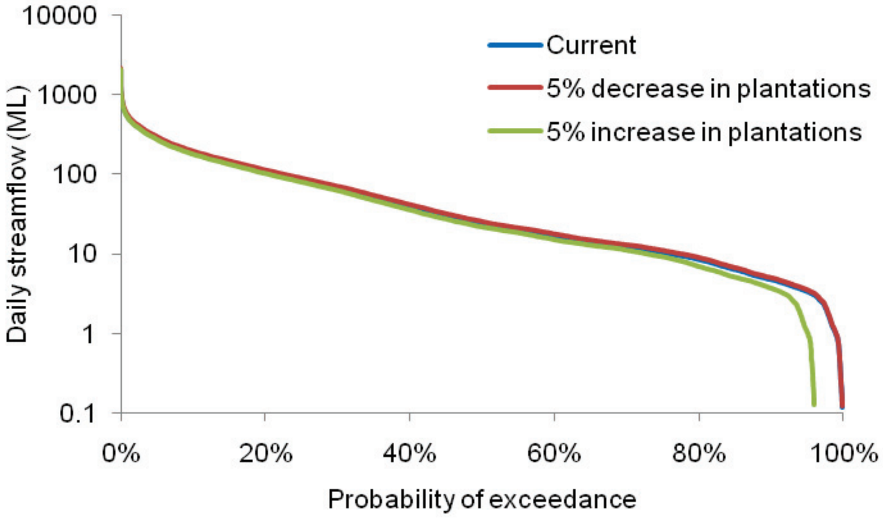


Figure 25 Flow duration curves at Sandalwood for the different land-use scenarios

Wellesley catchment

The Wellesley catchment has the potential for the largest increase in plantations. Current land-use estimates show plantations occupy less than 1% of the total area (Table 5). However agriculture, especially dryland agriculture, occupies the majority of the catchment. An extreme development scenario is for all agriculture, viticulture, horticulture and unused areas to become plantations, which equates to approximately a 50% increase in forest cover.

The Wellesley streamflow gauge (612039) is located at the downstream end of resource area 612_1_10_2. However, due to the irrigation returns within the observed flow record, the data is not suitable for conducting an FCFC analysis.

It would be expected that the current proportion of plantations will not significantly influence streamflow if cleared. However, if plantations are to substantially increase within the project area a substantial decrease in streamflow would be expected. This may have little effect on users as current use is dependent on the Harvey Water irrigation network rather than surface water abstraction from the Wellesley River. Furthermore as the Wellesley River is generally high in nutrients (nitrogen and phosphorus), developing plantations may assist in improving the quality of water. Further investigation into the possible downstream effects will be required prior to any plantation development in the Wellesley catchment.

Table 5 Land-use totals within the Wellesley and Sandalwood (upper Brunswick) catchments

Land use	**Area km^2**	
	Wellesley (612039)	**Sandalwood (612022)**
Annual horticulture	0.04	-
Cattle for beef	93	2.2
Cattle for dairy	43	0.4
Lifestyle block / hobby farm & rural residential / bush block	1.3	0.01
Pasture for hay	0.2	0.01
Perennial horticulture – trees	0.1	-
Quarry / extraction	3.0	7.0
Manufacturing/processing	-	7.7
Recreation / conservation	48	89
Rural residential/ bush block	0.5	-
Horses	1.4	-
Transport / access	1.3	0.04
Tree plantation	1.4	5.8
Unused – cleared – grass	0.8	2.8
Unused – uncleared – trees/shrubs	0.2	-
Urban residential	0.1	-
Utility	0.002	-
Viticulture	0.1	-
Water body	0.5	0.8
Wetland	3.3	-
Total	198	116
Forest cover	51 (26%)	95 (82%)
Current plantations	1.4 (1%)	5.8 (5%)
Potential plantations	144 (73%)	11 (10%)

Source: Kelsey 2010

3 Sustainable diversion volumes

Sustainable diversion limits provide a regional, hydrologic estimate of the sustainable yield of surface water resources. They have been developed as the basis for setting surface water abstraction entitlements and making other decisions in areas of the south-west of Western Australia where the level of surface water use is low. SKM (2008a, 2008b) provide further detail on the derivation of the SDL approach.

The SDL represents the maximum volume of water available for diversion, above which there is an unacceptable risk that additional extractions may degrade the environment. As the level of surface water use increases then detailed local investigations, such as environmental water requirement studies, are required to more accurately define, and possibly increase, the estimated sustainable yield.

Sustainable diversion limit volumes were directly calculated at five gauging stations in the lower Collie catchment (Table 6) and are based on four 'rules':

- a winter fill period during which diversions can occur (15 June to 15 October)
- a minimum flow threshold (MFT) above which diversions can occur
- a maximum daily rate of extraction (for pumped extractions)
- an annual volume associated with a specified reliability of supply.

Gauging stations outside the lower Collie area were also used to determine SDLs and are included here based on the gauge's hydrologic similarity to areas within the lower Collie area (Table 6).

3.1 Reliability of supply

The SDL volumes are calculated on the basis of an 80% reliability of supply. A reliability of 80% is typical of a reliability associated with agricultural uses.

The reliability of supply is defined as the probability that the SDL volume of water is able to be diverted, in accordance with the 'rules', from the surface water resource. An 80% reliability of supply means the SDL volume can be abstracted within the rules in eight out of ten years. In two out of ten years the full SDL volume is not able to be extracted given the constraints of the winter fill period, the minimum flow threshold and the maximum daily rate of extraction. Table 6 also shows the volume that is able to be extracted, within these constraints, in the minimum year.

The SDL volume and the reliability of supply are directly related. A lower level of reliability results in a higher volume of water being available for diversion and a larger impact on the resource. Conversely, a higher level of reliability results in a lower level of water available for diversion and a lesser impact on the resource.

Table 6 Sustainable diversion volume and streamflow information calculated directly from streamflow records at gauging stations in the lower Collie catchment and at indicator gauging stations outside lower Collie

Gauging station	Period of record used for SDL	Minimum flow threshold ML/day	Maximum extraction rate ML/day	SDL volume diverted at an 80% reliability of supply ML/year	Volume diverted in minimum flow year ML
612022	1/6/1980–31/12/2005	54.9	35.7	2 902	476
612023	1/6/1980–31/12/1998	33.0	19.7	1 177	529
612032	1/6/1990–31/12/2005	208	191	12 416	4 278
612039	1/6/1990–31/12/2005	62.1	108	6 560	2 603
612005	1/1/1975–31/12/1998	1.6	3.5	259	76
61206	1/1/1975–31/12/2007	46.1	38.8	2 814	1 380
611007	1/5/1991–31/12/2005	37.9	31.5	2 576	781
612004	1/1/1975–31/12/2005	7.6	8.9	695	94

Source: SKM 2008a

3.2 Regionalisation

For areas where gauged streamflow information was not available, a regional relationship based on climatic and physiographic catchment characteristics was applied to provide an estimate of the sustainable level of diversion. Sustainable diversion volumes at an 80% reliability of supply were estimated for the 24 resource areas in the lower Collie catchment by SKM (2008b) (Figure 26).

The volume of water diverted in the minimum year was also regionalised to the resource areas. As part of the SDL project, indicator streamflow gauges for all resource areas were selected based on a combination of proximity and hydrologic similarity measures (SKM 2008b). Using the SDL indicator gauges, estimates of the minimum volume diverted were calculated for all resource areas as shown below.

$$V_{\text{resource area min yr}} = SDL_{\text{resource area}} \times \frac{V_{\text{actual min yr at indicator gauge}}}{SDL_{\text{indicator gauge}}}$$

Where the terms have the following meanings :

$V_{\text{resource area min yr}}$	estimate of the volume of water able to be diverted in the minimum annual flow year for the resource area
$SDL_{\text{resource area}}$	the sustainable diversion limit volume at an 80% reliability of supply for the resource area as estimated by SKM (2008b)
$V_{\text{actual min yr at indicator gauge}}$	the volume of water able to be diverted if all SDL rules are complied with in the minimum annual flow year at the indicator gauge
$SDL_{\text{indicator gauge}}$	the sustainable diversion limit volume at an 80% reliability of supply at the indicator gauge as determined by SKM (2008a)

The resource areas, indicator gauges and SDL estimates are shown in Table 7.

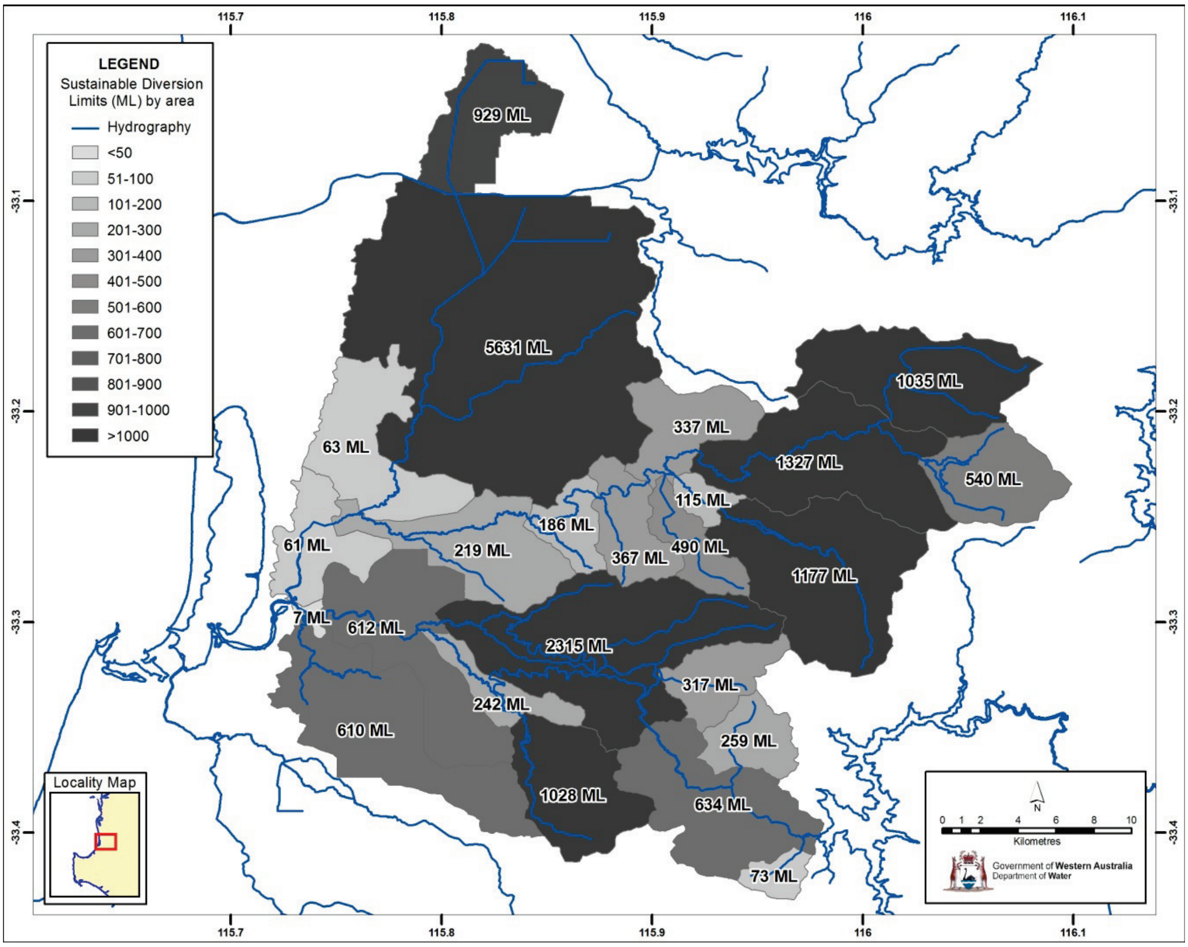


Figure 26 Sustainable diversion limits at an 80% reliability of supply (SKM 2008b)

Table 7 Sustainable diversion volume information for resource areas in the lower Collie catchment

Catchment	Resource area	Indicator gauging station	Volume diverted at an 80% reliability of supply ML/year*	Volume diverted in minimum year ML/year
Collie River	612_1_8_1	612005	73	21
	612_1_8_2	612005	259	76
	612_1_8_3	61206	469	255
	612_1_8_4	612005	300	98
	612_1_8_5	61206	1713	930
	612_1_8_6	611007	1028	312
	612_1_8_7	611007	242	73
	612_1_8_8	611007	612	186
	612_1_8_9	611007	610	185
	612_1_8_10	612032	7	2

Catchment	Resource area	Indicator gauging station	Volume diverted at an 80% reliability of supply ML/year*	Volume diverted in minimum year ML/year
Brunswick River	612_1_9_1	612004	540	76
	612_1_9_2	612022	1035	176
	612_1_9_3	612022	1327	225
	612_1_9_4	612023	1177	529
	612_1_9_5	612004	490	135
	612_1_9_6	612004	115	32
	612_1_9_7	612022	337	113
	612_1_9_8	612022	367	123
	612_1_9_9	612022	186	62
	612_1_9_10	612032	219	154
	612_1_9_11	612032	61	21
Wellesley River	612_1_10_1	612039	929	369
	612_1_10_2	612039	5631	2234
	612_1_10_3	612039	63	51

** Determined using the SDL methodology by SKM (2008a, 2008b)*

Uncertainty in the regional prediction equation for sustainable diversion volumes

The regional relationship developed by SKM (2008b) for the sustainable diversion volume was based on 140 gauged catchments. For these catchments, the SDL was calculated using the regional prediction equation and compared with the SDL calculated using gauged streamflows. The plot of the prediction equation results against the SDL calculated from observed data is presented in Figure 27. This shows a uniform distribution of residuals about the fitted regression equation.

The resulting error in the prediction equation was calculated as the ratio of the value from the equation to the observed value (Figure 28). The dashed black line in the plot shows the theoretical log-normal distribution of the error ratio. The actual error ratio closely approximates the dashed black line as per the standard assumption that errors in multiple linear regression analysis are normally distributed in the logarithmic domain.

In Figure 28 a ratio of one indicates that the prediction equation exactly matches the SDL calculated from observed streamflow data, larger than one indicates that the predicted is more than the SDL and less than one that the prediction is less than the SDL. For the catchments in the middle 80% of the theoretical distribution, the regression equation would produce an estimated SDL of between −63% and +131%

of the observed value. This is slightly greater than the level of error that is observed for the gauged catchments used to derive the regression equation

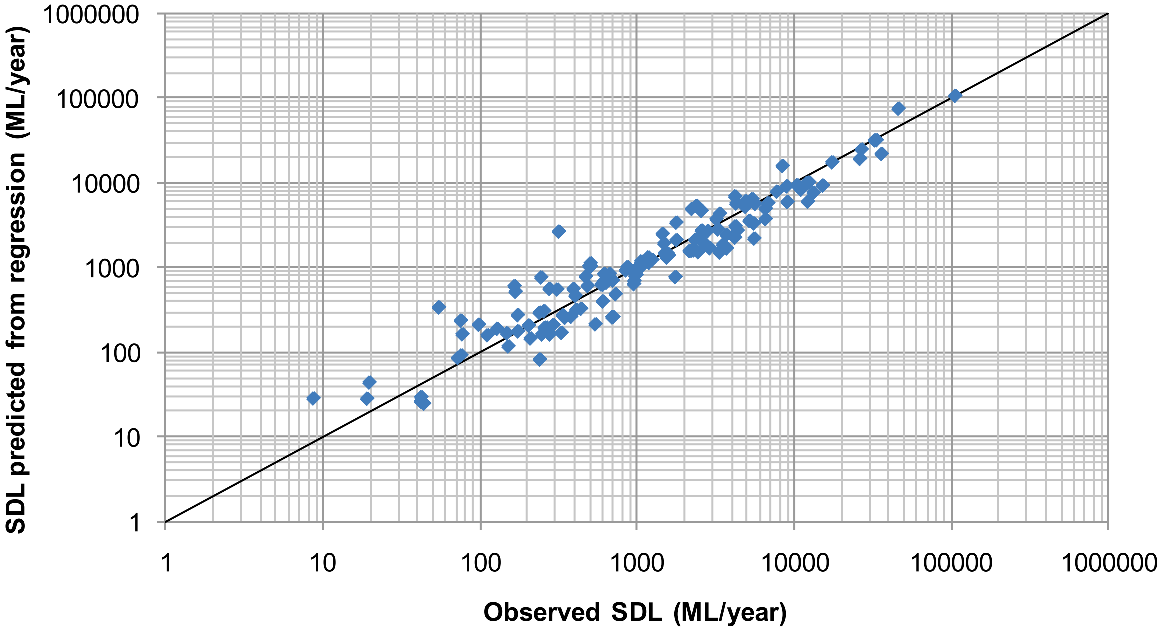


Figure 27 Comparison between the sustainable diversion limit predicted by SKM (2008b) regression equation and calculated from observed data for gauged catchments

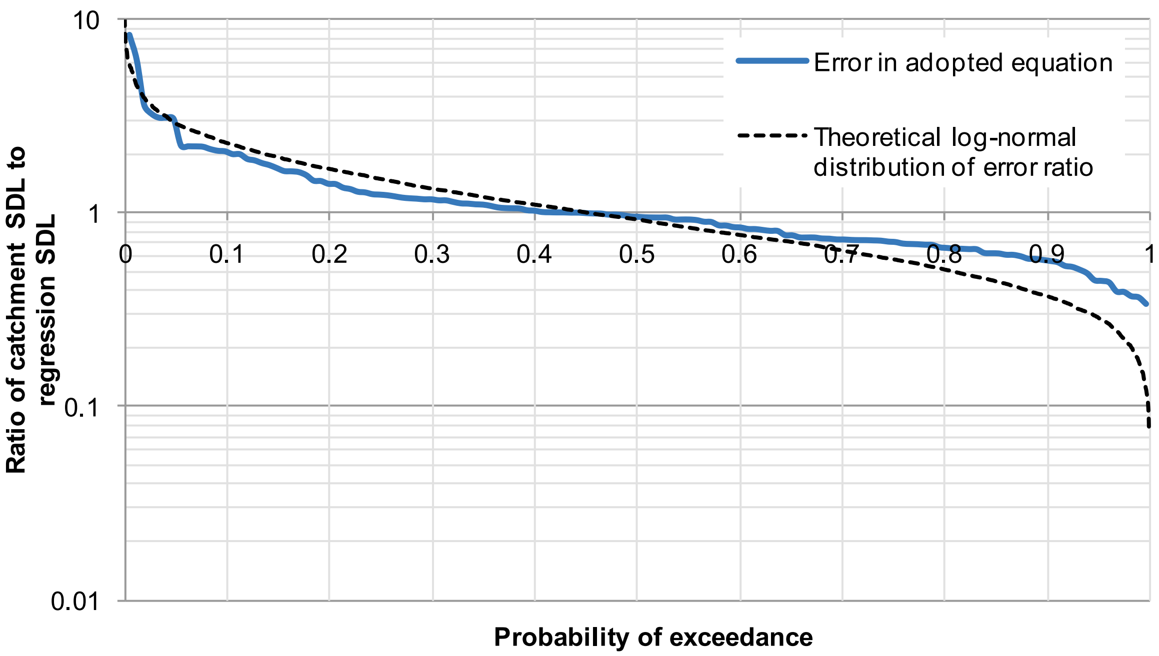


Figure 28 Ratio of the sustainable diversion limit estimated from the regression equation to the observed value for gauged catchments

3.3 Application to the lower Collie area

The SDL method was developed for areas with low levels of surface water use and modification (including regulation). An assessment of the current level of licensed and unlicensed surface water use needs to be made to decide if sustainable diversion limits are an appropriate sustainable yield estimation method.

Application of the SDL ‘rules’ to some areas of the lower Collie may be problematic as many of the coastal plain streams have been modified to increase their drainage capacity. The Wellesley River in particular is highly modified. A large artificial drainage network has also been established on the coastal plain.

As the SDL approach is based on maintaining the existing flow regime, its application to highly modified catchments needs to be assessed against defined management objectives for each area. Factors which may affect its application include:

- the ecological values of artificial drains
- whether abstracting water from artificial drains would improve or worsen downstream water quality
- whether abstraction outside the constraints of the SDL approach could provide a different flow regime resulting in an improved ecological environment.

The SDL volume is considered appropriate for application in catchments with low levels of surface water use, but the ‘rules’ surrounding abstraction may need to be considered on a case-by-case basis.

The lower Collie River is a regulated river with the Wellington Dam on the main channel (Wellington Dam demarcates the boundary of the lower Collie catchment). Although the SDL for the areas downstream of the dam have been estimated using a regional relationship and are therefore based on catchment flows, the regulation and management of the dam has resulted in a significantly modified flow regime (notably increased summer flows) and benefits may be gained from abstraction outside the constraints of the SDL approach.

4 Future climate

South-west Western Australia has experienced a drying climate since about 1975, with a reduction in annual rainfall in comparison with the long-term mean, and increased temperatures in the latter part of the 20th century. A subsequent reduction in runoff has been observed. The relationship between the reduction in runoff and the reduction in rainfall is non-linear.

In November 2004, the Water Resources Allocation Committee (of the then Water and Rivers Commission) endorsed an allocation note outlining the adoption of a standard, 28-year data period of 1975 to 2003 for surface water management decisions in south-west Western Australia (Loh 2004). This period was selected to provide reliable and '… unbiased estimates of the statistical properties of hydrologic data, expected to occur over the next ten years …'. Underlying this is the concept of a stationary climate where hydrologic data is expected to display variability within the same range experienced from 1975 to 2003.

Almost all global climate models (GCMs) used by the Intergovernmental Panel on Climate Change (IPCC) predict that south-west Western Australia will experience an even drier and warmer future (CSIRO 2009). This means that water resource assessments for the future need to be based on the most appropriate future climate scenarios rather than predications based on what has occurred previously.

The following sections look at the development of appropriate future climate scenarios and how these may affect runoff and water availability. Future estimates of streamflow and diversion volumes are assessed relative to the estimates derived for the historical baseline period of 1975 to 2007 – as outlined in section 2 and section 3. For convenience, this historical 33 year period is referred to as being 'centred on 1990'.

4.1 South-west Western Australia sustainable yields project

The CSIRO south-west Western Australia sustainable yields project (CSIRO 2009) produced reports examining the likely water yield of surface water and groundwater catchments in the south-west of Western Australia as a result of future climate changes and land management changes. As part of this project, climate (rainfall and areal potential evapotranspiration (APET)) and streamflow data representative of 2030 were produced.

The climate data was generated on 0.05° x 0.05° (approximately 5 km x 5 km) grid cells. Historical gridded daily climate data, interpolated from point measurements made by the Bureau of Meteorology, was obtained from 1 January 1975 to 31 December 2007 from the SILO data drill of the Queensland Government Department of Environment and Resource Management (<http://www.longpaddock.qld.gov.au/silo>). CSIRO (2009) refers to the historical baseline climate as Scenario A.

Global warming projections were derived consistent with the approach used by the IPCCs *Fourth assessment report* (known as AR4) (IPCC, 2007). Three warming scenarios outlining the change by ~2030 relative to ~1990 were examined (Charles et al 2010):

- low global warming of 0.7 °C (relates to the low end of the IPCC 'SRES B1' scenario)
- medium global warming of 1 °C (average of the low and high global warming scenarios)
- high global warming of 1.3 °C (relates to the high end of the IPCC 'SRES A1T' scenario).

Climate outputs from the 15 IPCC AR4 global climate models for the three warming scenarios that produced daily data were assessed. From these, future climate scenarios were generated by CSIRO (2009) by rescaling the historical climate data on a seasonal, daily and percentile basis. This produced 45 (15 GCMs by 3 global warming scenarios) series of daily rainfall and areal potential evapotranspiration that have the same length of data (33 years) and the same sequence of daily climate as the historical climate. CSIRO (2009) refer to these future climate scenarios as Scenario C.

