Modelling of streamflow reduction due to climate change in Western Australia – A case study

[1]Bari, M.A., [1]Berti, M.L., [2]Charles, S.P., [1]Hauck. E.J. and [1]M. Pearcey

[1] Department of Environment, PO Box 6740, Hay Street East, East Perth, W.A. 6892, Australia,
E-Mail: mohammed.bari@environment.wa.gov.au

[2] CSIRO Land and Water, Private Bag Number 5, Wembley, W.A. 6913, Australia

Keywords: *Climate change; Western Australia; LUCICAT model; Water resources.*

EXTENDED ABSTRACT

The population of the Perth-Bunbury region in Western Australia is 1.1 million and is predicted to increase to 3.1 million by 2050. At present about 40% of the Perth's water supply comes from surface water resources. Due to below-average rainfall for several decades, streamflow to reservoirs supplying the Perth metropolitan area has declined more than 40%. General Circulation Models (GCMs) predict that rainfall in this region is likely to decrease further due to projected climate change. The availability of water resources may diminish further and pose a significant threat to water supply, environment and biodiversity.

This paper presents a case study of the effect of a projected change in climate on the water yield of the Stirling Dam catchment, located in the south west of Western Australia. The study applied 40 realisations of current (1975 to 2004) and future (2035 to 2064) daily rainfall generated by statistically downscaling a single CSIRO Mk3 GCM simulation based on the IPCC SRES A2 emission scenario. The Land Use Change Incorporated Catchment Model (LUCICAT) was calibrated for the Stirling Dam catchment under existing conditions. The projected change in catchment runoff was then simulated using the downscaled rainfall. No change in land use, potential evaporation or evapotranspiration potential was assumed to occur when moving from the current to future climate.

The study found that when the IPCC SRES A2 emission scenario is applied to the CSIRO Mk3 GCM to produce two 30-year realisations, annual rainfall in the south west of Western Australia is projected to decrease 11% by the middle of this century, . Taking into account the assumptions and limitations of the study, the projected reduction in rainfall would likely result in a 31% reduction in annual water yield from the catchment. A sensitivity analysis revealed that a 10% increase in potential evaporation, coupled with the 11% decrease in rainfall, could result in water yield reductions of greater than 40%. Conversely a 10% decrease in potential evaporation with same rainfall decrease resulted in only a 9% reduction in water yield.

Confidence in the predictions of rainfall and runoff could be improved by using: (i) multiple GCMs and CO_2 emission scenarios, (ii) multiple catchments and (iii) better estimates of the Leaf Area Index (LAI) and potential evapotranspiration.

1 INTRODUCTION

In recent decades, increasing concern has developed over global climate change, trends and projections and the implication of these in areas such as water resources management. An Australian context of climate variability and climate change is well described in publications by the Australian Bureau of Meteorology (2003) and the Australian Greenhouse Office (2003).

At present, General Circulation Models (GCMs) have been used to estimate changes in precipitation and temperature globally (IPCC 2001). These models are able to project different climate regimes by accounting for changing levels of CO_2 and other gases in the atmosphere, and determining the resulting atmospheric conditions brought about by changes in circulation patterns. GCM outputs are most reliable at large scales, which can lead to problems when the intended use of GCM outputs is for regional scale applications, such as simulation of rainfall and temperature data for small catchments. The use of statistically downscaled GCM outputs to produce more spatially defined projections of rainfall and temperature is an emerging science that holds great promise for applications on such local scales (Wilby et al. 2004).

This study aims to apply statistically downscaled rainfall to a water resource catchment in south-west Western Australia to assess the impact of projected climate change on catchment water yield. The methodology adopted involves the coupling of statistically downscaled GCM climate projections with a catchment hydrology model. The Australian Greenhouse Office supported this study as a combined project between Western Australia's Department of Environment (formerly known as the Water and Rivers Commission), CSIRO Land and Water and Western Australia's Water Corporation.

