HYDROLOGICAL IMPACTS OF CLIMATE CHANGE ON INFLOWS TO PERTH, AUSTRALIA

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Abstract. The effects of climate change due to increasing atmospheric CO_2 on the major tributaries to the Swan River (Perth, Western Australia) have been investigated. The climate scenarios are based on results from General Circulation Models (GCMs) and 1000 year time series are produced using a stochastic weather generator. The hydrological implications of these scenarios are then examined using a conceptual rainfall-runoff model, CMD-IHACRES, to model the response of six catchments, which combine to represent almost 90% of the total flow entering the upper Swan River, and hence the Perth city urban area. The changes in streamflow varies considerably between catchments, exhibiting a strong dependence on the physical attributes of the catchment in question. The increase in the magnitudes of rare flood events despite significant decreases in mean streamflow levels found in some catchments emphasizes the importance of estimating changes in the nature of the precipitation (variance, length of storm and interstorm periods), along with changes in the mean, in climate change scenarios.

1. Introduction

1.1. BACKGROUND

It is likely that the industrially induced increase of greenhouse gases in the atmosphere could lead to changes of the Earth's climate. One of the most important aspects of global change science is an estimation of possible impacts of these climatic changes to the world water availability. This is particularly important for any work aimed at supporting the sustainable management and long-term planning of water resources. It is especially important in Australia where the supply of water resources is a major constraint for further development of large urban areas.

Most hydrologically-focused climate change impact studies assess changes in water availability as well as extreme events, particularly floods. These studies are generally performed in order to answer questions about the future water supply to large urban or intensive agricultural areas and, hence, are focused on major water supply catchments. This study undertakes a comprehensive analysis of climate change impacts on the hydrological regime of streams entering the Perth City

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area, Western Australia. The analysis is focused on the flooding regime and its implications for the city's urban storm water system, and therefore does not look explicitly at the water supply for urban consumption.

The problem of streamflow response to climate variation is stated in Nemec and Schaake (1982). A detailed overview of climate models employed for climate impacts assessment is outside the scope of the present paper, but relevant references can be found in Houghton et al. (1990, 1992), Leavesley (1994), Pittock (1988, 1993), Tucker (1988), and Whetton et al. (1994).

Climate impacts assessment for Australian catchments have also been implemented in some previous research works. Close (1988) modeled nine rivers of the Murray-Darling Drainage Division and estimated the possible climate impact on its water resources using the Murray-Darling Basin Commission empirical model. Nathan et al. (1988) applied a deterministic, conceptual rainfall-runoff model, HYDROLOG, to study the climate impact on runoff in the Myponga Weir catchment in Southern Australia and Moogerah Dam in Queensland. Whetton et al. (1993) investigated implications of climate change on floods and droughts in Australia. Chiew et al. (1995) followed the above approach using the Modified HYDROLOG model in order to model 28 benchmark catchments in Australia and estimate the climate impact on their streamflow. Schreider et al. (1997) analyzed the climate impacts on the water availability and extreme events such as floods and droughts in four Basins of the Murray-Darling Drainage Division (Goulburn, Ovens, Kiewa and Upper Murray). Climate change impacts on urban flooding in three Australian urban catchments were analyzed in Schreider et al. (1999).

We begin this paper with a short review of various climate change impact analysis methods followed by a justification of our model selection. Section 2 provides a description of the rainfall-runoff model used, an investigation into the validity of using temperature as a surrogate for potential evaporation and a short demonstration of the climate invariance of its parameters. A description of the study site is provided in Section 3. Section 4 outlines the modeling methodology used, the results of which are presented in Section 5. A brief discussion of the implications of these results can be seen in Section 6.

1.2. METHODS OF CLIMATIC CHANGE IMPACTS ANALYSIS AND ASSUMPTIONS

Where it may be generally accepted that the increasing concentrations of greenhouse gases in the atmosphere are causing climate change, there still exists considerable uncertainty in the magnitude, timing and spatial distribution of this change. Results from climate change impact studies, such as this one, depend critically on the climate change scenarios used. Several methods for creating climate scenarios exist, which cover a considerable range of complexity, cost and time demand.

