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Climate change and long term water availability in Western Australia - An experimental projection

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Abstract: The population of the Perth-Bunbury region in Western Australia is predicted to increase to 3.1 million by 2050. Water supply is a key issue, as below-average rainfall since the mid-1970s has led to about 40% decline in the streamflow. General Circulation Models (GCMs) project a further decrease in rainfall leading to diminished water resources in the future and posing a threat to water supply and the environment. In this experimental study we assess the impact of climate change at Serpentine Reservoir using data from eleven GCMs which contributed to the latest Intergovernmental Panel on Climate Change (IPCC) assessment report. Data from two emission scenarios (A2 and B1) were used and downscaled, using a state-of-the-art statistical downscaling model, to a 5 km resolution compatible with catchment modelling. The LUCICAT rainfall-runoff model was calibrated for the Serpentine catchment and then changes in runoff were projected using the downscaled rainfall data. Land use and potential evaporation were not changed for the future rainfall-runoff modelling. Nearly all GCMs projected reductions in rainfall by mid (2046-2065) and late (2081-2100) 21st century compared to 1981-2000 period. There was a significant variation in projected rainfall reductions between different GCMs and emission scenarios. Under the A2 climate scenario, there could be a further 14-24% reduction in rainfall, and this would result in a 49-69% reduction in reservoir inflow by the mid to end of the 21st century. Rainfall reduction under B1 scenario would be around 12% and corresponded to streamflow reduction of about 45-46%.

***Keywords**:* LUCICAT model, climate change, A2 and B1 scenarios, downscaling, Serpentine catchment.

1. INTRODUCTION

The south-west of Western Australia has experienced declining rainfall since the mid 1970s (IOCI, 2002). Several decades of below average rainfall and a recent succession of dry years has focused attention on water resource availability and reliability in south-west Western Australia. The Serpentine Catchment is a major water supply catchment within the Integrated Water Supply System for Perth, the capital city in Western Australia. It is located in the Darling Ranges, where most of the water-supply catchments are located. The Darling Ranges has experienced a decline in winter rainfall of up to 20% over the past 30 years, resulting in a 40% or more reduction in runoff to reservoirs supplying the Perth metropolitan area (IOCI 2002; Bari and Ruprecht, 2003; Water Corporation, 2009). The decline in the water yield of these catchments has resulted in a greater dependence on Perth's regional groundwater resources and has increased the potential for impact on coastal groundwater dependent ecosystems. In Australia, there have been some studies of the effects of climate change on water resources and catchment hydrology (Ritchie, et al., 2004; Charles, et al., 2009). In the south-west of Western Australia, there have been various studies relating to the impacts of climate change on water resources (Bari et al., 2005; Charles et al., 2007). However, most of these studies were focused on specific climate scenarios.

This paper focuses on the Serpentine water supply catchment in Western Australia and investigates the impacts of two climate change scenarios on streamflow and water yield through the application of LUCICAT (Land Use Change Incorporated CATchment) model. Recently developed 5 km grid rainfall generated by the Australian Bureau of Meteorology (Jones et al., 2009), and daily downscaled rainfall projections for two scenarios from 11 CGMs are used across the Serpentine catchments.

2. CATCHMENT DESCRIPTION

The Serpentine catchment is approximately 55 km south-east of Perth, Western Australia (Figure 1). The main land cover is jarrah (*Eucalyptus marginata*) forest, with only small parts cleared. The Jack Rocks sub-catchment was mined for bauxite in the 1990s, while parts of the Cameron West and Cameron Central sub-catchments were logged in 1995-96 and there has been selective logging within the Jayrup sub-catchment. Prescribed burning has a role in reducing the incidence of wildfires, regenerating native forests and conserving biodiversity. The climate is temperate, with hot dry summers and cool wet winters. Average annual rainfall varies from 680 mm in the east to 1150 mm in the west of the catchment. The Serpentine River is the main river and Big Brook is the main southern tributary. The annual pan evaporation ranges from 1600 to 1700mm.