Several decades of below average rainfall and a recent succession of dry years has focused attention on water resource reliablity in south-west Western Australia. Rodgers and Ruprecht (1999) assessed the impact of climate variability on surface water resources of the region, finding that major changes occurred in the hydrology of the forested catchments. This region has experienced a decline in winter rainfall of up to 20% over the past 30 years, which has resulted in a 40% or greater reduction in runoff to reservoirs supplying the Perth metropolitan area (Rodgers and Ruprecht 1999; IOCI 2001). The Perth-Mandurah Integrated Water Supply System (IWSS) has traditionally utilised the Darling Range Catchments as a potable water source, however the decline in catchment water yield has resulted in a greater dependence on Perth's regional groundwater resources and has increased the potential for impact on coastal groundwater dependent ecosystems.

To further add to the challenges now faced by water resources managers, future climate projections indicate a further decrease in rainfall in the south-west of Western Australia. The risks that such a decrease poses for the environment, water supply and water resources management are significant, especially with a steady increase in demand for water and the diminishing availability of traditional source options. This study investigates the impact of a projected climate change on inflows to the Stirling water supply dam in south-west Western Australia and will contribute toward a reassessment of surface water supply planning in the State.

2 CATCHMENT DESCRIPTION

Stirling Dam catchment (Figure 1) is located approximately 120 km south of Perth in the Darling Range and is used for irrigation and as a component of the Perth-Mandurah Integrated Water Supply Scheme.

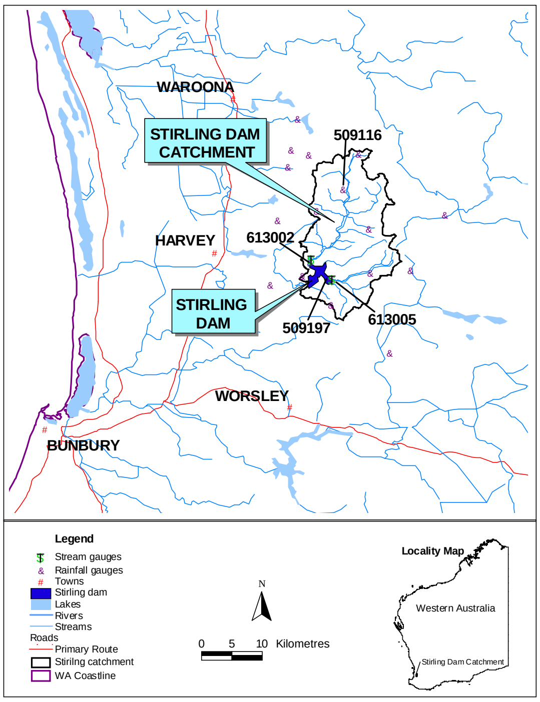

Figure 1. Location of Stirling Dam catchment

The Stirling Dam catchment covers an area of 250 km^2, and the mean annual inflow to Stirling

Reservoir for the period 1975 to 1994 was 49 GL (Gigalitres). The catchment forms part of state forest and is managed by the Department of Conservation and Land Management (CALM). The dominant species in the area are jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*) which form an upperstorey vegetation cover to a height of 20 to 35 m. There is also a well-defined understorey formed by trees and shrubs. Pine plantations exist around some parts of the dam area. The Forest Products Commission and CALM conduct logging and controlled burning as part of normal forestry operation, but on the whole, minimal clearing has taken place in the catchment. Dieback is also present within the catchment.

3 METHODOLOGY

3.1 Statistical Downscaling

The downscaling procedure provides multi-station, daily rainfall and temperature data for a network of 31 stations across south-west Western Australia (Berti et al. 2004). The Non-homogeneous Hidden Markov Model (NHMM) of Hughes et al. (1999) was used to downscale atmospheric predictors to multi-site, daily precipitation occurrence and then conditional multiple linear regression was used to simulate multi-site, daily precipitation amounts (Charles et al. 1999). The CSIRO GCM used in this study is denoted as the Mark 3 (Mk 3) version (Gordon et al. 2002). Two 30-year time-slices of daily GCM output representing a current and future period were extracted from a single continuous (transient) run using the IPCC A2 medium economic growth emissions scenario with steadily increasing greenhouse gas concentrations. The current period is centered on 1990 and runs from 1975 to 2004. The future period is centered on 2050 and runs from 2035 to 2064. This future period experiences a climate with approximately 1.7 times the equivalent CO_2 concentration of the present day. The statistical downscaling models were validated on observed data (Berti et al. 2004). Both summer and winter mid-21st century downscaled climate projections indicate an overall drying trend with fewer rain days (Figure 2), lower seasonal and extreme rainfall amounts, and higher maximum and minimum daily temperatures.

