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

The effects of climate change on streamflow in south-west Western Australia

Projections for 2050

Looking after all our water needs

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Department of Water

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Summary

The effects of declining rainfall and increasing temperatures on rivers and streams in south-west Western Australia has been widely reported. The associated decrease in streamflow has prompted the revision of water planning considerations.

In the absence of detailed investigations, previous studies have identified a basic ‘rule of thumb’ approach for assessing the changes in mean annual streamflow under the shifting rainfall and temperature conditions. Research from across Australia has found that typically a 1% change in mean annual rainfall would result in a 2–3% change in mean annual runoff. The approach is simplified and broad but can be applied regionally via geographic information systems, making it suitable for regional planning and decision-making processes.

This study uses a simple linear equation – based on the ‘rule of thumb’ and relating the projected change in rainfall and temperature to a projected change in streamflow for 2050 – to provide a rapid assessment tool of streamflow sensitivity to climate change in south-west Western Australia.

Rainfall and temperature generated by the Australian Commonwealth Scientific and Research Organisation (CSIRO) Mk3.5 general circulation model, under the A2 Special Report on Emissions Scenarios (SRES) emission scenario (IPCC 2000) for two time-slices centred around 1990 and 2050, were used to assess the future streamflow variations. The analysis was carried out in ANUSPLIN 4.2 and ArcGIS 9.2 Spatial Analyst and resulted in a number of maps of the streamflow differences on a regional scale.

Annually, the linear equation estimated reductions in mean annual streamflow for 2050 compared with 1990 values within a range of 12–63%. The largest streamflow decrease was estimated in areas with a projected rainfall decline of more than 15% and projected temperature rises greater than 11%.

Seasonally, the greatest streamflow decline was calculated in autumn and summer up to 90%. In addition, for regions where rainfall was projected to increase, the linear equation estimated increases in runoff for autumn and spring (up to 11%).

Estimates from the equation were compared with the results of detailed hydrologic modelling to assess whether this simple approach could be used as a readily available scoping tool. The results showed the approach provided annual time-scale estimates similar to the hydrologic modelling and could be applied as a first ‘test’ before decisions on commissioning detailed studies were made.

1 The climate elasticity of streamflow

The decline in runoff across south-west Western Australia has been widely observed and attributed to below-average rainfall since the mid-1970s (Ruprecht & Rodgers 1999; Bari & Ruprecht 2003; Li et al. 2005). Climate projections from general circulation models (GCMs) for 2050 indicate a continuing decline in rainfall and rise in temperatures throughout the much of the region (Charles et al. 1999; Charles et al. 2007; Johnson & Sharma 2009).

This study aimed to develop and test a simple method to broadly estimate the impacts of climate change on streamflow in south-west Western Australia.

A number of studies around the world have explored the sensitivity of streamflow to climatic change, many of them focusing on the sensitivity of streamflow to rainfall variations (Schaake & Chunzhen 1989; Xu 1999; Chiew 2006; Berti et al. 2004; Smith et al. 2009). A concept of ‘streamflow elasticity’ as the proportional change in mean annual streamflow divided by the proportional change in mean annual rainfall was developed by a number of investigations (Schaake & Chunzhen 1989; Sankarasubramaniam et al. 2001).

Research into the impact of rainfall on streamflow in 219 locations across Australia provided evidence that the rainfall elasticity of streamflow was within the 2–3.5% range (Jones et al. 2005; Chiew 2006). Detailed modelling projects conducted in Western Australia (Berti et al. 2004; Kitsios et al. 2008; Smith et al. 2009) led to a basic ‘rule of thumb’ approach for assessing the changes in mean annual streamflow for a given change in rainfall. Typically a 1% change in mean annual rainfall would result in a 2–3% change in mean annual runoff.

Detailed regional hydrological studies provide a valuable guide for managing possible future water reserves. However, these analyses are time- and resource-consuming and their predictive value is associated with a certain degree of uncertainty.

Climate elasticity of streamflow is a simple method to broadly assess the impact of climate change on streamflow and may have wide application in the management of water resources.

To test the applicability of climate elasticity of streamflow for water resource planning, a linear equation was applied to south-west Western Australia. Results derived from this equation were cross-checked with the results from detailed hydrological studies and they matched well. This means the simple method can be used in water resource planning to identify areas of concern for future climate which may require more detailed studies.

1.1 Purpose

Catchment management authorities in many regions of south-west Western Australia require urgent assessment of water resources for planning and allocation purposes. This has created the need for simple and readily available tools to assess streamflow sensitivity to rainfall at a regional scale. This study has tested one of these tools and found it can be broadly applied to scoping processes and provide results comparable with complex modelling applications.

This study estimates the streamflow sensitivity to projected changes in rainfall and temperature in the region using a simple approach based on a 'rule of thumb'. This streamflow sensitivity has been calculated using a simple linear equation, which relates rainfall and temperature to streamflow. The climate data used in the linear equation was generated by the CSIRO Mk3.5 GCM, which projected rainfall and temperature series under the A2 SRES emission scenario (IPCC 2000) for the year 2050.

Estimates derived from the equation were compared with results from detailed hydrological modelling to assess whether the simple method could be used as a readily available scoping tool.

2 Estimation of climate elasticity of streamflow

Future climate projections have been widely used in hydrological modelling to assess the effects of climate change on catchment yield (Jones et al. 2005; Chiew 2006; Nawaz & Bellerby 2007). Most of these investigations employed GCM outputs forced with different greenhouse gas emission scenarios, and were statistically downscaled from a regional to a local extent to reflect small-scale climatic processes.

Previous studies (Fu & Chen 2005; Fu et al. 2007) developed a methodology to approximate the impact of climate change on catchment hydrology using the ArcGIS Geostatistical Analyst. In this study, surfaces of projected rainfall, temperature and change in streamflow were created with the ANUSPLIN 4.2 software, and then analysed in ArcGIS 9.2 Spatial Analyst.

2.1 Method

The estimation of streamflow elasticity in south-west Western Australia was based on a simple linear equation relating projected changes in rainfall and temperature to streamflow (Equation 1):

Equation 1 $$\Delta Q = 3 \times \Delta P - 0.5 \times \Delta T$$

where: ΔQ is change in streamflow, (%); ΔP is change in rainfall $(future - current) \div current) \times 100$; and ΔT is change in temperature $(future - current) \div current) \times 100$.

Maps of potential changes in streamflow in the region are the final result of this analysis for climate representative of 2050, in areas where water resources are most heavily used and require planning considerations. Four steps were undertaken to accomplish this aim. They are listed below and illustrated in Figure 1:

- **Rainfall analysis** – rainfall was generated using the CSIRO Mk3.5 GCM under the A2 emission scenario centred around 1990 and 2050 for 47 meteorological stations located in the study area. These projected point rainfall series were interpolated to spline surfaces with ANUSPLIN 4.2. Then the interpolated rainfall surfaces were assessed with Spatial Analyst, an extension of ArcGIS 9.2, to calculate the projected change in rainfall.
- **Temperature description** – the temperature data, also from the CSIRO Mk3.5 GCM under the A2 emission scenario, was in a format of monthly differences between current and future projections (expressed in degrees celsius and percentages). These temperature series were interpolated with ANUSPLIN 4.2 to surfaces. Maps of projected temperature change were then produced with Spatial Analyst.

- **Calculations of change in streamflow** – a simple linear equation relating the projected change in rainfall and temperature to the projected change in streamflow was applied. The equation was solved in Spatial Analyst, which processed rainfall and temperature derived by ANUSPLIN 4.2. The final products were maps representing the streamflow differences on a regional scale.
- **Comparison with hydrologic modelling** – results from solving the linear equation in Spatial Analyst were compared with estimates from detailed hydrologic modelling (the dynamic water balance model and two lumped conceptual rainfall/ runoff models) for three catchments located in the study area.

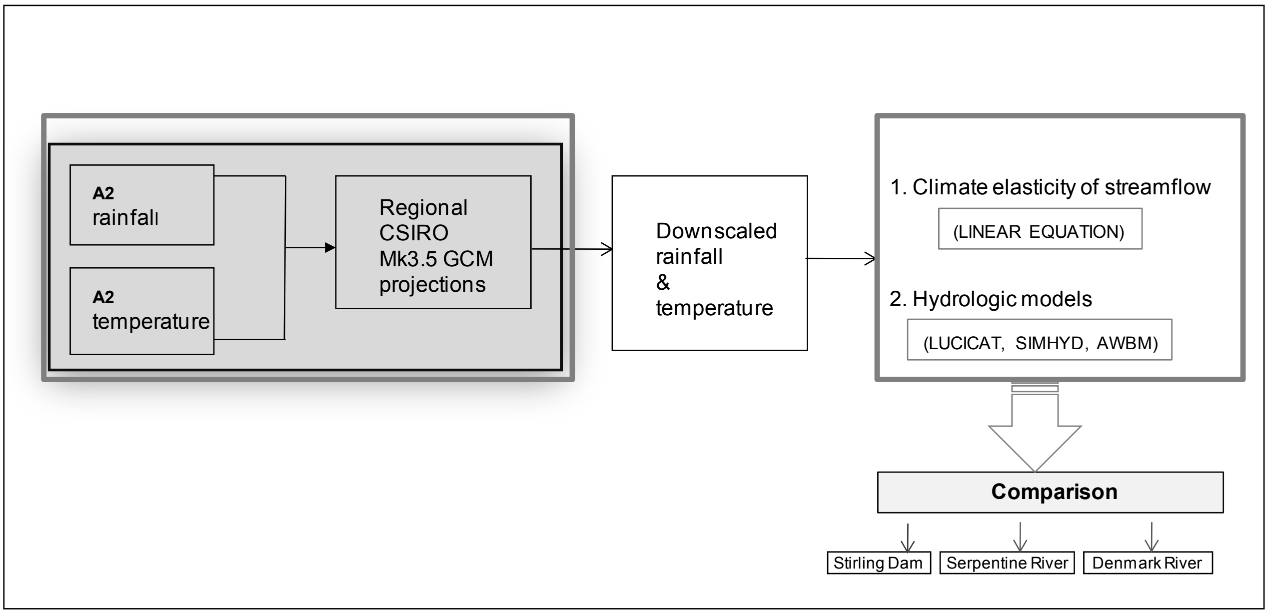

Figure 1 Project methodology schematic

2.2 Study area

The study area covered south-west Western Australia encompassing the Australian Water Resources Council (AWRC) basins from Moore-Hills Rivers (617) to Albany Coast (602) (Figure 2). This study focused on areas where water resources are used most heavily (areas such as the Avon River Basin [615] were excluded for this reason).

South-west Western Australia has a temperate climate (according to the Köppen classification system) dominated by mild wet winters and hot dry summers (BoM 2010).

Most annual rainfall (approximately 80%) falls from May to October. There is a general decrease in rainfall from south to north over the region and a slight increase from west to east across the Swan Coastal Plain before a steady decline inland of the Darling Plateau. The mean annual rainfall (1976–2003) varies from 309 mm in the north-eastern parts of the study area to 1192 mm within the Darling Plateau (Figure 2, Table 1).

A significant decrease in annual rainfall of about 10 to 15% has occurred since the mid-1970s (CSIRO 2009). This has been associated with an even larger (up to 40%) drop in streamflow supplying reservoirs in the region (Bari et al. 2004).

Temperatures in south-west Western Australia have increased by approximately 0.8℃ since 1910 (BoM 2010): most of this warming has occurred since 1950. This has been particularly evident in southern inland parts of the region, which show the greatest temperature rises during winter and spring.

South-west Western Australia has come under increasing urban and agricultural pressures, with population growth of 2.9% in 2009 (ABS 2009). The state has a population of 2.2 million, with 85% of people living in the south-west region (ABS 2009).

Future projections indicate that continued strong economic and population growth, together with a warming climate, may put further pressure on existing water resources. Therefore, planning to meet the growing water demand and sharing water between the environment and opposing users is of paramount importance.

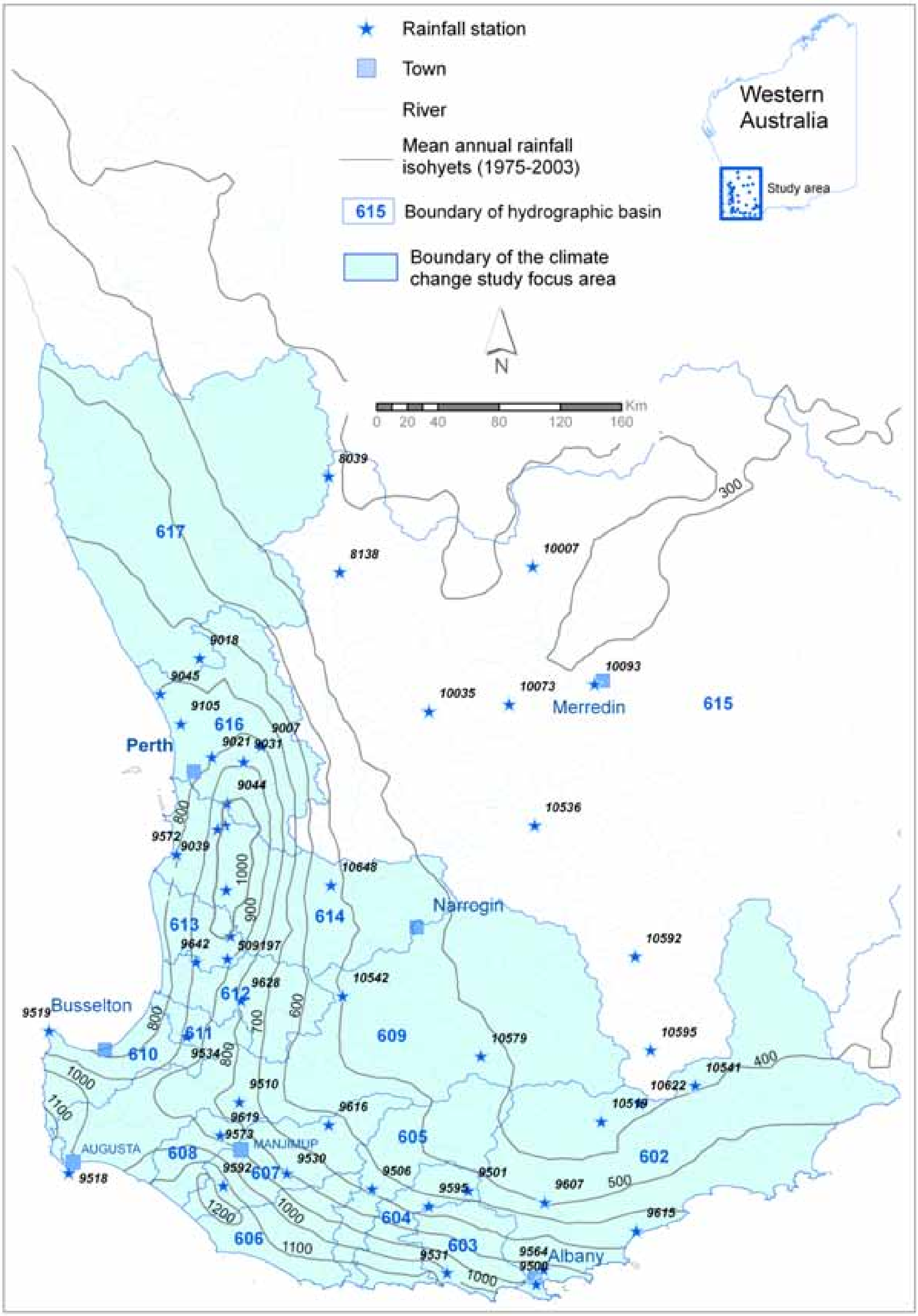

Figure 2 Location of the 47 meteorological stations within south-west Western Australia used in the study

2.3 Meteorological data

A network of 47 meteorological stations across the study area was selected according to data availability and proximity to significant water resources (Figure 2). Table 1 presents details of the chosen stations. Daily rainfall data recorded at these stations during 28 years (1976–2003) were used for statistical downscaling of regional climate data from the CSIRO's Mk3.5 GCM. This process is documented in detail elsewhere (Berti et al. 2004; Kitsios et al. 2008; Smith at al. 2009).