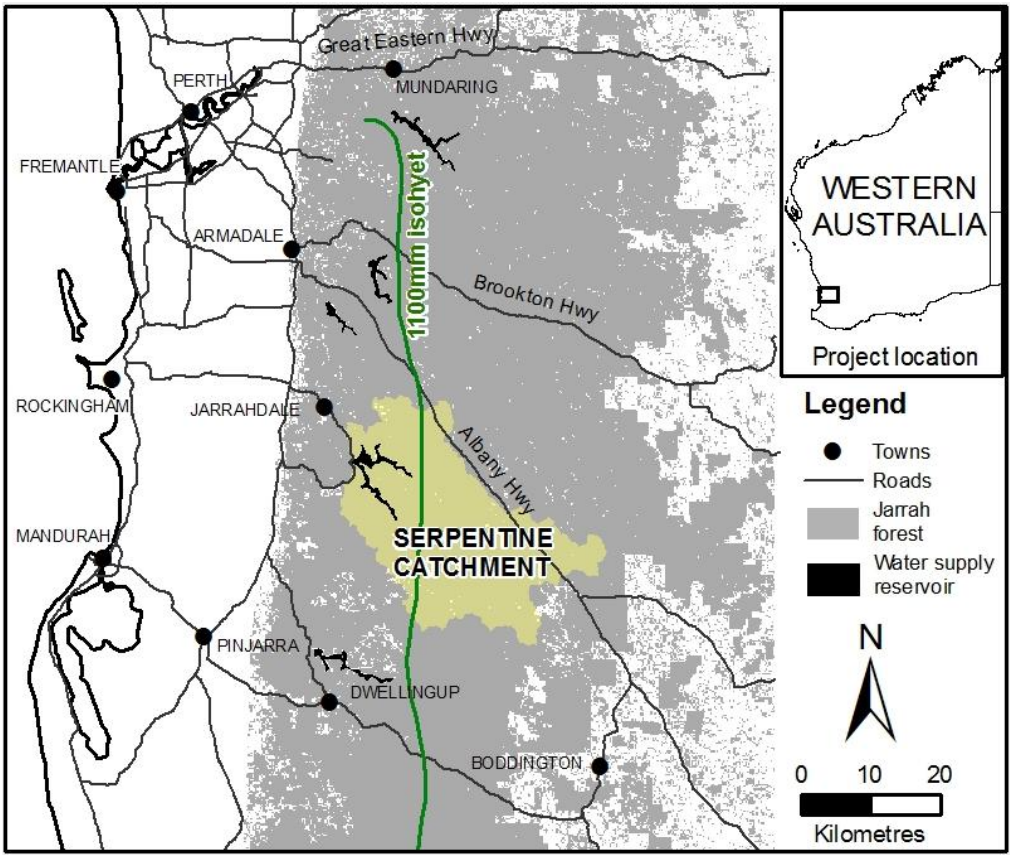

Figure 1 Location of the Serpentine water supply catchment

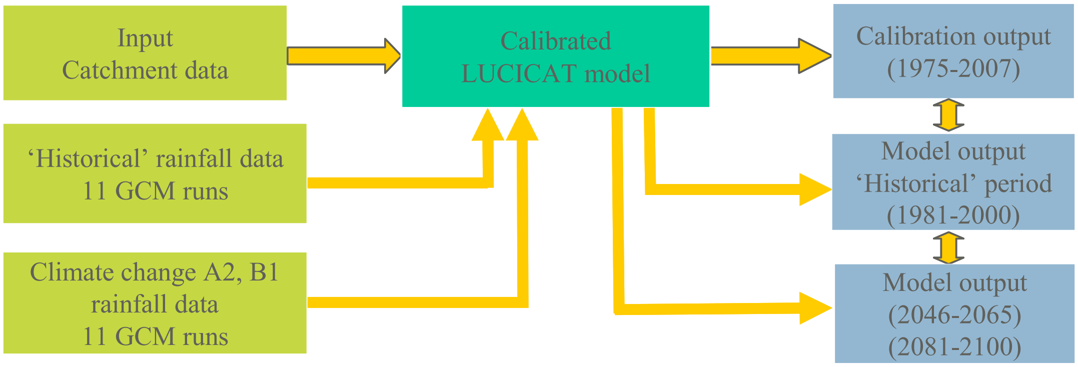

Figure 2 Schematic diagram of methodology

3. METHODOLOGY

Daily downscaled rainfalls were computed using variables from 11 GCMs for the periods 2046-2065 and 2081-2100. Two climate change scenarios were considered – A2 and B1. The four main components to this study are: (a) calibration of the LUCICAT rainfall-runoff model, (b) run LUCICAT model with 'Historical' (calibrated GCM) rainfall data and compare model output with the calibration, (c) simulation of the impacts of projected climate change scenario (A2, B1) on streamflow through running the LUCICAT model, and (d) analysis and assessment of the projected streamflow data (Figure 2).