It is important to emphasise that the future climate scenarios are not a prediction of the climate over the next 33 years, nor are they a forecast of the climate at 2030, but rather they are scenarios of observed data scaled by projected global temperature change between 1990 and 2030. Climate statistics for the scaled 33 years of data were reported in CSIRO (2009). For convenience, the statistics for this period are referred to as being 'centred on 2030'.

The historical and future climate data was used as input to calibrated Sacramento and IHACRES lumped conceptual rainfall-runoff models. The rainfall-runoff models were run on the 0.05° x 0.05° grid and the results were aggregated and averaged to report at a surface water catchment scale. All rainfall-runoff models were used in predictive mode with the projected climate to provide estimates of future runoff.

As of mid July 2010, the gridded climate data used by CSIRO (2009) is not publicly available. However the Department of Water has access to the historical and future climate and modelled runoff series at selected gauging stations used for model calibration and at additional streamflow reporting nodes. Streamflow reporting nodes are locations for where climate and runoff time series were produced but where calibration was not undertaken, even though they may coincide with a gauging station location.

4.2 Application of the sustainable yields project to the lower Collie area

Scenarios for assessment

Climate and runoff data representative of 2030 from the CSIRO south-west Western Australia sustainable yields project (CSIR0 2009) was available for the gauging stations and streamflow reporting nodes shown in Figure 29. The information from these sites was used to estimate future water yields in the lower Collie area.

The 15 global climate models provide a wide range of plausible future projections of rainfall and APET, and subsequently the range in runoff is also large. To ensure this variability is encompassed in the results, and the vulnerabilities of the water resources to these future climate projections is adequately assessed, a subset of the scenarios were selected to simplify the reporting process while still representing the range of impacts.

Three future climate scenarios (‘wet’, ‘median’ and ‘dry’ scenarios) were selected from a combination of the 45 scenarios produced by CSIRO (2009) based on the change in mean annual rainfall compared with the historical baseline climate. The wet, median and dry scenarios are defined as the 90th, 50th and 10th percentile of the change in mean annual rainfall. This is determined by ranking the change in mean annual rainfall for all 45 series from highest to lowest and selecting the 5th highest, 23rd highest and the 41st highest (5th lowest) values. The rainfall selected for each catchment can be chosen from different GCMs and different warming scenarios. The runoff sequences for the wet, median and dry scenarios are the runoff sequences generated by the CSIRO (2009) rainfall-runoff modelling with the selected wet, median and dry scenario rainfall.

The wet, median and dry scenarios were assessed in reference to the simulated historical baseline rainfall and runoff (referred to as Scenario A in CSIRO (2009)). The relative reductions between the simulated historical runoff and future runoff are applied to the observed streamflow statistics. This was necessary to ensure consistency when the future scenario results are compared to existing outputs, such as sustainable diversion limits, developed using gauged streamflow data.

The GCM and warming scenario that was selected for the wet, median and dry scenarios is shown for the gauged sites in the lower Collie area in Table 8. Explanation of the GCM names is given in Appendix B. The range of changes projected in the mean annual rainfall and mean annual streamflow under the wet, median and dry scenarios are also provided. The percentage change values are relative to the historical baseline period of 1975 to 2007.

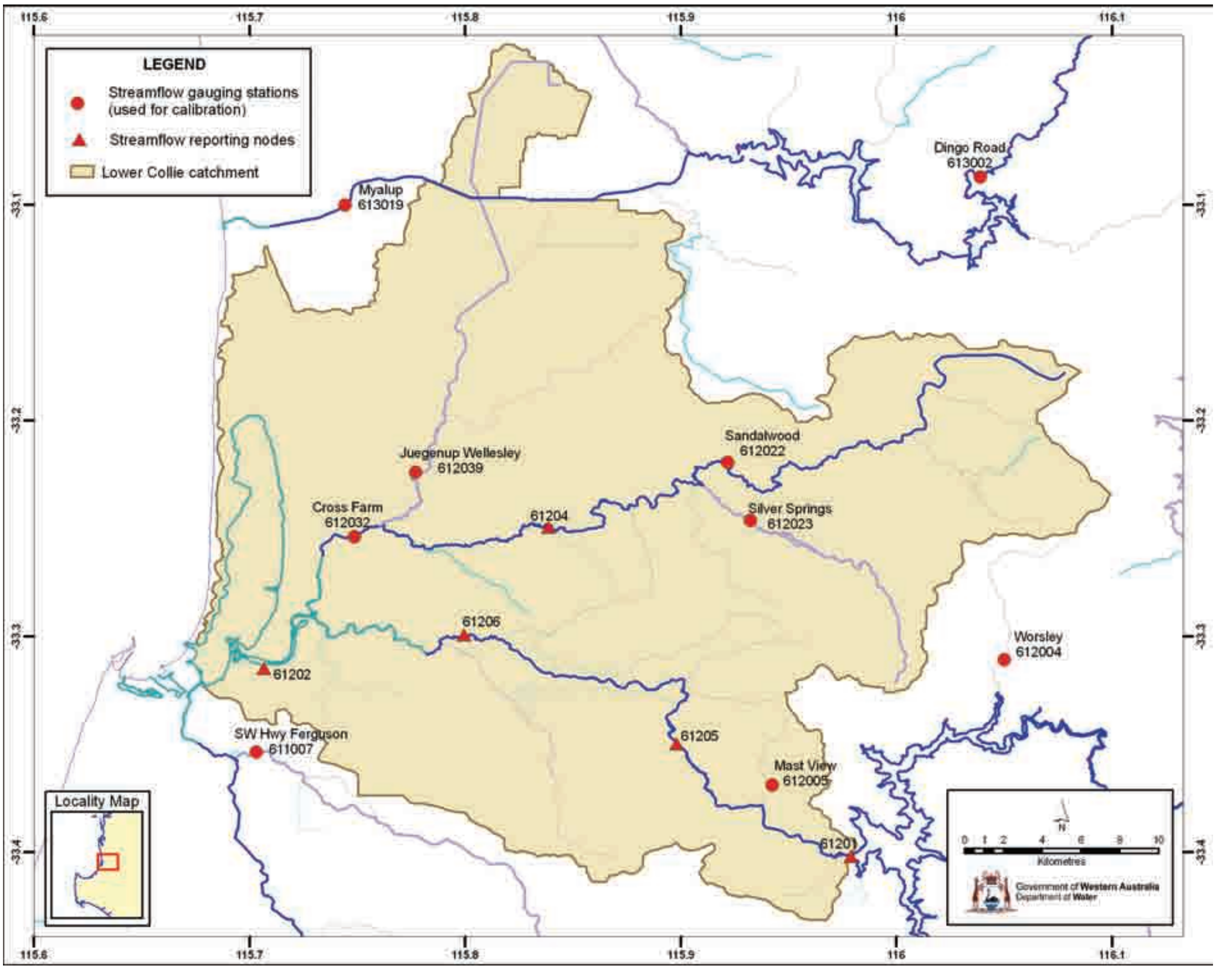


Figure 29 Streamflow gauging stations used in calibration (6 digit numbers) and streamflow reporting nodes (5 digit numbers) where future climate and runoff estimations were made by CSIRO (2009)

Across the lower Collie catchment the scenarios selected show the average change from the 1975 to 2007 period:

- Wet scenario: −2% change in mean annual rainfall and a −6% change in mean annual runoff
- Median scenario: −9% change in mean annual rainfall and a −24% change in mean annual runoff
- Dry scenario: −15% change in mean annual rainfall and a −40% change in mean annual runoff.

The uncertainty in the future climate projections can be seen in the variation of the rainfall (from 1% to 16% reduction in mean annual rainfall). The non-linear response between rainfall and runoff is also evident, in addition to the spatial variability, in the hydrologic response (from 5% to 49% reduction in mean annual streamflow) between the three scenarios.

Table 8 Change in mean annual rainfall and streamflow from the historical baseline of 1975 to 2007 for 2030 climate scenarios

Gauging station	Scenario	Mean annual rainfall	Mean annual streamflow	GCM, warming scenario
611007	Historical	914 mm	24 210 ML	
	Wet	−2%	−6%	NCAR_PCM, 1 °C
	Median	−8%	−22%	GFDL, 0.7 °C
	Dry	−15%	−39%	GFDL, 1.3 °C
612004	Historical	938 mm	4 937 ML	
	Wet	−1%	−5%	NCAR_PCM, 1 °C
	Median	−8%	−23%	GFDL, 0.7 °C
	Dry	−15%	−40%	GFDL, 1.3 °C
612005	Historical	1 024 mm	1 541 ML	
	Wet	−2%	−8%	NCAR_PCM, 1 °C
	Median	−9%	−33%	MRI, 0.7 °C
	Dry	−15%	−49%	MIUB, 1 °C
61206	Historical	971 mm	26 869 ML	
	Wet	−2%	−6%	NCAR_PCM, 1 °C
	Median	−9%	−27%	CCCMA_T47, 1 °C
	Dry	−15%	−40%	GFDL, 1.3 °C
612022	Historical	975 mm	23 721 ML	
	Wet	−2%	−6%	NCAR_PCM, 1 °C
	Median	−8%	−22%	GFDL, 0.7 °C
	Dry	−15%	−39%	GFDL, 1.3 °C
612023	Historical	1 004 mm	11 572 ML	
	Wet	−2%	−5%	NCAR_PCM, 1 °C
	Median	−8%	−21%	GFDL, 0.7 °C
	Dry	−15%	−37%	GFDL, 1.3 °C
612032	Historical	895 mm	117 688 ML	
	Wet	−2%	−5%	NCAR_PCM, 1 °C
	Median	−9%	−23%	GISS_AOM, 0.7 °C
	Dry	−15%	−38%	GFDL, 1.3 °C
612039	Historical	813 mm	61 240 ML	
	Wet	−1%	−5%	NCAR_PCM, 1 °C
	Median	−9%	−22%	MRI, 0.7 °C
	Dry	−16%	−36%	GFDL, 1.3 °C

Time-frame for assessment

For the future scenario modelling to be able to be used in an allocation planning setting, thought needs to be given to the maximum 'life' of the water yield estimates. It is envisaged that the allocation plan that has been produced using this round of hydrology work will be superseded with a statutory water management plan in the near future and therefore it is expected that a 10-year period will be sufficient in this round of surface water planning (pers. comm. C Mason). Consequently, estimates of future water yields centred on 2020 are also required for the lower Collie area.

Since no explicit projection for 2020 is given in the GCM modelling, a linear interpolation of the runoff between the historical baseline scenario and the wet, median and dry scenarios at 2030 was used to construct 2020 values. The interpolation was made for each day. This assumes that there is a linear growth in temperature change between conditions centred on 1990 and centred on 2030. For example, a high global warming scenario of 1.3 °C at 2030 is an annual growth of 0.0325 °C per year, or 0.325 °C per decade. The interpolation is explained pictorially for mean annual runoff in Figure 30. Climate statistics for the scaled 33 years of data are reported and are referred to as being 'centred on 2020'.

The range of change in the mean annual runoff under the wet, median and dry scenarios for the 2020 climate is provided for sites in the lower Collie area in Table 9. The percentage change in the mean annual runoff is relative to the historical baseline period of 1975 to 2007. The interpolation between the historical baseline climate and the wet, median and dry 2030 scenarios is evident with the percentage change in Table 9 being 75% of the change in Table 8.

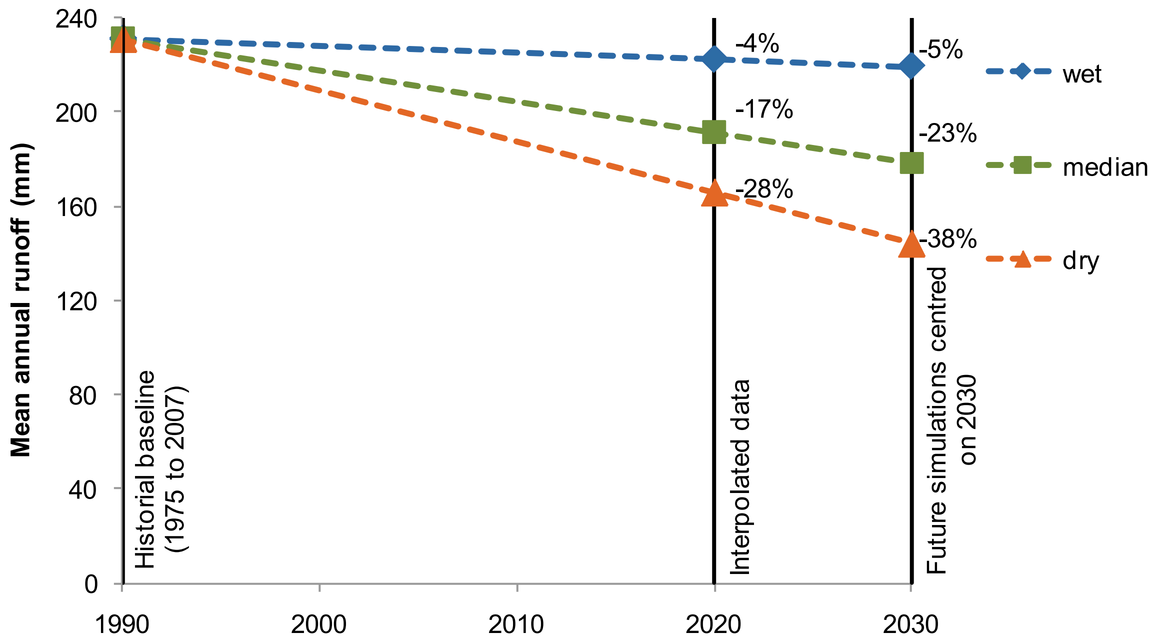


Figure 30 Interpolation between historical baseline centred on 1990 and future scenarios centred on 2030 to represent a climate centred on 2020 (data is for Cross Farm, 612032)

Table 9 Percentage change in mean annual runoff from the historical baseline of 1975 to 2007 for future climate scenarios centred on 2020

Gauging station	Wet scenario %	Median scenario %	Dry scenario %
611007	−4	−17	−29
612004	−4	−17	−30
612005	−6	−25	−37
61206	−4	−20	−30
612022	−4	−17	−29
612023	−4	−16	−28
612032	−4	−17	−28
612039	−3	−17	−27

Characteristics of the future runoff scenarios

To provide more insight into the range and uncertainty of future runoff scenarios at 2020 and 2030, the gauging station at Cross Farm on the Brunswick River was studied in more depth. The results are provided in this section.

The future runoff scenarios were assessed in relation to the historical baseline (1975 to 2007).

The combined observed and modelled annual streamflow (1975 to 2007) has an estimated mean annual flow of 118 GL. The minimum recorded annual flow of 36.7 GL was recorded in 2001 and the maximum recorded annual flow was 241 GL recorded in 1996. The coefficient of variation of annual flows is 0.42 and the natural variability in annual flows can be seen in Figure 31. A different way of demonstrating this variability is in a box plot (Figure 32) which shows the range of annual streamflows experienced.

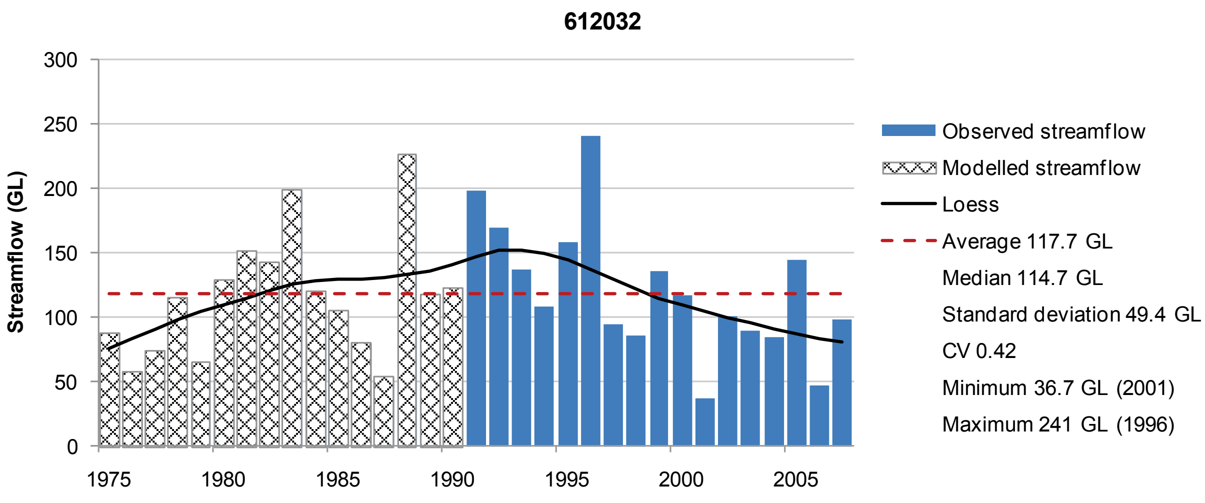


Figure 31 Annual flow series, including observed and estimated data, at Cross Farm (612032) on the Brunswick River

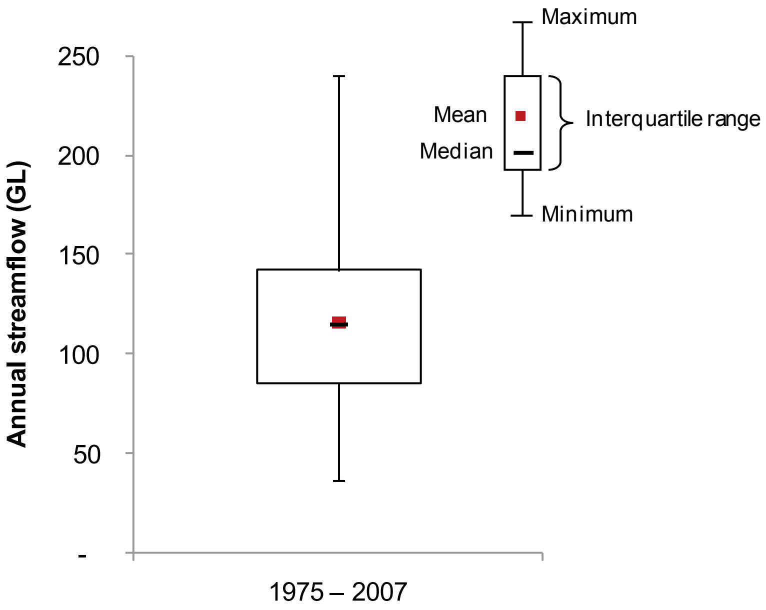


Figure 32 Box plot of observed and estimated annual streamflow characteristics for Cross Farm (612032)

There are a possible 45 future scenarios (15 GCMs by 3 global warming scenarios) and the variation within the annual streamflow is large (Figure 33). Of the 45 scenarios only three project a mean annual flow greater than the observed mean. The range of annual streamflow is also greater under the future scenarios than the observed range with the minimum annual flow up to 59% less than the observed minimum and the maximum annual flow only up to 3% greater than the observed maximum.

Three future climate scenarios (a 'wet', 'median' and 'dry') were defined from a combination of the 45 scenarios in Figure 33 and subsequently analysed. These three scenarios take into account the variability in the results from the GCMs while simplifying the analysis and reporting.

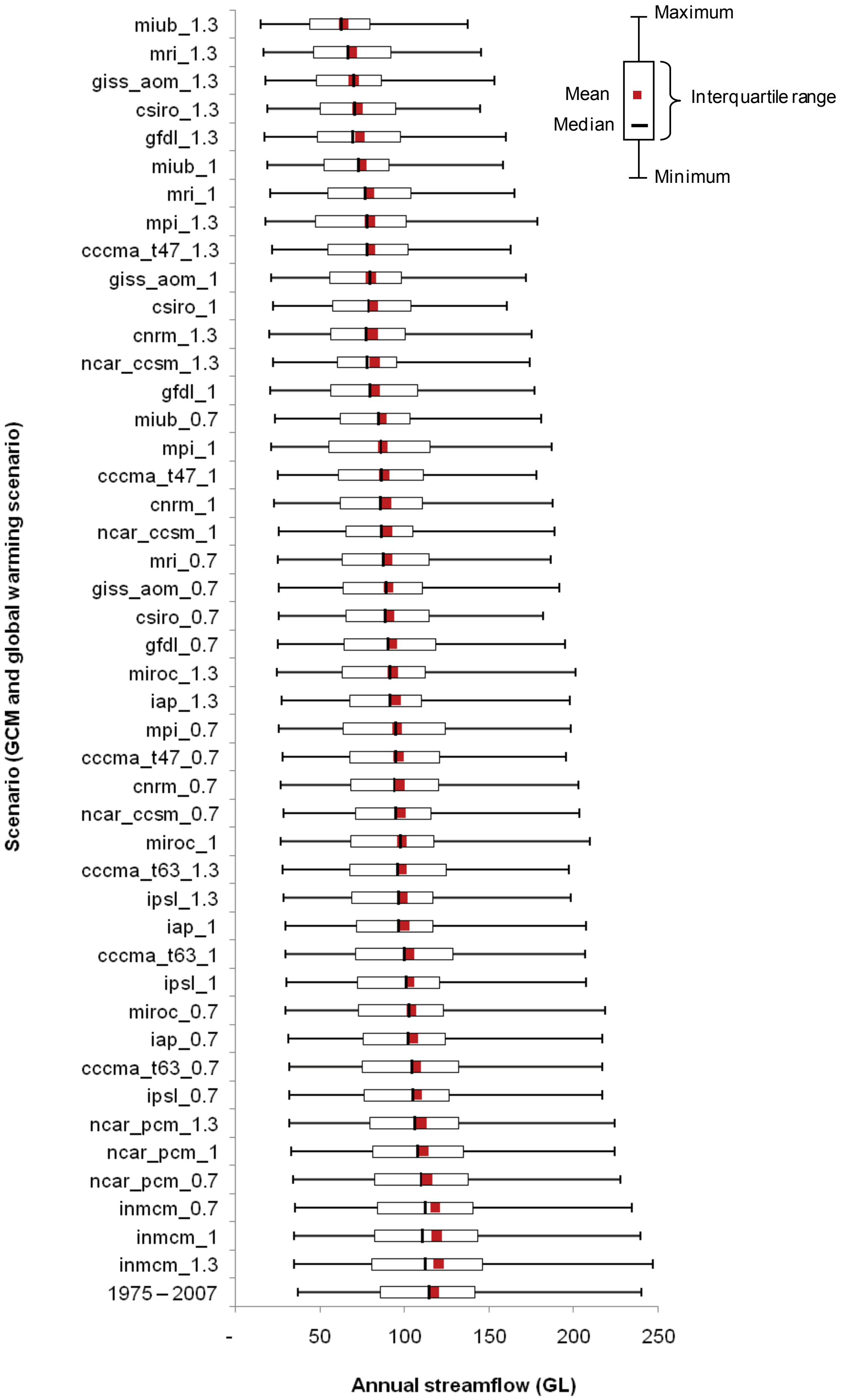


Figure 33 Box plots of annual streamflow characteristics for 45 future scenarios in relation to the 1975 to 2007 data for Cross Farm (612032)

The range of flows experienced under the future projections can be seen in the sequences of wet and dry years within the 33-year period. Significant variations can be seen in the annual streamflows and the estimated volume of water able to be diverted under the different conditions. A summary of the average of the 33-year period and the wettest and the driest one-year and three-year periods for the historical and selected wet, median and dry future scenarios are given in Table 10.

Table 10 Streamflow volumes for the historical and future scenarios centred on 2030

	Statistic	**Volume and change in volume**
Historical (1975 to 2007)	Long-term average (33-year period)	118 GL
	Minimum	36.7 GL
	Maximum	241 GL
	Wettest 3-year period	507 GL
	Driest 3-year period	219 GL
Wet scenario	Change in long-term average from current	−5%
	Change in minimum from current	−8%
	Change in maximum from current	−1%
	Change in wettest 3-year period from current	−3%
	Change in driest 3-year period from current	−6%
Median scenario	Change in long-term average from current	−23%
	Change in minimum from current	−29%
	Change in maximum from current	−19%
	Change in wettest 3-year period from current	−20%
	Change in driest 3-year period from current	−25%
Dry scenario	Change in long-term average from current	−38%
	Change in minimum from current	−53%
	Change in maximum from current	−32%
	Change in wettest 3-year period from current	−28%
	Change in driest 3-year period from current	−43%

The probability of achieving certain flow regimes also changes under the future climate scenarios. For example the historical minimum annual flow is 36.7 GL and occurs once in the 33-year historical period, giving a 3% probability of occurrence in any given year. In the future projections the probability of getting an annual flow lower than the historical minimum is increased. Under the wet scenario two of the 33 years will be less than the historical minimum (6% chance of occurrence in any given year). This chance is increased further under the median and dry future scenarios with the probabilities of the annual flows being lower than the historical minimum of 15% and 21% respectively.