Table 1 Meteorological station details

	Station no	Station name	Latitude	Longitude	Elevation (m)	Observed mean annual rainfall (1976-2003) (mm)
1	***8039***	***Dalwallinu PO****	***-30.28***	***116.66***	***335***	***353***
2	***8138***	***Wongan Hills Research Stn****	***-30.84***	***116.73***	***305***	***375***
3	9007	Chidlow PO	-31.86	116.26	300	795
4	9018	Gingin PO	-31.35	115.90	92	634
5	9021	Perth Airport	-31.93	115.98	15	738
6	9023	Jarrahdale	-32.33	116.05	230	1066
7	9031	Mundaring Weir	-31.96	116.16	300	911
8	9039	Serpentine	-32.35	116.01	120	897
9	9044	Wungong Dam	-32.20	116.06	200	1037
10	9045	Yanchep Park	-31.56	115.67	20	716
11	9105	Wanneroo	-31.73	115.79	30	742
12	9500	Albany	-35.03	117.88	3	880
13	9501	Arundel	-34.48	117.48	260	549
14	9506	Bangalup	-34.47	116.92	180	679
15	9510	Bridgetown PO	-33.96	116.14	150	766
16	9518	Cape Leeeuwin	-34.37	115.13	13	963
17	9519	Cape Naturaliste	-33.54	115.02	109	783
18	9530	Deeside	-34.38	116.42	140	789
19	9531	Denmark PO	-34.96	117.36	20	998
20	9534	Donnybrook	-33.57	115.83	63	910
21	9538	Dwellingup Forestry	-32.71	116.06	267	1192
22	9564	King River	-34.94	117.92	12	836
23	9572	Mandurah Park	-32.50	115.77	15	820
24	9573	Manjimup	-34.25	116.14	287	940
25	9592	Pemberton	-34.45	116.04	174	1138
26	9595	Perillup	-34.57	117.25	300	646
27	9607	White Gums	-34.55	117.93	150	443
28	9615	Warriup	-34.72	118.47	20	658
29	9616	Westbourne	-34.09	116.66	280	661
30	9619	Wilgarrup	-34.15	116.02	240	777
31	9628	Collie	-33.36	116.15	204	830
32	9642	Wokalup	-33.13	115.88	30	924
33	***10007***	***Bencubbin****	***-30.81***	***117.86***	***359***	***309***
34	***10035***	***Cunderdin****	***-31.66***	***117.25***	***236***	***360***
35	***10073***	***Kellerberrin****	***-31.62***	***117.72***	***250***	***305***
36	***10093***	***Merredin Research Stn****	***-31.50***	***118.22***	***318***	***317***
37	10519	Borden PO	-34.07	118.26	220	380
38	10536	Corrigin	-32.33	117.87	295	360
39	10541	Nyerilup	-33.86	118.81	280	383
40	10542	Darkan PO	-33.33	116.74	280	486
41	10579	Katanning PO	-33.69	117.56	310	451
42	***10592***	***Lake Grace PO****	***-33.10***	***118.46***	***286***	***341***
43	***10595***	***Pingrup South****	***-33.65***	***118.55***	***290***	***329***
44	10622	Ongerup	-33.97	118.49	286	386
45	10648	Wandering PO	-32.68	116.68	280	545
46	509116	Harvey River	-32.98	116.08	280	1175
47	509197	Tallanalla Creek	-33.12	116.07	172	1081

* Meteorological stations used for downscaling of projected rainfall, but were outside the focus area.

3 Climate change projections - rainfall

The projected rainfall was the dominant factor in estimating future changes in streamflow. Therefore it was important to verify how well it replicated the observed climate over the current period. The following section presents the process of examining projected and observed rainfall data processed with ANUSPLIN 4.2 and ArcGIS 9.2. This process had four stages (listed below and shown in Figure 3):

- **Description of the projected rainfall** (Section 3.1).
- **Numerical analysis of the projected rainfall** – this included the correlation between mean observed and current rainfall in annual and seasonal time-steps (Section 3.2).
- **Spatial examination of the rainfall surfaces created in ANUSPLIN 4.2** – this was based on examination of the interpolation of rainfall point data to spline surface. Annual and seasonal rainfall surfaces were compared with mean observed point rainfall records from 47 sites within the study area (Section 3.3).
- **Spatial analysis of projected rainfall change** – surfaces created by ANUSPLIN 4.2 in conjunction with ArcGIS 9.2 were used to calculate the projected change in rainfall for 2050.This change was expressed in millimetres when describing the difference between future and current projected rainfall; and in percentage when describing a ratio (future-current/current projected rainfall) (Section 3.4).

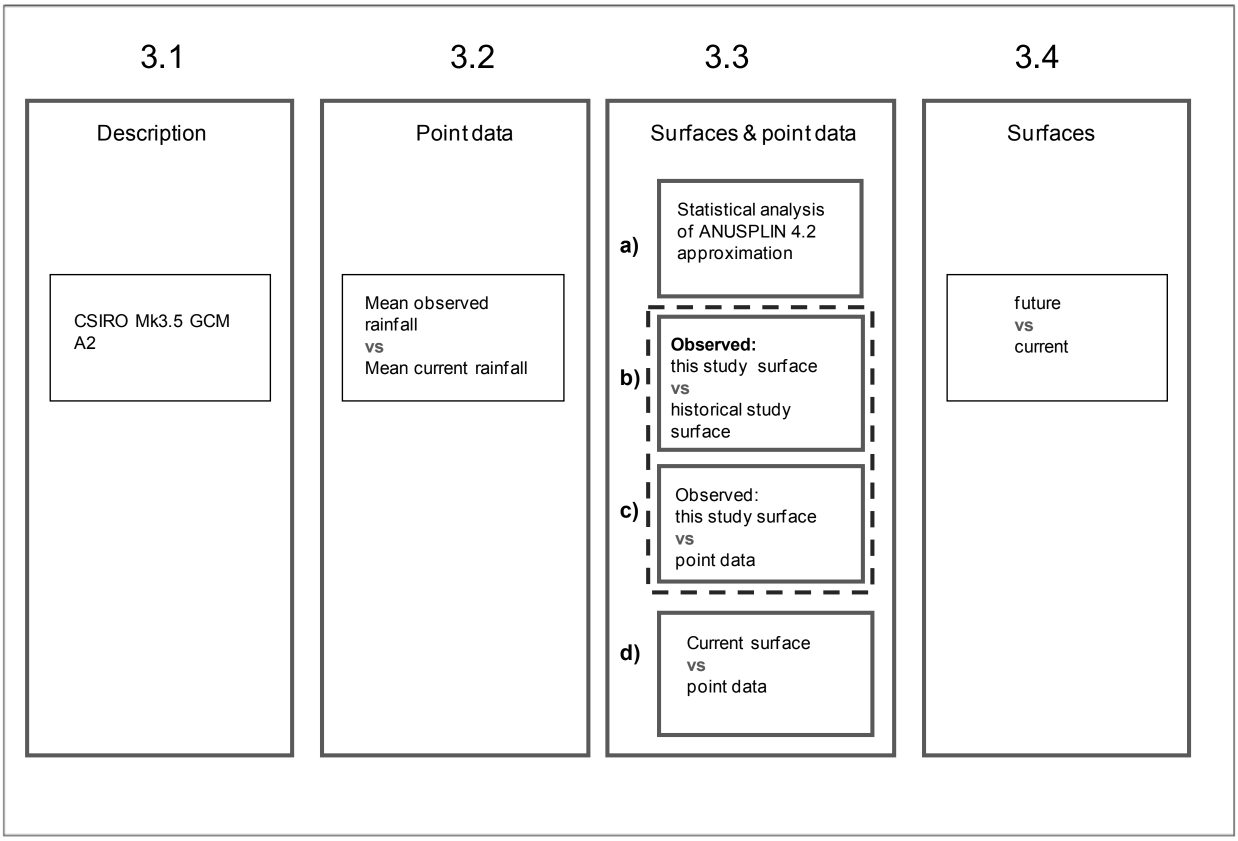

Figure 3 Process for evaluation of the current rainfall

3.1 GCMs and A2 emission scenario

Previous studies (Berti et al. 2004; Kitsios et al. 2008; Smith et al. 2009) assessed possible future changes in catchment streamflow under the changing climate using the Land Use Change Incorporated Catchment (LUCICAT) model and projected rainfall series. The hydrological response of three catchments was investigated: the Stirling Dam, Serpentine River and Denmark River catchments.

In all these studies, the future climate change was represented by rainfall series generated by statistically downscaling the atmospheric predictors obtained from GCMs. Downscaled rainfall datasets were created for meteorological stations across south-west Western Australia. This process is described in detail in Berti et al. (2004), Kitsios et al. (2008) and Smith at al. (2009).

This study analysed the rainfall and temperature series for 47 stations within the study area generated by the CSIRO Mk3.5 GCM under the A2 SRES emissions scenario for two 28-year time-slices centred around 1990 and 2050.

A range of future greenhouse gas emission scenarios were developed in 2000 by the Intergovernmental Panel on Climate Change (IPCC) to represent possible future social, economic and environmental developments. The A2 scenario is based on high population and economic growth.

Downscaled GCM rainfall was in the form of 40 daily series and was analysed in two 28-year time-slices: 'current' centred around 1990 (1976–2003) and 'future' centred around 2050 (2036–63).

3.2 Comparison between observed and downscaled GCM rainfall for the current period (1976-2003)

The initial comparison between observed and downscaled GCM current rainfall involved comparison of point data (observed and downscaled) at each of the 47 meteorological stations within the study area.

Mean annual and monthly values calculated from each projected series have been averaged across 40 series and compared with the mean observed rainfall (1976–2003) at the 47 stations.

Annual results – point data

The mean annual downscaled GCM rainfall (centred around 1990) correlated strongly (R^2=0.99) to observed data for the 47 stations used for downscaling (Figure 4).

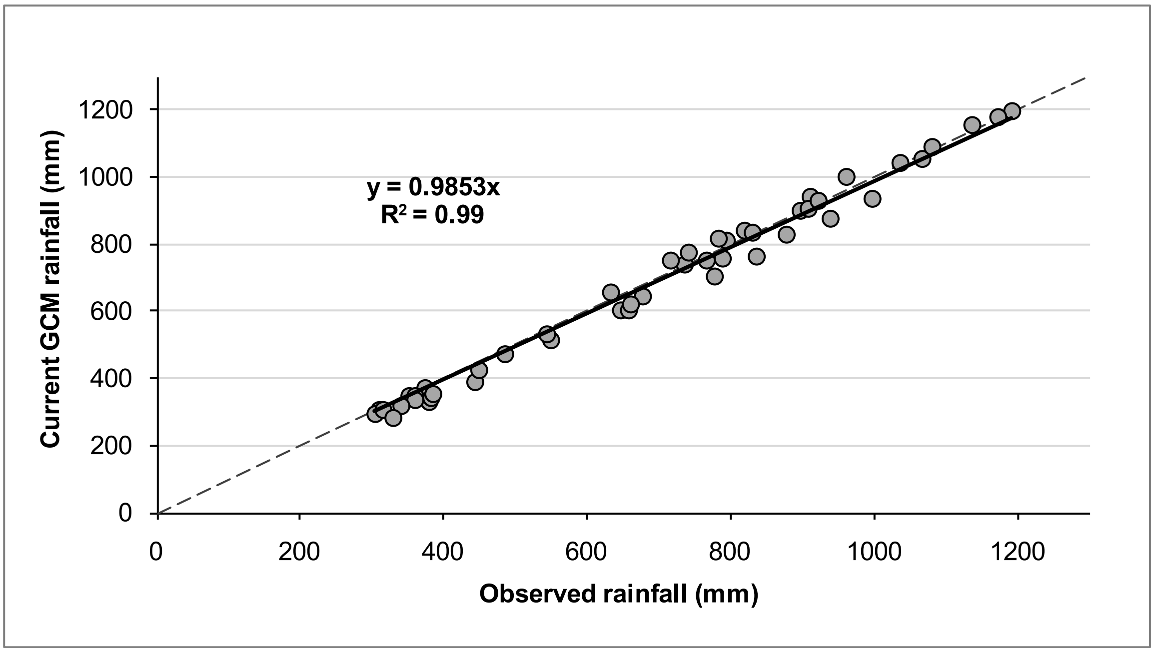

Figure 4 Comparison of observed and current Mk3.5 GCM downscaled mean annual rainfall for 47 stations within the study area

Annual rainfall statistics were calculated for each meteorological station used in this study. The summary results are in Table 2; the details are in Table 13 in Appendix A. Table 2 shows examples of statistics calculated for sites grouped in two categories: a) minimum and maximum observed rainfall; b) minimum and maximum percentage change.

Table 2 Summary of statistics showing similarity between mean annual observed and current rainfall for 47 stations within the study area

			Mean annual rainfall		
		Station no	Observed (mm)	Current (mm)	Difference (%)
a)	Min mean observed rainfall	10073	**305**	291	-4
	Max mean observed rainfall	9538	**1192**	1197	0.4
b)	Min % change	9039	897	900	**0.3**
	Max % change	10595	329	283	**-14**

The mean annual downscaled current series underestimated by 4% the lowest mean observed rainfall at Bencubbin (10073) and was close to the highest mean observed rainfall at Dwellingup Forestry (9538) – slightly overestimating it by 0.4%.

The lowest percentage difference (0.3%) was calculated for Serpentine (9039) and the highest (-14%) for Pingrup South (10595), which is located in the low rainfall zone.

Seasonal results

The monthly current rainfall was aggregated into four seasonal groups:

- summer: January, February, March
- autumn: April, May, June
- winter: July, August, September
- spring: October, November, December.

Seasonally, the projected rainfall series compared most strongly with the observed records for winter (R^2=0.99) and autumn (R^2=0.90) (figures 5c and 5b). The weakest correlation occurred in summer (R^2=0.6) with projected values being underestimated (Figure 5a). The relationship between observed rainfall in spring and the downscaled GCM series was strong (R^2=0.85) with a tendency for the current series to overestimate observed rainfall (Figure 5d).

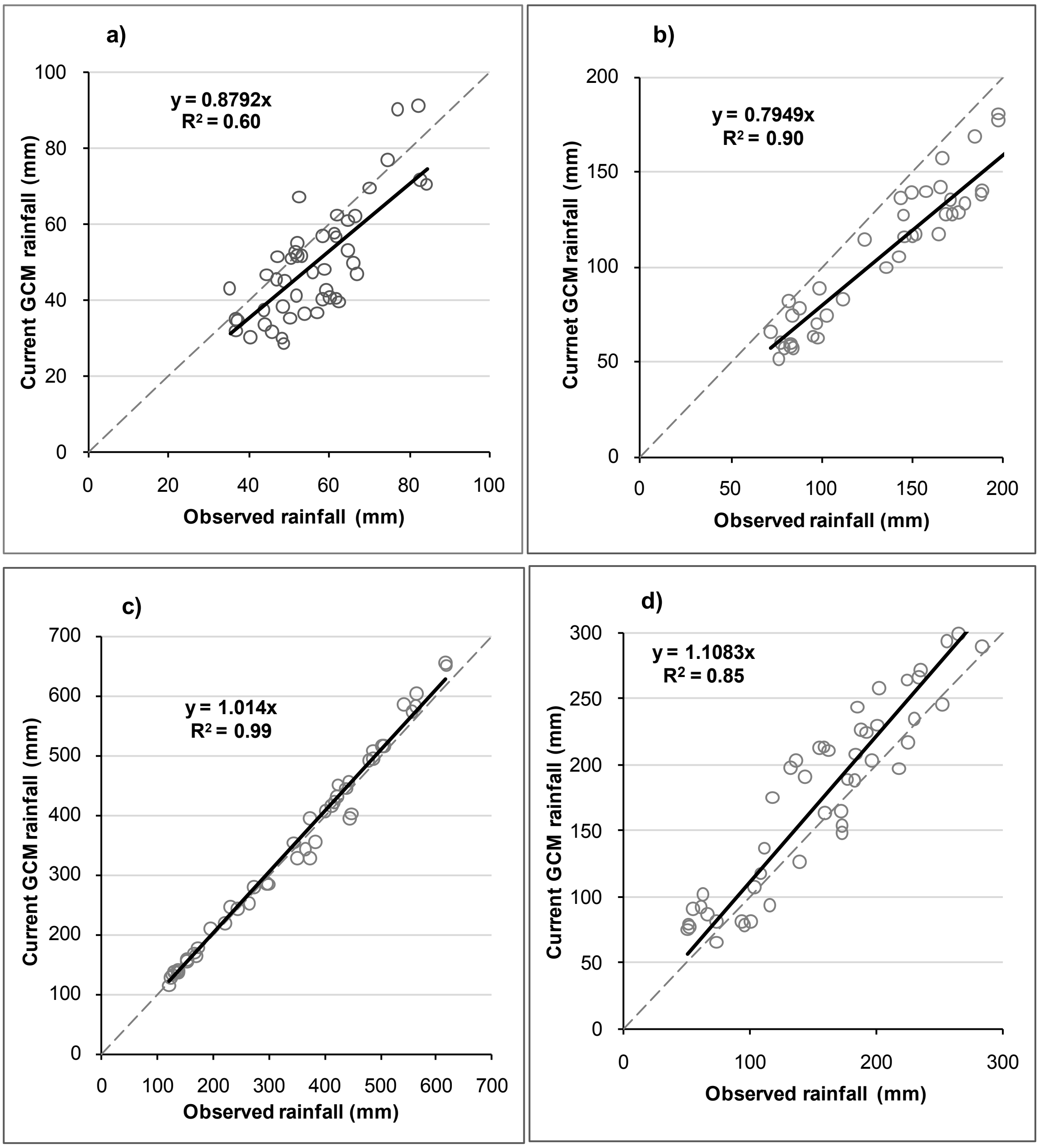

Figure 5 Comparison of observed and current Mk3.5 GCM downscaled mean seasonal rainfall for: a) summer b) autumn c) winter and d) spring for 47 stations within the study area

Figure 6 illustrates examples of monthly distribution of observed and projected rainfall for the sites included in Table 2. Projected rainfall at Kellerberrin 10073 (minimum mean observed rainfall), Dwellingup 9538 (maximum mean observed rainfall) and Serpentine 9039 (minimum percentage change) stations was higher than the observed rainfall for the winter and autumn months (figures 6a and 6b). Also, the shift in highest rainfall was apparent in the winter months from June–July for observed rainfall to July–August for projected rainfall. This observation has been reported in previous Western Australian studies that used the CSIRO Mk3 and Mk3.5 downscaled rainfall (Berti et al. 2004; Kitsios et al. 2008; Smith et al. 2009).