One of the simplest approaches is to use scenarios based on changes to long term seasonal mean values of climate descriptors (as determined for example by GCM runs) to transform present-day climatic time series. This approach has been used in previous studies (Feddema, 1999; Mehrotra, 1999; Schreider et al., 1997), but has several limitations. Primarily, this approach takes no account of any changes in the variability of the relevant climate descriptors.

The direct use of GCMs as the basis for creating climate scenarios has the advantage of estimating changes in climate due to increased greenhouse gases for a large number of climate variables in a physically consistent manner. These climate variables are consistent with each other within a region and around the world. A major disadvantage of using GCMs is that, although they accurately represent global climate, they are often inaccurate when simulating current regional climate. To overcome this regional inaccuracy the use of regional (limited area) climate models (Giorgi et al., 1994; McGregor and Walsh, 1993) or stochastic downscaling of relevant meteorological variables (Bates et al., 1998; Hughes, 1993; Hughes and Guttorp, 1994) has been promoted in several studies. Both of these methods share the disadvantage of being costly and time demanding. The use of regional climate models depends intimately on the GCM-supplied boundary conditions, and so may not correct for errors, while the stochastic downscaling technique assumes that synoptic scale relationships are constant over time.

Another approach, used here, utilizes a stochastic weather generator to create extended time series for various climate descriptors (Bates et al., 1993; Charles et al., 1993; Semenov and Barrow, 1997). These stochastic weather models, fitted to current climatic time series, can be adapted to the generation of synthetic series for future climate using the method presented by Wilks (1992). Adjustments to the model parameters are made in a manner consistent with the changes in monthly statistics derived from comparisons of GCM runs for control and doubled CO_2 conditions. In this study we have used the output statistics of the CSIRO9 GCM (McGregor et al., 1993) to look at a $2 \times CO_2$ future climate scenario. When compared with other GCM results, this model is among the models predicting the most severe changes, hence we have also included a scenario that embodies about half of the $2 \times CO_2$ predicted change which we will refer to as $1.5 \times CO_2$. These scenarios are consistent with the broad range of global warming projections based on increased atmospheric concentrations of greenhouse gases. They are physically plausible and estimate daily precipitation and mean temperature, which are then used to drive the hydrological model. By using a 1000 year long daily time series it is expected that the potential range of climate variability under each of the CO_2 scenarios, would be captured.

Other implicit assumptions involve the role of vegetation in the climate system. Here we have assumed that the overall vegetation response for a given precipitation and temperature input will remain similar over the next century while greenhouse gas concentrations increase. However, the vegetation cover and/or its evapotranspiration response may change with future changes in climatic patterns of temperature, precipitation, solar radiation, as well as fertilization and stomatal resistance effects related to increases in carbon dioxide. It is worth noting that most

GCMs currently use a static model of the land surface where surface characteristics such as roughness length, albedo, soil and vegetation parameters are specified at the start of a run and do not change regardless of any prolonged change in the predicted climate.

Several studies have investigated the impact of climate on vegetation structure (Busby, 1988; Monserud et al., 1993). They imply some movement of vegetation types, in particular the shrinking of boreal zones and the increasing elevation of the tree line in alpine regions. Since our study area doesn't contain any boreal type vegetation, and the period over which the above increases in CO_2 are expected to occur (about 70 years) is too short for forests to grow over considerable areas, we would not expect any significant natural migration of vegetation types. Of course, vegetation structure in a region can change quite rapidly and radically due to direct human intervention. Here we have assumed that any change in land management practices will be minor enough to have no significant impact.

Studies have investigated the biological response of some plants to increased CO_2 in the atmosphere, an introductory overview of which can be found in Kristiansen (1993). While this response varies between species a few general points can be made. There are changes in stomatal conductance associated with higher CO_2 levels, which lead to reduced water exchange per unit leaf area. The higher levels of CO_2 also lead to enhanced leaf growth. These two effects can, depending on species, offset each other in terms of total evapotranspiration response (Lins et al., 1997). Until further knowledge becomes available it seems reasonable to assume that the net effect of these changes on a vegetation stand, which contains many species, will be within the measurement and model error. Thus the assumption that the overall vegetation response will remain similar to that over recent history for the time covered by this study seems quite plausible.