3.2 Application of the LUCICAT Model

The LUCICAT (Land Use Change Incorporated CATchment) model was used to investigate the impact of the statistically downscaled GCM projections on catchment yield (Berti et al. 2004).

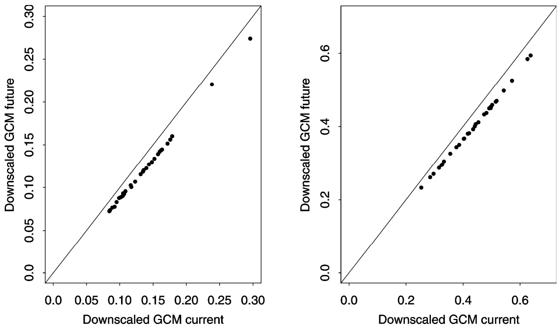

Figure 2. Precipitation probabilities for current and mid-21st century Summer (left) and Winter (right)

The Stirling Dam catchment was divided into 33 subcatchments ranging from 2.4 to 12 km^2 in size. The model generally provided an accurate prediction of observed streamflow. At the Harvey River Dingo Road and Blackbutt Point gauging stations, there was less than 1% and 7% difference respectively between the predicted and observed annual flow for the period 1974 to 1999. A statistical t-test shows that this difference is not significant at the 99% confidence limit. At both the gauging stations, a tendency toward over-prediction can be seen in the modelling of the monthly peak flows (Figure 3). The correlation between the monthly observed and predicted flows was approximately 0.9 for Dingo Road and approximately 0.95 for Blackbutt Point.

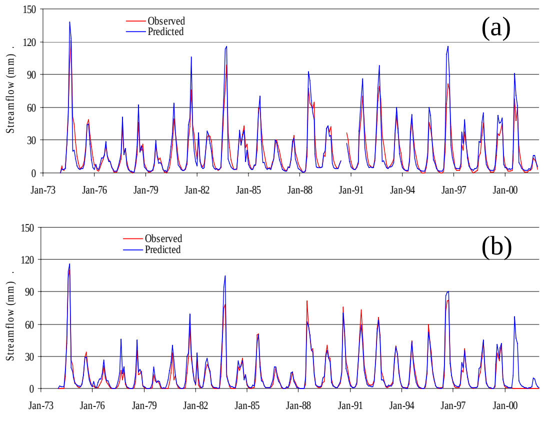

Figure 3. Observed and predicted monthly streamflow at (a) Dingo Road and (b) Blackbutt Point

The daily simulation of the low-flow year (1979) was compared to the observed streamflow at Dingo Road (Figure 4a). During the period January to May, when the base flow component was dominant, the model prediction was very close to the observed. For May and June the model generally over-predicted the daily flow. Over all, the trend in observed and predicted daily flow was very consistent. Comparing the observed and predicted daily flow at the Blackbutt Point for the average-flow year 1990, it can be seen that the two matched reasonably well (Figure 4b). The model predicted the daily peak flow very well, while slightly under-predicting the streamflow during the period October to December when the interflow and base flow component was dominant.