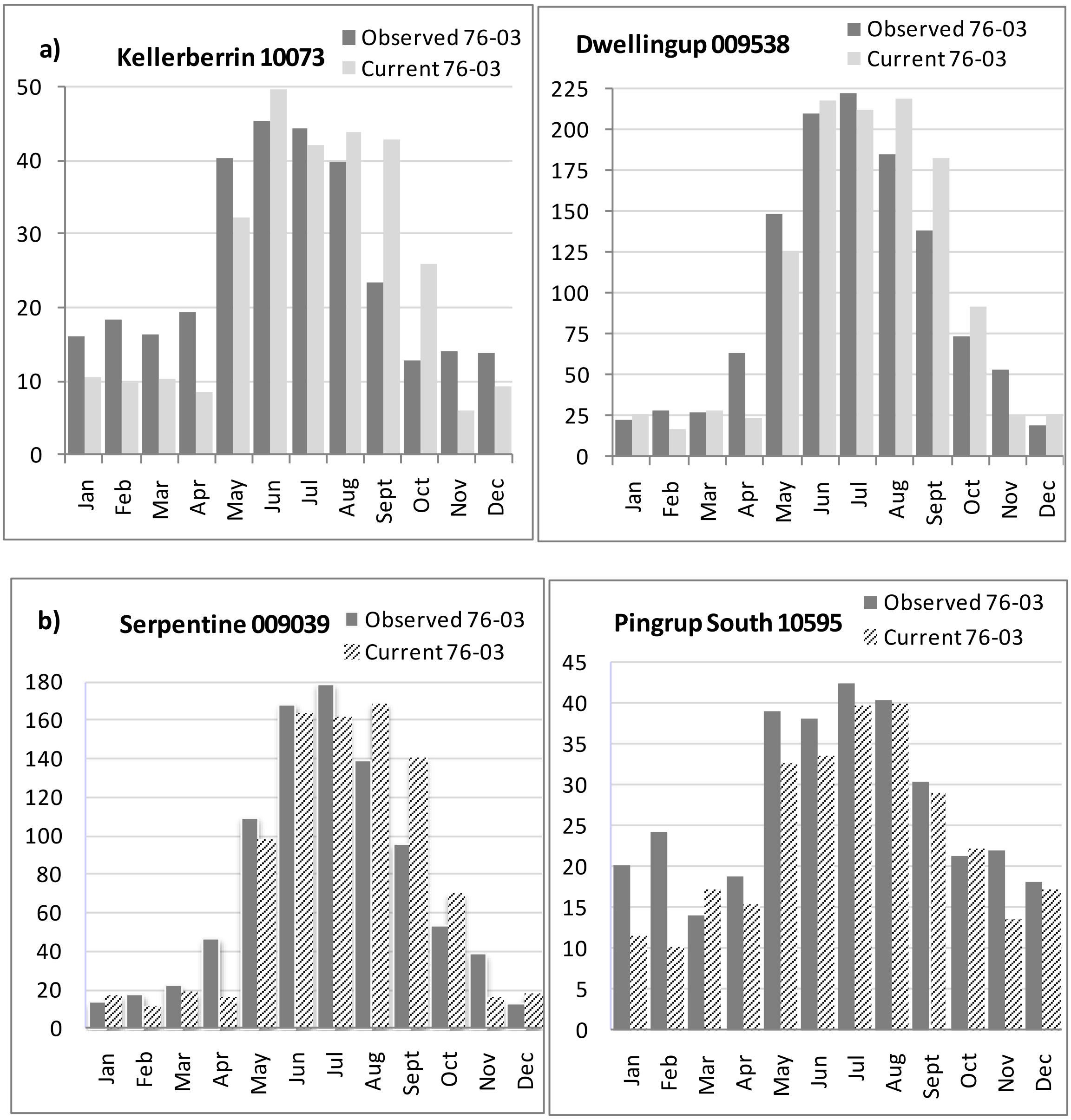

Figure 6 Comparison of observed and current Mk3.5 GCM downscaled mean monthly rainfall for rainfall stations with: a) min and max mean observed rainfall, b) min and max percentage change

3.3 Spatial analysis of downscaled GCM rainfall – interpolation of point data to spline surface

This study aimed to produce a set of maps to spatially represent the projected change in streamflow driven by the projected change in climate. These maps were generated in ANUSPLIN 4.2 and the Spatial Analyst, which is an ArcGIS 9.2 extension. Generated surfaces of projected rainfall were statistically and qualitatively examined to determine their reliability.

This section provides:

a) a brief description of ANUSPLIN 4.2

b) statistical results of ANUSPLIN 4.2 approximations of observed and current rainfall
c) comparison between ANUSPLIN 4.2 observed rainfall surfaces (from the historical record and this study) and observed point data
d) comparison between ANUSPLIN 4.2 current rainfall surface and observed point data.

a) ANUSPLIN 4.2 description

A three-dimensional spline surface was matched with the point rainfall data from 47 stations to provide rainfall estimates across south-west Western Australia. The ANUSPLIN 4.2 software (Hutchinson 2003) was applied to develop surfaces of rainfall estimates for annual and seasonal time-steps for observed and projected rainfall series. ANUSPLIN 4.2 employs thin-plate smoothing splines as the interpolation technique.

The spline interpolation uses the point data and additional variables that may affect the outcome of the surfaces; for example, elevation. In this study, the elevation was represented by outputs from a Digital Elevation Model (DEM).

To assess the most favourable fitted surface, Hutchinson (2003) recommended a number of statistical indicators. The best fit is accomplished when:

1. The generalised cross validation (GCV) is minimised. GCV is a measure of a predictive error of the fitted surface. A low GCV value indicates the surface represents well the spatial distribution of rainfall.
2. The root mean square error divided by the mean is less than 10%.
3. The signal is approximately half the number of data points. Signals larger than this may suggest inadequate data.
4. The signal to noise (error) ratio is less than 1 (the error should be equal to or greater than the signal).
5. Rho (the smoothing parameter) is maximised. An exact interpolation is achieved when Rho is close to 0.
6. There are no large residuals from the fitted surface.

b) Statistical results of ANUSPLIN 4.2 approximation

ANUSPLIN 4.2 produced 19 output files in ASCII format with mean annual and seasonal values for observed data (1976–2003) and the Mk3.5 GCMs series: current (1976–2003) and future (2036–64). These files were transformed to rainfall grids in Spatial Analyst.

The statistical results of the ANUSPLIN 4.2 mean annual rainfall approximations are shown in Table 3 and the mean seasonal rainfall approximations in Table 4.

The statistical results of the spline model goodness-of-fit suggest the rainfall surfaces approximated from the 47 points are a reasonable representation of the spatial variation in rainfall within the study area for both annual and seasonal time-steps.

Four of the recommended measures were satisfactorily fulfilled, while two criteria related to the number of data points (signal and signal divided by error) indicated that the model required more data to create more accurate estimates.

The generalised cross validation (GCV) may be considered low because the maximum value for annual approximation was 3.17 (Table 3) and 1.66 for seasonal surfaces (Table 4). These mean that the created surfaces represent the spatial trends in rainfall relatively well.

The root mean square error divided by the mean was less than 10% for all datasets (annual and seasonal).

The smoothing parameter (Rho) was close to 0 in all runs, implying an exact interpolation, and it may be assumed that the residuals were not large (less than two).

The signal was greater than half the data points and hence the signal divided by the noise (error) was greater than one. The high signal implies the data became exactly interpolated and the spline model was unstable and needed additional data. This should be expected considering only 47 data points were used over so large an area.

Table 3 Statistical results of ANUSPLIN 4.2 approximation of annual observed and projected rainfall surfaces

	Annual		
	Observed *1976-2003*	Current *1976-2003*	Future *2036-2064*
Generalised cross validation (GCV)	**2.6**	3.17	2.36
Root mean square error divided by mean (RTMSE/mean)	**0.103%**	0.114%	0.103%
Signal	**34**	35	36.6
Signal/error	**2.62**	2.92	3.52
Smoothing parameter (Rho)	**0.00306**	0.0026	0.00197
Large residuals	**No**	No	No

Table 4 Statistical results of ANUSPLIN 4.2 approximation of seasonal observed and projected rainfall surfaces

	Seasonal											
	Observed (1976-2003)				Current (1976-2003)				Future (2036-2064)			
	Summer	***Autumn***	***Winter***	***Spring***	*Summer*	*Autumn*	*Winter*	*Spring*	*Summer*	*Autumn*	*Winter*	*Spring*
Generalised cross validation (GCV)	**0.145**	**0.543**	**1.29**	**0.712**	0.287	0.307	2.28	0.694	0.425	0.210	1.66	0.566
Root mean square error / mean (RTMSE/mean)	**0.341%**	**0.233%**	**0.137%**	**0.246%**	0.536%	0.203%	0.208%	0.207%	0.817%	0%	0.181%	0.186%
Signal	**23.4**	**31.8**	**37.1**	**33.9**	27.9	35.4	31.8	35.5	22.6	47	34.9	37
Signal/error	**0.99**	**2.09**	**3.75**	**2.59**	1.46	3.05	2.09	3.09	0.93	0	2.88	3.7
Smoothing parameter (Rho)	**0.0152**	**0.00435**	**0.00177**	**0.00313**	0.00774	0.00242	0.00435	0.00236	0.0169	6.47E-11	0.00264	0.00183
Large residuals	**No**	**No**	**No**	**No**	No	No	No	No	No	No	No	No

a) Comparison between ANUSPLIN 4.2 surfaces (historical and this study) and observed point data

Durrant & Bowman (2004) used ANUSPLIN 4.2 to create 1975–2003 mean annual rainfall isohyets for Western Australia and part of the Northern Territory using observed data from 779 stations. This study employed ANUSPLIN 4.2 to create rainfall surfaces from data from only 47 sites. Mean annual rainfall values from both surfaces (historical and this study) were compared with the mean observed records at 47 stations within the study area to test if the number of data points was critical in creating rainfall grids. The annual statistics of this comparison are summarised in Table 5.

Both rainfall surfaces (created from observed data at 47 and 779 points) correlated well with the mean annual rainfall observed at the 47 stations, with a coefficient of efficiency (E) equal to 0.96 and coefficient of determination (R^2) of 0.96 and 0.97 respectively (Figure 5).

Table 5 Annual statistics for ANUSPLIN 4.2 approximation from observed records: using 47 and 779 data points and downscaled GCM current series for 47 sites

Annual		Observed	Observed		***Current***
		Observed	ANUSPLIN 4.2 **(47)**	ANUSPLIN 4.2 **(779)**	***ANUSPLIN 4.2 (47)***
Mean	*(mm)*	**695**	**691**	**680**	***676***
Standard deviation	*(mm)*	267	260	253	***269***
MAE(0)	*(mm)*		37	33	***52***
RMSE(0)	*(mm)*		7.0	7.2	***4.9***
E(1)			0.96	0.96	***0.94***
R^2			0.96	0.97	***0.95***

*E(1) = means perfect score

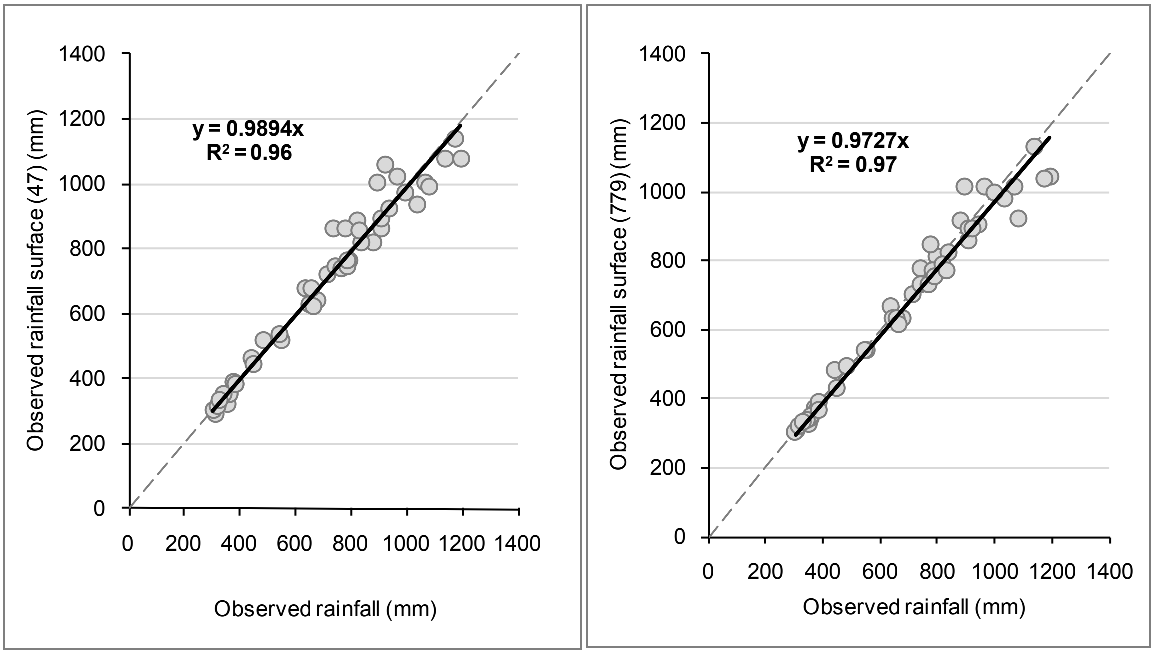

Figure 7 Comparison of mean annual rainfall: a) observed rainfall surface created with ANUSPLIN 4.2 from data from 47 stations versus observed rainfall (point data) recorded at 47 stations, b) observed rainfall surface created with ANUSPLIN 4.2 from data from 779 stations versus observed rainfall (point data) recorded at 47 stations

Visual examination of both surfaces, included in Figure 8 (no statistics remain for the 779 point dataset), supports the finding that the observed data from 47 stations approximated a similar rainfall surface to that from 779 points. This gives some confidence that a small number of stations (47) sufficiently reflect the spatial distribution of rainfall across the study area.