3.1 Climate Scenarios and Downscaling

Statistically downscaled rainfall data were obtained from the Australian Bureau of Meteorology's Statistical Downscaling Model (SDM) based on an analogue approach (Timbal et al., 2009). The daily GCM data were extracted from the Coupled Model Inter-comparison Project Number 3 (CMIP3), assembled as part of the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment of Climate Change Science (Solomon et al., 2007). As daily data are required to perform the statistical downscaling, only 11 GCM outputs were used in this study. The models were ranked according to a measure of sensitivity (ΔT, Table 1). The daily climate data were available for three time-slices: 1961-2000; 2046-2065 and 2081-2100. Two emission scenarios were considered: A2, a very heterogeneous world with increasing population and technologically fragmented economic development, and B1, a global solution to economic, social and environmental sustainability (IPCC, 2001). The calibration and validation of the SDM was performed as part of an Australia-wide application (Timbal et al., 2009) using the high quality rainfall dataset assembled by the National Climate Centre (Lavery et al., 1997). Once the SDM has been calibrated it can be applied to any suitable observations within the same climate region. That flexibility was applied to the 5km grid resolution rainfall (Jones et al., 2009) generated as part of the Australian Water Availability Project (AWAP). Initial application was in the south-west of Western Australia which covers the Serpentine catchment.

Table 1 Selected GCMs from CMIP3 data base

Originating group	Country	Model	Grid size (km)	ΔT (^{0}C)
CSIRO	Australia	CSIRO3.5	~200	2.11
CSIRO	Australia	CSIRO3.0	~400	2.11
NASA/Goddard Institute for Space Studies	USA	GISSR	~300	2.12
Canadian Climate Centre	Canada	CCM	~300	2.47
Meteorological Research Institute	Japan	MRI	~300	2.52
Geophysical fluid Dynamics Lab	USA	GFDL2	~300	2.53
Meteo-France	France	CNRM	~200	2.81
Geophysical fluid Dynamics Lab	USA	GFDL1	~300	2.98
Institut Pierre Simon Laplace	France	IPSL	~300	3.19
Centre for Climate Research	Japan	MIROC	~300	3.35
Max Plank Institute for Meteorology DKRZ	Germany	MPI	~200	3.69

4. THE LUCICAT MODEL

4.1 The Model

The LUCICAT model is a semi-distributed hydrological model. A large catchment is divided into smaller Response Units to take into account the spatial distribution of rainfall, pan evaporation and land use. Each of the Response Units is represented by 'simplified hill-slope' and a fundamental 'building-block' model is applied. Catchment attributes such as soil depth, rainfall, pan evaporation, land use change, groundwater level and salt storage are incorporated into the building-block model (Bari & Smettem 2006). The building-block model consists of: (i) Dry, Wet and Subsurface stores, (ii) a saturated Groundwater Store, and (iii) a transient Streamzone Store. The transient Streamzone Store represents the groundwater induced saturated areas along the stream zone. The fluxes between the top layer Dry and Wet Stores represent the water movement in the unsaturated zone. The dynamically varying saturated stream zone areas represent surface runoff. The Groundwater Store controls the groundwater and salt fluxes to the stream zone. Generated flow from each of the Response Units is routed downstream by the Muskingum-Cunge routing scheme (Miller & Cunge, 1975). Water and salt balances of the lakes, farm dams and reservoirs in the catchment are also computed. The model runs in the LUCICAT Live framework (Bari et al., 2009).

4.2 Model Set Up

The application of the LUCICAT model for the Serpentine catchment involved data preparation, Response Units delineation, calibration and validation. The catchments were divided into 87 Response Units, based on digital elevation models. Daily rainfall and Morton Wet Surface Potential Evaporation (Morton, 1983) series on a 5 km grid were obtained from the Bureau of Meteorology Australian Water Availability Project (http://www.csiro.au/awap/) and then calculated for each of the Response Units using the reciprocal distance weighting method. Response Unit attributes, stream node network, surface topography, land use history and Leaf Area Indices were developed using ArcGIS and the MAGIC system.