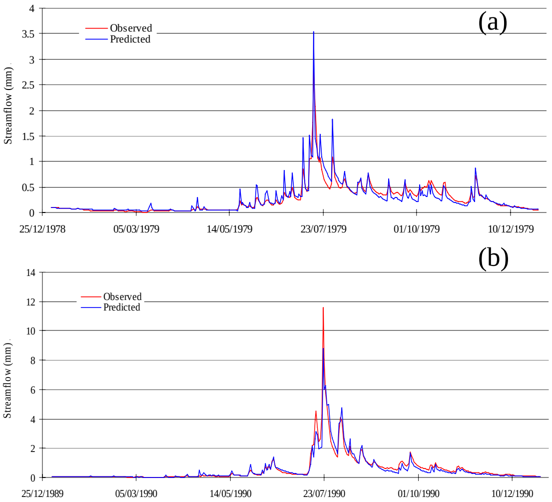

Figure 4. Observed and predicted streamflow at (a) Dingo Road and (b) Blackbutt Point

The predicted monthly inflow to the Stirling Dam compared well to the figures derived using the Water Corporation's reverse water balance calculation. A correlation coefficient greater than 0.9 supports the accuracy of the LUCICAT calibration. The predicted average (1972-1998) annual catchment yield of 53.9 GL compares well with the reverse water balance figure of 52.2 GL. Both inflow series have relatively low coefficients of variation, similar means and similar values at the 10th percentile range. The main difference occurs at the higher flow end with the calibrated LUCICAT inflows being greater than the reverse water balance figures at the 90th percentile. This may occur as the LUCICAT figures do not take into account dam overflows, scour and evaporation from the dam surface.

4 RAINFALL DOWNSCALING AND YIELD PREDICTION

4.1 Rainfall

One thousand realisations of current and future daily rainfall and temperature were generated through the downscaling of the current and future atmospheric predictors. To capture the range and variability while reducing the LUCICAT running-time, it was calculated that analysing 40 randomly selected realisations would be statistically valid. The GCM downscaled mean monthly rainfall, for both the current and future, exhibit differences to the observed mean monthly rainfall (Figure 5). Despite the shift in intra-annual peak, the catchment average current GCM downscaled rainfall is only 2% greater than that calculated using the observed data. This margin of error is within the limits found in previous studies (Wood et al, 1997) and will tend to overestimate runoff response.

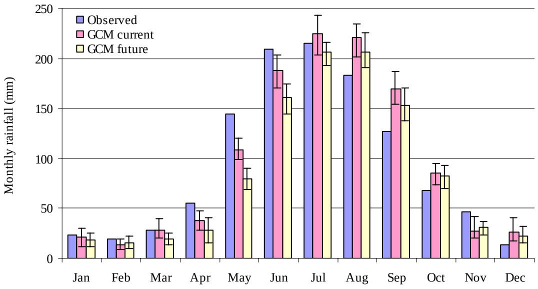

Figure 5. Comparison of mean monthly rainfalls

The downscaled annual rainfall for the future is on average 11% lower than the current downscaled annual rainfall. This is consistent with previous peojections of rainfall decrease due to climate change for south-west Western Australia. Except for February and November, the mean monthly rainfall under future climate would be lower than the current state (Figure 5). The largest change in mean monthly rainfall total (mm) is predicted to occur in May. An early winter (May/June) decrease is consistent with the observed mid-1970s rainfall decrease experienced by the region (IOCI, 2001).

4.2 Dam Inflow

To assess the change in yield that could occur following a change in climate, the LUCICAT model was run using the current and future GCM downscaled rainfall. A slight bias toward over-prediction of inflow can be seen when using the current GCM downscaled rainfall (Figure 6). This can be attributed to the higher average annual rainfall produced under the current GCM climate.

Comparing the annual 10th and 90th percentile flow volumes reveals that the current downscaled rainfall produces a smaller streamflow range, and thus a smaller annual variation, than the observed case (Table 1). On average the current predicted inflow is about 9% greater than the annual inflow generated using observed rainfall. The shift in peak rainfall to July – August (in the GCM downscaled GCM realisations) contributes to this increase in streamflow.