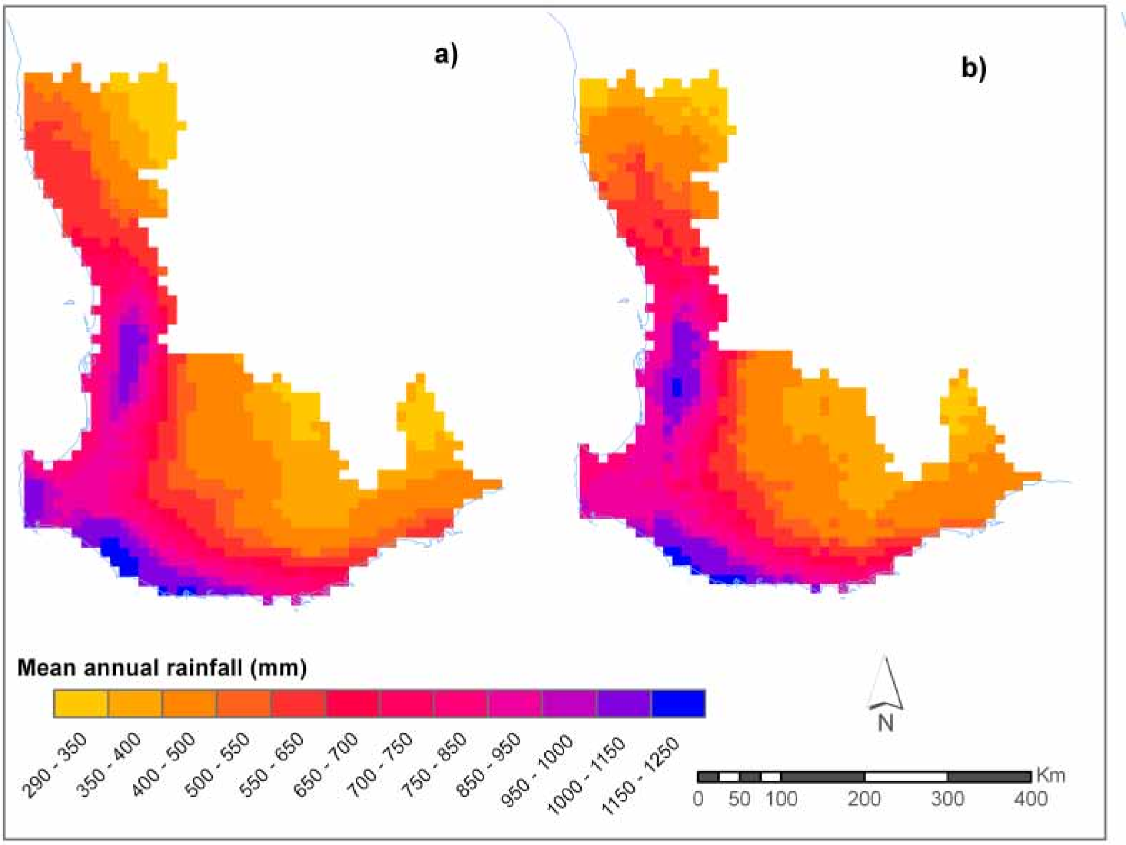

Figure 8 Mean annual rainfall surfaces created with ANUSPLIN 4.2 from: a) 779 data points of observed rainfall (1975–2003) (Durrant & Bowman 2004), and b) 47 data points of observed rainfall (1976–2003) within study area

a) Comparison between ANUSPLIN 4.2 current rainfall surface and observed point data

The goodness-of-fit of the ANUSPLIN 4.2 results was also assessed by comparing the created current rainfall surface with the observed records from 47 meteorological stations (Figure 9, Table 5).

Rainfall values extracted from the grid generated from the downscaled GCM current series showed slightly weaker correlation to observed point data (R^2=0.95) (Figure 9) than values obtained from the grid interpolated from observed records. Figure 10 presents the ANUSPLIN 4.2 interpolation of the mean annual current series from 47 points and this surface is similar to that of Figure 8.

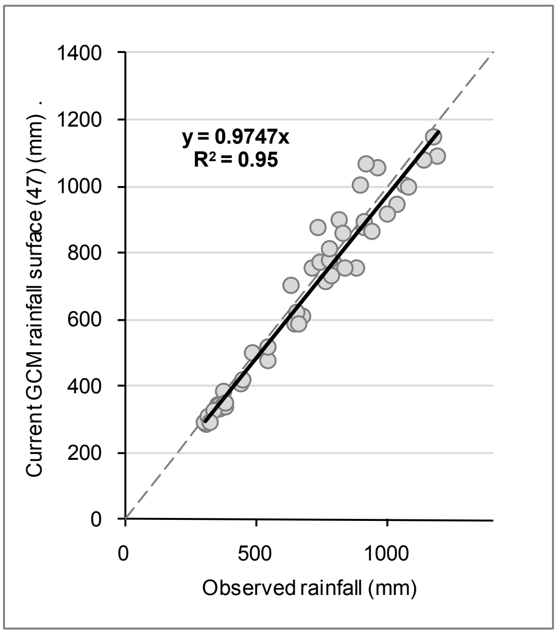

Figure 9 Comparison of ANUSPLIN4.2 surface created from mean annual current rainfall for 47 rainfall stations versus mean annual observed rainfall at these stations

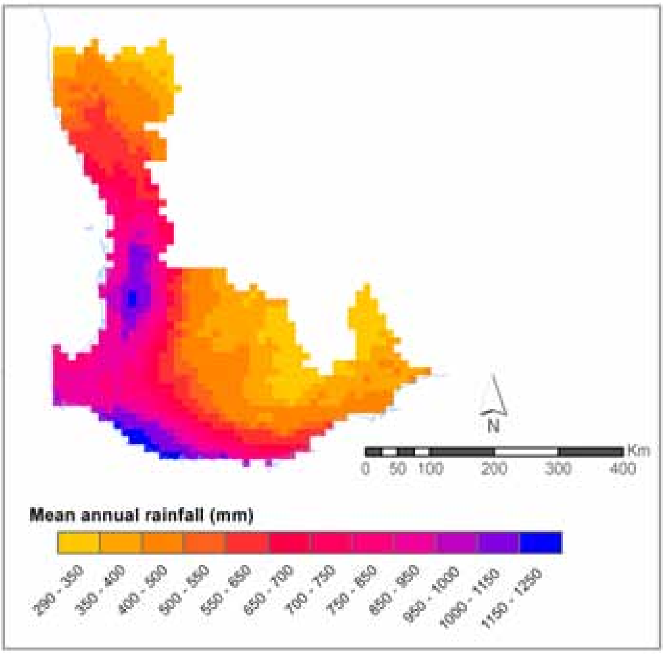

Figure 10 Rainfall surface created with ANUSPLIN 4.2 from mean annual current rainfall (1976–2003) at 47 stations within the study area

An analysis of seasonal surfaces created from observed and current rainfall series is included in Appendix B.

3.4 Spatial analysis of projected rainfall change – future (2050) versus current (1990)

Future change in rainfall refers to change between two periods centred around 2050 and 1990.

Rainfall surfaces created with ANUSPLIN 4.2 in conjunction with ArcGIS 9.2 were used to calculate the projected change in rainfall for 2050. This change was expressed in millimetres when it described the difference between future and current projected rainfall; and in percentage when describing a ratio, (future-current)/current projected rainfall.

Comparison between future and current rainfall projections showed the mean annual rainfall decline was within a range of 2.5 to 19% (15–120 mm) (Table 6).

Seasonally, the future rainfall projections were up to 37% less than the current (particularly in summer) and up to 5.5% more (in autumn and spring) for regions around Albany and Esperance (Table 6).

The spatial distribution of annual seasonal rainfall change created from the Mk3.5 GCM projections is shown in Figure 11, and the seasonal changes in figures 12 and 13. The largest decline in annual rainfall (within the 15–19 % range) was projected for the central and northern part of the study area (Figure 11a), while projections for the southern regions estimated a decrease of up to 6% (Figure 11b).

Table 6 Summary results of projected rainfall change for 2050 within the study area

	Annually	Seasonally			
		Summer	Autmn	Winter	Spring
Rainfall change (%)	***-19 - -2.5***	-37 - +4.5	-28 - +6	-15 - -1	-16 - +4.5
Rainfall change (mm)	***-120 - -15***	-23 - +2	-36 - +5.5	-61 - -3	-19 - +3

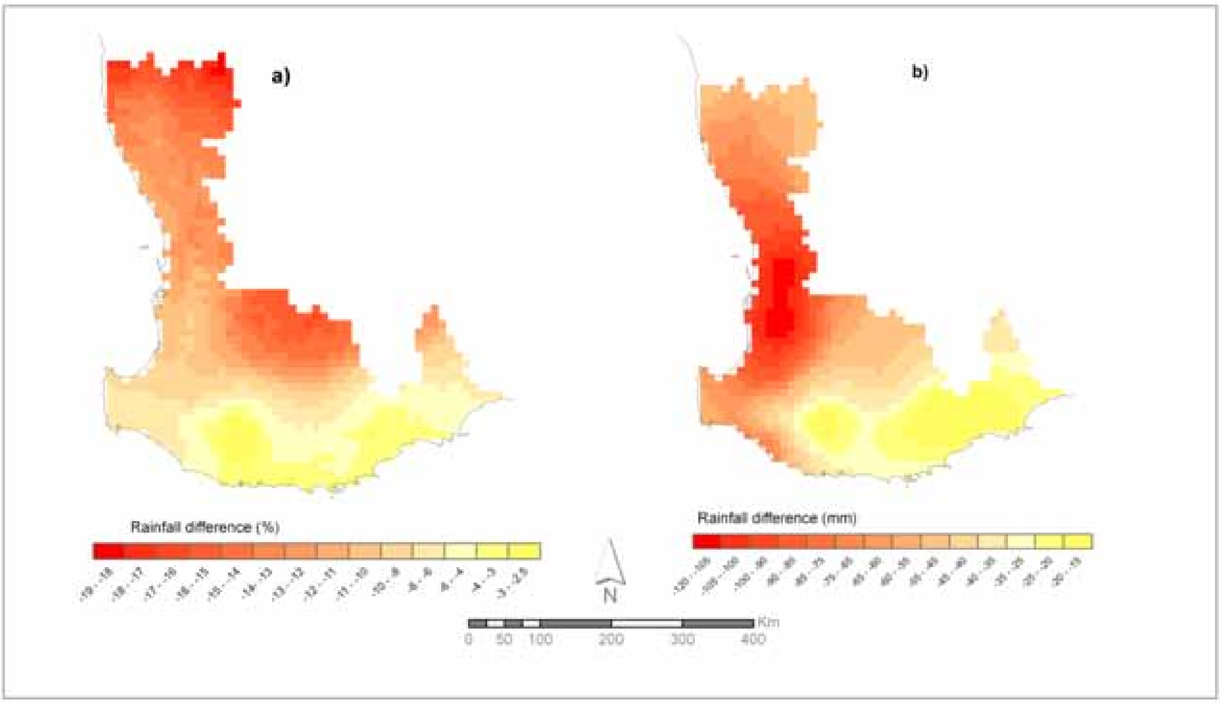

Figure 11 Change in mean annual rainfall for 2050: a) percentage b) millimetres

Seasonal rainfall difference maps (Figure 12) show the most significant reductions in summer for most of the study area (up to 37%) and autumn for districts outside of the South Coast region. The increase in rainfall (up to 4.5%) was projected for small portions of the study area in all seasons but winter, mainly for the southern parts.

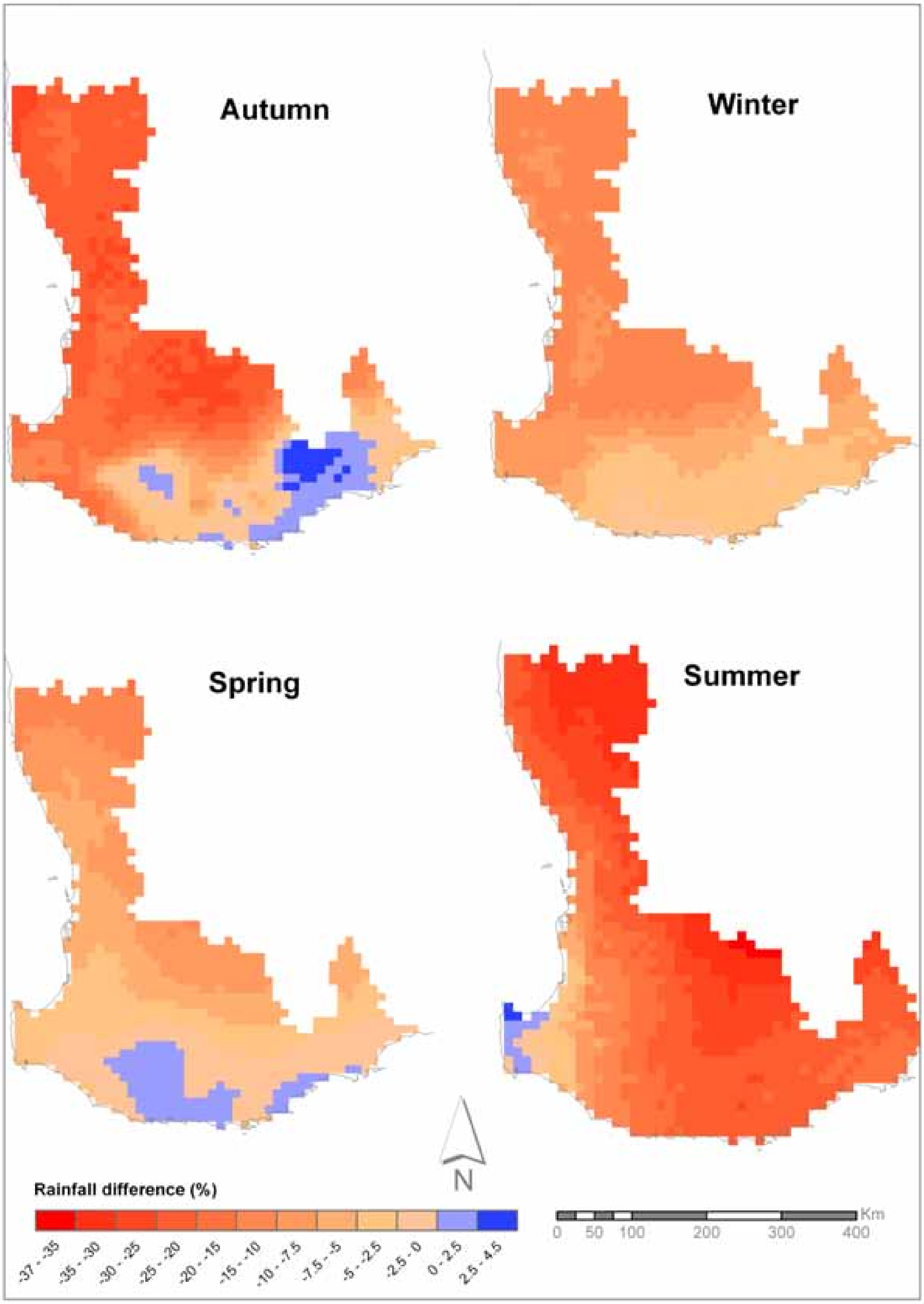

Figure 12 Percentage change in mean seasonal rainfall for 2050

Figure 13 shows the seasonal rainfall difference expressed in millimetres. The winter months were projected to receive up to 62 mm less rainfall in areas around Perth that are densely populated and use water resources heavily. The largest increase in rainfall (up to 5.5 mm) was projected for autumn and spring for sites near Denmark and Esperance.

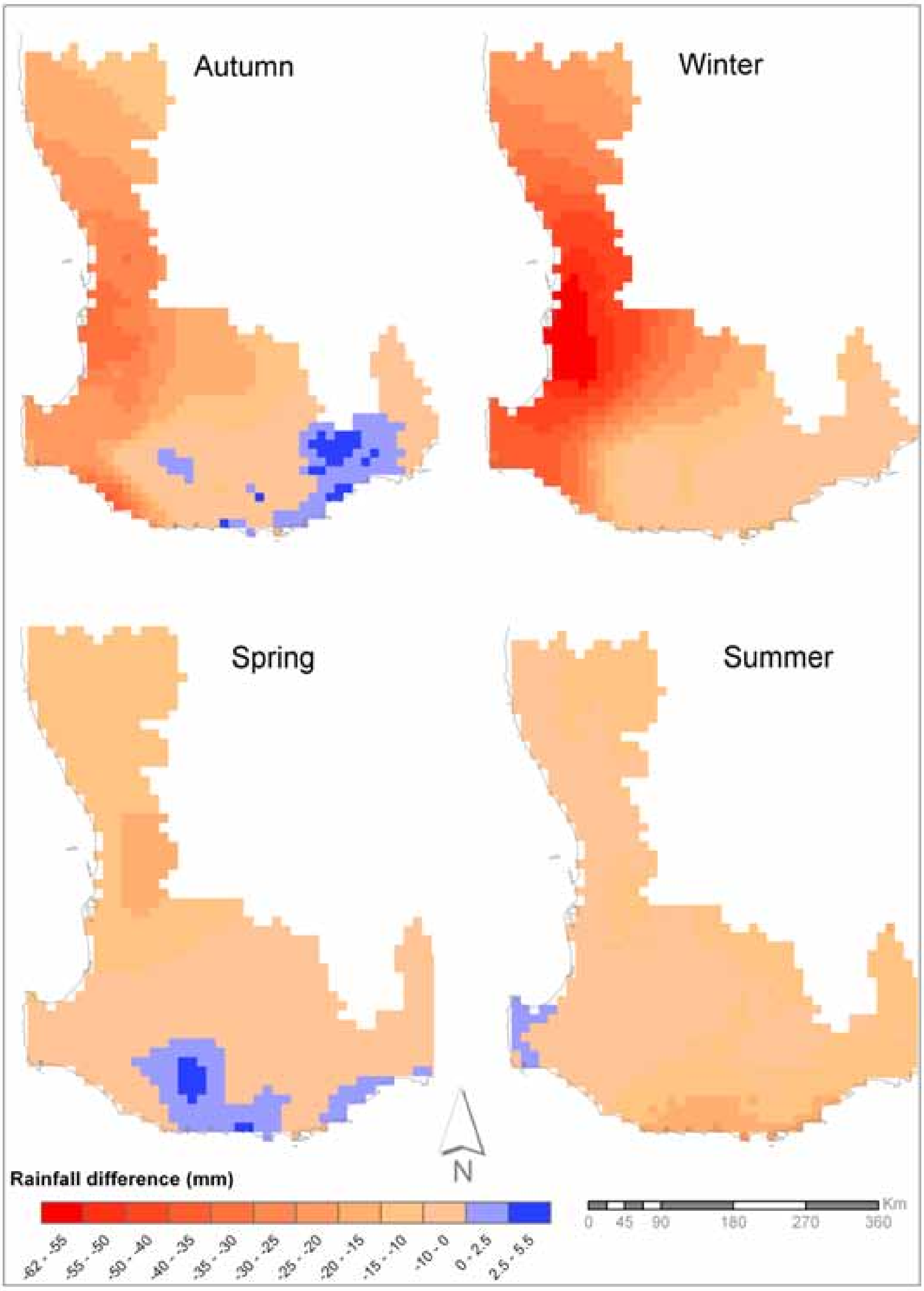

Figure 13 Change in mean seasonal rainfall expressed in millimetres for 2050

4 Climate change projections – temperature

The temperature data available for this analysis was in a format of monthly differences between future and current projections (expressed in degrees celsius and percentages). This format did not allow for comparison with observed data.