This result can also be demonstrated by comparing histograms of the annual flows under each scenario. These show the frequency of annual streamflows that fall within 25 GL intervals. The frequencies have been normalised to give a range of 0 to 1 for ease of comparison between plots. Histograms are shown for each scenario as well as each timeframe (Figure 34).

The histograms display a slight positive skew to the distribution. This indicates that the mean of the streamflow is greater than the median and there are relatively few higher annual flows in the drier scenarios, and as time progresses. The absence of higher annual flows (above 150 GL per year) and increase in the occurrence of lower annual flows (below 50 GL per year) can be seen in the future scenarios. The decrease in the range of streamflow is particularly apparent in the dry scenario for 2030. The histograms also highlight that the mean annual flow decreases through time and from the wet to dry scenarios in comparison with the historical.

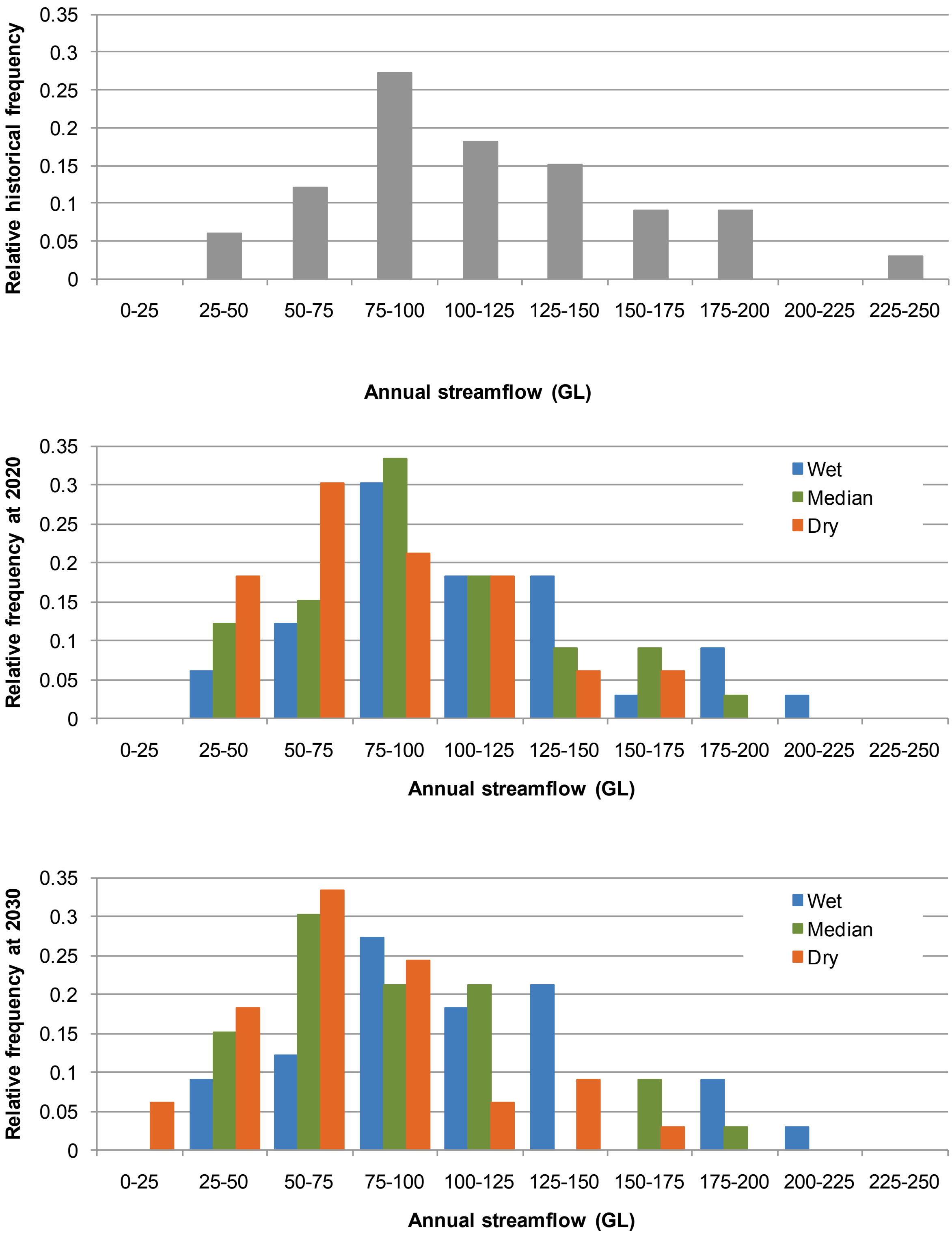


Figure 34 Histograms of annual streamflow for Cross Farm (612032) for the historical period and wet, median and dry future climate scenarios centred on 2030 and interpolated at 2020

Allocation planning scenario

The 45 future climate scenarios provide a range of plausible scenarios of how the future climate may develop. As described earlier, three climate scenarios, wet, median and dry, were defined and used for more detailed analysis. In each of these scenarios, the main outcome is that river flows will be reduced and hence less surface water will be available.

To be able to make practical use of the results, a single scenario is chosen to reliably inform allocation planning decisions. The selection of the scenario needs to be based on comparison of recent climate trends with the scenarios and an assessment of the acceptable level of risk to supply, the water resource and social and ecological systems.

Allocation decisions based on the ‘dry’ scenario risks restricting current and future development. Using the ‘wet’ scenario has the opposite risk of over-estimating the water that will be available. It was decided that the ‘median’ scenario represented the best balance of risk and so it has been adopted for use in allocation planning for the lower Collie area (pers. comm. C Mason). The implications of this for streamflow and sustainable diversion limits are discussed in the following sections.

4.3 Annual streamflow — future climate

The median future scenario estimates were assessed further to provide an indication of the possible reduction in the mean annual flow and the minimum annual flow at the indicator gauging stations used in this study (Table 11). The percentage reduction in mean annual streamflow is less than the percentage reduction in the minimum annual streamflow.

Table 11 Change in mean and minimum annual streamflow from the current volumes, for the median future climate scenario centred on 2020 and 2030

Site		Current	2020	2030
612022	Mean annual streamflow volume (ML)	23 721	19 725	18 393
	Change in mean annual streamflow volume from current (%)		−16.8	−22.5
	Minimum annual streamflow volume (ML)	6 934	5 256	4 697
	Change in minimum annual streamflow volume from current (%)		−24.2	−32.3
612023	Mean annual streamflow volume (ML)	11 572	9 716	9 097
	Change in mean annual streamflow volume from current (%)		−16.0	−21.4
	Minimum annual streamflow volume (ML)	3 865	2 893	2 557
	Change in minimum annual streamflow volume from current (%)		−25.1	−33.9
612032	Mean annual streamflow volume (ML)	117 688	97 476	90 738
	Change in mean annual streamflow volume from current (%)		−17.2	−22.9
	Minimum annual streamflow volume (ML)	36 702	29 002	26 157
	Change in minimum annual streamflow volume from current (%)		−21.0	−28.7
612039	Mean annual streamflow volume (ML)	61 240	51 040	47 640
	Change in mean annual streamflow volume from current (%)		−16.7	−22.2
	Minimum annual streamflow volume (ML)	19 134	15 313	14 039
	Change in minimum annual streamflow volume from current (%)		−20.0	−26.6
612005	Mean annual streamflow volume (ML)	1 541	1 155	1 026
	Change in mean annual streamflow volume from current (%)		−25.1	−33.4
	Minimum annual streamflow volume (ML)	229	125	90
	Change in minimum annual streamflow volume from current (%)		−45.7	−61.0

Site		Current	2020	2030
61206	Mean annual streamflow volume (ML)	26 869	21 476	19 678
	Change in mean annual streamflow volume from current (%)		−20.1	−26.8
	Minimum annual streamflow volume (ML)	10 574	7 858	6 952
	Change in minimum annual streamflow volume from current (%)		−25.7	−34.3
611007	Mean annual streamflow volume (ML)	24 953	20 757	19 358
	Change in mean annual streamflow volume from current (%)		−16.8	−22.4
	Minimum annual streamflow volume (ML)	10 311	7 924	7 128
	Change in minimum annual streamflow volume from current (%)		−23.2	−30.9
612004	Mean annual streamflow volume (ML)	4 937	4 083	3 798
	Change in mean annual streamflow volume from current (%)		−17.3	−23.1
	Minimum annual streamflow volume (ML)	555	360	295
	Change in minimum annual streamflow volume from current (%)		−35.1	−46.8

Irrigation

An assumption was made that the irrigation supplied and subsequent irrigation return would remain the same under the future climate scenarios as that estimated in Section 2.6.

The reliance on irrigation supply may increase if south-west Western Australia becomes even drier and warmer in the future, which almost all global climate models predict will occur. Conversely, the volume of irrigation water use, and hence return flows, would reduce if water use efficiency was promoted and/or the open channel irrigation supply network was piped.

Regionalisation

The mean annual flow and minimum annual flow have been regionalised to the resource areas using the approach outlined in Section 2.5.

To ensure consistency between the future scenario estimates and the observed historical values, the relative reductions between the simulated historical runoff and future runoff were applied to the observed streamflow statistics.

A manual check was made to ensure that the flows for the individual resource areas add up to the simulated future scenario flows at known points (calibration gauges). For nested catchments (catchments that have an upstream gauged subcatchment), the observed upstream flow time-series was subtracted from the downstream flow time-series before the manual check was performed. This approach identified inconsistencies in the minimum annual flows where the difference in streamflow volumes between nested catchments resulted in a very small, or negative, volume of water to distribute over the resource areas. This was due to the modelling approach undertaken in the south-west sustainable yields project (CSIRO 2009) where each site was calibrated and simulated independently of nested catchments. In addition, there was greater error in calibration to the individual annual flows than to the mean annual flows (CSIRO 2009). If this problem occurred, the streamflow in the resource area was assigned a value of zero.

The regionalised mean and minimum annual flow estimates under the median scenario centred on 2020 are shown for each resource area in Table 12 and spatially in Figure 35 for mean annual flow and Figure 36 for the minimum annual flow.

Table 12 Annual flow information for resource areas in the lower Collie catchment under the median scenario centred on 2020

Catchment	Resource area	Indicator gauging station	Mean annual flow ML/year	Minimum annual flow ML/year
Collie River	612_1_8_1	612005	466	51
	612_1_8_2	612005	1 192	128
	612_1_8_3	61206	2 586	1 202
	612_1_8_4	612005	3 825	294
	612_1_8_5	61206	14 244	6 747
	612_1_8_6	611007	9 714	2 756
	612_1_8_7	611007	3 980	1 164
	612_1_8_8	611007	6 800	1 610
	612_1_8_9	611007	7 900	3 676
	612_1_8_10	612032	95	45
Brunswick River	612_1_9_1	612004	4 715	833
	612_1_9_2	612022	6 106	1 734
	612_1_9_3	612022	9 032	2 801
	612_1_9_4	612023	9 773	2 990
	612_1_9_5	612004	3 616	797
	612_1_9_6	612004	1 517	249
	612_1_9_7	612022	3 293	1 101
	612_1_9_8	612022	3 114	1 300
	612_1_9_9	612022	3 099	801
	612_1_9_10	612032	2 146	344
	612_1_9_11	612032	851	302
Wellesley River	612_1_10_1	612039	6 026	2 891
	612_1_10_2	612039	46 065	12 721
	612_1_10_3	612039	628	361

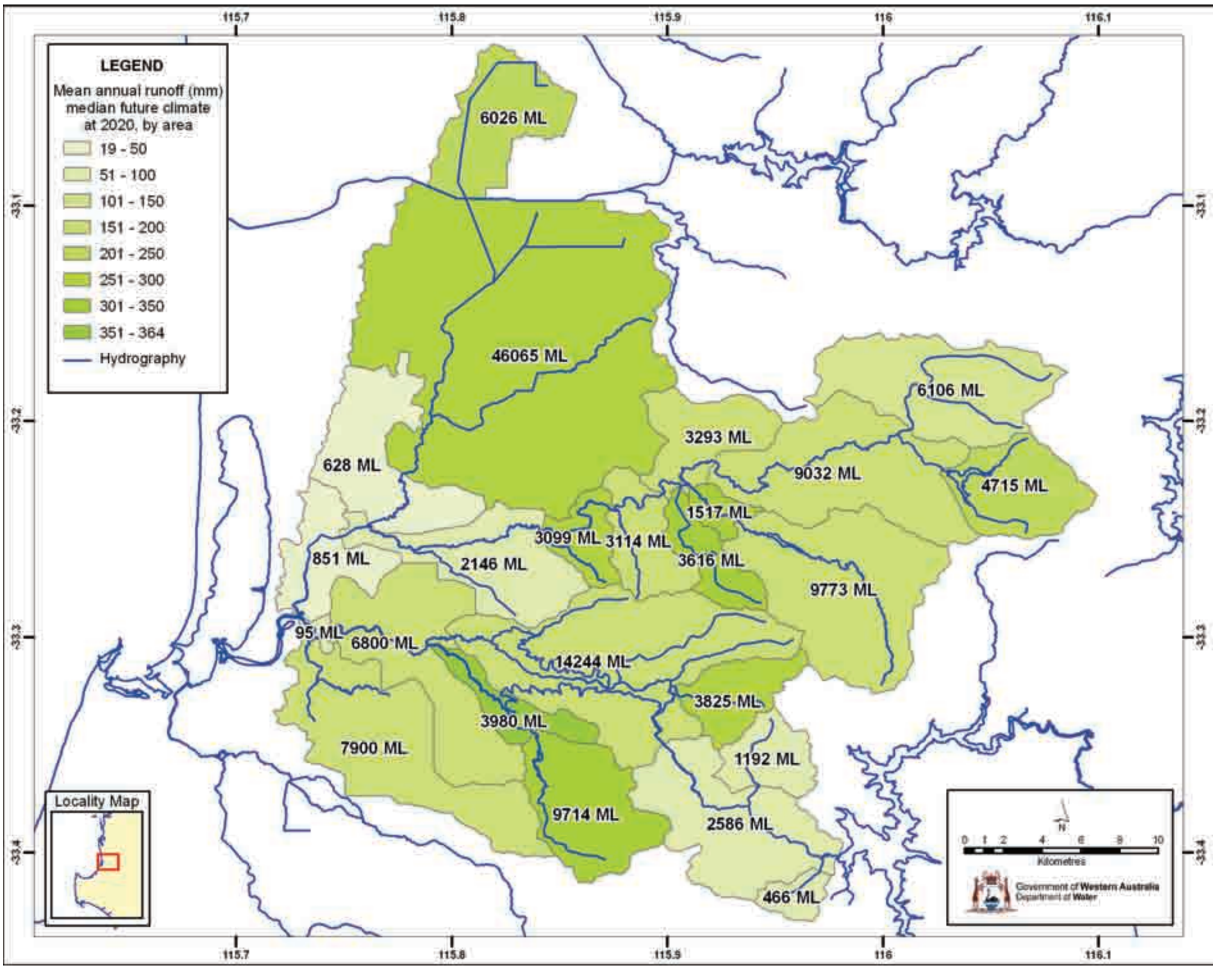


Figure 35 Mean annual runoff and flow in the lower Collie catchment under the median future climate scenario centred on 2020

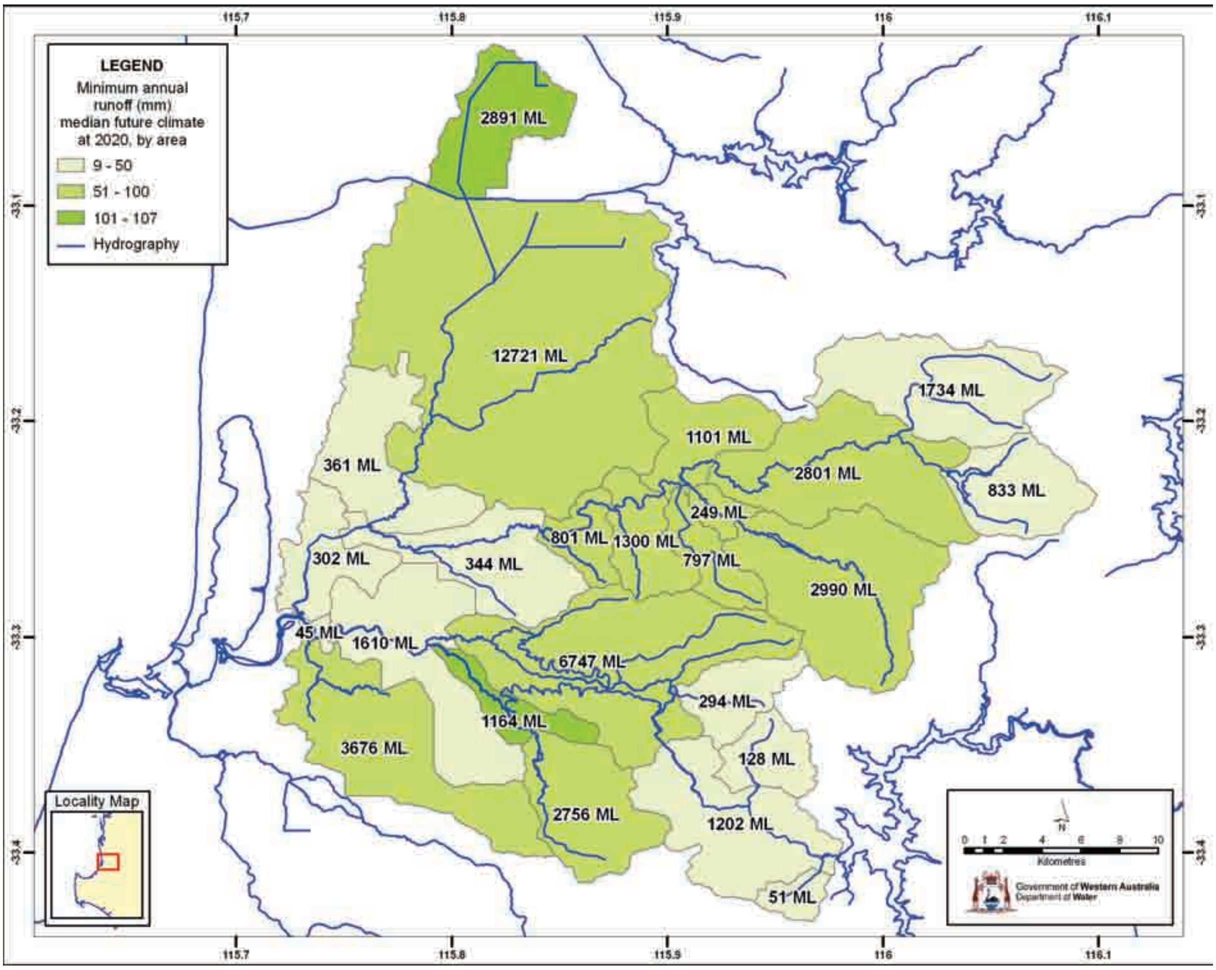


Figure 36 Minimum annual runoff and flow in the lower Collie catchment under the median future climate scenario centred on 2020

4.4 Sustainable diversion volumes — future climate

Sustainable diversion volumes, and the volume of water diverted in the minimum flow year, have been shown in Table 6, Section 3.1, for each gauging station. These were determined using observed streamflow data, so it is now necessary to assess the effect the future climate scenarios have on the volumes of water diverted by users and the volumes of water remaining in the river. The wet, median and dry scenarios were applied to the original SDL rules and volumes used the prepare Table 6.

The original SDL rules were based on the premise that the flow regime, after extractions, must be within the range of the observed (post 1975) winter fill period flow regime (SKM 2008a). Flow duration curves were used to assess the envelope of the natural variability in the flow regime.

The gauging station at Sandalwood on the Brunswick River (612022) is used as an example. The SDL rules for this site are:

- minimum flow threshold 54.9 ML/day
- maximum extraction rate 35.7 ML/day
- SDL volume of 2902 ML/year at an 80% reliability of supply.

Four plots of flow duration curves are provided (Figure 37) that show:

- grey lines for the envelope of observed flows from 1981 to 2005 (as used to determine the original SDLs)
- a thick blue line for the total flow duration curve under the current and possible future scenarios centred on 2030
- a dashed blue line for the flow duration curve post-SDL extractions.

In all four cases, the total flow duration curve after extractions remains within the observed and modelled range of streamflow. This illustrates that the SDL framework is a conservative hydrologic approach. Figure 37 also shows that the impact of SDL diversions is minor in comparison with the reduction in streamflow under the future climate scenarios.

The extent to which the flow duration curve is affected by the SDL extractions does change depending on the scenario. The most noticeable change is the percentage of time the flow is above or below the minimum flow threshold. Extractions are allowed 35% of the time based on historical data but this reduces to 21% of the time under the dry scenario.

As the time available to take water reduces, the mean annual volume able to be extracted is also reduced under each scenario at Sandalwood. Although the volume available for extraction reduces, the percentage reduction is less than the percentage reduction in water remaining in the river and the total mean annual streamflow (Table 13). The proportion of SDL to mean annual flow therefore increases under the future scenarios.

Maintaining current SDL rules under a drier flow regime not only reduces the water available but also the reliability of supply. The specified reliability of supply of 80% is based on historical flow data. Under the future scenarios, the reliability with which the annual SDL volume can be extracted is severely reduced at Sandalwood. To maintain the reliability of supply at 80%, the SDL volume would need to be significantly reduced (Table 14). The reductions are similar to the reduction in mean annual flow under the scenarios. The volume diverted in the minimum year also reduces and this demonstrates that the concept of a reliability of supply of 100% is problematic in a non-stationary climate.

The figures for Sandalwood have been reported centred on 2030. The reductions are not as severe when centred on 2020. The reliabilities of supply of the current SDL volumes and the reduction in divertible volumes required to maintain the reliability of supply at 80% under the future scenarios at 2020 and 2030 are shown for the indicator gauging stations used in this study in Appendix C.

The impact of the estimated future diversion volumes was simulated assuming all SDL rules are complied with. There is a reduced opportunity to extract water under drier flow regimes. It may be possible to extract more water by reducing the minimum flow threshold, increasing the maximum extraction rate, or extending the winter fill period to allow more opportunities for diversion.

An expert panel assessed changing the SDL rules under future climate scenarios for catchments in Victoria (SKM 2009). Due to the uncertainty in the hydrology under future warming, and hence in any ecological consequences, the panel found it difficult to justify any changes from the existing rules used to define SDLs. There was no strong ecological justification for changing the minimum flow threshold, maximum extraction rate or the winter fill period as it would result in an unacceptable level of risk to the environment.

These findings are also applicable here. Further investigation would be required by the expert panel involved in deriving SDLs for Western Australia (SKM 2008a) to review the acceptable level of risk to the environment of any changes to the SDL rules. Alternatively, if the level of surface water use approaches the SDL volume, then detailed, local investigations, such as ecological water requirement studies, are required to more accurately define, and possibly increase, the estimated sustainable yield.

Projected flow regimes at Sandalwood suggest that the current sustainable diversion volumes could be considered a reasonable estimate of available water under future scenarios if extracted within the constraints of the SDL framework (Figure 37). However users are able to extract water outside the constraints of the SDL framework which leads to increased volumes able to be extracted, increased reliabilities of supply and reduced volumes of water remaining in the river. In practice, the flow regime resulting from actual extractions will be different from the projected flow regime and there is a risk that the flow regime may be outside the envelope of natural variability. To reduce this risk, estimated diversion volumes based on the median future climate scenario have been adopted for use in allocation planning for the lower Collie area (pers. comm. C Mason).