4.3 Calibration and Results

The seven key sensitive physically meaningful parameters, which may vary from one catchment to another, were copied from previous applications and then calibrated by trial and error to obtain a better match between the recorded and the simulated streamflow data. The model performance was evaluated over 1975-2007 through the LUCICAT Live framework (Bari et al., 2009) by analysing graphs and comparing other statistical criteria. The performance criteria includes: (1) joint time series plots, (2) scatter diagram, (3) flow-period Error Index, (4) Nash-Sutcliffe Efficiency, (5) Explained Variance, (6) Correlation Coefficient, (7) overall water balances, and (8) flow duration curves. Reservoir monthly inflow was computed based on rainfall, pan evaporation, water level, draw and release (Water Balance) supplied by Water Corporation (Jeevaraj, C., Pers. Comm., 2009). LUCICAT predicted inflow for the 1975-2007 period was 1% higher than that of the Water Balance method. Figure 3 illustrates the results of the calibration for the annual inflow into the reservoir and the water level.

4.3.1 Annual Streamflow

The annual simulated streamflow at all the gauging stations generally matched the observed records. The comparison of the simulated and the observed flows indicates that the model represents the flow generation very well. Average annual inflows to the reservoir calculated from the Water Balance method and LUCICAT calibration were 55 and 54.9 mm respectively. The highest mean annual runoff was generated from the Jack Rocks sub-catchment. The observed and predicted mean annual runoffs were 85.3 and 86.8 mm respectively. Predicted mean annual streamflow was within ±5% of observed records of all gauging stations. The rainfall has been declining systematically over the last 30 years in the south-west of Western Australia (IOCI, 2002). Due to a reduction in rainfall, the annual streamflow generated has also declined (Bari & Ruprecht, 2003). Given that the climatic trend is moving towards producing lower flow years, the model should perform adequately and represent the flow generation process for the period of simulation (1960 to 2007). The model predicted the low (10th percentile) and high (90th percentile) flows very well for all gauging stations and R^2 for annual streamflow ranged from 0.8 to 0.9.

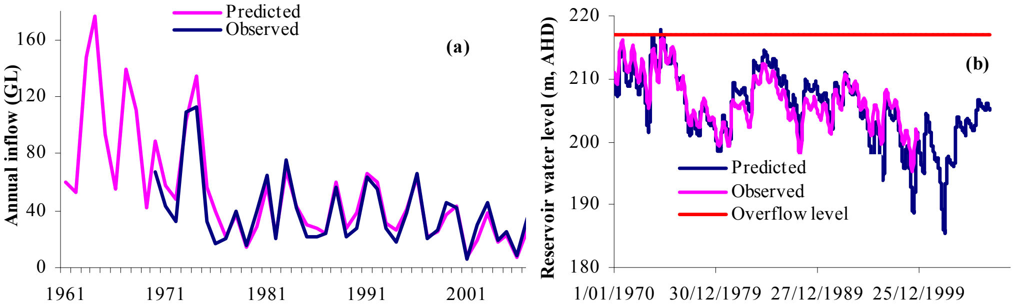

Figure 3 Reservoir (a) annual inflow and (b) water level

The model also simulated the spatial distribution of runoff – daily, monthly and annual. Generally higher runoff was associated with the greater amount of annual rainfall received within a catchment. For example in 1988, an high-flow year, annual runoff from different Response Units ranged from 9.5 mm to 368 mm.