Similar to the results for rainfall, the projected temperature change analysis was conducted in ANUSPLIN 4.2, which produced the spline temperature surfaces. Spatial Analyst was then used to calculate and produce maps of temperature differences, as quantity (in degrees celsius) and as a ratio of current temperature (percentage).

Mean annual temperature change (current to future) was projected to increase within the range of 7.5 to 11.5% (1.4–2.3℃) (Figure 14) while seasonal temperatures were estimated to increase within the range of 6.6 to 16% (mainly in autumn and winter) (Table 7).

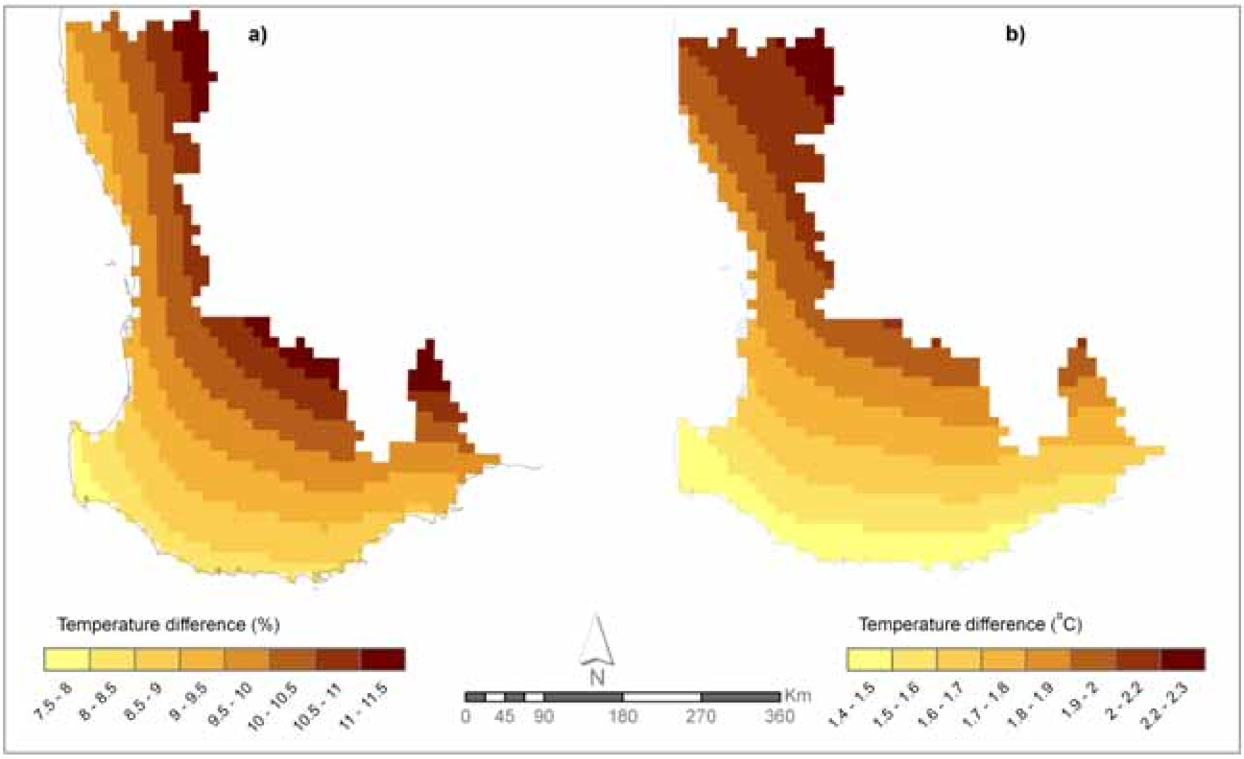

Figure 14 Change in mean annual temperature for 2050: a) in percentage b) in degrees celsius

A summary of annual and seasonal temperature changes within the study area is included in Table 7, while seasonal maps of spatial temperature change distribution are shown in Appendix C.

Table 7 Summary of annual and seasonal temperature changes within the study area

	Annually	Seasonally			
		Summer	Autumn	Winter	Spring
Temperature change (%)	***7.5 - 11.5***	6.6 - 8.8	8.8 - 13.8	8.8 - 16.0	6.6 - 9.1
Temperature change (^{o}C)	***1.4 - 2.3***	1.5 - 2.6	1.7 - 2.8	1.3 - 2.1	1.1 - 1.8

5 Streamflow response to projected climate change in 2050

The simple linear equation tested in this study originated from previous research conducted in Australia and United States. A project conducted by Schaake & Chuzhen (1989) introduced a concept relating change in streamflow to change in climatic variables and named it elasticity of streamflow. Sankarasubramaniam et al. (2001) presented a non-parametric estimator ε_p which links historical climate and streamflow data (Equation 2).

Equation 2

$$\varepsilon_p = \text{median}\left(\frac{Qt - \bar{Q}}{Pt - \bar{P}} \times \frac{\bar{P}}{\bar{Q}}\right)$$

where:

$\bar{Q}$= mean annual streamflow

Q_t= annual streamflow

$\bar{P}$= mean annual rainfall

P_t= annual rainfall

The non-parametric estimator (ε_p) provides a simple estimate of streamflow sensitivity to climate change and may be used in broad water resource investigations before more detailed modelling studies are conducted. However, this estimator does not take into account changes in rainfall distribution and frequency, land use or interaction between the atmosphere and land surface.

The Australian research (Chiew 2006) provided estimates of the rainfall elasticity of streamflow for 219 catchments across Australia. These estimates were within the range of 2.0–3.5%. Detailed Western Australian hydrological modelling investigations showed that a 1% change in mean annual rainfall could result in a 3% change in mean annual streamflow.

A simple linear equation (Equation 2) for estimation of streamflow sensitivity to changes in rainfall and temperature was formed, based on the evidence from previous studies and tested at annual and seasonal time-steps:

Equation 1 $$\Delta \mathrm{Q} = 3 \times \Delta \mathrm{P} - 0.5 \times \Delta \mathrm{T}$$

where: ΔQ is change in streamflow, (%); ΔP is change in rainfall $((future - current) \div current) \times 100$; and ΔT is change in temperature $((future - current) \div current) \times 100$.

The following section explains an approach to relate a projected climate change (represented by changes in rainfall and temperature) to streamflow. The presented method produced a set of maps, easily accessible from ArcGIS 9.2, of spatial distribution of projected streamflow change across the study area.

The equation was solved with Spatial Analyst, an ArcGIS 9.2 extension, using future and current rainfall and temperature grids created with ANUSPLIN 4.2. The spatial representation of calculated changes in mean annual streamflow is shown in Figure 15.

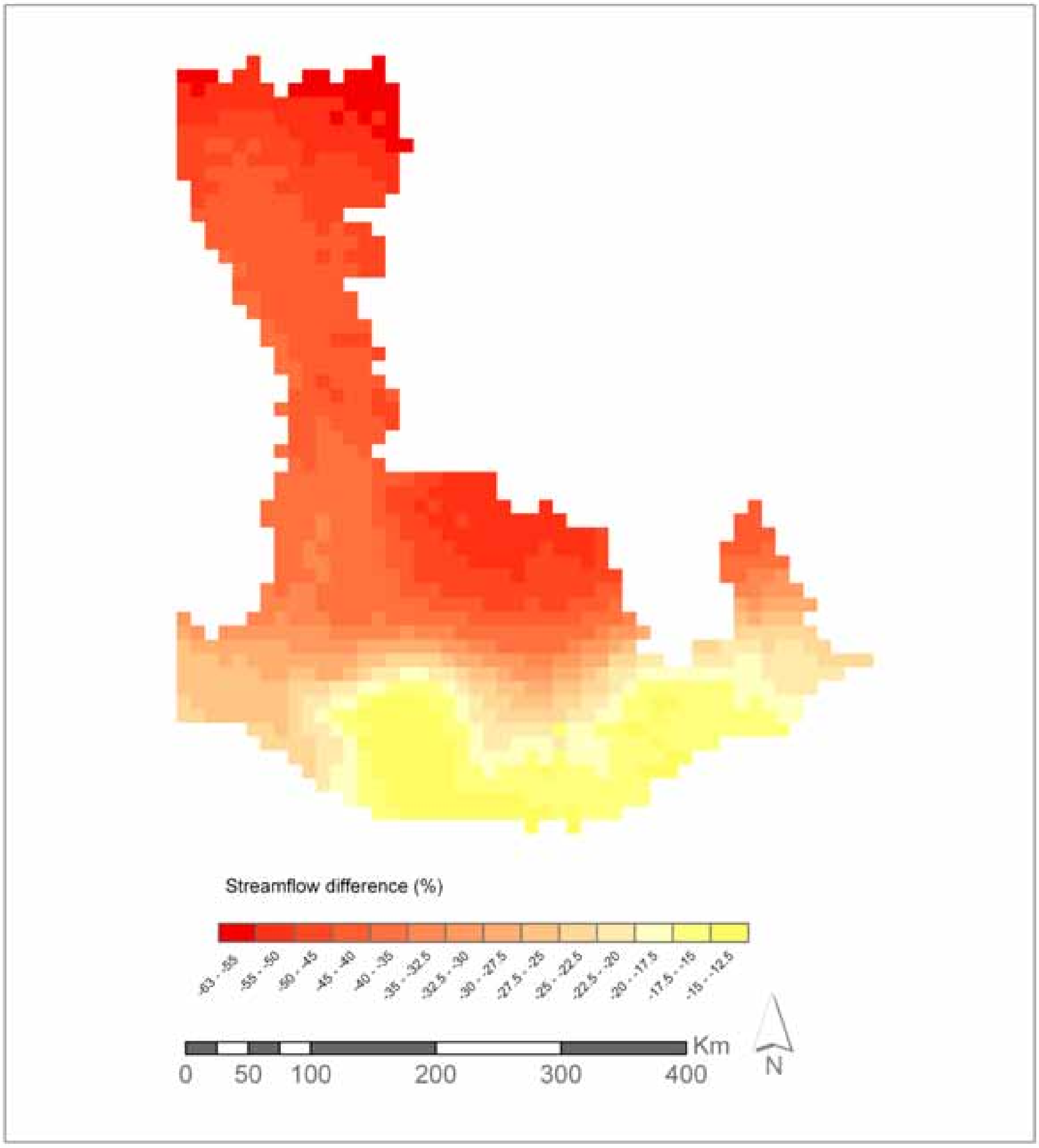

Figure 15 Mean annual streamflow difference for 2050 estimated using the linear equation

Calculated reductions in mean annual streamflow for 2050 compared with 1990 values were within a range of 12.5 to 63% throughout the region. The equation estimated the highest mean annual streamflow reductions (up to 63%) for areas where projected rainfall decline was greater than 15% and temperature increase up 11%.

A similar pattern was evident in the seasonal comparison of estimates from the linear equation (Figure16). Seasonal streamflow reduced by up to 90% in autumn and summer for parts of the region where rainfall was projected to decline by more than 20% and temperature to increase by more than 10%. The spring and winter estimates showed a reduction in streamflow of up to 50%.

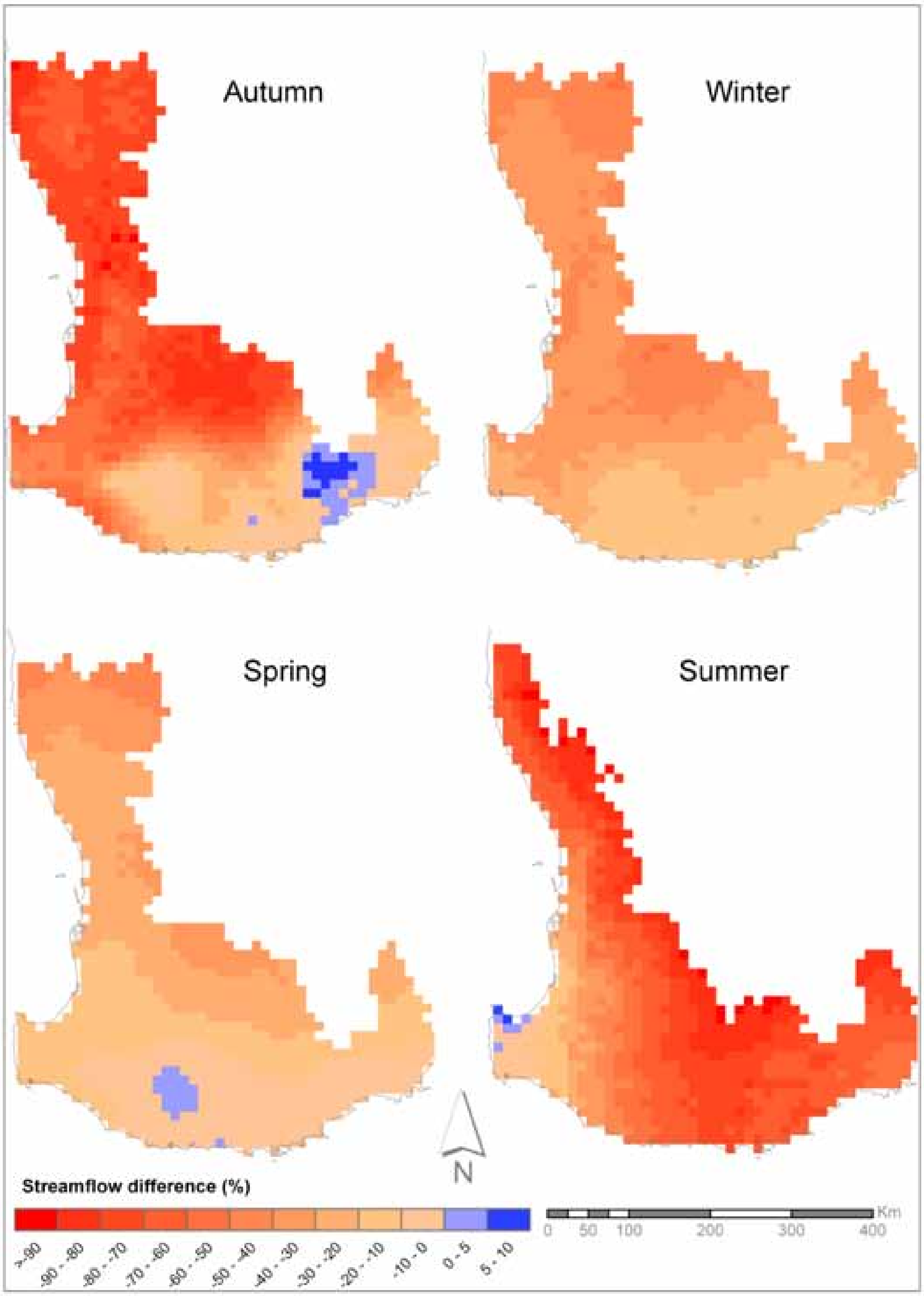

Figure 16 Mean seasonal streamflow difference for 2050 estimated using the linear equation

In regions where rainfall was projected to increase, the equation estimated an increase in runoff for summer, autumn and spring within a range of 2 to 10%. A summary of annual and seasonal streamflow changes for the study area is shown in Table 8.

Table 8 Summary of annual and seasonal streamflow changes for 2050 in the study area

	Annually	Seasonally			
		Summer	Autumn	Winter	Spring
Streamflow change (%)	***-63 - -13***	-90 - +10	-90 - +11	-51 - -7	-51 - +2

6 Comparison between results from the linear equation and those from detailed hydrologic modelling

A number of detailed climate change studies have been conducted for specific catchments within the study region of south-west Western Australia.

In this study, a simple linear equation has been used to calculate changes in streamflow for given changes in rainfall and temperature.

The usefulness of the streamflow elasticity approach (represented by the linear equation) can be validated by comparison with results from detailed hydrologic modelling.