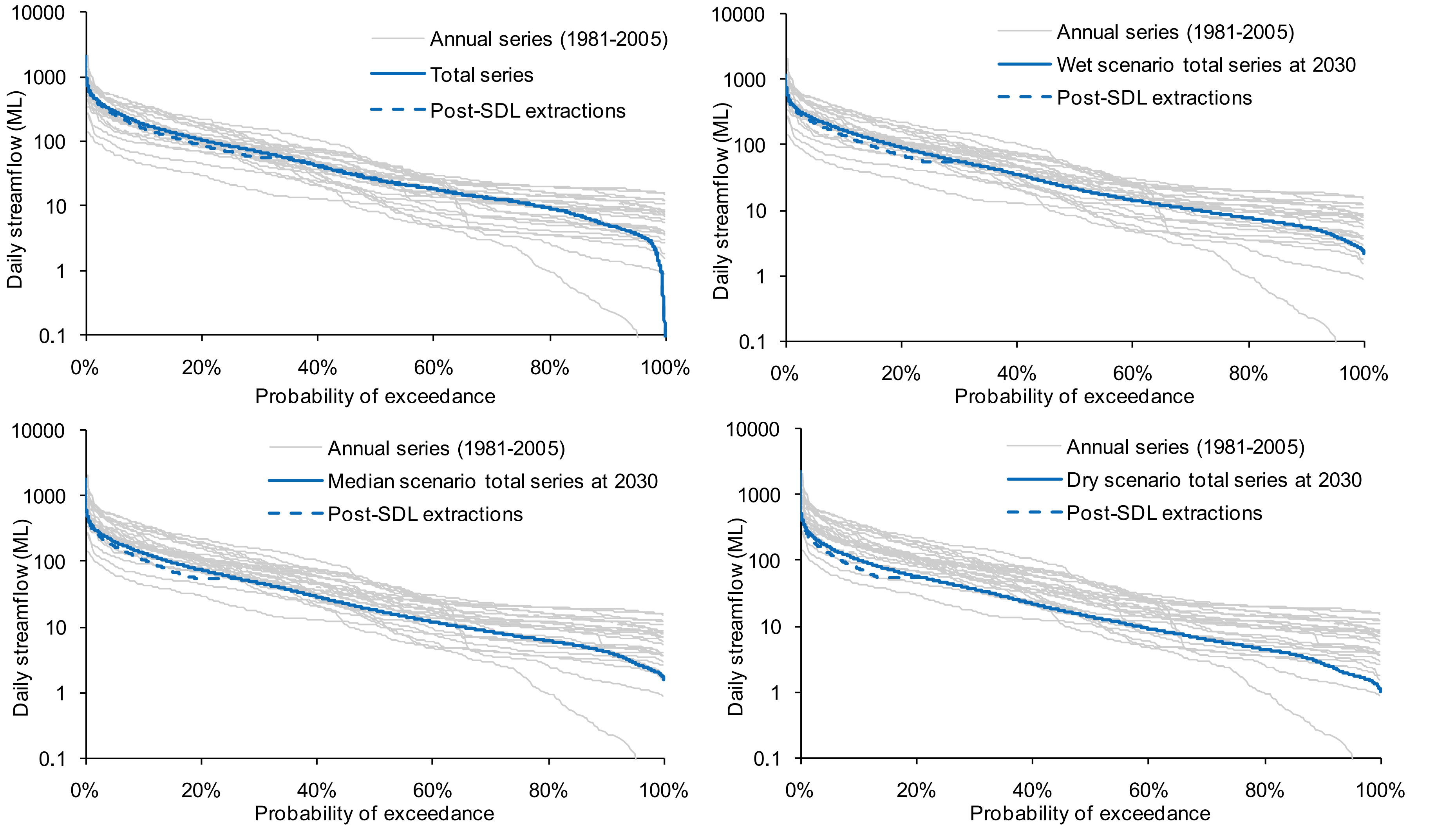


Figure 37 Flow duration curves at Sandalwood on the Brunswick River showing the current SDL volume extracted under different future scenarios centred on 2030 (grey lines show the observed year-to-year natural variability in daily streamflow)

Table 13 Change in mean annual streamflow volume, mean annual volume extracted and the mean annual volume remaining in the river based on the current SDL volumes at Sandalwood on the Brunswick River for future scenarios centred on 2030

Site		Current (1980 – 2005)	Wet	Median	Dry
612022	Mean annual streamflow volume (ML)	25 727	24 278	19 949	15 643
	Change in mean annual streamflow volume from current (%)		−5.6	−22.5	−39.2
	Mean annual volume extracted (ML)	2 679	2 617	2 308	1 809
	Change in mean volume extracted from current (%)		−2.3	−13.9	−32.5
	Mean annual volume remaining in river (ML)	23 047	21 661	17 641	13 834
	Change in volume remaining in river from current (%)		−6.0	−23.5	−40.0

Table 14 Reliabilities of supply of the current SDL volumes and the reduction in divertible volumes required to maintain the reliability of supply at 80% at Sandalwood on the Brunswick River for future scenarios centred on 2030

Site		Current (1980 – 2005)	Wet	Median	Dry
612022	Reliability of current SDL volume (%)	80	59	35	21
	Volume to maintain 80% reliability (ML)	2 902	2 607	2 020	1 157
	Reduction from current SDL to maintain 80% reliability (%)		−10	−30	−60
	Volume diverted in minimum year (ML)	476	361	159	43

Regionalisation

Volumes diverted at an 80% reliability of supply and the volume diverted in the minimum year under the median 2020 scenario have been regionalised for the 24 resource areas in the lower Collie catchment (Table15 and spatially in Figure 38). The estimates were regionalised based on scaling the estimated diversion volume under the median 2020 scenario at the indicator gauge by the ratio of the current SDL volume at a resource area to the current SDL volume at the indicator gauge. As per the analysis at Sandalwood, the volume of water available and the reliability of supply reduce under the drier scenarios and at 2030. This is shown for the indicator gauges in Appendix D. As the resource areas do not have historical data to calculate reliabilities of supply they are assumed to have the same reliabilities as the indicator gauges.

Table 15 Estimated diversion volumes for resource areas in the lower Collie catchment under the median future scenario centred on 2020

Catchment	Resource area	Indicator gauging station	Volume diverted at an 80% reliability of supply ML/year	Volume diverted in minimum year ML/year
Collie River	612_1_8_1	612005	59	8
	612_1_8_2	612005	211	30
	612_1_8_3	61206	371	204
	612_1_8_4	612005	243	41
	612_1_8_5	61206	1356	747
	612_1_8_6	611007	831	183
	612_1_8_7	611007	195	43
	612_1_8_8	611007	494	109
	612_1_8_9	611007	493	109
	612_1_8_10	612032	6	2
Brunswick River	612_1_9_1	612004	444	40
	612_1_9_2	612022	799	87
	612_1_9_3	612022	1024	111
	612_1_9_4	612023	981	303
	612_1_9_5	612004	406	7
	612_1_9_6	612004	95	2
	612_1_9_7	612022	262	6
	612_1_9_8	612022	286	6
	612_1_9_9	612022	145	3
	612_1_9_10	612032	184	10
	612_1_9_11	612032	52	13

Catchment	Resource area	Indicator gauging station	Volume diverted at an 80% reliability of supply ML/year	Volume diverted in minimum year ML/year
Wellesley River	612_1_10_1	612039	826	298
	612_1_10_2	612039	5004	1806
	612_1_10_3	612039	56	4

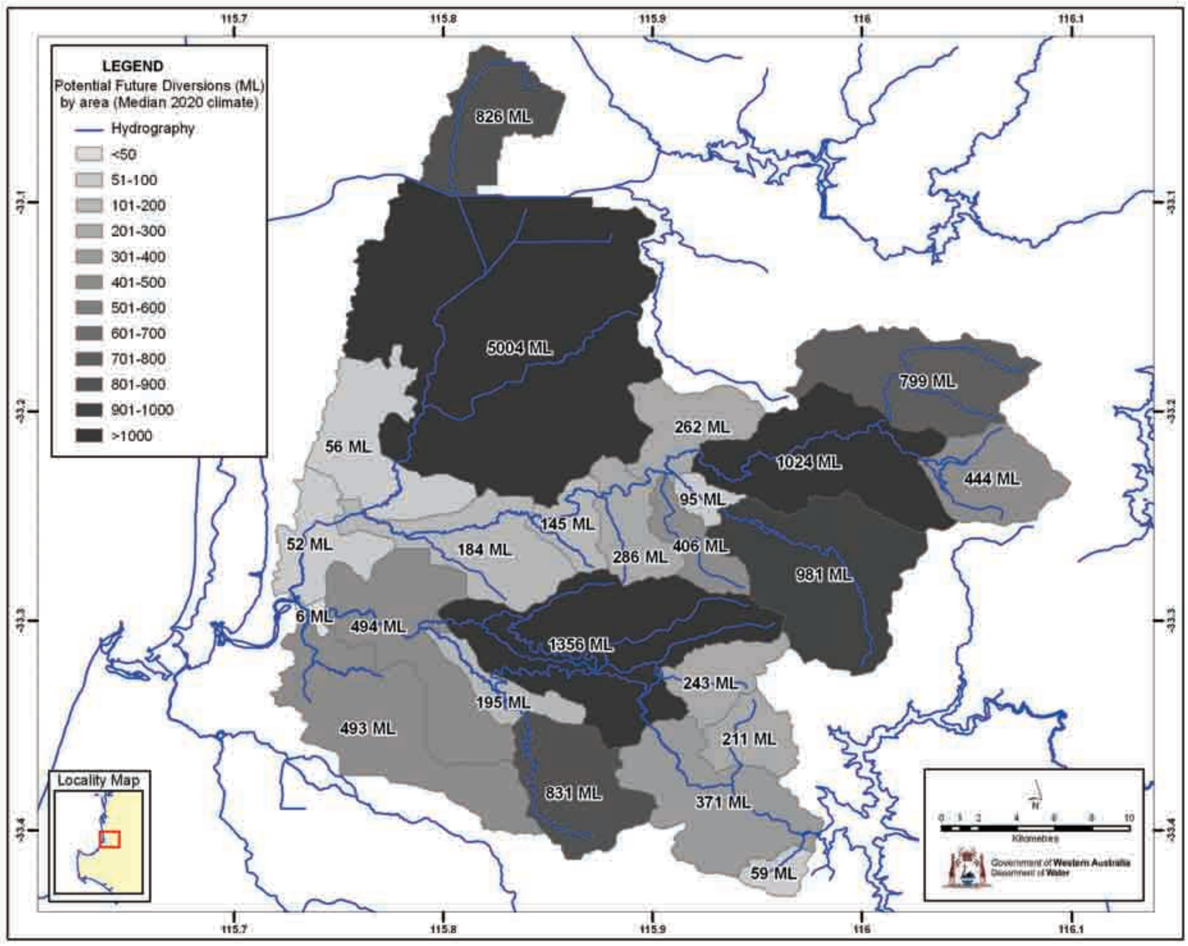


Figure 38 Estimated future diversion at an 80% reliability of supply under a median future climate scenario centred on 2020

4.5 Further work

There is currently no definitive approach that is generally accepted for incorporating climate change projections in hydrological modelling. It is recommended that the following outline be adopted so future studies conducted by the department are consistent in their approach. This will be particularly important with the emergence of new climate projections.

There are a number of sources of climate projections for Australia. The derivation of the data differs with each source and practitioners need to be aware of the strengths and weaknesses of the different methods. Some aspects to take into consideration include:

- the method used to generate catchment scale climate data (that is, statistical downscaling, dynamic downscaling or rescaling historical time series)
- assessment of a range of global climate models to account for uncertainty in the GCM projections of local climate:
  - CSIRO (2009) used 15 GCMs with daily future climate series but there are now more GCMs with daily data available
  - ongoing research by climate scientists to select better performing GCMs across regions, such as the subset of GCMs recommended by Charles et al (2010) as relatively better performing for Australia
- assessment of a range of global warming scenarios, to highlight the uncertainty, in line with projections presented by the Intergovernmental Panel on Climate Change.

A scenario based approach is recommended for all studies. In this approach a representative selection of future scenarios should be assessed to account for uncertainty, to encompass variability and to simplify the reporting process. It is recommended that the following scenarios are examined and presented together to represent the possible range of future hydrologic conditions:

- historical scenario (post 1975)
- wet scenario defined as the 90th percentile of the change in mean annual rainfall (this provides a positive limit of the range)
- median scenario defined as the 50th percentile of the change in mean annual rainfall
- dry scenario defined as the 10th percentile of the change in mean annual rainfall (this provides a negative limit of the range).

A historical wet scenario may also need to be considered to assess the maximum volumes of a water resource. The selection of scenarios can also depend on the purpose and scale of the study (region, basin or catchment).

It is recommended that future climate projections be incorporated into studies with the following preference:

1 *Adopt climate data representative of 2030 as input to hydrologic models.*

  Currently the best available information is the gridded climate data from the CSIRO south-west Western Australia sustainable yields project (CSIR0 2009). However in some cases, there are insufficient resources, or insufficient time available, to develop and calibrate hydrologic models for use with this data.

2 *Adopt the runoff data from the CSIRO south-west Western Australia sustainable yields project (CSIR0 2009).*

Where surface water hydrologic models suitable to use with the gridded climate data do not yet exist, and there is insufficient time to develop and calibrate such models, then the CSIRO (2009) runoff data for 2030 should be used. However, it is recommended that the scenarios (wet, median and dry) be selected on the basis of changes in rainfall, rather than runoff.

This approach was adopted in this study, as the gridded climate data used by CSIRO (2009) was not publicly available and suitable hydrologic models did not exist.

3 *Adopt the climate since 1997 as input to hydrologic models.*

For areas where future climate projections are not available at the catchment scale it may be acceptable to assume the future climate is a continuation of the post-1997 climate. CSIRO (2009) found that the post-1997 climate is generally comparable to their wet scenario climate at 2030. This means that this approach may over estimate future hydrologic yields. In addition, this option may not represent the full variability of the climate as the period of record is short and may be biased by wet or dry years.

Once practitioners have undertaken studies and presented the possible range of future climatic and hydrologic conditions it is the role of water managers to determine the most appropriate scenario for a specific purpose. It is recommended that a risk based approach be used.

Water managers also need to allow for ongoing scenario development. This includes developments in the future climate projections and accounting for changes in resulting hydrologic variability. This ensures that adjustments can be made into the future to account for any uncertainties.

For this study, the results have been estimated based on a median scenario at 2020. It is possible to review the climate projections and water yield estimates based on the gridded data (when available), any new findings of climate projections and/or improvements in GCMs and the observed variability. Management of the water resource can then be adapted accordingly.

5 Summary of streamflow and sustainable diversion volumes for current and future climates

Table 16 combines the figures from tables 2, 7, 12 and 15. It compares diversion volumes under the current climate and under the median climate projection for 2020.

Table 16 Summary of streamflow and sustainable diversion volumes for current and future climates

Catchment	Resource area	Indicator gauging station	Mean annual flow ML/year		Minimum annual flow ML/year		Volume diverted at an 80% reliability of supply ML/year		Volume diverted in minimum year ML/year	
			Current climate	Median 2020	Current climate	Median 2020	Current climate*	Median 2020	Current climate	Median 2020
Collie River	612_1_8_1	612005	602	466	92	51	73	59	21	8
	612_1_8_2	612005	1 541	1 192	229	128	259	211	76	30
	612_1_8_3	61206	3 055	2 586	1 474	1 202	469	371	255	204
	612_1_8_4	612005	4 851	3 825	516	294	300	243	98	41
	612_1_8_5	61206	16 819	14 244	8 263	6 747	1 713	1 356	930	747
	612_1_8_6	611007	11 664	9 714	3 601	2 756	1 028	831	312	183
	612_1_8_7	611007	4 745	3 980	1 468	1 164	242	195	73	43
	612_1_8_8	611007	8 029	6 800	1 895	1 610	612	494	186	109
	612_1_8_9	611007	9 323	7 900	4 555	3 676	610	493	185	109
	612_1_8_10	612032	113	95	57	45	7	6	2	2

Catchment	Resource area	Indicator gauging station	Mean annual flow ML/year		Minimum annual flow ML/year		Volume diverted at an 80% reliability of supply ML/year		Volume diverted in minimum year ML/year	
			Current climate	Median 2020	Current climate	Median 2020	Current climate*	Median 2020	Current climate	Median 2020
Brunswick River	612_1_9_1	612004	5 636	4 715	1 175	833	540	444	76	40
	612_1_9_2	612022	7 294	6 106	2 202	1 734	1 035	799	176	87
	612_1_9_3	612022	10 790	9 032	3 557	2 801	1 327	1 024	225	111
	612_1_9_4	612023	11 572	9 773	3 865	2 990	1 177	981	529	303
	612_1_9_5	612004	4 408	3 616	1 200	797	490	406	135	7
	612_1_9_6	612004	1 849	1 517	376	249	115	95	32	2
	612_1_9_7	612022	4 012	3 293	1 492	1 101	337	262	113	6
	612_1_9_8	612022	3 794	3 114	1 762	1 300	367	286	123	6
	612_1_9_9	612022	3 777	3 099	1 085	801	186	145	62	3
	612_1_9_10	612032	2 577	2 146	412	344	219	184	154	10
	612_1_9_11	612032	1 013	851	386	302	61	52	21	13
Wellesley River	612_1_10_1	612039	7 067	6 026	3 629	2 891	929	826	369	298
	612_1_10_2	612039	54 174	46 065	15 505	12 721	5 631	5 004	2 234	1 806
	612_1_10_3	612039	738	628	422	361	63	56	51	4

** Determined using the SDL methodology by SKM (2008a, 2008b)*

Appendices

Appendix A — Hydrologic summaries

The first table below describes the entries of the subsequent tables, which give the hydrologic characteristics at the gauging stations used in this study.

Component	**Description**
Climate zones	Description of the climate across the region (Bureau of Meteorology 2010).
Mean annual rainfall Mean annual APET	Rainfall and areal potential evapotranspiration values determined for the 1975 to 2007 period (CSIRO 2009).
Mean annual flow Mean annual runoff	Mean annual flow values determined using a combination of observed and modelled (CSIRO 2009) data for the 1975 to 2007 period. The mean annual runoff (mm) is the mean annual flow (in ML) divided by the catchment area (km^2).
Runoff coefficient	Calculated by dividing the mean annual runoff by the mean annual rainfall. This indicates the annual rainfall to runoff response of the catchment.
Coefficient of variation	The annual coefficient of variation of the streamflow. Calculated by dividing the standard deviation of the annual flows by the mean annual flow.
Geomorphology	Describes the relief, landscape and underlying geology of the gauged catchment. Provided by the Public Works Department (1984), unless otherwise stated.
Landforms	Indicates the principal landforms comprising the catchment. The percentages quoted are approximate and only intended to illustrate the relative proportions of the components. The map units cited were derived from the *Atlas of Australian Soils* (Northcote et al 1967) and the *Atlas of Natural Resources: Darling system* (DCE 1980) unless otherwise stated.
Natural vegetation	The descriptions of the natural vegetation were derived from the *Vegetation Survey of W.A*. (Beard 1980) in which the map units are defined in terms of floristic composition, structure of the dominant stratum and density of the foliage cover.
Clearing	The extent of clearing within the catchments has been provided by Landsat imagery or CSIRO (2009).

Component	Description
Land use	The comments on land use briefly describe the nature of the disturbance to the natural regime. Sourced from CSIRO (2009), DoW (2010) and *GIS cadastral information* (DLI 2010).
Regulation	Upstream developments that might modify the runoff regime are noted.
Water quality	General information regarding the catchment water quality (DoW 2008).
Hydrologically similar gauge	A streamflow gauge with similar catchment and runoff characteristics (SKM 2008b).
Establishment	Classification of the gauging station or function (Public Works Department 1984).
Data quality	Describes the accuracy of the streamflow record. Quality 1 Very good record 2 Very good record – corrections applied 3 Good record – correction/estimations applied 4 Estimated record – good 5 Estimated record – fair 10 Estimated record – not reviewed 11 Theoretical rating 12 Estimated rating 152 Not available 255 No records
Rating curve	Provides the range of measured and rated flows.
Observed streamflow plots	Annual streamflow: observed annual flow record with pre- and post-1975 mean, if available. Locally weighted scatterplot smoothing (LOESS) curve shown if record is greater than 10 years to highlight trends. Low flows: 90th percentile of daily flows: if no graph is shown then the 90th percentile of observed daily flows was equal to 0. High flows: 10th percentile of daily flows. Peak annual streamflow: maximum observed daily streamflow value from each year. Annual flow duration curves and monthly flow duration curves for the observed period of record. Average monthly streamflow showing the mean and median monthly streamflow for the observed period of record .

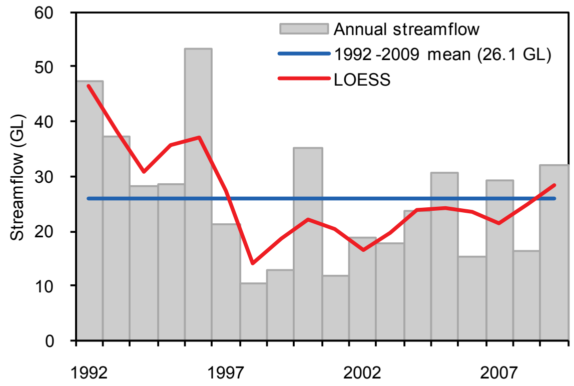
Component	Description
Rainfall and runoff under future climate scenarios table	Mean annual rainfall, mean annual runoff, the difference between the mean annual rainfall and runoff from the historical values and the runoff coefficient under future climate scenarios, averaged across the catchment. This information is based on CSIRO (2009) with historical data for the period 1975 to 2007, recent data for the period 1997 to 2007 (repeated sequence) and future wet, median and dry scenarios centred on 2030. The wet, median and dry scenarios were selected based on change in mean annual rainfall.