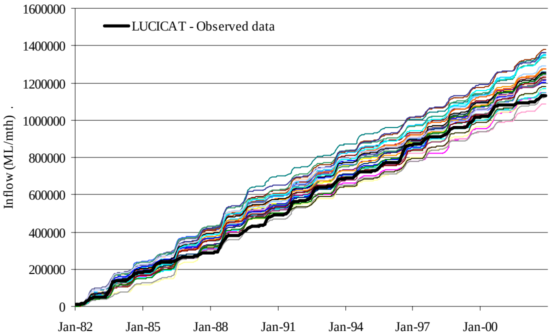

Figure 6. Comparison of dam inflows

Table 1. Comparison of annual dam inflow statistics

Streamflow Statistic	Observed Data (1982 – 2002)	Current GCM (1982 – 2002)	Future GCM (2042 – 2062)
Median (GL)	48.8	57.1	38.2
10th Percentile (GL)	28.5	38.7	24.5
90th Percentile (GL)	88.7	81.4	62.3
Coefficient of Variation	0.40	0.31	0.39
Mean (GL)	53.9	59.1	41.1
Standard Deviation (GL)	21.4	18.6	15.9

The response of climate change is also evident through the changes in Stirling Dam inflow statistics for the future (Table 1). Interestingly, the coefficient of variation is higher under the future climate compared to the current GCM and highlights the changes in frequency of events as well as a change in event magnitude. On average the annual inflow to the reservoir under future climate is predicted to be 31% lower than the inflow for current GCM downscaled rainfall. This result is consistent with previous estimates of streamflow decrease due to climate change (Jones and Page 2001; Chiew and McMahon 2002). The magnitude of this reduction in streamflow highlights the serious implications of a change in climate for the abundance and availability of surface water resources.

Comparing the monthly reservoir inflows generated by the LUCICAT model using the observed, current and future GCM downscaled rainfalls shows a significant seasonal bias (Figure 7). The mean monthly reservoir inflows under future climate conditions are predicted to be lower than the current state. The largest volume decrease in average monthly flow occurs in winter, with an approximate 4500 ML reduction in inflow to Stirling Dam in August (Figure 7). The largest proportional reduction in inflow occurs in May, when there is on average 60% less inflow to the reservoir. The timing of these reductions may have significant effects on water quality and downstream ecosystem health.

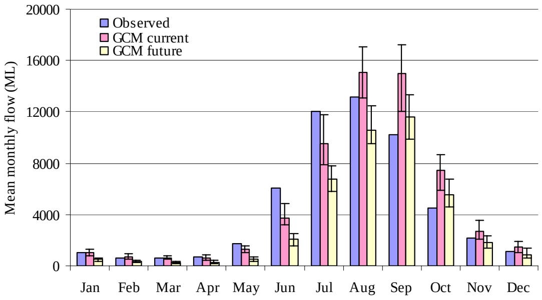

Figure 7. Comparison of mean monthly inflow

4.3 Catchment Water Balance

Four LUCICAT simulations were selected for each climate regime to assess the impacts on different streamflow components. The predicted water balance components for the observed and current GCM downscaled rainfalls compare well (Table 2). The LUCICAT output obtained using the future downscaled rainfall predicted that each of the water balance components would decrease. Using the current GCM downscaled rainfall, interflow was the largest contributor to streamflow followed by baseflow and then surface runoff, while in the future, interflow would remain the largest contributor of water balance followed by surface runoff and baseflow. Baseflow would have the largest reduction of 43% under the future climate (Table 2). This significant decrease can be linked to a decline in conceptual groundwater levels and soil moisture across the catchment under a future climate regime. A reduction in groundwater levels can lead to a reduction in baseflow, stream zone saturated areas and surface runoff.

Table 2 Water balance partitioning of LUCICAT simulations

Water Balance Component	Observed (1982-2002) (mm)	Current GCM (1982-2002) (mm)	Future GCM (2042-2062) (mm)	Difference: (Current-Future)/Current (%)
Rainfall – Total	1131	1142	1051	8
Evapotranspiration – Total	899	899	871	3
Streamflow – Total*	214	233	167	28
- Surface Runoff	34.7	39.5	28.4	28
- Interflow	153	165	129	22
- Baseflow	44.7	48.2	27.4	43
Runoff Coefficient (%)	18.9	20.4	15.9	22

*Total streamflow is less than the sum of the individual streamflow components due to transmission and evaporation losses.