The three catchments considered in this comparison were those of Stirling Dam, Serpentine River and Denmark River (Figure 17). In all these complex modelling studies the Land Use Change Incorporated Catchment (LUCICAT) model was applied to estimate the impacts of projected rainfall decline on streamflow.

Additionally, two simple rainfall-runoff models were tested on the Denmark River catchment. The rainfall series projected by the CSIRO MK3.5 GCM were available for the Denmark River study only. Rainfall series from MK3.0 were used in the Stirling Dam and Serpentine River investigations.

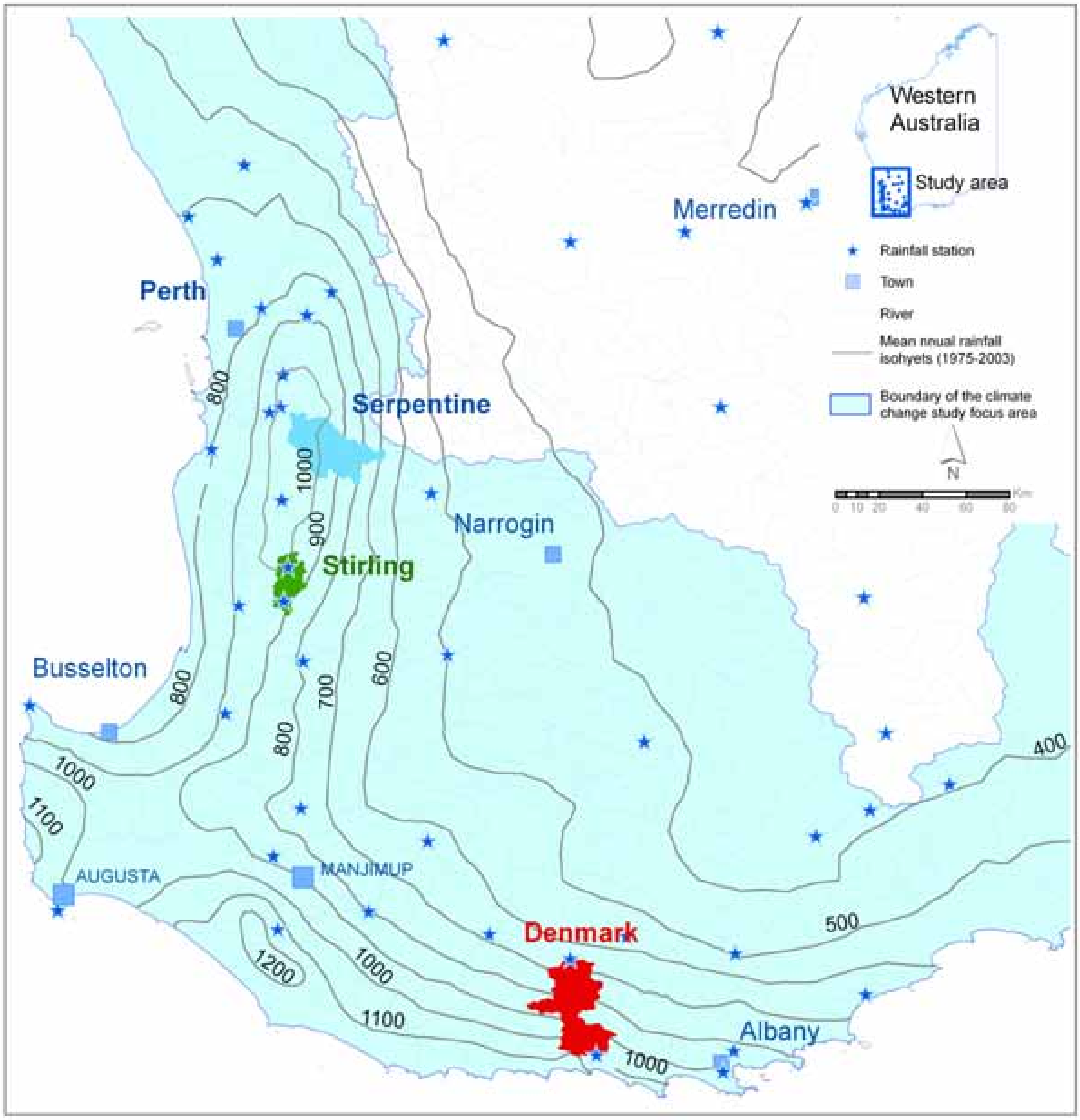

Figure 17 Location of the three modelled catchments: Stirling Dam, Serpentine River and Denmark River

The three investigated catchments are located in areas that require appraisal from catchment management authorities to plan and allocate water resources. Stirling Dam and Serpentine River catchments feed water to the Perth-Mandurah Integrated Water Supply Scheme, and the Denmark River catchment is used as a water resource for the town of Denmark. The Stirling Dam and Serpentine River catchments are within a 120 km radius south of Perth, while Denmark River is located in the state's southern region, 414 km from Perth.

The Stirling Dam and Serpentine River catchments have areas of 250 and 664 km^2 respectively and are fully forested; whereas 16% of the 502 km^2 Denmark River catchment area has been cleared for agriculture.

The observed mean annual rainfall for the period 1976–2003 was approximately 1000 mm for all three catchments (Table 9).

6.1 Projected rainfall and temperature change in three catchments

Rainfall and temperature changes projected by the CSIRO Mk3.5 GCM for 2050 for the Stirling, Serpentine and Denmark catchments are summarised in Table 9.

Table 9 Summary of annual and seasonal rainfall and temperature changes for 2050 for the three modelled catchments

			Stirling Dam (509197)		***Serpentine Dam (9023)***		Denmark (9531)	
			%	*mm*	***%***	***mm***	*%*	*mm*
Annual	**Rainfall**	Mean observed		*1081*		***1066***		*998*
		Mean current		*1091*		***1051***		*935*
		Mean future		*974*		***933***		*903*
		Change	***-11***	*-117*	***-11***	***-118***	***-3***	-32
			%	*°C*	***%***	***°C***	*%*	*°C*
		Temperature change	***9.6***	*1.8*	***10.0***	***1.9***	***8.5***	*1.5*
Seasonal change	**Rainfall (%)**	Summer	*-12.7*		***-18.0***		*-22.7*	
		Autumn	*-18.4*		***-21.8***		*-2.1*	
		Winter	*-9.6*		***-10.1***		*-2.2*	
		Spring	*-4.2*		***-6.3***		*0.7*	
	Temperature (%)	Summer	*8.0*		***8.3***		*6.9*	
		Autumn	*11.1*		***11.5***		*9.9*	
		Winter	*11.6*		***12.2***		*10.2*	
		Spring	*7.7*		***7.9***		*7.0*	

Annual rainfall projections for the Stirling Dam and Serpentine River catchments were similar, with an 11% reduction by 2050, which translates to a slightly greater than 100 mm decline. The projected annual rainfall decline for Denmark River catchment was only 3% (28 mm) by 2050.

The projected annual temperature increase by 2050 was within a range of 8.5 to 10%, which equates to an increase of up to 1.9℃.

Seasonally, the largest rainfall reduction was projected for summer in the Denmark River catchment (up to 22%). The smallest decline was projected for spring for all three catchments, with a small increase projected for the Denmark River catchment (0.7%).

Temperature projections showed an increase ranging from 6.9% in summer for the Denmark River catchment to a 12.2% increase in winter for the Serpentine River catchment.

6.2 Hydrological modelling

Previous studies applied the LUCICAT model to the three catchments within the region: Stirling Dam (Berti et al. 2004), Serpentine River (Kitsios et al. 2008) and Denmark River (Smith et al. 2009) to estimate the impacts of projected rainfall decline on streamflow. Additionally, two simple rainfall-runoff models, the Australian Water Balance Model (AWBM) and SIMHYD, were tested on the Denmark River catchment.

The LUCICAT model is a dynamic model that produces daily streamflow and salt-load series from land-use changes across a catchment.

Calibrated streamflow values from the LUCICAT model were strongly correlated with observed records for all three catchments – the coefficient of determination (R^2) between the observed and modelled annual figures was approximately 0.9 for all three catchments (Berti et al. 2004; Kitsios et al. 2008; Smith et al. 2009). Also, the coefficients of variation for observed series were relatively low, between 0.41 for Stirling Dam and 0.66 for the Denmark River. LUCICAT produced similar coefficient of variation values for all of the catchments (Table 10).

AWBM and SIMHYD are lumped conceptual daily rainfall-runoff models, which simulate streamflow using daily rainfall and evaporation inputs. They have been widely used and tested across Australia (Jones et al. 2005; Chiew et al. 2002). These models were applied to the Denmark River catchment with results reported at the Mt Lindesay gauging station. Both models provided accurate estimates of the observed data with a coefficient of determination (R^2) of approximately 0.83 and 0.89 and a Nash-Sutcliffe coefficient of efficiency (E) of 0.84 and 0.90 (Table 10) respectively.

Table 10 Calibration summary of observed and modelled annual runoff statistics for three modelled catchments within the study area

	Calibration period			LUCICAT	AWBM	SIMHYD
				Annual statistics		
Stirling Dam	1972-2002		Obs	Modelled		
		CV *(mm)*	**0.41**	0.40		
		R^2		0.90		
Serpentine River	1981-2004		Obs	Modelled		
		CV *(mm)*	**0.50**	0.60		
		R^2		0.99		
Denmark River *(Mt Lindesay)*	1975-1994		Obs		Modelled	
		CV *(mm)*	**0.66**	0.58	0.64	0.62
		R^2		0.95	0.83	0.89
		E		0.89	0.84	0.90

*CV = coefficient of variation

6.3 Projected streamflow change estimated by hydrological modelling and the linear equation

Results derived from the linear equation used in this study to determine streamflow change under projected climate change were cross-checked with the results from detailed hydrological studies.

Annual streamflow change

Annual streamflow reductions obtained from the linear equation were relatively similar to streamflow reductions predicted by the hydrologic models (Table 11).

Overall, the equation estimates showed a larger decline in streamflow than the LUCICAT modelling outcomes. These overestimations were 13% and 18% for the Stirling Dam and Denmark River catchments respectively and 28% for the Serpentine River catchment.

Table 11 Projected mean annual streamflow change for 2050 estimated by LUCICAT, AWBM, SIMHYD, and the linear equation for three catchments within the study area

		Stirling Dam		Serpentine Dam		Denmark *(Mt Lindesay)*	
Catchment area (km^2)		250		664		502	
		Mk3.0		*Mk3.0*		*Mk3.5*	
Rainfall change (%)		*-11*		*-12*		*-4*	
			ratio		ratio		ratio
Streamflow change (%)	LUCICAT	**-31**	**2.8**	**-30**	**2.4**	**-13**	**3.3**
	AWBM					-12	**3.0**
	SIMHYD					-11	**2.8**
Rainfall change (%)		*-10.1*		*-11.2*		*-3.3*	
Temperature change (%)		*9.6*		*10.0*		*8.5*	
			ratio		ratio		ratio
Streamflow change (%)	**LINEAR EQ**	**-35.1**	**3.5**	**-38.6**	**3.4**	**-14.2**	**4.3**

Seasonal streamflow change

Overall, the seasonal estimates from the linear equation did not match well with the modelling results (Table 12).

The best correlation of values from the linear equation and the LUCICAT model was for the Stirling Dam catchment for all seasons.

The linear equation results did not match the modelling estimates for summer and autumn for the Denmark and Serpentine catchments (Table 12). In contrast, the linear equation approximation was comparable with hydrologic modelling results for winter and spring in the Stirling and Serpentine catchments, and for winter in the Denmark River catchment (Table 12).

The linear equation calculated slightly greater streamflow reductions than LUCICAT in the Stirling Dam area for autumn and winter (2% and 9% respectively); while for summer and spring the equation's estimates were lower (12% and 41% respectively).

For the Serpentine River catchment, modelling and linear equation values were close for winter and spring – the equation calculated greater reductions by 6% and 9% respectively. Streamflow reductions from the equation for summer and autumn were significantly higher than from LUCICAT (74% and 55% respectively).

Table 12 Projected mean seasonal streamflow change for 2050 estimated by LUCICAT, AWBM, SIMHYD, and linear equation for three catchments within the study area

		Stirling Dam			*Serpentine Dam*			Denmark *(Mt Lindesay)*				
		LUCICAT	**LINEAR EQ**		*LUCICAT*	***LINEAR EQ***		LUCICAT	AWBM	SIMHYD	**LINEAR EQ**	
				ratio			*ratio*					ratio
Streamflow change (%)	Summer	-47	**-42**	**3.3**	*-15*	***-58***	***3.2***	-52	-23	-35	**-72**	**3.4**
	Autumn	-60	**-61**	**3.3**	*-32*	***-71***	***3.3***	-43	-7	-7	**-11**	**5.4**
	Winter	-32	**-35**	**3.6**	*-34*	***-36***	***3.6***	-11	-10	-11	**-12**	**5.3**
	Spring	-24	**-17**	**3.9**	*-21*	***-23***	***3.6***	-17	-15	-9	**-1**	**2.0**

The Denmark River catchment was modelled by three hydrological models and the results of this work were compared with estimates from the linear equation.

The LUCICAT outputs and the values from the linear equation were similar only for winter, while the results for the remaining seasons were not comparable.

The AWBM model gave slightly lower percentages of streamflow change than the linear equation streamflow reductions for autumn and winter, while the model's summer and spring values were not similar to the linear equation estimates.

The SIMHYD compared favourably with the linear equation only for winter, when the estimated decline in streamflow was 11% and 12% respectively.

Overall, across the four methods analysed here, only estimates for winter showed consistency with the linear equation and projected higher reductions within 10% (with the exception of the AWBM, which gave 17% lower values than the linear equation).

However, the linear equation results for the annual time-step mirrored relatively closely the hydrological modelling results for the three catchments used in this study.

7 Discussion

7.1 Climate projections – how well they reflect the observed data

In this study a simple linear equation, derived from previous investigations and relating the projected change in rainfall and temperature to a projected change in streamflow for 2050, has been used as a rapid assessment tool of streamflow sensitivity to climate change in south-west Western Australia.

Rainfall and temperature generated by the CSIRO Mk3.5 GCM under the A2 SRES emission scenario for two time-slices centred around 1990 and 2050 were used to assess the future streamflow variations. The analysis was carried out in ANUSPLIN 4.2 and ArcGIS 9.2 Spatial Analyst and resulted in a number of maps of the potential streamflow differences on a regional scale.

The methodology and analysis employed in this study was based on rainfall and temperature data recorded at 47 stations sparsely distributed across the study area. The availability of observed records influenced the quality of projections obtained from the CSIRO Mk3.5 GCM and this is an important factor when drawing conclusions from this study's results. Assessing the goodness-of-fit between observed and projected rainfall, which were compared for a 28-year period (1976–2003), was important in making a judgement about how similar the GCM's future climate projections were to the real-life observations.

Annual comparison results between observed and projected (current) rainfall showed that the CSIRO Mk3.5 GCM downscaled rainfall mirrored the observed rainfall reasonably well. The best and weakest fits were found for stations located in the high rainfall zone (mean annual rainfall approximately 830 mm). Downscaled GCM current rainfall was higher than the observed for 17 stations: all in areas with greater than 700 mm of rainfall annually. The largest underestimation of rainfall (14%) occurred in stations from low rainfall zones where mean annual totals did not exceed 450 mm (Table 13).

Seasonal comparison showed a shift in peak rainfall from June–July (observed) to July–August (current). This shift has been documented in previous studies conducted in the region (Berti et al. 2004; Kitsios et al. 2008; Smith et al. 2009).

Correlation between observed and current rainfall was weakest over summer when projected values were consistently underestimated. This observation correlates with the annual difference values, when the most significant underestimation (-11% up to 14%) was calculated for stations with annual rainfall below 450 mm.

ANUSPLIN 4.2 software was used to create spline rainfall surfaces from a small number of data points. Spatial and statistical examination of the rainfall surfaces provided reasonable evidence that these surfaces sufficiently reflected the spatial distribution of rainfall across the study area. Comparisons of surfaces from ANUSPLIN 4.2 showed that the number of data points was not critical in creating rainfall grids – surfaces from 779 data points correlated strongly with surfaces produced from 47 data points.

The temperature data used in this study (in the form of monthly differences between future and current projections) did not allow for comparison with observed data. It is therefore impossible to draw objective conclusions about the accuracy of the Mk3.5 GCM temperature projections.

However, a number of studies (Xu 1999; Johnson & Sharma 2009; Johnson & Sharma 2009) have researched the reliability of variables obtained from GCMs, such as rainfall, temperature and air pressure. Johnson & Sharma (2009) developed a quantitative measure to assess the ability of different GCMs to project a range of variables. Their study found that projections of temperature and pressure were the most consistent (showing the most agreement across all tested GCMs), while rainfall projections were the most disparate. Johnson & Sharma also tested, among others, projections of the CSIRO Mk3.5 GCM under the A2 emission scenario for 2050. These results support this study's qualitative assumption about the reliability of temperature projections from the CSIRO Mk3.5 GCM.