South West Highway **Ferguson River**

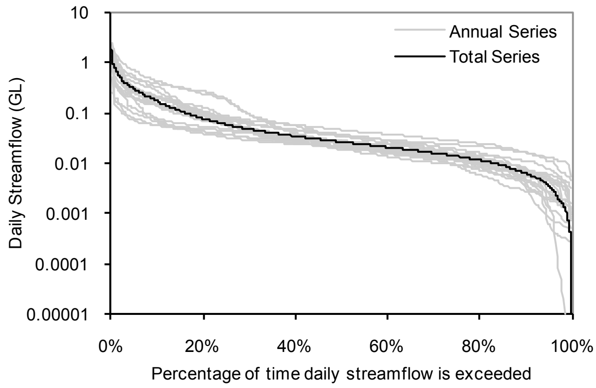
611007 **Preston River Basin**

Catchment characteristics	
Catchment area	145 km^2
Climate zone	Temperate, with a distinctly dry (and warm) summer
	1975–2007
Mean annual rainfall	914 mm
Mean annual APET	1365 mm
Mean annual flow	25.0 GL
Mean annual runoff	172 mm
Runoff coefficient	19%
Coefficient of variation	0.44
Geomorphology	Low to moderate relief; mainly dissected plateau with lateritic soils over Archean granitic and metamorphic rocks, portion of coastal lowlands with sandy soils and Phanerozoic sedimentary rocks.
Landforms	Map units; Atlas of Natural Resources Darling System WA
	Flat plains with medium textured deposits; yellow duplex soils
	Sandplain with low dunes and many intervening swamps; iron and humus podzols; peats and clays
	Very steep slopes with shallow red and yellow earths and much rock outcrops
	Gently undulating divides with duricrust, gravels and grey sands
Natural vegetation	Map units; Vegetation Survey of WA
Clearing	50 % cleared
Land use	
Regulation	None
Water quality	Fresh; median TDS value of 610 mg/L
Hydrologically similar gauge	612047

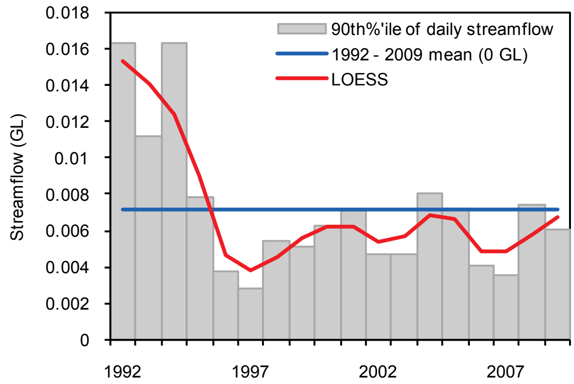
Gauging station details								
Location	Latitude	33° 21´ 13´´ S	AMG Grid	379339 mE				
	Longitude	117° 18´ 54´´ E	Zone 50	6308748 mN				
Period of record	1992 to 2009							
Establishment	Hydrologic network – primary areal catchment							
Data quality	1	2	3	4	5	11	12	255
	77.84%	2.83%	3.70%	4.17%	3.71%	7.35%	0.37%	0.01%
Rating curve	Minimum discharge measurement				0.002 GL			
	Maximum discharge measurement				1.246 GL			
	Percentage of recorded flow covered by confirmed rating				96.71%			



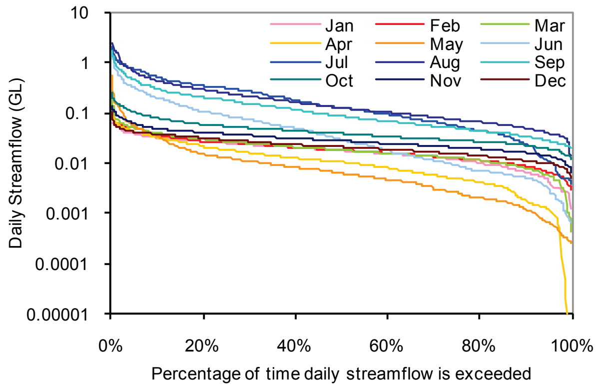
Annual streamflow at South West Highway gauge



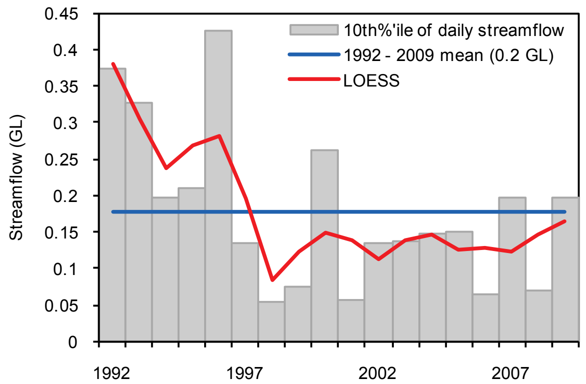
Annual flow duration curves for 1992 to 2009



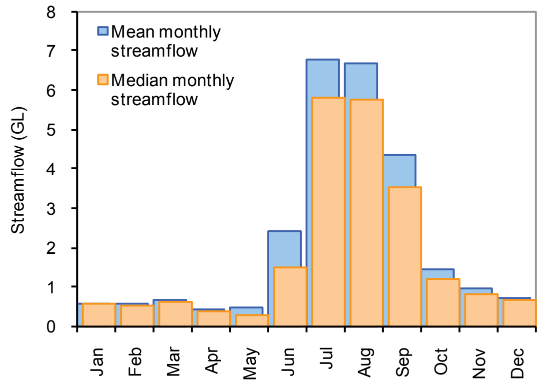
Low flows: 90th percentile of daily flows



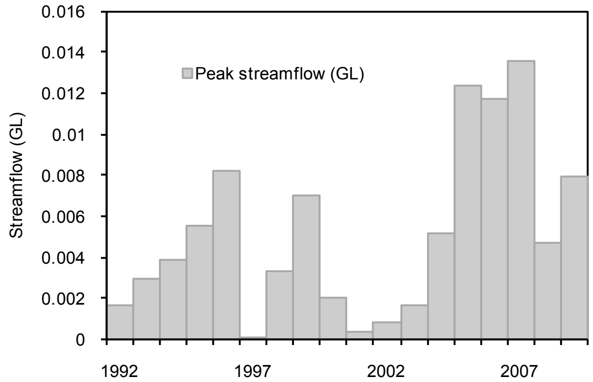
Monthly flow duration curves for 1992 to 2009



High flows: 10th percentile of daily flows



Average monthly streamflow for 1992 to 2009



Peak annual streamflow

Rainfall and runoff under future climate scenarios

Climate scenario	Mean annual rainfall (mm)		Mean annual streamflow (GL)		Runoff coefficient
Historical	914		25.0		19%
Recent	874	(−4%)	23.3	(−6%)	18%
Wet	9□0	(−2%)	23□5	(−6%)	18%
Median	830	(−8%)	19.4	(−22%)	16%
Dry	747	(−15%)	15.2	(−39%)	14%

Worsley	**Hamilton River**
612004	**Collie Basin**

Catchment characteristics

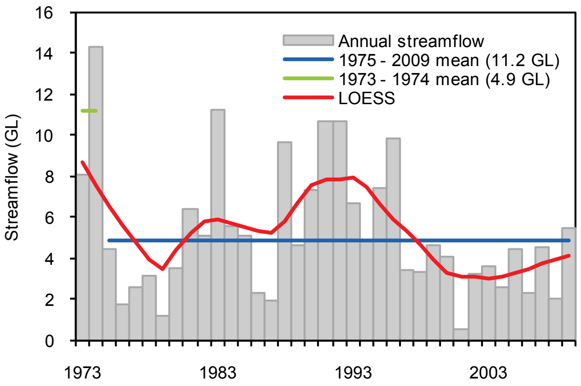
Catchment area	32.28 km^2
Climate zone	Temperate, with a distinctly dry (and warm) summer
	1975 – 2007
Mean annual rainfall	938 mm
Mean annual APET	1354 mm
Mean annual flow	4.94 GL
Mean annual runoff	153 mm
Runoff coefficient	16%
Coefficient of variation	0.58
Geomorphology	Low relief; undulating plateau, bauxite laterite soils over Archean granitic rocks.
Landforms	Map units; Atlas of Natural Resources Darling System WA
	55% – Dwellingup Laterite Plateau; uplands, duricrust, gravels and grey sands over mottled clays
	45% – Yarragil Uplands Valleys; sandy gravels on slopes, orange earths on swampy valley floor.
Natural vegetation	Map units; Vegetation Survey of WA
	100% – eMc Forest; jarrah-marri forest – affected by dieback disease.
Clearing	4% cleared
Land use	State forest reserve
Regulation	None
Water quality	Fresh
Hydrologically similar gauge	612047

Gauging station details

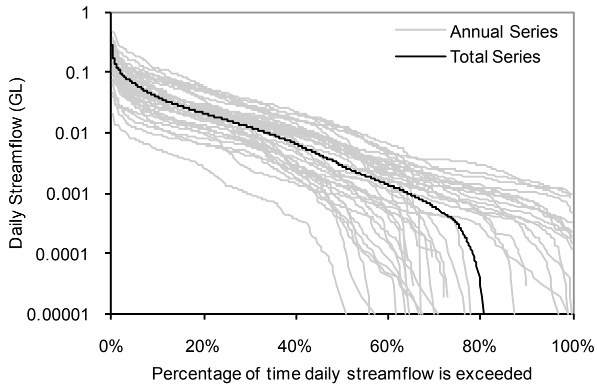
Location	Latitude	33° 18´ 39´´ S	AMG Grid	411589 mE
	Longitude	116° 3´ 1´´ E	Zone 50	6313848 mN
Period of record	1972 to 2009			
Establishment	Hydrologic network – primary areal catchment			

Data quality	1	2	3	4	5	10	11	12	255
	90.3%	5.89%	1.12%	0.62%	0.95%	0.07%	0.73%	0.23%	0.01%

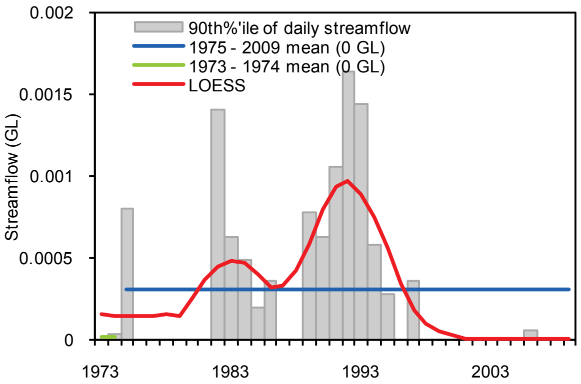
Rating curve	Minimum discharge measurement	0.000 GL
	Maximum discharge measurement	0.558 GL
	Percentage of recorded flow covered by confirmed rating	100 %



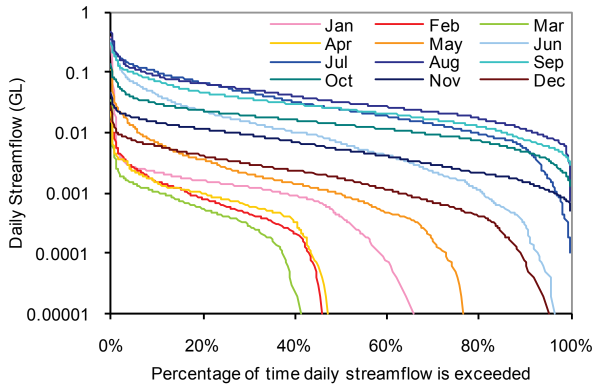
Annual streamflow at Worsley gauge



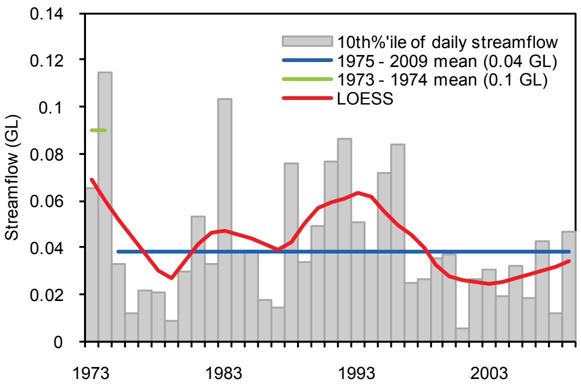
Annual flow duration curves for 1973 to 2009



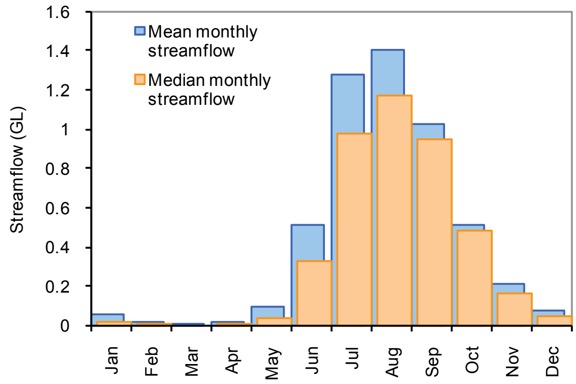
Low flows: 90th percentile of daily flows



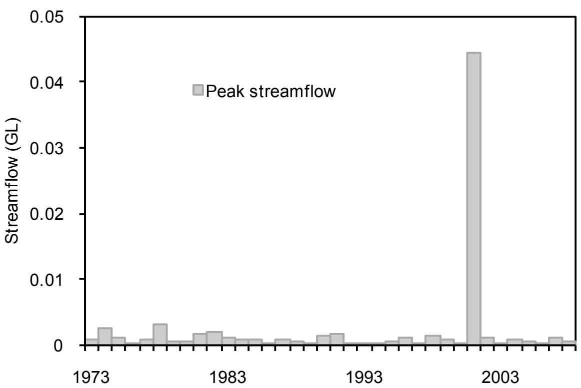
Monthly flow duration curves for 1973 to 2009



High flows: 10th percentile of daily flows



Average monthly streamflow for 1973 to 2009



Peak annual streamflow

Rainfall and runoff under future climate scenarios

Climate scenario	Mean annual rainfall (mm)		Mean annual streamflow (GL)		Runoff coefficient
Historical	938		4.94		16%
Recent	869	(−7%)	4.12	(−17%)	15%
Wet	924	(−1%)	4.67	(−5%)	16%
Median	863	(−8%)	3.80	(−23%)	14%
Dry	798	(−15%)	2.95	(−40%)	11%

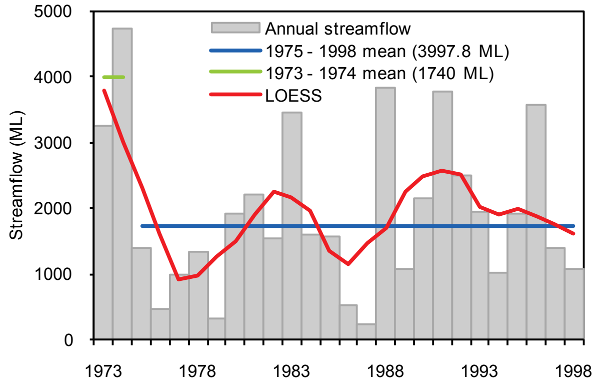
Mast View	**Stones Brook**
612005	**Collie Basin**

Catchment characteristics

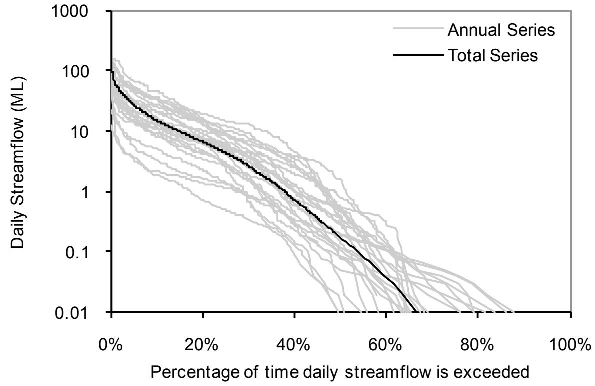
Catchment area	12.9 km^2
Climate zone	Temperate, with a distinctly dry (and warm) summer
	1975 – 2007
Mean annual rainfall	1024 mm
Mean annual APET	1382 mm
Mean annual flow	1.54 GL
Mean annual runoff	119 mm
Runoff coefficient	12%
Coefficient of variation	0.65
Geomorphology	Low to moderate relief; dissected plateau, bauxite laterite soils over Archean granitic and metamorphic rocks.
Landforms	Map units; Atlas of Natural Resources Darling System WA
	45% – Dwellingup Laterite Plateau; uplands; duricrust, gravels and sands over mottled clay soils
	15% – Yarragil Uplands Valleys; sandy gravels on slopes, orange earths on swampy valley floor
	40% – Helena Incised Valleys; steep slopes, some red and yellow earths, much rock outcrop
Natural vegetation	Map units; Vegetation Survey of WA
	100% – eMc Forest; jarrah-marri forest – some virgin Blackbutt
Clearing	No significant clearing within catchment.
Land use	State forest reserve – Management Priority Area
Regulation	None
Water quality	Fresh
Hydrologically similar gauge	612004

Gauging station details

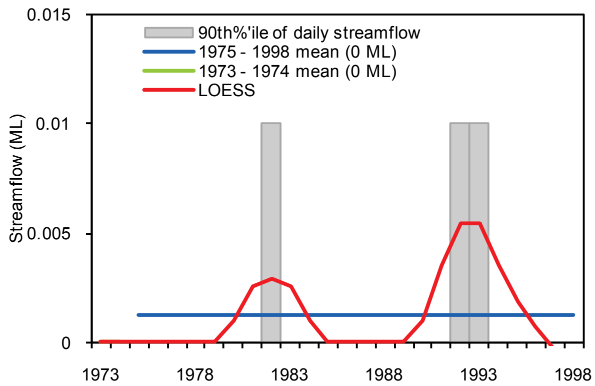
Location	Latitude	33° 22´ 9´´ S	AMG Grid	401619 mE	
	Longitude	115° 56´ 33´´ E	Zone 50	6307298 mN	
Period of record	1972 to 1999				
Establishment	Hydrologic network – primary areal catchment				
Data quality	1	2	3	10	255
	91.42%	5.52%	2.40%	0.65%	0.01%
Rating curve	Minimum discharge measurement			0.00 GL	
	Maximum discharge measurement			0.22 GL	
	Percentage of recorded flow covered by confirmed rating			100 %	



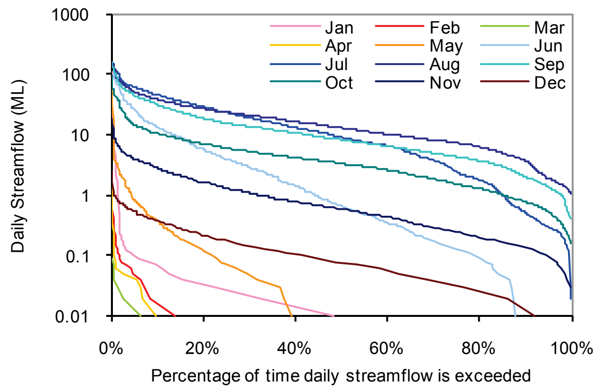
Annual streamflow at Mast View gauge



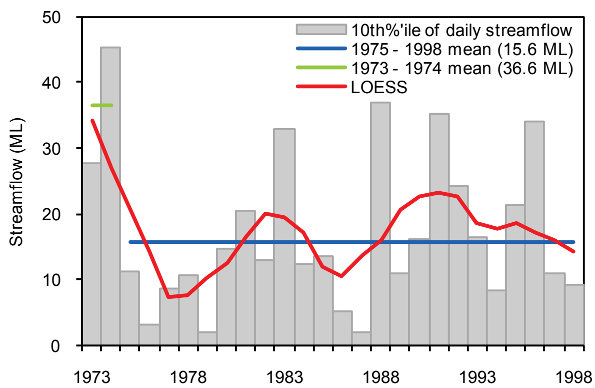
Annual flow duration curves for 1973 to 1998



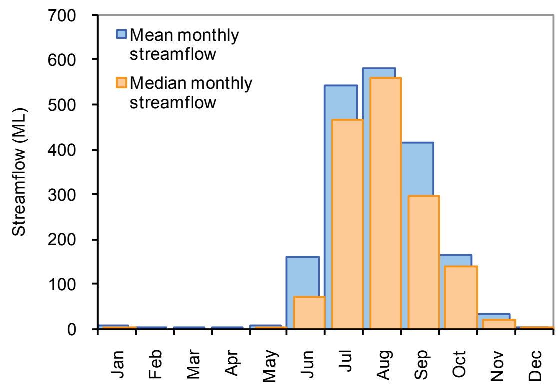
Low flows: 90th percentile of daily flows



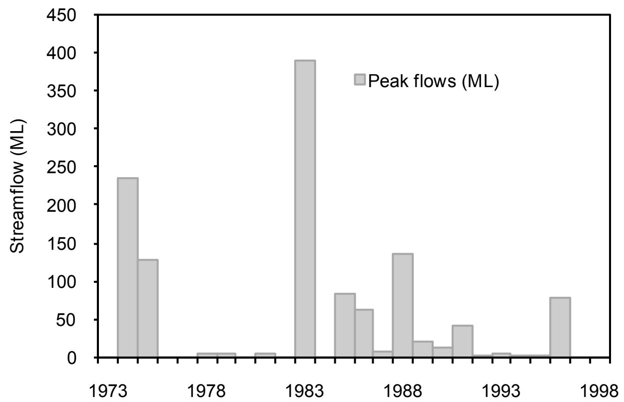
Monthly flow duration curves for 1973 to 1998



High flows: 10th percentile of daily flows



Average monthly streamflow for 1973 to 1998



Peak annual streamflow

Rainfall and runoff under future climate scenarios

Climate scenario	Mean annual rainfall (mm)		Mean annual streamflow (GL)		Runoff coefficient
Historical	1024		1.54		12%
Recent	914	(−11%)	1.02	(−34%)	9%
Wet	1008	(−2%)	1.42	(−8%)	11%
Median	934	(−9%)	1.03	(−33%)	9%
Dry	868	(−15%)	0.78	(−49%)	7%

Falcon Road	**Falcon Brook**
612012	**Collie Basin**

Catchment characteristics

Catchment area	5.45 km^2
Climate zone	Temperate, with a distinctly dry (and warm) summer
	1975 – 2007
Mean annual rainfall	1024 mm
Mean annual APET	1382 mm
Mean annual flow	487 ML
Mean annual runoff	89.3 mm
Runoff coefficient	9%
Coefficient of variation	0.64
Geomorphology	Moderate relief; dissected plateau, bauxite laterite soils over Archean granitic and metamorphic rocks.
Landforms	Map units; Atlas of Natural Resource Darling System WA 40% – Dwellingup Laterite Plateau; uplands, duricrust. Gravels and sands over mottled clays 60% – Helena Valley Slopes; very steep slopes, some red and yellow earths, much rock outcrop.
Natural vegetation	Map units; Vegetation Survey of WA 100% – eMc Forest; Jarrah-marri forest, Blackbutt in valley
Clearing	No significant clearing within catchment.
Land use	State forest reserve.
Regulation	None
Water quality	Fresh
Hydrologically similar gauge	611221

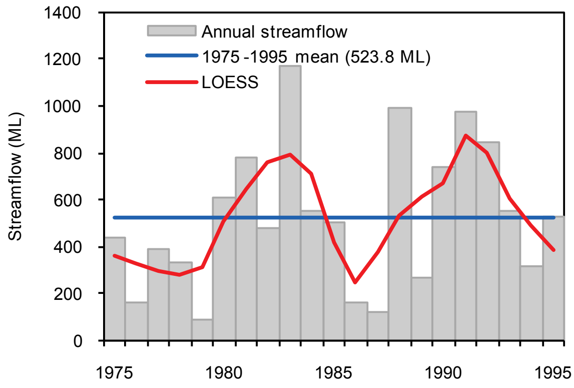
Gauging station details

Location	Latitude	33° 24´ 31´´ S	AMG Grid	404289 mE
	Longitude	115° 58´ 14´´ E	Zone 50	6302948 mN

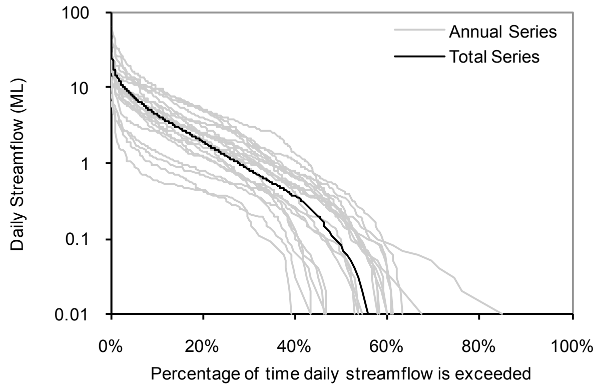
Period of record	1974 – 1996
Establishment	Hydrologic network – primary areal catchment

Data quality	1	2	3	10	152	255
	98.03%	1.48%	0.17%	0.24%	0.07%	0.01%

Rating curve	Minimum discharge measurement	0.00 ML
	Maximum discharge measurement	68.6 ML
	Percentage of recorded flow covered by confirmed rating	100 %