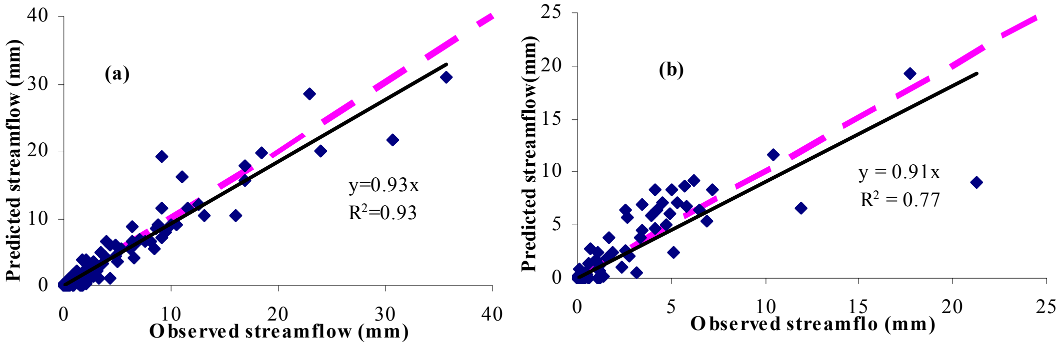

Figure 4 Monthly observed and predicted streamflow – (a) River Road and (b) Jayrup catchments

4.3.2 Monthly Streamflow

For the simulation period, the relationships between the observed and predicted monthly streamflow for most of the gauging stations were strong. The model occasionally poorly predicted some of the high-flow months and this was consistent at most of the gauging stations. Figure 4 shows the relationship between the monthly observed and the simulated streamflow for River Road and Jayrup sub-catchments. Overall the coefficient of determination (R^2) ranged from 0.75 to 0.9 for all the gauging stations within the catchment.

4.3.3 Daily Streamflow

Daily simulated and observed streamflow hydrographs matched very well for all of the gauging stations

(Figure 5). At the Big Brook catchment, the model predicted very well the duration of the flow, peaks and recessions for 1988, a high-flow year. At the Jack Rock catchment, the predicted streamflow started about a month earlier than observed for a recent very low-flow year (Figure 5b), and then ceased flow slightly earlier as well. Overall, the model predicted the flow duration, peaks and recessions very well for all gauging stations.

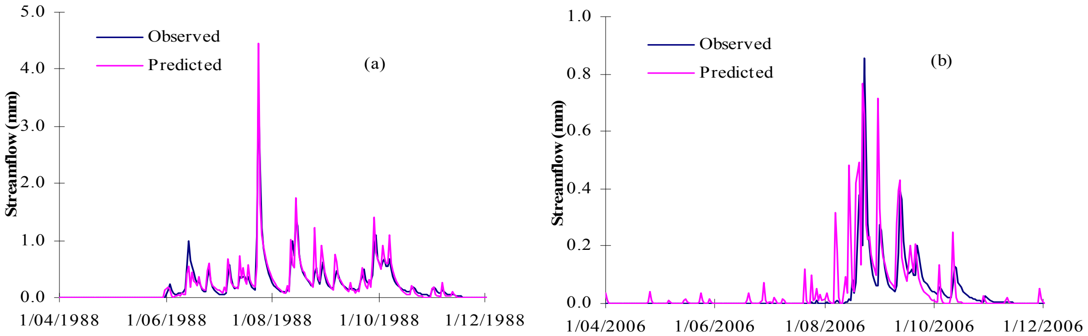

Figure 5 Observed and predicted daily streamflow (a) Big Brook and (b) Jack Rock catchments

5. PREDICTIONS UNDER CLIMATE SCENARIOS

The calibrated LUCICAT model was then run to assess the change in catchment yield that could occur following a change in climate under IPCC AR4 A2 and B1 scenarios as projected by eleven GCMs (Table 1). The Morton PE data was extended to 2100 and all climate change scenarios were introduced in 2001. The Leaf Area Indices and land use remained unchanged from 2001 onward. The daily rainfall data, as downscaled from GCMs, for the periods 1971-2000 and 2046-2065 were extended respectively to cover the gaps of 2001-2044 and 2065-2080 and a continuous rainfall series of 1961-2100 period was developed. All LUCICAT model simulations started in 1971 with calibrated initial condition.