7.2 Climate elasticity of streamflow – comparison with hydrological models

Modelling future streamflow using GCM projections with hydrologic models has many advantages, but it is time- and resource-consuming. This study has demonstrated the value of using a simple linear equation as a quick and practical tool to identify areas requiring further research.

Numerous studies (Schaake & Chunzhen 1989; Chiew 2006; Fu et al. 2007; Smith et al. 2009) have demonstrated the high sensitivity of streamflow to changes in climatic conditions. Application of the linear equation confirmed this sensitivity and estimates from the equation mirrored modelling results closely, especially on an annual basis. The seasonal results from the equation showed less agreement with modelling estimates, especially in summer and autumn. The equation estimates showed that streamflow change was greater than rainfall change – in Western Australia a 1% change in mean annual rainfall may result in a 3% change in mean annual streamflow (Berti et al. 2008; Smith et al. 2009).

Comparison of the equation estimates with the hydrologic modelling results presented in this study did not identify which of these approximated more precisely the projected changes in streamflow. The hydrologic models and simple linear equation cannot define all of the complex catchment hydrologic processes. However, they provide a good indication of what might be expected under various future climate scenarios. The similarity between equation estimates and results from more complex models gives us confidence in the equation's usefulness as a tool for determining areas where streamflow is likely to be most affected by changing climate. However, the comparison was not made to suggest the best method for determining the impact of climate change on streamflow.

8 Conclusion

The simple method of assessing streamflow sensitivity to projected changes in rainfall and temperature has provided, on an annual time-scale, similar estimates to more complex hydrologic modelling.

Annually, the linear equation used in the study calculated reductions in mean annual streamflow for 2050 compared with 1990 values in the range of 12 to 90% throughout the region. The largest streamflow decreases were estimated in areas with a projected rainfall decline of more than 20% and a projected temperature rise greater than 11%. The linear equation results mirrored the hydrological modelling results for the three catchments used for validation.

Seasonally, the greatest streamflow decline was calculated in autumn and summer (up to 90%), when the projected rainfall reductions were greater than 20% and temperature rise was between 8 and 12% (these estimates did not correlate with the outputs from the hydrological models). In regions where rainfall was projected to increase, the linear equation estimated an increase in runoff for autumn and spring.

Complex hydrological modelling is time consuming, requires complicated dataset inputs and has multiple constraints and uncertainties. Findings from this study show that the simple method produces broad estimates of future streamflow changes that are comparable with outputs from complex hydrological models. These projections, in turn, may be useful guides in water resource planning and allocation processes.

In addition, the simple method enables assessment of areas where limited information is available. The graphic representations of streamflow sensitivity to climate change can be broadly applied to assessing individual catchment areas or entire regions on an annual or seasonal basis. The easily-derived maps from the elasticity method allow visual assessment of areas of interest. They may be applied as a first ‘test’ for identification of places at risk before decisions on commissioning detailed studies are made.

Appendices

Appendix A — Rainfall

The percentage difference for mean annual observed and downscaled GCM current rainfall was calculated for each individual meteorological station to assess the accuracy of the projected rainfall (Table 13).

Table 13 Percentage difference for mean annual observed and current rainfall calculated for 47 meteorological stations within the study area

		Mean rainfall (mm)		
	Station no	**observed**	**current**	**Difference (%)**
1	***8039***	***353***	***349***	***-1.2***
2	***8138***	***375***	***373***	***-0.5***
3	9007	795	808	**1.6**
4	9018	634	659	**4.0**
5	9021	738	742	**0.5**
6	9023	1066	1051	**-1.4**
7	9031	911	938	**3.1**
8	9039	897	900	**0.3**
9	9044	1037	1045	**0.8**
10	9045	716	752	**5.1**
11	9105	742	776	**4.5**
12	9500	880	829	**-5.8**
13	9501	549	511	**-7.0**
14	9506	679	644	**-5.1**
15	9510	766	752	**-1.8**
16	9518	963	1000	**3.9**
17	9519	783	815	**4.0**
18	9530	789	760	**-3.7**
19	9531	998	935	**-6.3**
20	9534	910	906	**-0.5**
21	9538	1192	1197	**0.4**
22	9564	836	764	**-8.7**
23	9572	820	843	**2.7**
24	9573	940	873	**-7.1**
25	9592	1138	1152	**1.2**
26	9595	646	603	**-6.7**
27	9607	443	388	**-12.5**
28	9615	658	601	**-8.7**
29	9616	661	622	**-5.9**
30	9619	777	703	**-9.5**
31	9628	830	836	**0.7**
32	9642	924	928	**0.5**
33	***10007***	***309***	***307***	***-0.8***
34	***10035***	***360***	***346***	***-3.7***
35	***10073***	***305***	***291***	***-4.3***
36	***10093***	***317***	***305***	***-3.6***
37	10519	380	329	**-13.3**
38	10536	360	335	**-6.9**
39	10541	383	342	**-10.7**
40	10542	486	470	**-3.3**
41	10579	451	422	**-6.4**
42	***10592***	***341***	***319***	***-6.5***
43	***10595***	***329***	***283***	***-13.8***
44	10622	386	353	**-8.6**
45	10648	545	532	**-2.3**
46	509116	1175	1180	**0.5**
47	509197	1081	1091	**1.0**

Appendix B — ANUSPLIN 4.2

Comparison of surfaces created by ANUSPLIN 4.2 with observed point data

Tables 14 and 15 show statistics comparing seasonal grids created from observed and projected to observed values at 47 stations. The similarity was evident and relatively strong for all time-scales.

Table 14 Annual and seasonal statistics comparing the observed and created by ANUSPLIN 4.2 rainfall surfaces from the observed data for 47 meteorological stations within the study area

		Annual	Summer	Autumn	Winter	Spring
Observed mean	*(mm)*	***695***	**56**	**148**	**337**	**154**
ANUSPLIN 4.2 mean (47)*	*(mm)*	***691***	**56**	**148**	**334**	**153**
Observed standard deviation	*(mm)*	***267***	12	51	156	65
ANUSPLIN 4.2 standard deviation	*(mm)*	***260***	10	50	154	63
MAE(0)	*(mm)*	***37.4***	2.6	7.2	17.9	9.4
RMSE(0)	*(mm)*	***7.0***	0.1	1.1	4.5	0.9
E(1)**		***0.96***	0.92	0.96	0.97	0.96
R^2		***0.96***	0.89	0.96	0.97	0.96

*ANUSPLIN 4.2 rainfall surface was created from the observed rainfall data

**E(1)= means perfect score

Table 15 Annual and seasonal statistics comparing the observed and created by ANUSPLIN 4.2 rainfall surfaces from the current rainfall series for 47 meteorological stations within the study area

		Annual	Summer	Autumn	Winter	Spring
Observed mean	*(mm)*	***695***	56	148	337	154
ANUSPLIN 4.2 mean (47)*	*(mm)*	***676***	49	117	337	172
Observed st dev	*(mm)*	***267***	12	51	156	65
ANUSPLIN 4.2 st dev	*(mm)*	***269***	13	41	157	69
MAE(0)	*(mm)*	***52.3***	9.4	31.2	21.8	28.3
RMSE(0)	*(mm)*	***4.9***	1.1	6.4	4.1	6.3
E(1)**		***0.94***	**0.07**	**0.48**	**0.96**	**0.70**
R^2		***0.95***	**0.55**	**0.88**	**0.96**	**0.79**

*ANUSPLIN 4.2 rainfall surface was created from the downscaled GCM current series

**E(1)=means perfect score

Figure 18 shows the seasonal comparison between observed point data and the observed rainfall surface created by ANUSPLIN 4.2 using 47 points. The weakest relationship between observed mean seasonal rainfall and rainfall values from surfaces created by ANUSPLIN 4.2 using mean current rainfall was for summer (R^2= 0.55) and the strongest for winter (R^2= 0.96) (figures 18a and 18c).

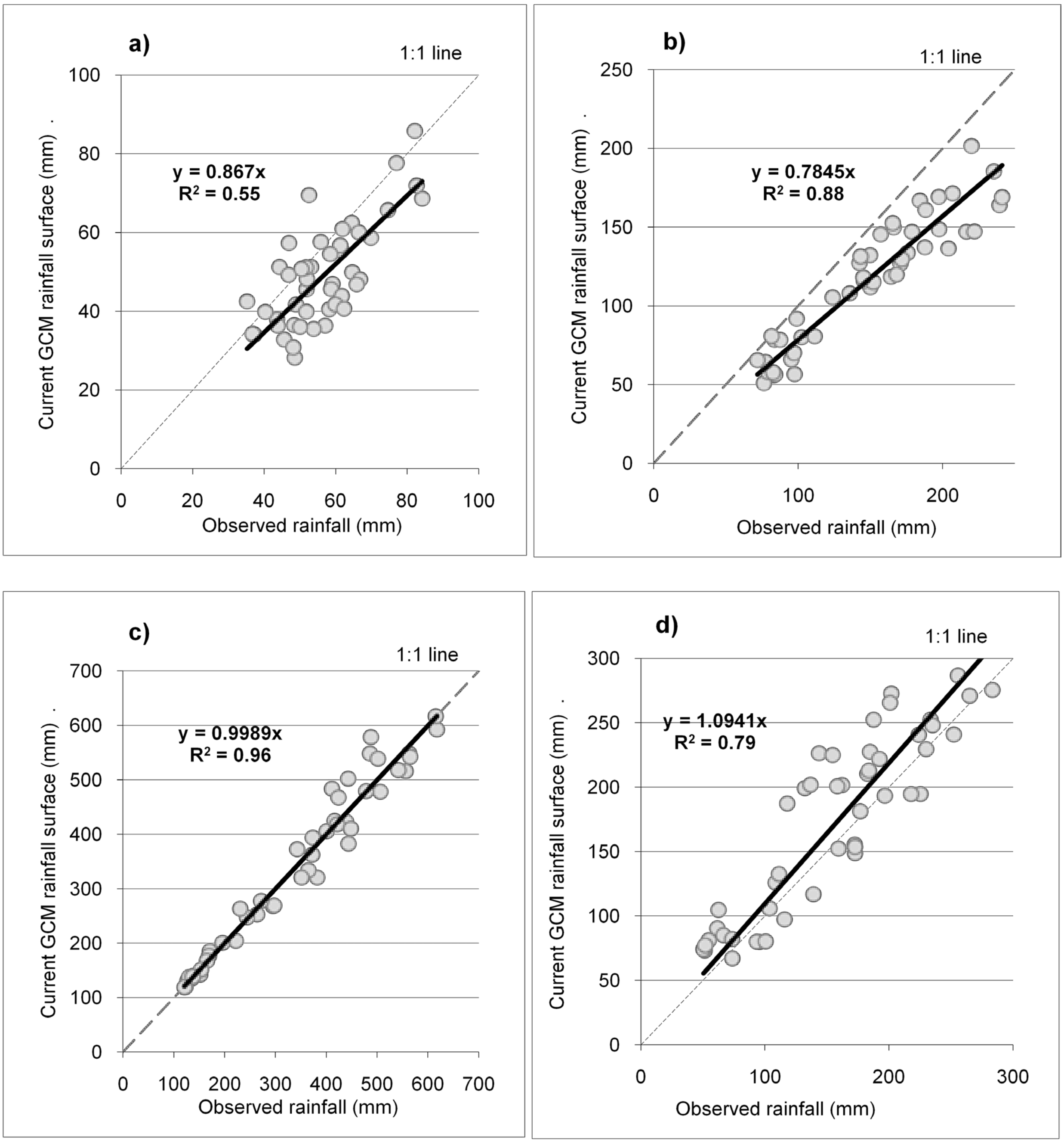

Figure 18 Seasonal comparison between observed and current rainfall values created by ANUSPLIN 4.2 at 47 meteorological stations: a) summer, b) autumn, c) winter and d) spring

Appendix C — Temperature

Maps of spatial temperature change within the study area for 2050 are shown in Figure 19 (expressed in degrees celsius) and Figure 20 (expressed in percentage change).

The temperature projections illustrate that seasonally the highest temperature increases may be expected in autumn (up to 2.8℃) and in summer (up to 2.6℃) in areas of the northern parts of Moore-Hills Rivers (617) basin. The lowest temperature rise, from 1.1 ℃ to 1.7℃, was consistently projected for southern regions of the study area for all seasons.

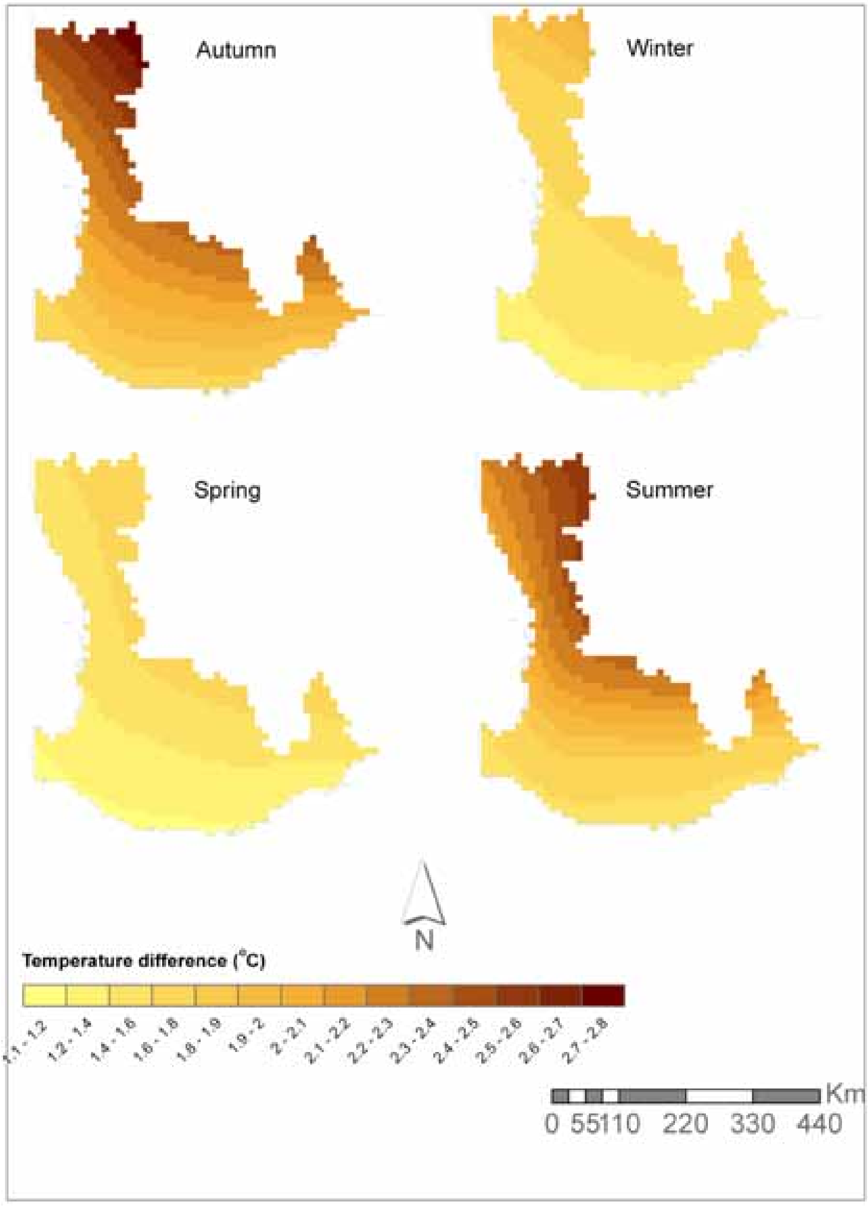

Figure 19 Projected seasonal temperature change for 2050 expressed in degrees celsius within the study area

Seasonal maps of temperature change expressed in percentage showed the highest rise (up to 16%) in winter on the eastern fringes of the study area.