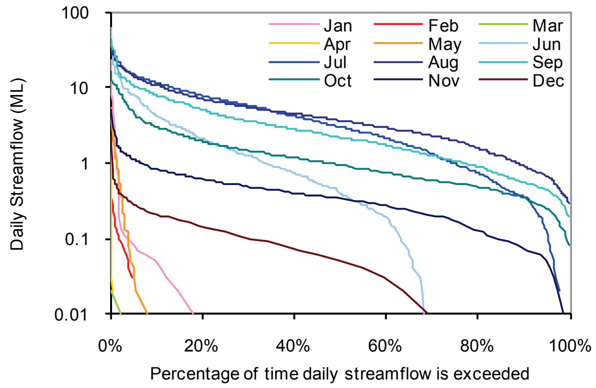


Annual streamflow at Falcon Road gauge

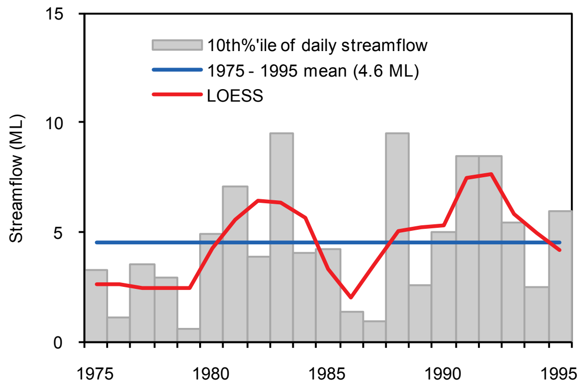


Annual flow duration curves for 1975 to 1995

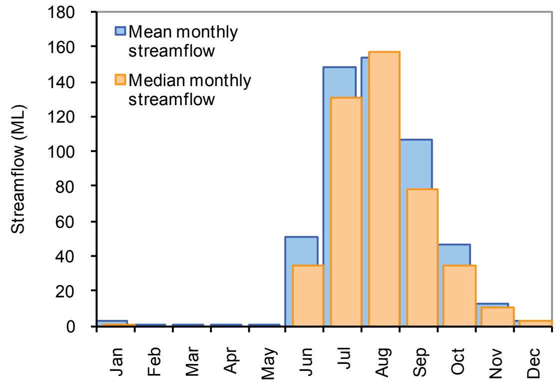
Low flows: 90th percentile of daily flows



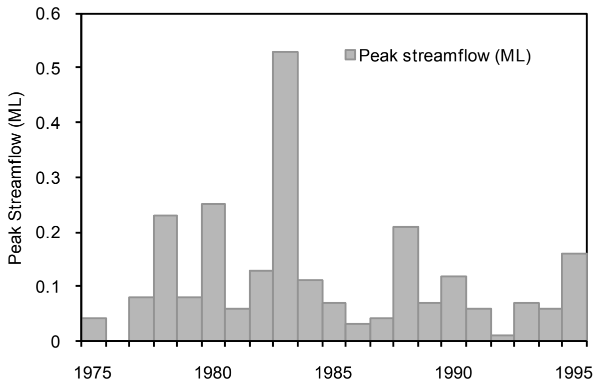
Monthly flow duration curves for 1975 to 1995



High flows: 10th percentile of daily flows



Average monthly streamflow for 1975 to 1995



Peak annual streamflow

Rainfall and runoff under future climate scenarios

Climate scenario	Mean annual rainfall (mm)		Mean annual streamflow (ML)		Runoff coefficient
Historical	1024		487		9%
Recent	914	(−11%)	321	(−34%)	6%
Wet	1008	(−2%)	449	(−8%)	8%
Median	934	(−9%)	324	(−33%)	6%
Dry	868	(−15%)	246	(−49%)	5%

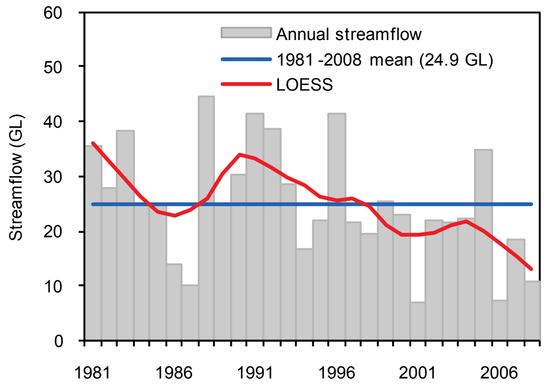
Sandalwood	**Brunswick River**
612022	**Collie Basin**

Catchment characteristics

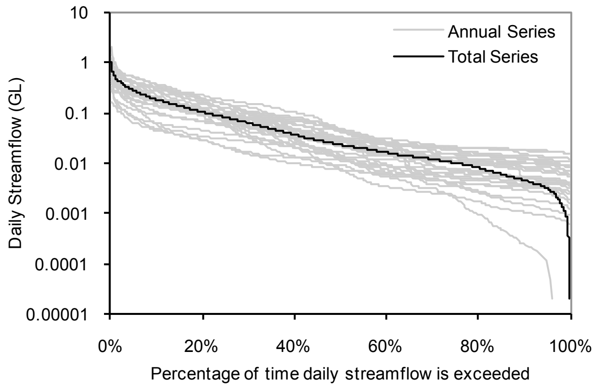
Catchment area	116 km^2
Climate zone	Temperate, with a distinctly dry (and warm) summer
	1975 – 2007
Mean annual rainfall	974 mm
Mean annual APET	1369 mm
Mean annual flow	23.7 GL
Mean annual runoff	204 mm
Runoff coefficient	21 %
Coefficient of variation	0.43
Geomorphology	Moderate relief; dissected plateau, lateritic soils over Archean granitic and metamorphic rocks.
Landforms	Map units; Atlas of Natural Resources Darling System WA 30% – Dwellingup Laterite Plateau; uplands – duricrust gravels and sands over mottled clay soils 30% – Yarragil Uplands Valleys; sandy gravels on slopes, orange earths on swampy valley floors 40% – Murray/Lowdon Valley Slopes; steep slopes, rock outcrops, red and yellow earths
Natural vegetation	Map units; Vegetation Survey of WA 100% – eMc Forest; jarrah-marri forest – severely affected by dieback disease.
Clearing	19 % cleared
Land use	Part state forest reserve and part private timber leases, a few small mixed farms.
Regulation	None. Raw water dam and caustic mud lakes in extreme headwaters.
Water quality	Fresh; median TDS value of 147 mg/L
Hydrologically similar gauge	612047

Gauging station details

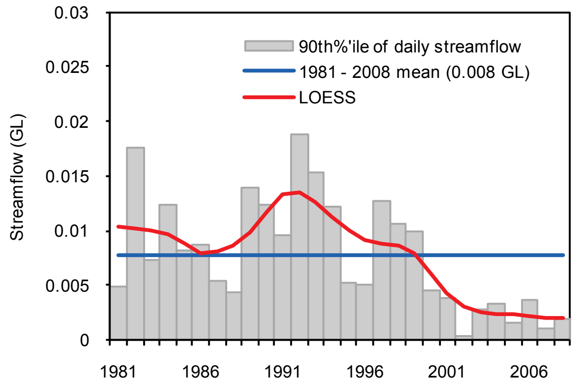
Location	Latitude	33° 13´ 11´´ S	AMG Grid	399539 mE		
	Longitude	115° 58´ 20´´ E	Zone 50	6323848 mN		
Period of record	1980 to date					
Establishment	Hydrologic network – primary areal catchment					
Data quality	1	2	3	10	11	255
	97.8%	0.75%	0.62%	0.59%	0.18%	0.02%
Rating curve	Minimum discharge measurement			0.005 GL		
	Maximum discharge measurement			0.995 GL		
	Percentage of recorded flow covered by confirmed rating			88.2 %		



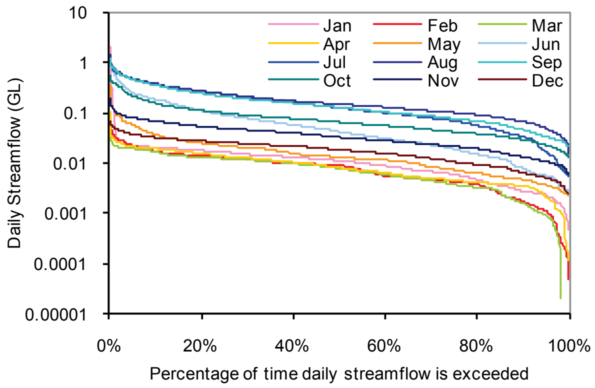
Annual streamflow at Sandalwood gauge



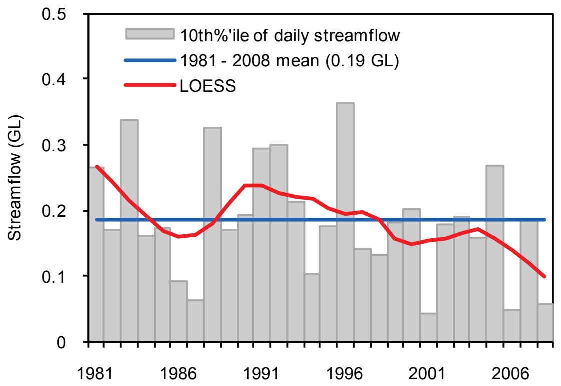
Annual flow duration curves for 1981 to 2008



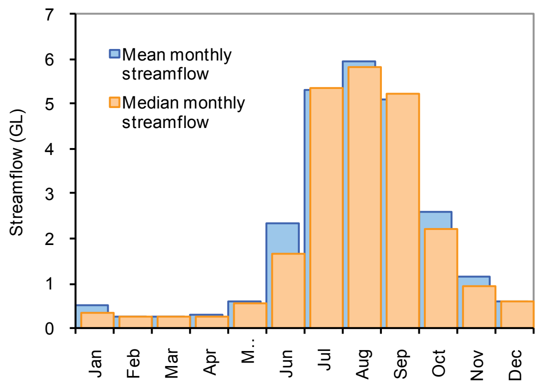
Low flows: 90th percentile of daily flows



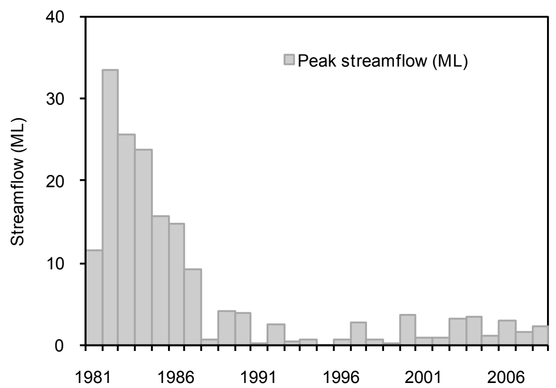
Monthly flow duration curves for 1981 to 2008



High flows: 10th percentile of daily flows



Average monthly streamflow for 1981 to 2008



Peak annual streamflow

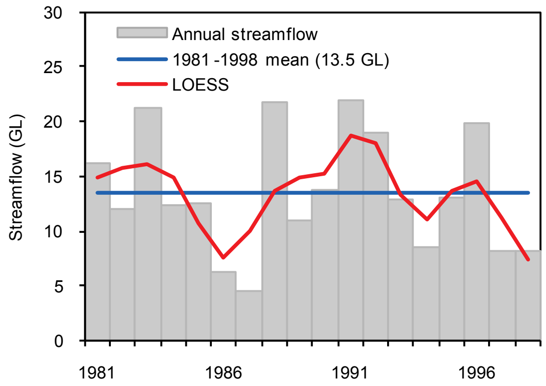
Rainfall and runoff under future climate scenarios

Climate scenario	Mean annual rainfall (mm)		Mean annual streamflow (GL)		Runoff coefficient
Historical	975		23.7		21%
Recent	905	(−7%)	19.9	(−16%)	19%
Wet	960	(−2%)	22.4	(−6%)	20%
Median	895	(−8%)	18.4	(−22%)	18%
Dry	827	(−15%)	14.4	(−39%)	15%

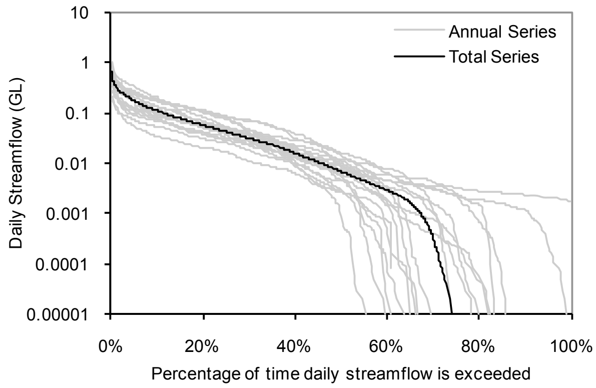
Silver Springs	**Lunenburgh River**
612023	**Collie Basin**

Catchment characteristics	
Catchment area	56.3 km^2
Climate zone	Temperate, with a distinctly dry (and warm) summer
	1975 – 2007
Mean annual rainfall	1004 mm
Mean annual APET	1365 mm
Mean annual flow	11.6 GL
Mean annual runoff	206 mm
Runoff coefficient	20 %
Coefficient of variation	0.43
Geomorphology	Moderate relief; dissected plateau, lateritic soils over Archean granitic and metamorphic rocks
Landforms	Map units; Atlas of Natural Resources Darling System WA 30% – Dwellingup Laterite Plateau; uplands – duricrust gravels and sands over mottled clay soils 20% – Yarragil Uplands Valleys; sandy gravels on slopes, orange earths on swampy valley floors 50% – Murray/Lowdon Valley Slopes; steep slopes, rock outcrops, red and yellow earths
Natural vegetation	Map units; Vegetation Survey of WA 100% – eMc Forest; jarrah-marri forest – severely affected by dieback disease
Clearing	15 % cleared
Land use	Part state forest reserve, part private timber leases, a few small mixed farms
Regulation	None
Water quality	
Hydrologically similar gauge	612022

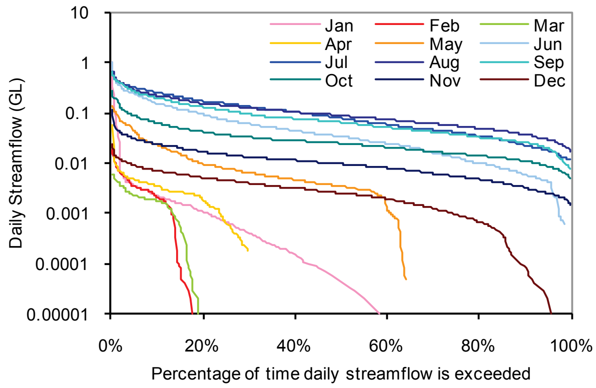
Gauging station details					
Location	Latitude	33° 14′ 47′′ S	AMG Grid	400539 mE	
	Longitude	115° 53′ 58′′ E	Zone 50	6320898 mN	
Period of record	1980 to 1999				
Establishment	Hydrologic Network – Secondary areal catchment.				
Data quality	1	2	3	10	
	98.2%	0.8%	0.2%	0.8%	
Rating curve	Minimum discharge measurement				0.014 GL
	Maximum discharge measurement				0.810 GL
	Percentage of recorded flow covered by confirmed rating				73%



Annual streamflow at Silver Springs gauge

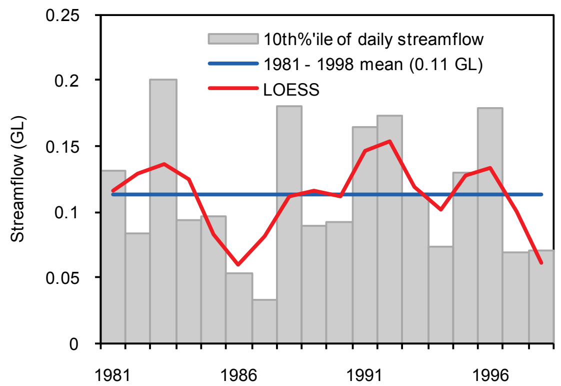


Annual flow duration curves for 1981 to 1998

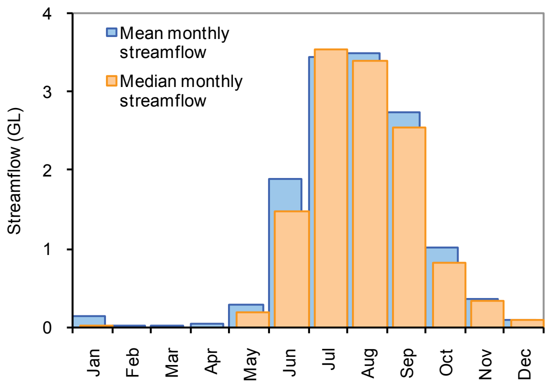


Low flows: 90th percentile of daily flows

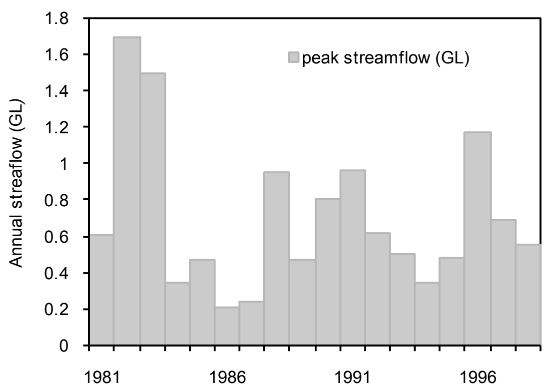
Monthly flow duration curves for 1981 to 1998



High flows: 10th percentile of daily flows



Average monthly streamflow for 1981 to 1998



Peak annual streamflow

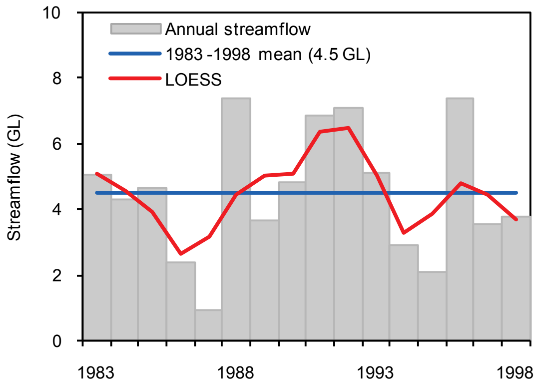
Rainfall and runoff under future climate scenarios

Climate scenario	Mean annual rainfall (mm)		Mean annual streamflow (GL)		Runoff coefficient
Historical	1004		11.6		20%
Recent	911	(−9%)	9.23	(−20%)	18%
Wet	988	(−2%)	11.0	(−5%)	20%
Median	921	(−8%)	9.10	(−21%)	18%
Dry	851	(−15%)	7.24	(−37%)	15%

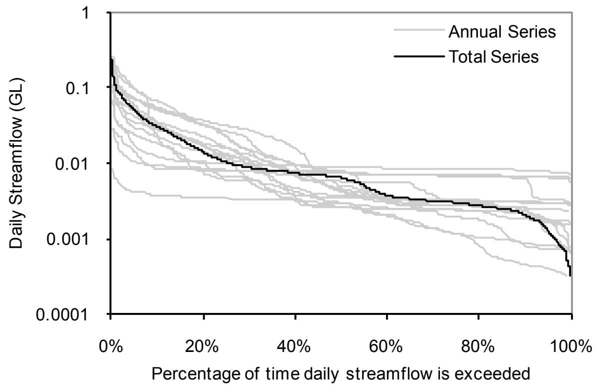
Worsley Refinery	**Augustus River**
612024	**Collie Basin**

Catchment characteristics	
Catchment area	23.5 km^2
Climate zone	Temperate, with a distinctly dry (and warm) summer
	1975 – 2007
Mean annual rainfall	938 mm (612004)
Mean annual APET	1354 mm (612004)
Mean annual flow	3.72 GL
Mean annual runoff	158 mm
Runoff coefficient	17%
Coefficient of variation	0.51
Geomorphology	Low relief; undulating plateau, bauxite laterite soils over Archean granitic rocks
Landforms	Map units; Atlas of Natural Resources Darling System WA 10% Sandy gravels on the slopes; orange earths in swampy floors 20% Deeply incised valleys with red and yellow earths on slopes; narrow alluvial terraces 70 % Gently undulating landscape with duricrust on ridges; sands and gravels in shallow depressions
Natural vegetation	Map units; Vegetation Survey of WA
Clearing	67% cleared (GHD land use survey 2010)
Land use	Conservation areas with a large processing plant within the catchment.
Regulation	Worsley reservoir
Water quality	Fresh
Hydrologically similar gauge	612004

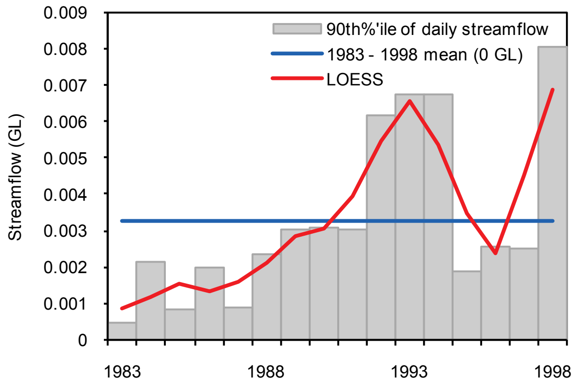
Gauging station details					
Location	Latitude	33° 13´ 22´´ S	AMG Grid	409339 mE	
	Longitude	116° 1´ 37´´ E	Zone 50	6323598 mN	
Period of record	1983 to 1998				
Establishment	Hydrologic Network – Secondary areal catchment.				
Data quality	1	2	10	152	
	98.91%	0.83%	0.13%	0.13%	
Rating curve	Minimum discharge measurement				N/A
	Maximum discharge measurement				N/A
	Percentage of recorded flow covered by confirmed rating				N/A



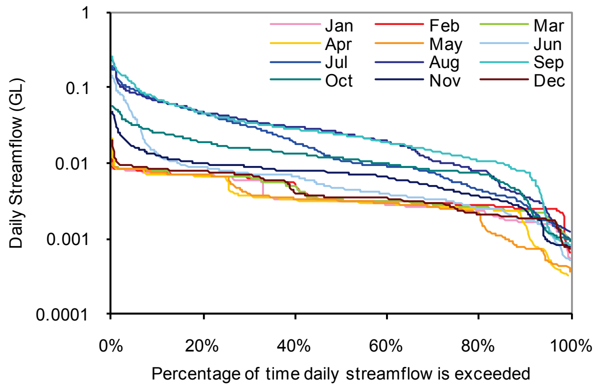
Annual streamflow at Worsley Refinery gauge



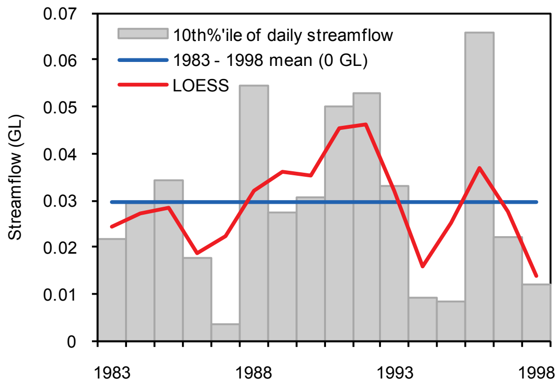
Annual flow duration curves for 1983 to 1998



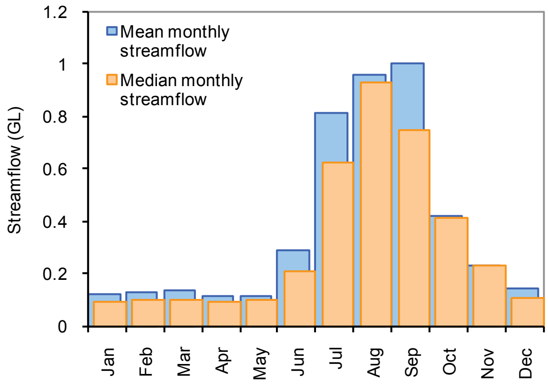
Low flows: 90th percentile of daily flows



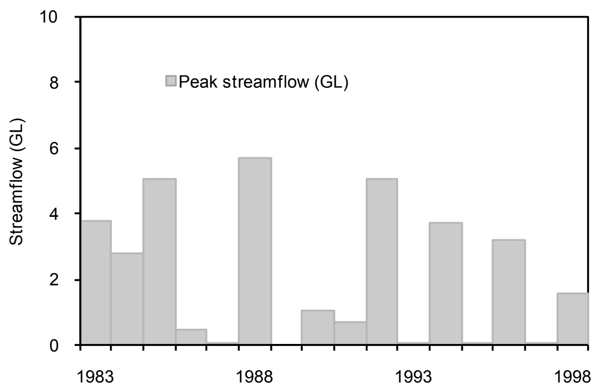
Monthly flow duration curves for 1983 to 1998