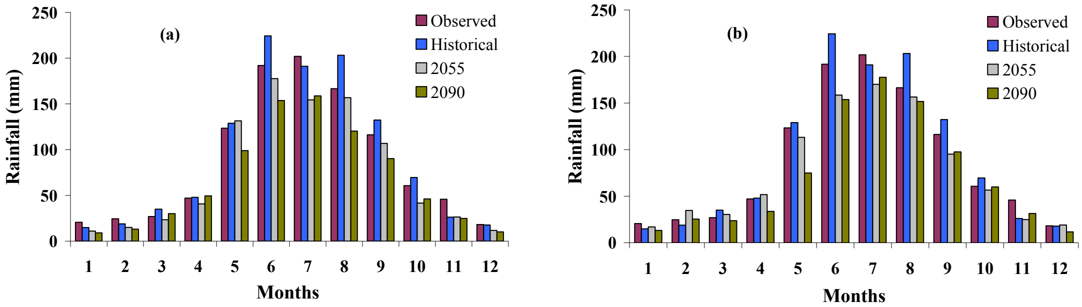

Figure 6 Canadian Climate Center Model projected within year rainfall distribution (a) A2 and (b) B1 scenarios

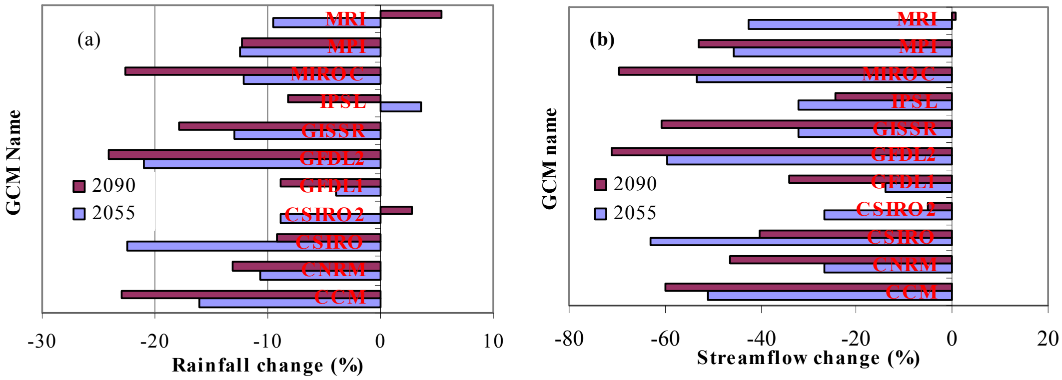

Figure 7 Changes in average annual (a) rainfall and (b) reservoir inflow under the B1 scenario

5.1 Rainfall

In the 'Historical' simulation, mean annual rainfall (1981-2000) of all 11 GCMs was 2% higher than observed and ranged between ±5%. However, there were significant variations in monthly rainfall distribution compared to observed data for the 2046-65 and 2081-2100 periods (reported as 2055 and 2090 respectively). Figure 6 shows CCM rainfall as an example but this trend was similar in all other GCMs. In the winter wet months of

June to August predicted rainfall was higher than observed during the ‘Historical’ period and was projected to decline during 2055 and 2090 climate for both A2 and B1 scenarios. Under A2 scenario mean annual rainfall reductions were projected to be 15% and 24% respectively during the 2055 and 2090 climates. Rainfall reduction under B1 scenario would be less than A2, about 12%. But there was a large variation in rainfall projections between different GCMs (Figure 7a).

5.2 Streamflow

Inflow to Serpentine reservoir and all other gauging stations were computed based on rainfall projections for A2 and B1 scenarios. During the ‘Historical’ simulation, projected mean annual inflow to the reservoir was 57 GL compared to the calibrated inflow of 38 GL. This large anomaly could be due to the within and between year distribution of rainfall (Figure 6, Figure 8) and the number of rainy days. The variations in reservoir inflows between different years were much higher than that of rainfall (Figure 8).

The response to projected climate change is evident through the reduction in flow to the reservoir for the future (Figure 8b). Compared to ‘Historical’ simulation, average annual inflow to the reservoir under A2 climate is projected to be 49% and 69% lower by mid (2055) end of the century (2090). If B2 climate prevails, the inflow reductions would be slightly lower, 45% and 46% respectively, by the mid and late 21st century. However, like rainfall, there are significant differences in projected inflow reductions between different GCMs (Figure 7b). If the present demand continues the reservoir is predicted to vary significantly due to inflow reduction under both A2 and B1 climates. The magnitude of these inflow reductions and reservoir water balance highlights serious implications for the abundance and availability of surface water resources in the south-west of Western Australia.