4.4 Sensitivity Analysis

As it is not certain how land use or evapotranspiration will change with different climatic conditions, sensitivity analysis was performed involving Leaf Area Index (LAI) and potential evapotranspiration. The analysis revealed that the Stirling Dam catchment is more sensitive to a reduction in LAI than an increase. A 10% reduction in LAI results in a 10% decrease in the reduction to dam inflow, whereas a 10% increase in LAI results in an increase of 8% in the reduction to dam inflow. This finding identifies the need for a better understanding of vegetation change that may be expected under a future climate, so that these responses can be incorporated into climate change studies and thus improve the accuracy of the modelling results. The catchment is more sensitive to a change in potential evapotranspiration than to a change in LAI. Combined with a rainfall change, 10% reductions and increases in potential evaporation lead to reductions in inflow to Stirling Dam of 9% and 41%, respectively. This illustrates that the catchment is more sensitive to a decrease in potential evapotranspiration than an increase.

5 DISCUSSION

The use of statistically downscaled rainfall in hydrological modelling is still an emerging science. The downscaling provides regional information about the impact of climate change on water resources potentially suitable for hydrological modelling (Hay et al, 2000). Investigating predictor selection for the NHMM has shown that it provides climate change projections consistent with the large scale rainfall projections obtained from climate models. Downscaling studies have often found that the predictors and method of downscaling used to generate scenarios has a strong influence on the magnitude of the predicted climate change (Hay et al. 2000; Leavesley 1994). The marked shift in the intra-annual peak between the observed and current GCM rainfall (Figure 5) highlights this issue. Several studies have shown that outputs from different GCMs deliver significantly different projections of future climate change (Nijssen et al 2001). For more confident predictions it is necessary to compare outputs from several GCMs and emission scenarios.

Temperature changes are generally included in climate change modelling studies as a change in potential evapotranspiration. While it is usually implied that an increase in temperature would result in an increase in potential evaporation, recent studies using observed pan evaporation data have found that in some cases increases in temperature have been accompanied by decreases in pan evaporation (Roderick and Farquahar 2002). Further work is needed to clarify how these findings relate to actual and potential evapotranspiration and ultimately catchment yield. The response of native vegetation to a change in climate is uncertain. How plant water use change under a warmer and drier climate needs further investigation.

For predicting runoff under different climatic conditions it has been argued that no calibration of model parameters should take place (Leavesley 1994). The basis for this argument is that in this way the model does not become biased to any particular climate. Wood et al (1997) proposed that as long as the differences between the observed and current GCM climates are modest, then transferring the calibrated parameter set should be acceptable. In relation to this study, with a distinct shift from a June – July peak (observed rainfall) to a July – August peak (current GCM downscaled rainfall), it may be argued that calibrated parameters of the LUCICAT model may not be ideal for applications using the GCM downscaled rainfall.

Predicted decrease in inflow to the Stirling Dam due to climate change would effectively result in a further under-performance of the surface water supply systems. Options for future sources of supply will need to seriously consider strategies that include increased groundwater use, demand management, water reuse and desalinisation. The projected drier climate would also cause altered flow regimes and loss in biodiversity. An adaptive response would be necessary to maintain environmental values in riverine environments and ecological communities (Gitay et al., 2002).

6 CONCLUSIONS

After generating multiple 30-year data sets of current and future downscaled daily rainfall, and transposing these rainfall figures into the LUCICAT hydrological model, the study was able to predict that inflow to Stirling Dam could decrease by 31% under projected future climate conditions in the 2035 – 2064 period. This decrease results from a projected 11% drop in future rainfall, and is governed by the assumptions and limitations of the study. These results are based on the analysis of 40 current and future downscaled simulations obtained from a single CSIRO Mk3 GCM projection based on 1.7 times CO_2, (IPCC SRES A2 emission scenario). Sensitivity analysis showed that if, in addition to the rainfall decline, the LAI was to decrease across the catchment by 10% then the reduction in inflow to Stirling Dam might be closer to 20%. If potential evapotranpiration increased by 10% when rainfall decreased there would be a 41%

reduction in inflow. Research into these sensitivities is ongoing.