High flows: 10th percentile of daily flows



Average monthly streamflow for 1983 to 1998



Peak annual streamflow

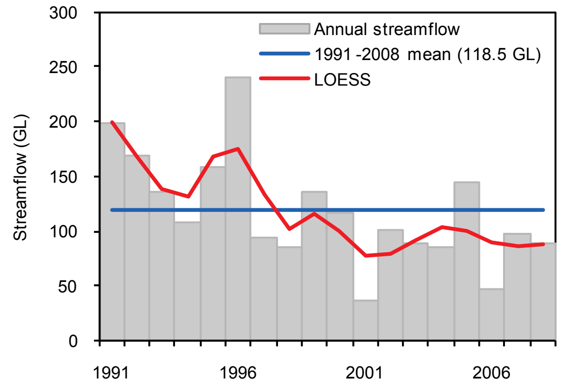
Rainfall and runoff under future climate scenarios

Climate scenario	Mean annual rainfall (mm)		Mean annual streamflow (GL)		Runoff coefficient
Historical	938		3.72		17%
Recent	869	(−7%)	3.11	(−17%)	15%
Wet	924	(−1%)	3.52	(−5%)	16%
Median	863	(−8%)	2.86	(−23%)	14%
Dry	798	(−15%)	2.23	(−40%)	12%

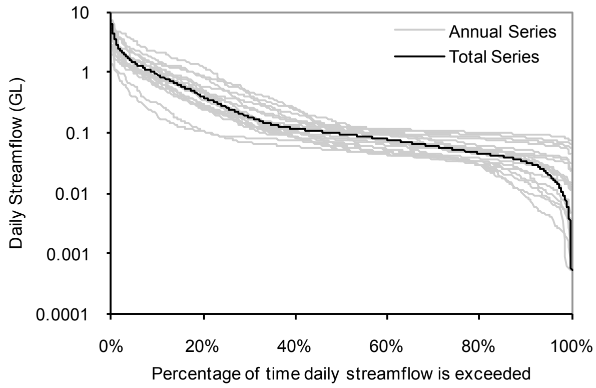
Cross Farm	**Brunswick River**
612032	**Collie Basin**

Catchment characteristics	
Catchment area	509 km^2
Climate zone	Temperate, with a distinctly dry (and warm) summer
	1975 – 2007
Mean annual rainfall	895 mm
Mean annual APET	1391 mm
Mean annual flow	118 GL
Mean annual runoff	231 mm
Runoff coefficient	26%
Coefficient of variation	0.42
Geomorphology	Low relief; coastal plains, alluvial and colluvial soils over Phanerozoic sedimentary rocks
Landforms	The lower catchment is dominated by the Lowden landform with the Murray landform in the forested river valleys and the Yarragil landform in the upper reaches of the catchment (Department of Conservation and Environment, 1980).
Natural vegetation	Map units; Vegetation Survey of WA
	100% – eMc Forest; jarrah-marri forest – severely affected by dieback disease
Clearing	50.5 % (GHD land use survey)
Land use	Majority of land use is for either recreation/conservation or unirrigated agriculture. Some small plantations within the catchment
Regulation	Beela Dam – approximately 30 km upstream
Water quality	Marginal; median TDS value of 686 mg/L and high levels of phosphorus and nitrogen
Hydrologically similar gauge	612039

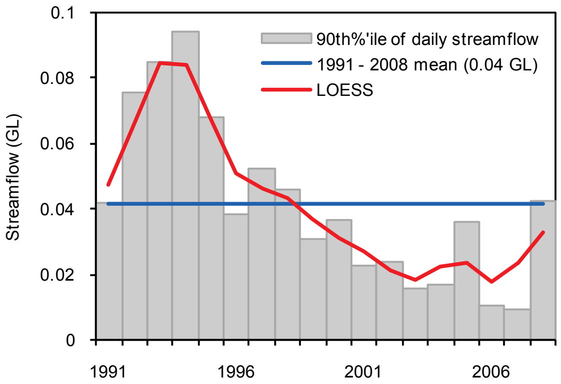
Gauging station details							
Location	Latitude	33° 15´ 14´´ S	AMG Grid	383436 mE			
	Longitude	115° 50´ 37´´ E	Zone 50	6319879 mN			
Period of record	1991 to date						
Establishment	Hydrologic network – primary areal catchment						
Data quality	1	2	3	4	10	11	255
	76.83%	10.03%	5.91%	0.51%	0.07%	6.64%	0.01%
Rating curve	Minimum discharge measurement			0.02 GL			
	Maximum discharge measurement			8.35 GL			
	Percentage of recorded flow covered by confirmed rating			100 %			



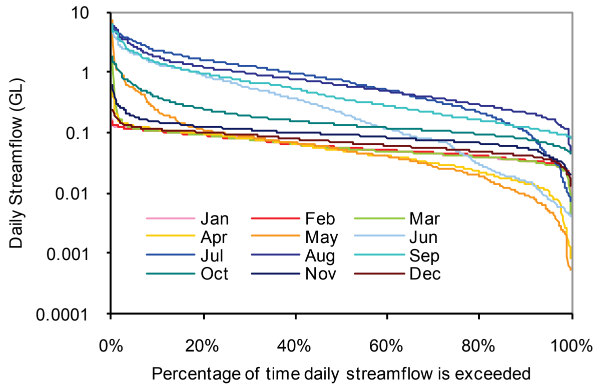
Annual streamflow at Cross Farm gauge



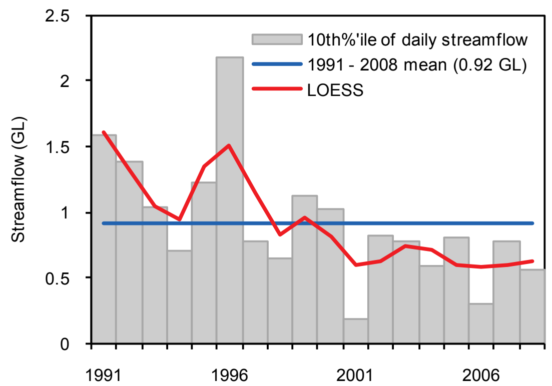
Annual flow duration curves for 1991 to 2008



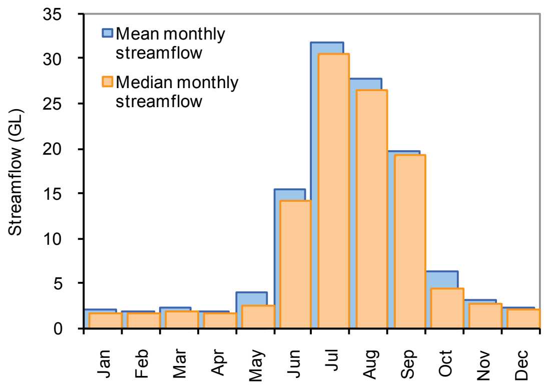
Low flows: 90th percentile of daily flows



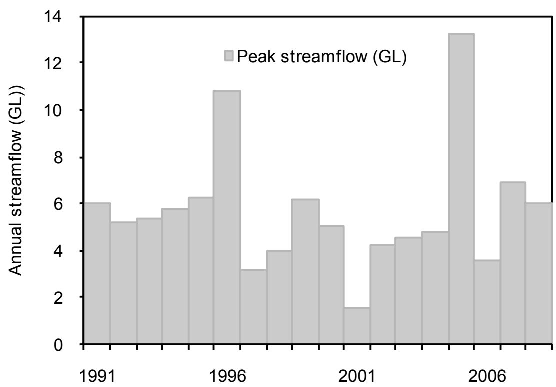
Monthly flow duration curves for 1991 to 2008



High flows: 10th percentile of daily flows



Average monthly streamflow for 1991 to 2008



Peak annual streamflow

Rainfall and runoff under future climate scenarios

Climate scenario	Mean annual rainfall (mm)		Mean annual streamflow (GL)		Runoff coefficient
Historical	895		118		26%
Recent	836	(−6%)	103	(−13%)	24%
Wet	881	(−2%)	112	(−5%)	25%
Median	818	(−9%)	91	(−23%)	22%
Dry	756	(−15%)	73	(−38%)	19%

Juegenup Wellesley	**Wellesley River**
612039	**Collie Basin**

Catchment characteristics

Catchment area	209 km^2
Climate zone	Temperate, with a distinctly dry (and warm) summer
	1975 – 2007
Mean annual rainfall	813 mm
Mean annual APET	1412 mm
Mean annual flow	61.2 GL
Mean annual runoff	293 mm
Runoff coefficient	36%
Coefficient of variation	0.35
Geomorphology	Low relief; coastal plains, alluvial and colluvial soils over Phanerozoic sedimentary rocks
Landforms	Majority of soils are alluvial sands and clays. Bassendean sands (dune formation) and associated wetlands occur west of the river. (Wellesley River restoration plan, WRRP).
Natural vegetation	Riparian zone is dominated by Flooded Gum and Swamp Paperbark. (WRRP)
Clearing	83 % cleared
Land use	Irrigated and unirrigated agriculture occupy a majority of the area. Small plantations, recreation and conservation areas.
Regulation	Harvey River diversion drain
Water quality	Brackish; median TDS value of 1036 mg/L. High nutrients and suspended solids with a median concentration of 32mg/L. (WRRP)
Hydrologically similar gauge	612032

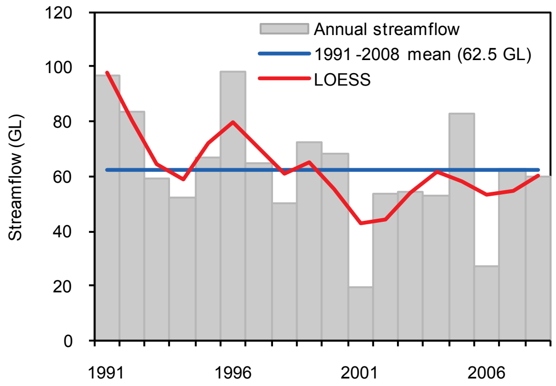
Gauging station details

Location	Latitude	33° 13´ 27´´ S	AMG Grid	386039 mE
	Longitude	115° 47´ 5´´ E	Zone 50	6323198 mN

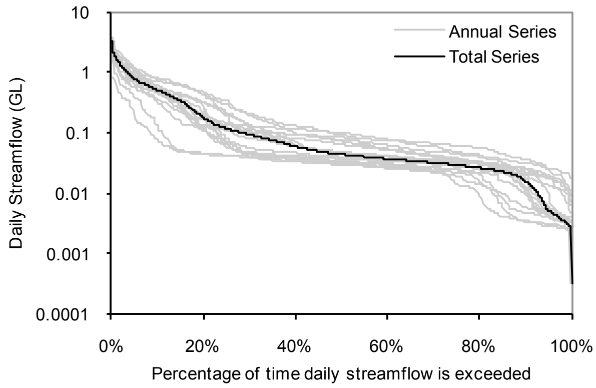
Period of record	1991 to date
Establishment	Hydrologic network – primary areal catchment

Data quality	1	2	3	4	10	11	12	255
	57.5%	1.88%	2.85%	2.44%	3.48%	8.38%	23.5%	0.01%

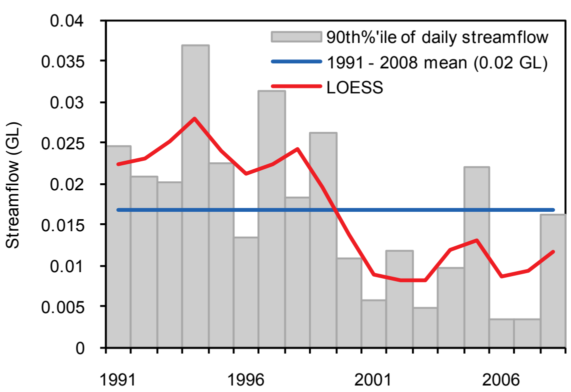
Rating curve	Minimum discharge measurement	0.004 GL
	Maximum discharge measurement	3.46 GL
	Percentage of recorded flow covered by confirmed rating	97.38 %



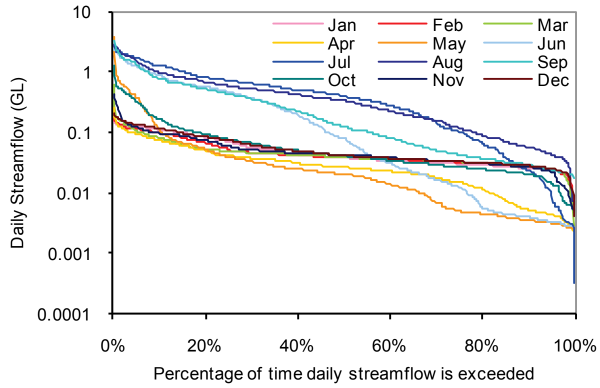
Annual streamflow at Wellesley gauge



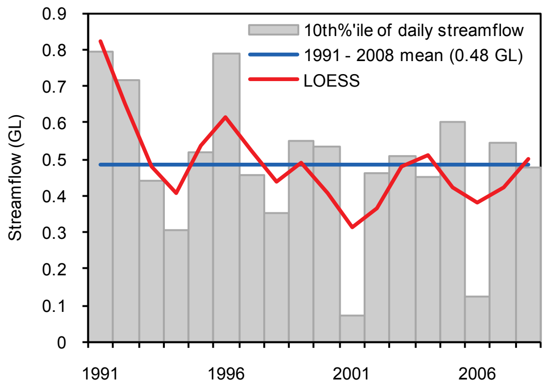
Annual flow duration curves for 1991 to 2008



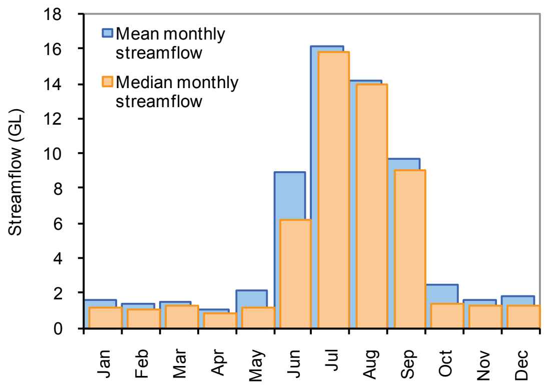
Low flows: 90th percentile of daily flows



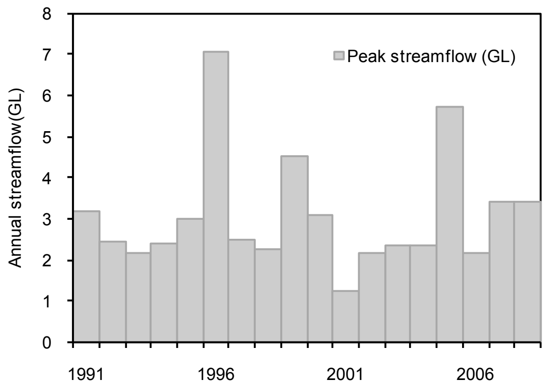
Monthly flow duration curves for 1991 to 2008



High flows: 10th percentile of daily flows



Average monthly streamflow for 1991 to 2008



Peak annual streamflow

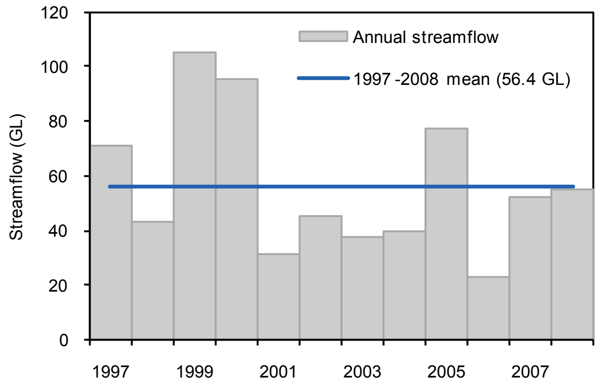
Rainfall and runoff under future climate scenarios

Climate scenario	Mean annual rainfall (mm)		Mean annual streamflow (GL)		Runoff coefficient
Historical	813		61.2		36%
Recent	770	(−5%)	55.6	(−9%)	35%
Wet	801	(−1%)	58.4	(−5%)	35%
Median	740	(−9%)	47.6	(−22%)	31%
Dry	685	(−16%)	39.2	(−36%)	27%

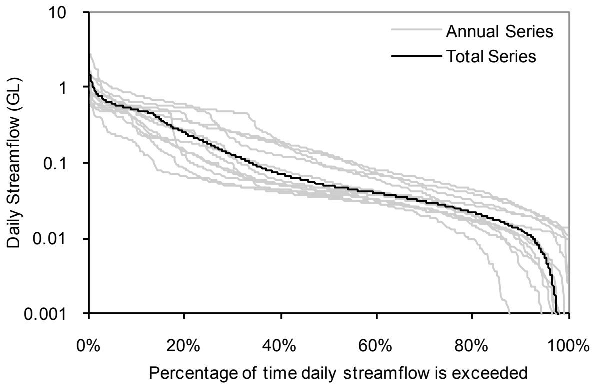
Rose Road	**Collie River**
612043 – modelled as 61206 in CSIRO (2009)	**Collie Basin**

Catchment characteristics	
Catchment area	84.9 km^2
Climate zone	Temperate, with a distinctly dry (and warm) summer
	1975 – 2007
Mean annual rainfall	971 mm
Mean annual APET	1365 mm
Mean annual flow	26.9 GL
Mean annual runoff	316 mm
Runoff coefficient	33%
Coefficient of variation	0.44
Geomorphology	Low to moderate relief; undulating, dissected plateau, laterite soils over Archean granitic and metamorphic rocks, small areas of Permian sediments.
Landforms	Map units; Atlas of Natural Resources Darling System WA
Natural vegetation	Map units; Vegetation Survey of WA
Clearing	35% cleared
Land use	State forest reserve
Regulation	Wellington Dam and reservoir upstream
Water quality	Marginal; median TDS value of 929 mg/L
Hydrologically similar gauge	611007

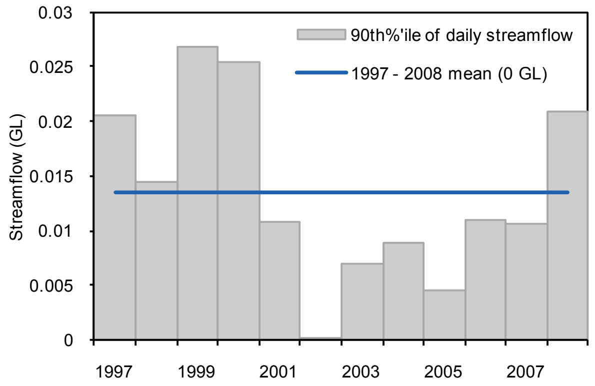
Gauging station details								
Location	Latitude	33° 14´ 2´´ S	AMG Grid	397306 mE				
	Longitude	115° 53´ 51´´ E	Zone 50	6322230 mN				
Period of record	1997 to date							
Establishment	Hydrologic network – primary areal catchment							
Data quality	1	2	3	4	5	10	11	255
	68.48%	9.46%	1.06%	3.19%	1.18%	1.83%	14.77%	0.04
Rating curve	Minimum discharge measurement				0.01 GL			
	Maximum discharge measurement				7.52 GL			
	Percentage of recorded flow covered by confirmed rating				92.5 %			



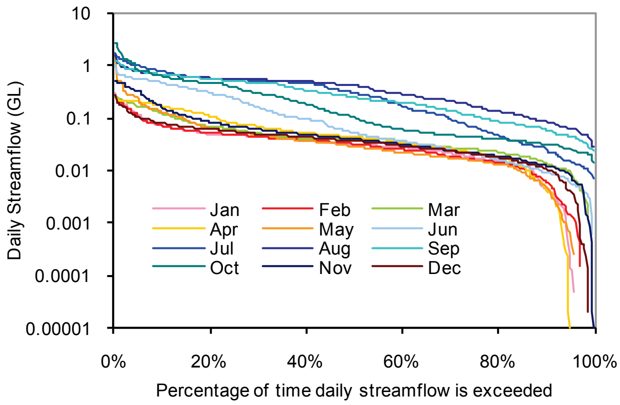
Annual streamflow at Rose Road gauge



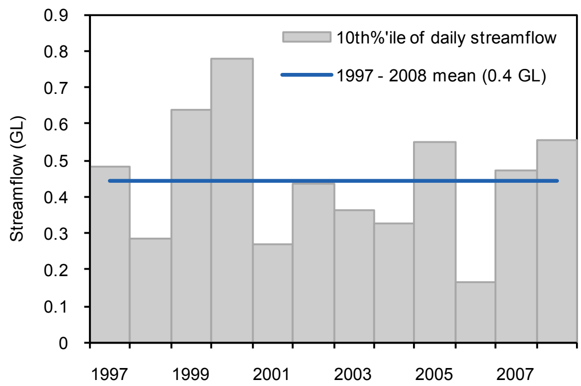
Annual flow duration curves for 1997 to 2008



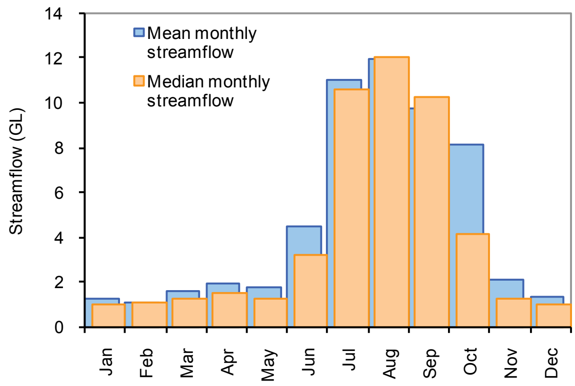
Low flows: 90th percentile of daily flows



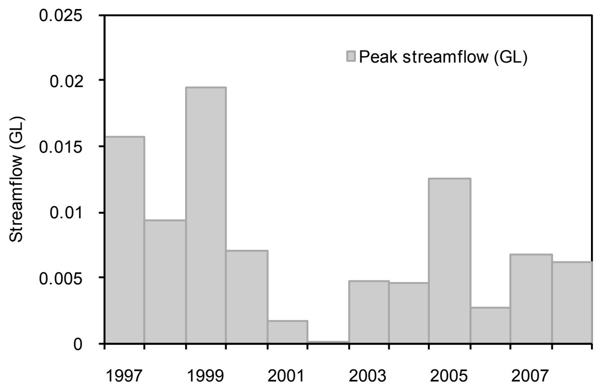
Monthly flow duration curves for 1997 to 2008



High flows: 10th percentile of daily flows



Average monthly streamflow for 1997 to 2008



Peak annual streamflow

Rainfall and runoff under future climate scenarios

Climate scenario	Mean annual rainfall (mm)		Mean annual streamflow (GL)		Runoff coefficient
Historical	971		26.9		33%
Recent	892	(−8%)	22.2	(−17%)	29%
Wet	956	(−2%)	25.3	(−6%)	31%
Median	886	(−9%)	19.7	(−27□)	26%
Dry	821	(−15%)	16.2	(−40%)	23%

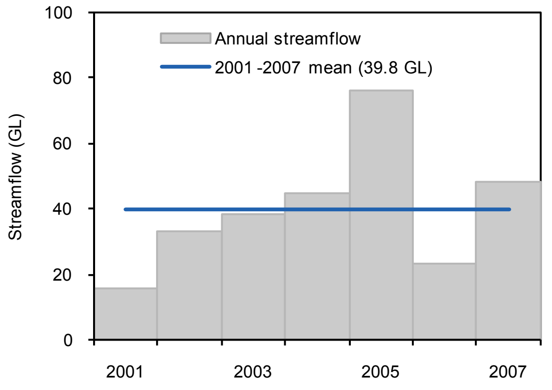
Beela	**Brunswick River**
612047	**Collie Basin**