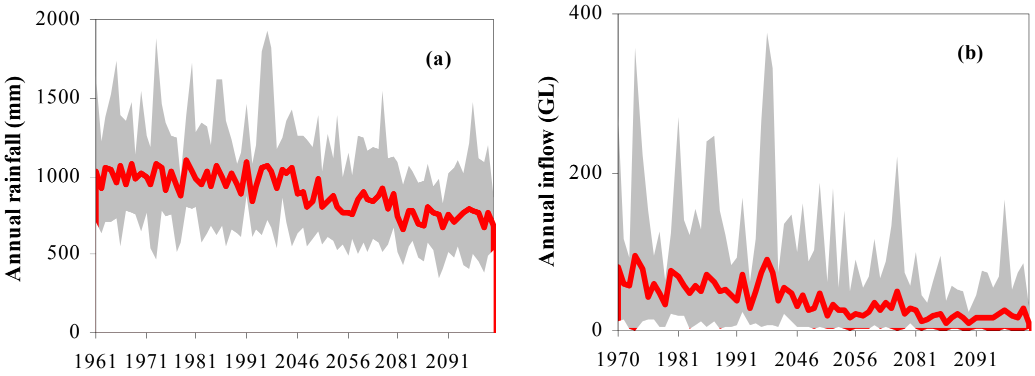

Figure 8 Projected changes in (a) rainfall and (b) inflows under scenario A2

5.3 Water Balance

The LUCICAT outputs obtained from future climate change scenarios (A2 and B1) show that each of the water balance components would decrease further. Interflow is the largest contributor to streamflow followed by baseflow and surface runoff. Interflow was projected to remain the largest contributor in the future climate. Baseflow would have the largest proportional reduction under the future climate and can be linked to a decline in conceptual groundwater levels and soil moisture across the catchment. A reduction in groundwater levels can lead to a reduction in baseflow, stream zone saturated areas and surface runoff. These findings are similar to other studies undertaken in Western Australia (Bari et al, 2005; Charles et al, 2007).

5.4 Flow Durations

Two gauging stations, Big Brook and Jack Rocks were taken as examples to show how the flow durations will change under future climate scenarios. In the ‘Historical’ simulation, only the mid-flow events were predicted to be higher than observed at the Jack Rocks (Figure 9a) while at the Big Brook predicted runoff was higher at the mid to high-flow magnitudes (Figure 9c). Both the A2 and B1 simulations show that daily runoff is predicted to decrease under future climates and indicate that streams would flow less frequently than the ‘Historical’ period. Reduction in flow-duration has implications on stream zone ecology, flora and fauna, and environmental water allocation.

6. DISCUSSION

The use of downscaled rainfall data in modelling is still an emerging science. It provides catchment-scale information about the impact of climate change on water resources (rainfall, temperature and potential evaporation) potentially suitable for hydrological modelling. Downscaling studies have often found that the predictors and the method of downscaling used to generate rainfall have a strong influence on the magnitude of the projected change. The marked shift and bias in intra-annual peaks (Figure 6) highlights this issue and needs further investigation.