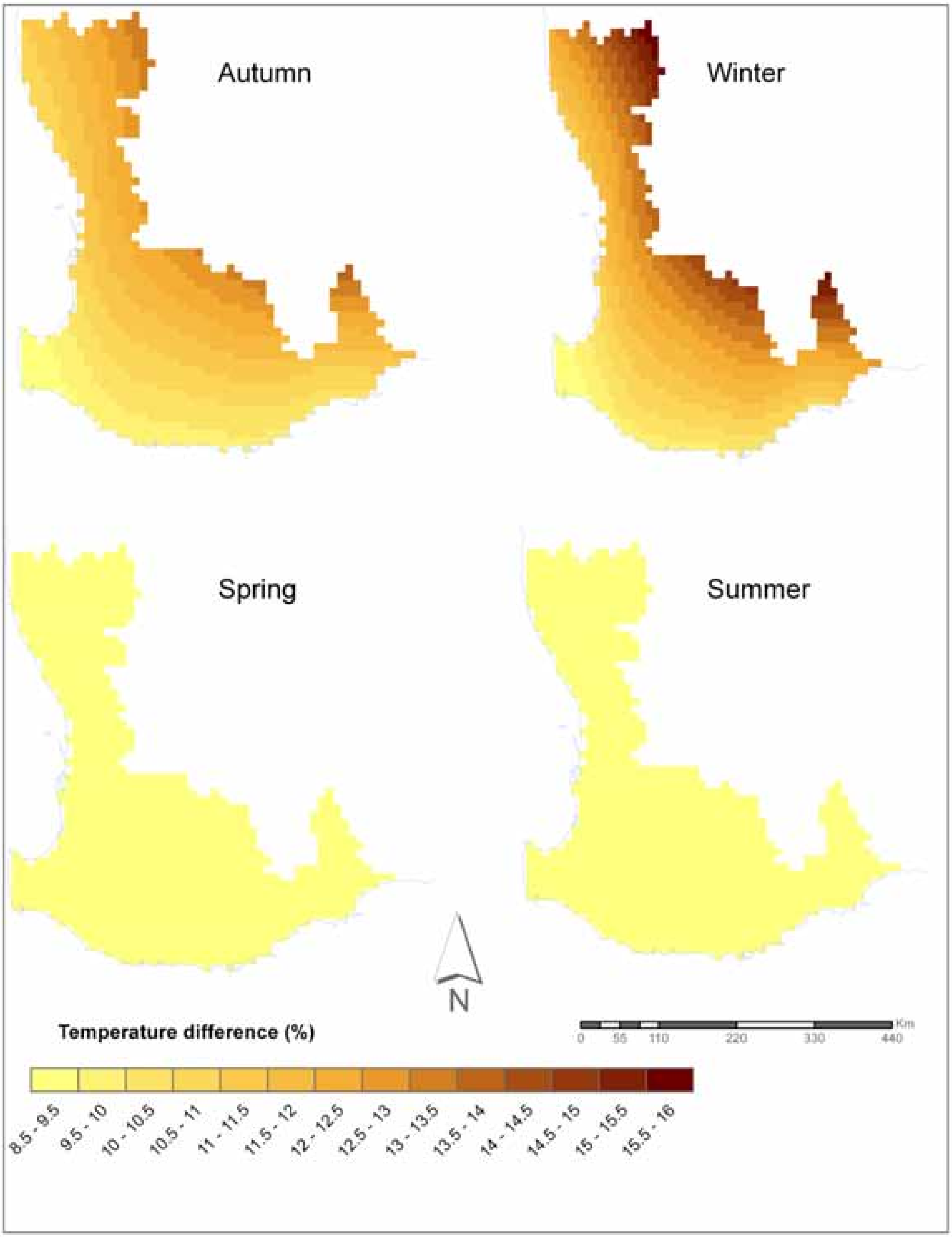

Figure 20 Projected seasonal temperature change for 2050 expressed in percent within the study area

Appendix D — Comparison of rainfall for three modelled catchments

Figure 21 presents the relationship between observed and projected rainfall at the three catchments used in previous studies for hydrological modelling.

Seasonal rainfall distribution displayed a similar pattern for the Stirling Dam and Serpentine River sites:

- the current summer rainfall was the same as observed and the future slightly lower
- the current projections for autumn were significantly lower than the observed – approximately 30% – and the future decline was approximately 21% for both catchments
- the winter current projections were higher than observed records – 7% at Stirling Dam and 3% at Serpentine River – while an approximate 10% decline in the future was projected for both stations
- the spring observed rainfall was lower than the current for both sites (up to 15%) and the future projections showed a rainfall decline of 5% for Stirling Dam and 7% for Serpentine River.

The Denmark River catchment is located approximately 200 km south of the Stirling Dam site and the rainfall pattern was different. Observed rainfall at the Denmark Post Office station (9531) was slightly higher than the current projections for all seasons, except for summer. The projected change between current and future showed a small decrease for autumn and winter (approximately 3%), a 20% decline for summer and an increase of 1% in spring at this site.

Figure 21 shows the annual comparison between mean observed and current rainfall for three meteorological stations: Tallanalla Creek 509197 (Stirling Dam catchment), Jarrahdale 9023 (Serpentine River catchment) and Denmark Post Office 9531 (Denmark River catchment). The GCM series showed a similar overestimating pattern in projected current rainfall for the Stirling Dam and Serpentine catchments. Overall the projected current mean annual rainfall was 0.9% higher than observed for the Stirling Dam and 1.4% lower in the Serpentine River catchment. The current mean annual rainfall series for the Denmark River catchment were 6% lower than observed data but they reflected closely the observed pattern.

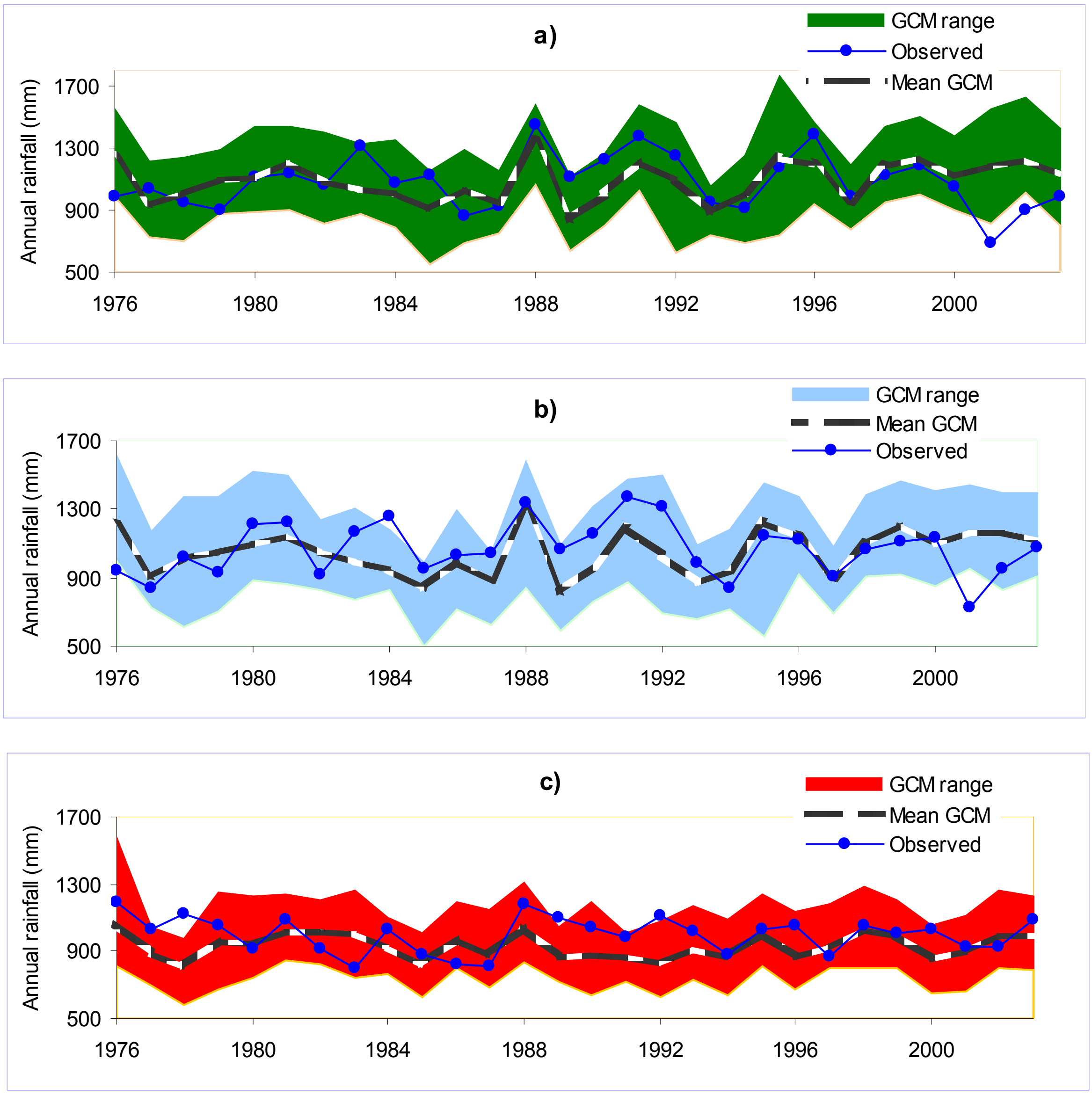

Figure 21 Mean annual observed and current rainfall for three modelled catchments: a) Stirling Dam b) Serpentine River c) Denmark River

Figure 22 illustrates the seasonal pattern of observed, GCM Mk3.5 current and GCM Mk3.5 future rainfall for the three tested catchments.

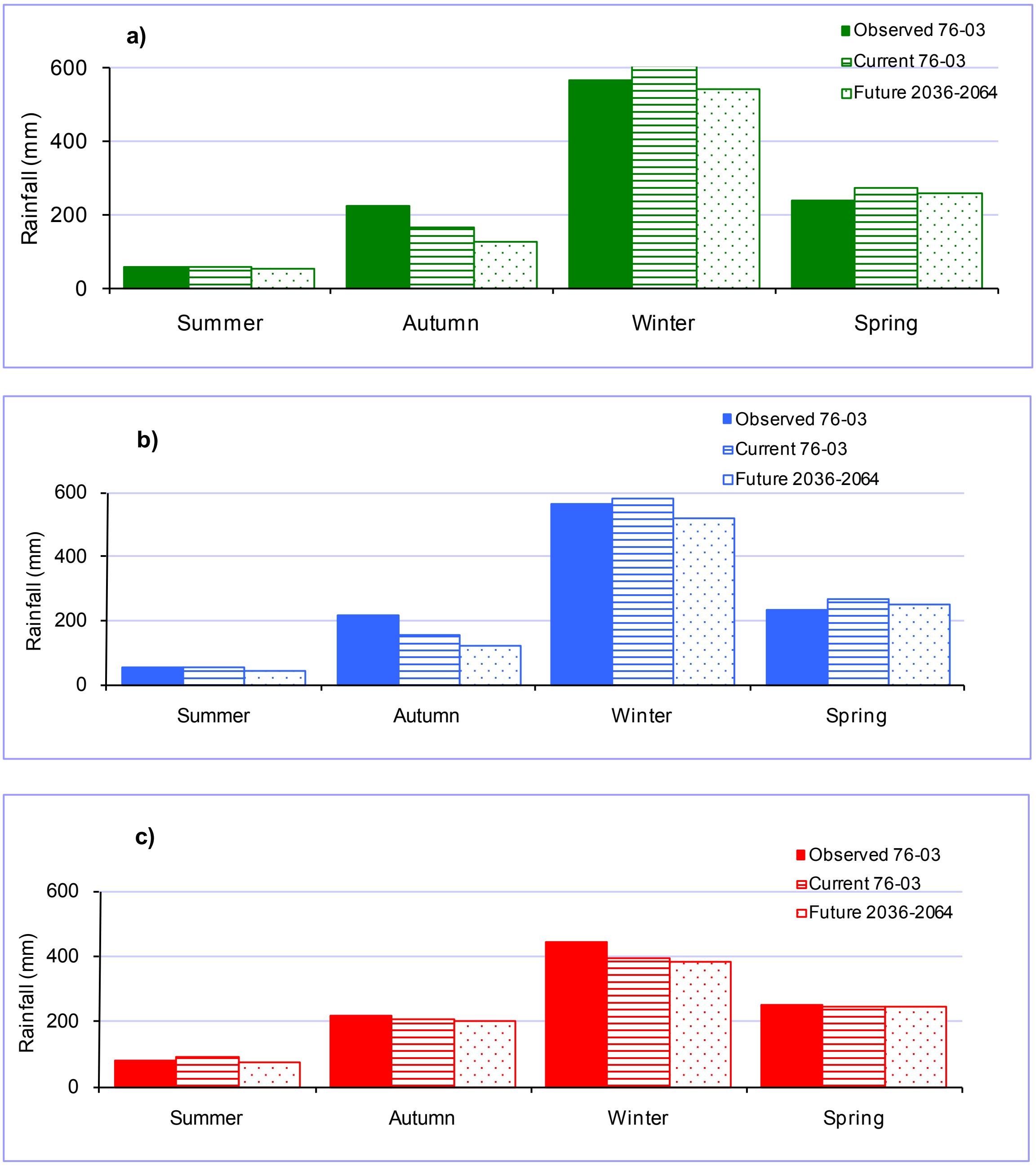

Figure 22 Mean seasonal observed, current and future rainfall for: a) Stirling Dam catchment (509197), b) Serpentine River catchment (9023) and c) Denmark River catchment (9531) for 2050

The monthly rainfall distribution shown in Figure 23 confirms what has been previously noted in other studies: shift of the peak in projected rainfall from July to August at all three presented stations (Berti et al. 2004; Kitsios et al. 2008; Smith et al. 2009).

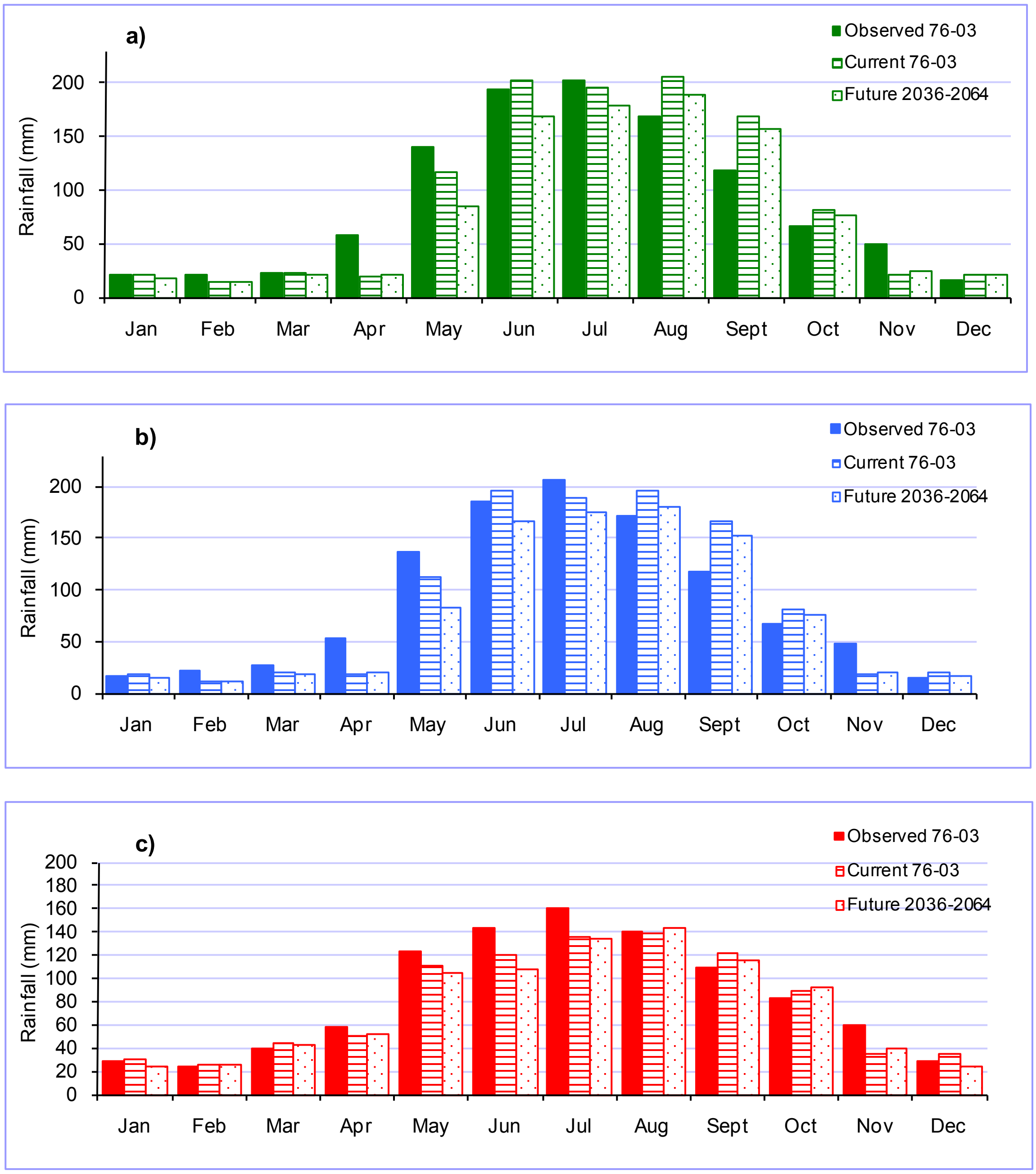

Figure 23 Mean monthly observed, current and future rainfall for three modelled catchments: a) Stirling Dam b) Serpentine River c) Denmark River

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