Catchment characteristics

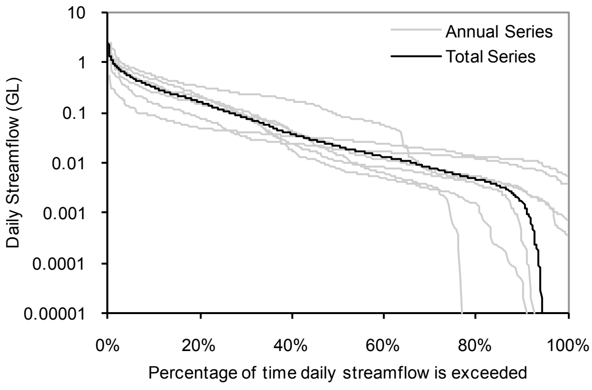
Catchment area	209 km^2
Climate zone	Temperate, with a distinctly dry (and warm) summer
	1975 – 2007
Mean annual rainfall	973 mm
Mean annual APET	1374 mm
Mean annual flow	40.9 GL
Mean annual runoff	196 mm
Runoff coefficient	20%
Coefficient of variation	0.43
Geomorphology	Moderate relief; dissected plateau, lateritic soils over Archean granitic and metamorphic rocks
Landforms	Map units; Atlas of Natural Resources Darling System WA 30% – Dwellingup Laterite Plateau; uplands – duricrust gravels and sands over mottled clay soils 20% – Yarragil Upland Valleys; sandy gravels on slopes, orange earths on swampy valley floor 50% – Murray/Lowdon etc Valley Slopes; steep slopes, rock outcrops, red and yellow earths.
Natural vegetation	Map units; Vegetation Survey of WA 100% – eMc; Jarrah-marri forest, severely affected by dieback disease
Clearing	23% cleared according to GHD land use survey
Land use	Largely state forest reserve, with some unirrigated agriculture
Regulation	Beela Dam
Water quality	Fresh; median TDS value of 192 mg/L
Hydrologically similar gauge	612022

Gauging station details

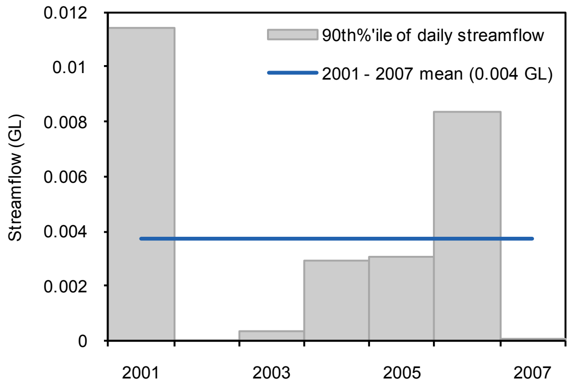
Location	Latitude	33° 14´ 2´´ S	AMG Grid	397306 mE
	Longitude	115° 53´ 51´´ E	Zone 50	6322230 mN
Period of record	2000 to date			
Establishment	Hydrologic network – primary areal catchment			
Data quality	11	12		
	99.9%	0.1%		
Rating curve	Minimum discharge measurement			0.013 GL
	Maximum discharge measurement			1.074 GL
	Percentage of recorded flow covered by confirmed rating			41 %



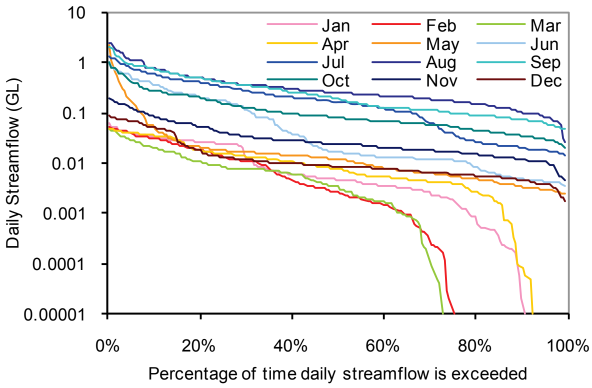
Annual streamflow at Beela gauge



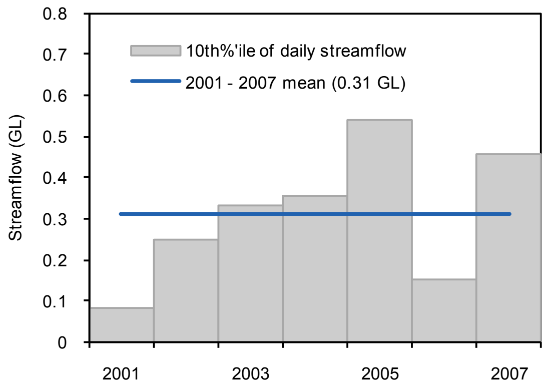
Annual flow duration curves for 2001 to 2007



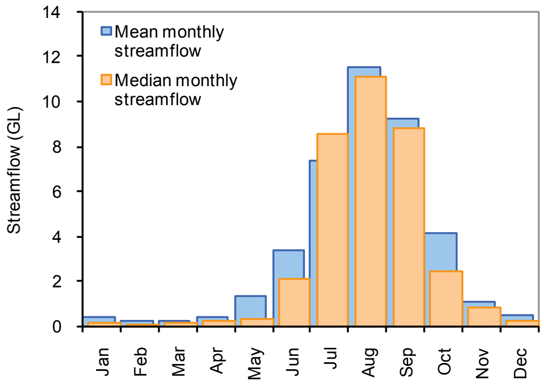
Low flows: 90th percentile of daily flows



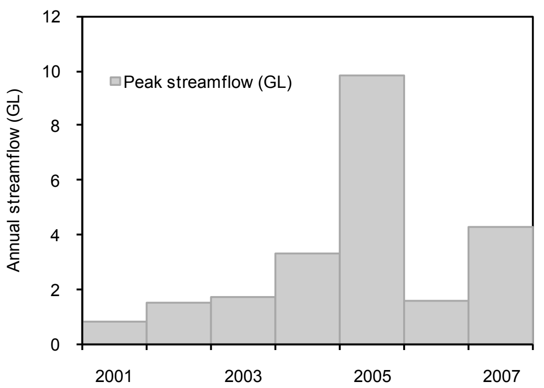
Monthly flow duration curves for 2001 to 2007



High flows: 10th percentile of daily flows



Average monthly streamflow for 2001 to 2007



Peak annual streamflow

Rainfall and runoff under future climate scenarios

Climate scenario	Mean annual rainfall (mm)		Mean annual streamflow (GL)		Runoff coefficient
Historical	973		40.9		20%
Recent	899	(−8%)	33.9	(−17%)	18%
Wet	958	(−2%)	38.6	(−5%)	19%
Median	893	(−8%)	31.7	(−22%)	17%
Dry	824	(−15%)	24.9	(−39%)	14%

Olive Hill	**Brunswick River**
612152	**Collie Basin**

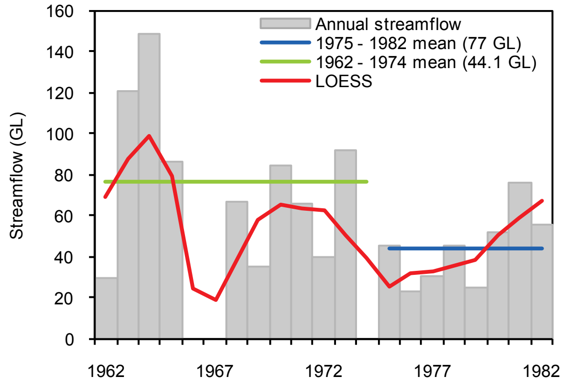
Catchment characteristics

Catchment area	225 km^2
Climate zone	Temperate, with a distinctly dry (and warm) summer
	1975 – 2007
Mean annual rainfall	973 mm
Mean annual APET	1374 mm
Mean annual flow	44.0 GL
Mean annual runoff	196 mm
Runoff coefficient	20%
Coefficient of variation	0.43
Geomorphology	Low to moderate relief; dissected plateau with lateritic souls over Archean granitic and metamorphic rocks
Landforms	Map units; Atlas of Natural Resources Darling System WA 30% – Dwellingup Laterite Plateau; uplands – duricrust gravels and sands over mottled clay soils 20% – Yarragil Upland Valleys; sandy gravels on slopes, orange earths on swampy valley floor 50% – Murray/Lowdon etc Valley Slopes; steep slopes, rock outcrops, red and yellow earths
Natural vegetation	Map units; Vegetation Survey of WA 100% – eMc; Jarrah-marri forest, severely affected by dieback disease
Clearing	About 25% of catchment cleared, much of it during the 1960s
Land use	State forest and some unirrigated agriculture occupy the majority of the catchment (GHD land-use survey)
Regulation	Beela Dam – 4 km upstream
Water quality	Fresh during period of record. Long-term average TSS vales of 230 mg/L
Hydrologically similar gauge	612047

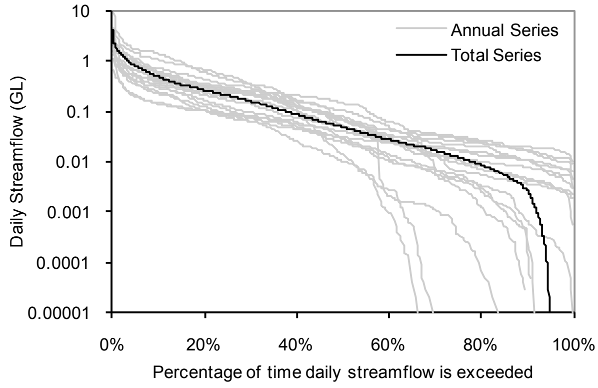
Gauging station details

Location	Latitude	33° 14´ 28´´ S	AMG Grid	395039 mE
	Longitude	115° 52´ 24´´ E	Zone 50	6321398 mN
Period of record	1961 to 1983			
Establishment	Hydrologic network – secondary areal catchment.			
Data quality	1	2	10	152
	96.46%	1.97%	0.04%	1.53%
Rating curve	Minimum discharge measurement			0.00 GL
	Maximum discharge measurement			8.22 GL
	Percentage of recorded flow covered by confirmed rating			94.9%

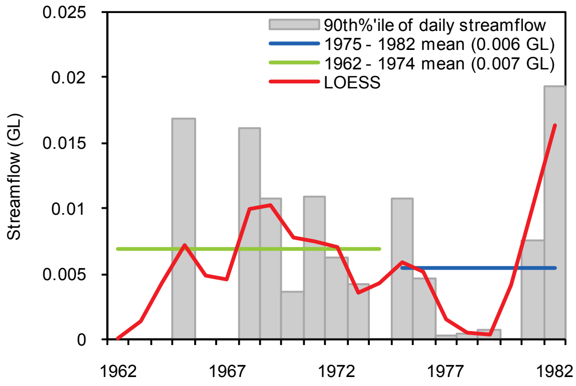
Years excluded from analysis
1966, 1967, 1974



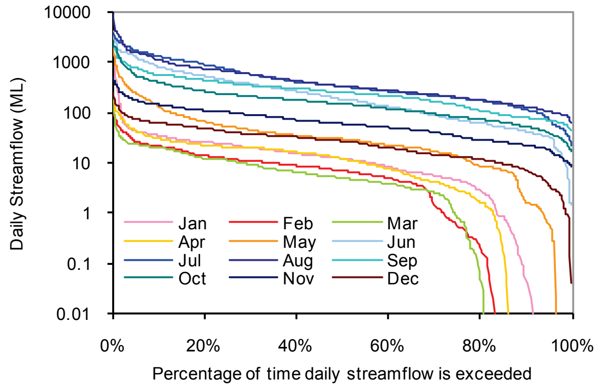
Annual streamflow at Olive Hill gauge



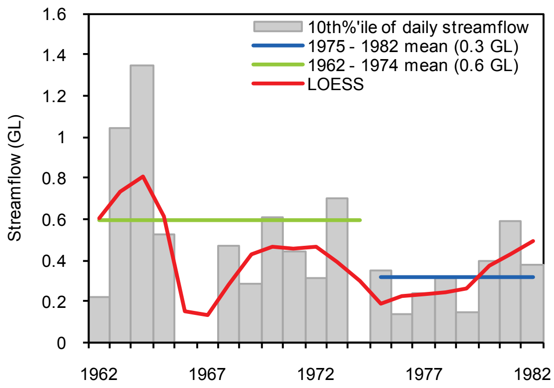
Annual flow duration curves for 1962 to 1982



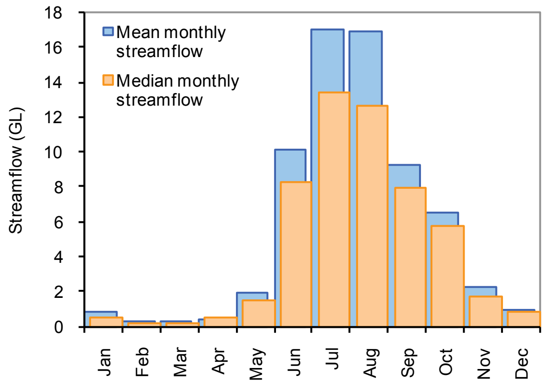
Low flows: 90th percentile of daily flows



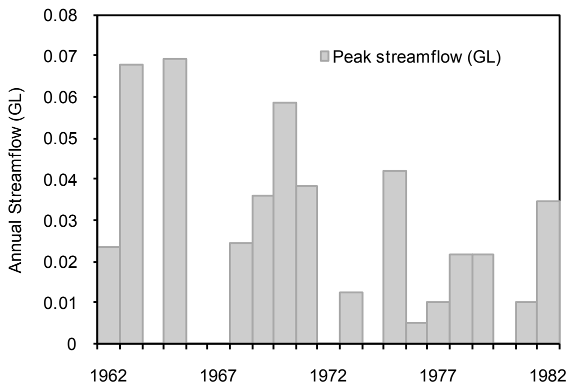
Monthly flow duration curves for 1962 to 1982



High flows: 10th percentile of daily flows



Average monthly streamflow for 1962 to 1982



Peak annual streamflow

Rainfall and runoff under future climate scenarios

Climate scenario	Mean annual rainfall (mm)		Mean annual streamflow (GL)		Runoff coefficient
Historical	973		44.0		20%
Recent	899	(−8%)	36.4	(−17%)	18%
Wet	958	(−2%)	41.6	(−5%)	19%
Median	893	(−8%)	34.1	(−22%)	17%
Dry	824	(−15%)	26.8	(−39%)	14%

Appendix B — Global climate models used by CSIRO (2009)

Global climate model	Modelling group and country
CCCMA T47	Canadian Centre for Climate Modelling and Analysis (grid resolution T47), Canada
CCCMA T63	Canadian Centre for Climate Modelling and Analysis (grid resolution T63), Canada
CNRM	Meteo-France, France
CSIRO-MK3.0	CSIRO, Australia
GFDL 2.0	Geophysical Fluid Dynamics Lab, USA
GISS-AOM	NASA/Goddard Institute for Space Studies (Atmosphere Ocean Model), USA
IAP	LASG/Institute of Atmospheric Physics, China
INMCM	Institute of Numerical Mathematics, Russia
IPSL	Institute Pierre Simon Laplace, France
MIROC-M	Centre for Climate Research, Japan
MIUB	Meteorological Institute of the University of Bonn, Germany Meteorological Research Institute of KMA, Korea
MPI-ECHAM5	Max Planck Institute for Meteorology DKRZ (European Centre Hamburg), Germany
MRI	Meteorological Research Institute, Japan
NCAR-CCSM	National Center for Atmospheric Research (Community Climate System Model), USA
NCAR-PCM1	National Center for Atmospheric Research (Parallel Climate Model), USA

Appendix C — Estimated divertible volumes at 2020 and 2030

Reliabilities of supply of the current SDL volumes and the reduction in divertible volumes required to maintain the reliability of supply at 80% at indicator gauging stations for the lower Collie catchment at 2020

Gauging Station		Current	Wet 2020	Median 2020	Dry 2020
612022	Reliability of current SDL volume	80%	62%	41%	29%
	Volume to maintain 80% reliability	2 902	2 670	2 231	1 735
	Reduction from current SDL to maintain 80% reliability		−8%	−23%	−40%
	Volume diverted in minimum year	476	390	222	101
612023	Reliability of current SDL volume	80%	74%	56%	35%
	Volume to maintain 80% reliability	1 177	1 110	961	794
	Reduction from current SDL to maintain 80% reliability		−6%	−18%	−32%
	Volume diverted in minimum year	529	468	275	148
612032	Reliability of current SDL volume	80%	79%	79%	68%
	Volume to maintain 80% reliability	12 416	1 1809	10 494	8 544
	Reduction from current SDL to maintain 80% reliability		−5%	−15%	−31%
	Volume diverted in minimum year	4 278	3 747	2 732	1 559

Gauging Station		Current	Wet 2020	Median 2020	Dry 2020
612039	Reliability of current SDL volume	80%	91%	88%	79%
	Volume to maintain 80% reliability	6 560	6 291	5 830	5 100
	Reduction from current SDL to maintain 80% reliability		−4%	−11%	−22%
	Volume diverted in minimum year	2 603	2 470	2 106	1 487
612005	Reliability of current SDL volume	80%	79%	62%	53%
	Volume to maintain 80% reliability	259	246	211	170
	Reduction from current SDL to maintain 80% reliability		−5%	−19%	−34%
	Volume diverted in minimum year	76	65	29	11
61206	Reliability of current SDL volume	80%	74%	62%	44%
	Volume to maintain 80% reliability	2 814	2 640	2 193	1 746
	Reduction from current SDL to maintain 80% reliability		−6%	−22%	−38%
	Volume diverted in minimum year	1 380	1 284	947	565

Gauging Station		Current	Wet 2020	Median 2020	Dry 2020
611007	Reliability of current SDL volume	80%	76%	56%	44%
	Volume to maintain 80% reliability	2 576	2 436	2 065	1 676
	Reduction from current SDL to maintain 80% reliability		−5%	−20%	−35%
	Volume diverted in minimum year	781	634	459	272
612004	Reliability of current SDL volume	80%	79%	74%	62%
	Volume to maintain 80% reliability	695	664	566	459
	Reduction from current SDL to maintain 80% reliability		−4%	−19%	−34%
	Volume diverted in minimum year	94	81	43	19

Reliabilities of supply of the current SDL volumes and the reduction in divertible volumes required to maintain the reliability of supply at 80% at indicator gauging stations for the lower Collie catchment at 2030

Gauging Station		Current	Wet 2030	Median 2030	Dry 2030
612022	Reliability of current SDL volume	80%	59%	35%	21%
	Volume to maintain 80% reliability	2 902	2 607	2 020	1 157
	Reduction from current SDL to maintain 80% reliability		−10%	−30%	−60%
	Volume diverted in minimum year	476	361	159	43
612023	Reliability of current SDL volume	80%	71%	50%	29%
	Volume to maintain 80% reliability	1 177	1 092	893	549
	Reduction from current SDL to maintain 80% reliability		−7%	−24%	−53%
	Volume diverted in minimum year	529	442	208	83
612032	Reliability of current SDL volume	80%	79%	76%	41%
	Volume to maintain 80% reliability	12 416	11 594	9 704	6 540
	Reduction from current SDL to maintain 80% reliability		−7%	−22%	−47%
	Volume diverted in minimum year	4 278	3 534	2 169	885

Gauging Station		Current	Wet 2030	Median 2030	Dry 2030
612039	Reliability of current SDL volume	80%	91%	82%	74%
	Volume to maintain 80% reliability	6 560	6 210	5 522	4 319
	Reduction from current SDL to maintain 80% reliability		−5%	−16%	−34%
	Volume diverted in minimum year	2603	2427	1779	894
612005	Reliability of current SDL volume	80%	76%	53%	38%
	Volume to maintain 80% reliability	259	241	192	122
	Reduction from current SDL to maintain 80% reliability		−7%	−26%	−53%
	Volume diverted in minimum year	76	60	13	1
61206	Reliability of current SDL volume	80%	74%	53%	32%
	Volume to maintain 80% reliability	2 814	2 583	1 958	1 414
	Reduction from current SDL to maintain 80% reliability		−8%	−30%	−50%
	Volume diverted in minimum year	1 380	1 253	698	385

Gauging Station		Current	Wet 2030	Median 2030	Dry 2030
611007	Reliability of current SDL volume	80%	76%	50%	26%
	Volume to maintain 80% reliability	2 576	2 381	1 869	1 398
	Reduction from current SDL to maintain 80% reliability		−8%	−27%	−46%
	Volume diverted in minimum year	781	562	364	203
612004	Reliability of current SDL volume	80%	79%	71%	35%
	Volume to maintain 80% reliability	695	653	522	369
	Reduction from current SDL to maintain 80% reliability		−6%	−25%	−47%
	Volume diverted in minimum year	94	77	34	7

Appendix D — Reliability of median 2020 diversion volumes – dry 2020 and median and dry 2030 scenarios

Gauging Station		Median scenario volume at 2020	Reliability under dry scenario at 2020 %	Reliability under median scenario at 2030 %	Reliability under dry scenario at 2030 %
612022	Divertible volume at 80% reliability	2 231	44.1	67.6	35.3
	Volume diverted in minimum year	222	94.1	100	88.2
612023	Divertible volume at 80% reliability	961	52.9	73.5	41.2
	Volume diverted in minimum year	275	91.2	94.1	82.4
612032	Divertible volume at 80% reliability	10 494	76.5	79.4	61.8
	Volume diverted in minimum year	2 732	97.1	100	94.1
612039	Divertible volume at 80% reliability	5 830	85.3	88.2	79.4
	Volume diverted in minimum year	2 106	100	100	97.1
612005	Divertible volume at 80% reliability	211	67.6	76.5	50.0
	Volume diverted in minimum year	29	94.1	94.1	91.2

Gauging Station		Median scenario volume at 2020	Reliability under dry scenario at 2020 %	Reliability under median scenario at 2030 %	Reliability under dry scenario at 2030 %
61206	Divertible volume at 80% reliability	2 193	70.6	73.5	47.1
	Volume diverted in minimum year	947	88.2	91.2	88.2
611007	Divertible volume at 80% reliability	2 065	73.5	76.5	52.9
	Volume diverted in minimum year	459	97.1	100	94.1
612004	Divertible volume at 80% reliability	566	73.5	76.5	64.7
	Volume diverted in minimum year	43	100	100	94.1

Shortened forms

AHD	Australian height datum
APET	Areal potential evapotranspiration
CSIRO	Commonwealth Scientific and Industrial Research Organisation
FCFC	Forest Cover Flow Change tool
FDC	Flow duration curve
GCM	Global climate models
IPCC	Intergovernmental Panel on Climate Change
MAF	Mean annual flow
MinAF	Minimum annual flow
MFT	Minimum flow threshold
RPE	Regional prediction equation
SDL	Sustainable diversion limit
WQIP	Water quality improvement plan

Glossary

Abstraction The permanent or temporary withdrawal of water from any source of supply, so that it is no longer part of the resources of the locality.

The withdrawal of water from any source of supply.

Allocation limit Annual volume of water set aside for use from a water resource.

Catchment The area of land from which rainfall run-off contributes to a single watercourse, wetland or aquifer.

Climate change A change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.

Dam Embankments constructed to store or regulate surface water flow. A dam can be constructed in or outside a watercourse.

Reliability The frequency with which water allocated under a water access entitlement is able to be supplied in full. Referred to in some states as ‘high security’ and ‘general security’.

Reservoir A natural or artificial place where water is collected and stored for use, especially water for supplying a community, irrigating land, furnishing power, etc

Streamflow The net flow of water through a stream channel that integrates all contributing components, e.g., overland flow, interflow, and groundwater discharge

Surface water Water flowing or held in streams, rivers and other wetlands on the surface of the landscape.

Sustainable diversion limit A regional, hydrologic estimate of the sustainable yield of surface water resources as determined by SKM (2008a, 2008b)

Sustainable diversion volume The volume of water able to be diverted as determined by the Sustainable Diversion Limit methodology.

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