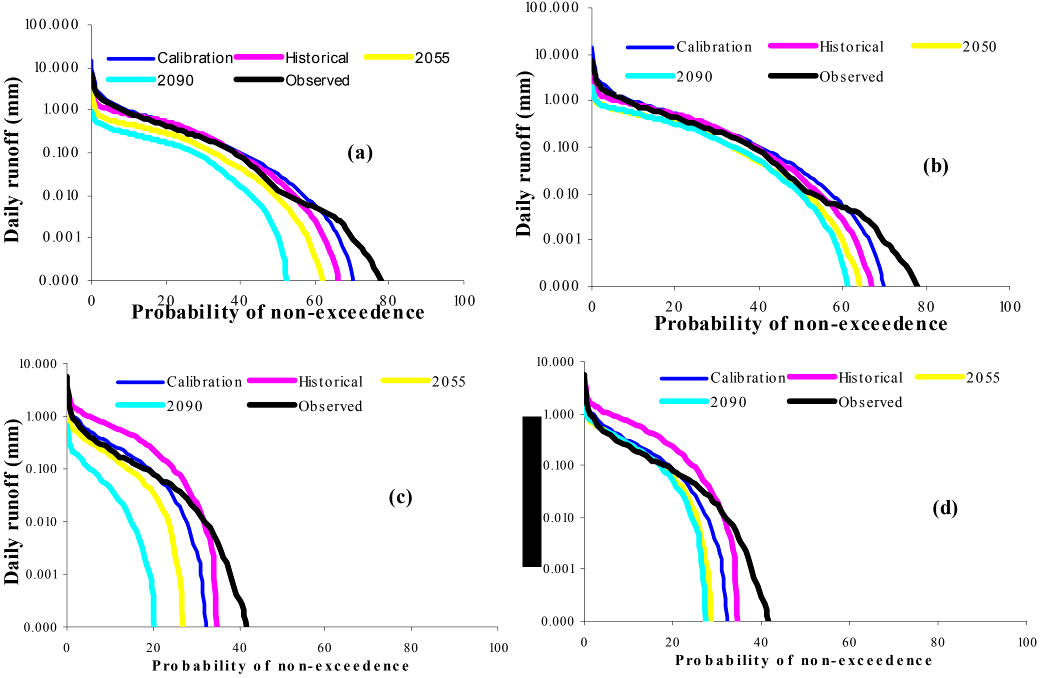

Figure 9 Flow duration curves (a) Jack Rocks A2, (b) Jack Rocks B1, (c) Big Brook A2, and (d) Big Brook B1

The LUCICAT model was run with the calibrated parameters, and driven with projected rainfall series for each of the scenarios. Model parameters related to evapotranspiration, land use and soil properties were assumed to remain unchanged until 2100. Wood et al. (1997) proposed that if the differences between the observed and the current GCM climates are modest, then transferring the calibrated parameter set for projections would be acceptable. In this study, with a distinct difference ('Historical' compared to observed) in winter rainfall (Figure 6), it may be argued that the LUCICAT calibrated parameter set may not be ideal for projecting the impacts of climate change on water resources.

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 evapotranspiration, recent studies have found that in some cases increases in temperature have been accompanied by decreases in pan evaporation (Roderick et el., 2009). 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 changes under a warmer and drier climate needs further investigation.

Decreases in inflow to Serpentine Reservoir due to projected climate change would effectively impose further limitations on the surface water supply systems in Western Australia. Options for future sources of supply will need to consider groundwater use, increased surface water yield through better forest management, demand management, water reuse and desalinisation. The projected drier climate would also cause altered flow regimes and loss in biodiversity and therefore adaptive responses would be necessary to maintain ecological communities.

7. SUMMARY AND CONCLUSIONS

Streamflow to the Serpentine Reservoir supplying Perth has decreased significantly due to reduced rainfall over the last 33 years. Average annual inflow (1981-2000) was 38 GL and ranged between 20 to 69 GL. A simple distributed conceptual water balance model, LUCICAT, was calibrated and the predicted mean annual inflow to the reservoirs was 1% greater than that of other estimates. The predicted streamflow was within ±5% of the observed data for all gauging stations within the catchment.

Eleven GCMs were selected from those which contributed to the latest IPCC assessment report. Data from emission scenarios A2 and B1 were extracted from CIMP3 and then downscaled through an Analogue Method for catchment modelling. All GCMs projected relative reductions in rainfall by mid (2055) and late (2090) 21st century compared to 1981-2000 period. There was a significant variation in projected rainfall reductions between different GCMs and emission scenarios. Under an A2 scenario mean annual rainfall reductions were projected to be 14% and 24% respectively during the 2055 and 2090 climates. Rainfall reduction under B1 scenario would be around 12% for both the time periods.

The LUCICAT model set up was then used to predict the catchment yield for all climate change scenarios. During the 'Historical' simulation, projected mean annual inflow to the reservoir was 57 GL compared to the calibrated inflow of 38 GL. This large difference is probably due to the within and between year distribution of downscaled rainfall and number of rainy days. Compared to the 'Historical' simulation, average annual inflow to the reservoir under the A2 climate is projected to be 48% and 69% lower respectively by mid (2055) and end of the century (2090) respectively. Under the B1 climate scenario, the inflow reductions would be about 45%. The magnitude of these inflow reductions and reservoir water balance highlights serious implications for the availability of surface water resources in the south-west of Western Australia.

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