7 ACKNOWLEDGMENTS

The authors gratefully acknowledge the Australian Greenhouse Office's contribution and support towards this project.

8 REFERENCES

Australian Bureau of Meteorology, (2003), 'The greenhouse effect and climate change", Commonwealth of Australia, ISBN: 0642 70636 0.

Australian Greenhouse Office, Pittock, B. (Ed) (2003), 'Climate change: An Australian guide to the science and potential impacts', Commonwealth of Australia, ISBN: 1 920840 12 5.

Berti, M.L., Bari, M.A., Charles, S.P., & Hauck, E.J., 2004, *Climate change, catchment runoff and risks to water supply in the south-west of Western Australia*, Department of Environment.

Charles, S.P., Bates, B.C. & Hughes, J.P., 1999, A spatio-temporal model for downscaling precipitation occurrence and amounts, *Journal of Geophysical Research* 104: 31657-31669.

Chiew, F.H. and McMahon, T.A. 2002, 'Modelling the impacts of climate change on Australian streamflow, *Hydrological Processes*, 16: 1235-1245.

Gitay, H., Suarez, A., Watson, R.T. and D.J. Dokken, 2002: Climate Change and Biodiversity. Intergovernmental Panel on Climate Change, Technical Paper V, Geneva, 77 pp. <htpp://www.ipcc.ch/>.

Gordon, H.B., Rotstayn, L.D., McGregor, J.L., Dix, M.R., Kowalczyk, E.A., O'Farrell, S.P., Waterman, L.J., Hirst, A.C., Wilson, S.G., Collier, M.A., Watterson, I.G. & Elliott, T.I., 2002, *The CSIRO Mk3 Climate System Model*. Technical Paper No. 60. CSIRO Atmospheric Research: Aspendale, Victoria, Australia 130 pp.

Hay, L.E., Wilby, R.L. and Leavesley, G.H. 2000, A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States, *Journal of the American Water Resources Association*, Vol 36, No 2, pp 387-397.

Hughes, J.P., Guttorp, P. & Charles S.P., 1999, A non-homogeneous hidden Markov model for precipitation occurrence, *Applied Statistics* 48: 15-30.

IOCI,. 2001, *Second Research Report - Towards Understanding Climate Variability in south western Australia*. Indian Ocean Climate Initiative Panel, East Perth. pp193.

IPCC, 2001: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

Jones, R.N. and Page, C.M., 2001, Assessing the risk of climate change on the water resources of the Macquarie River catchment, *Integrating Models for Natural Resources Management Across Disciplines, Issues and Scales*, 2: 673-678.

Leavesley, G.H., 1994, Modeling the effects of climate change on water resources - a review, *Climatic Change*, 28: 159-177.

Nijssen, B., O'Donnell, G.M., Hamlet, A.F., and Lettenmaier, D.P., 2001, Hydrologic sensitivity of global rivers to climate change, *Climatic Change*, 50: 143-175.

Roderick, M.L. and Farquahar, G.D., 2002, The cause of decreased pan evaporation over the past 50 years, *Science*, 298: 1410-1411.

Rodgers, S.J. and Ruprecht, J.K., 1999, The Effect of Climate Variability on Streamflow in South Western Australia, Water and Rivers Commission SWH 25.

Wilby, R.L., Charles, S.P., Zorita, E., Timbal, B., Whetton, P., and Mearns, L.O., 2004: "Guidelines for Use of Climate Scenarios Developed from Statistical Downscaling Methods". *Published on-line*, supporting material to the Intergovernmental Panel on Climate Change, 27pp.

Wood, A.W., Lettenmaier, D.P. and Palmer, R.N., 1997, Assessing climate change implications for water resource planning, *Climatic Change*, 37: 203-228