1.3. MODEL SELECTION

The stochastic weather generator used in this study is based on the WGEN generator described by Richardson and Wright (1984). Its modified form and adaption to the generation of synthetic climatic series can be found in Bates et al. (1994). WGEN simulates daily precipitation occurrence and amount, maximum and minimum temperature, and solar radiation. Precipitation occurrence is described by a two state (wet or dry), first-order Markov chain wherein the transition probabilities for a given location are allowed to vary through an annual cycle. Precipitation amounts on wet days (rainfall greater than 0.3 mm) have their variation characterized using a gamma distribution. Standardized temperature and solar radiation components are represented as a first-order, trivariate autoregressive process conditioned upon whether the day is wet or dry. WGEN produces stochastic realizations of the variables above maintaining the statistical relationships established from observation.

Wheater et al. (1993) described three types of rainfall-runoff models which could be used for predicting the stream discharge effects of climatic variations: metric, physically-based and conceptual. Metric models are based primarily on observations and seek to characterise system response from these data. Physically-based models use a more classical mathematical-physics formulation of component processes, based on continuum mechanics, and numerical solution techniques to solve the relevant equations. Conceptual type models vary considerably in complexity but are always based on a representation of internal storages and the fluxes between them which are associated with particular hydrological components and processes.

Metric models contain too little process description to be used to make predictions on independent periods not used for model calibration, hence have little applicability for simulating future climate impacts. Physically based models require large computation and data resources. They also have the disadvantage of containing large numbers of parameters, which introduces serious ambiguity in the identification of the parameter values. The catchments chosen for consideration here have been instrumented for a relatively long period, meaning that streamflow, precipitation and temperature data are available for decades in the majority of gauging sites in these regions. Thus, conceptual lumped rainfall-runoff models seem to be the most suitable type of model for the streamflow analysis required in the region selected and for the particular purposes of this study. The model CMD-IHACRES falls within this class of models. The number of parameters (five or seven) to be fitted is small compared with other conceptual models, yet its performance has been impressive across a range of hydroclimatologies.

In the present study the CMD-IHACRES rainfall-runoff model (Evans and Jakeman, 1998), which is based on the IHACRES model (Jakeman and Hornberger, 1993; Jakeman et al., 1990), was employed for predicting the future climate impacts on streamflow. It is a hybrid metric-conceptual model based on the Instantaneous Unit Hydrograph (IUH) technique. The method represents total streamflow response as a linear convolution of the IUH with rainfall excess or effective rainfall, which is in turn a non-linear function of measured rainfall and temperature. The evaporative losses from the catchment are dealt with through a Catchment Moisture Deficit (CMD) accounting scheme.

One advantage of the CMD-IHACRES model is that its parameters reflect the average, lumped properties of the catchment considered. This provides the ability to predict spatially averaged streamflow response. Therefore, the CMD-IHACRES application is suitable even in circumstances which lack spatially distributed catchment input. Being structurally simpler than physically-based models, the conceptual models can easily utilize records of hydrological data for calibration.

Perhaps the most significant argument for the use of conceptual hydrological model CMD-IHACRES in the present work is that the model parameters reflect the geomorphological and vegetation characteristics of the catchment considered and are little affected by regional climate conditions (Jakeman et al., 1993; Post and

Jakeman, 1996). A demonstration of this parameter climate invariance is given in Section 2.1. CMD-IHACRES parameter values can therefore be established under present climatic conditions and then used without reference to the observed streamflow data. This type of model can be used for streamflow prediction for estimated future climatic conditions, assuming that the catchment properties considered (landscape, vegetation, building and road structure for the urban catchments) will not change considerably.

2. Rainfall-Runoff Model Description

The CMD-IHACRES module structure consists of a non-linear loss module, which converts observed rainfall to effective rainfall or rainfall excess, and a linear streamflow routing module, which extends the concept from unit hydrograph theory that the relationship between rainfall excess and total streamflow (not just quick flow) is conservative and linear.

The linear module allows any configuration of stores in parallel or series. From the application of CMD-IHACRES to many catchments it has been found that the best configuration is generally two stores in parallel, except in semi-arid regions or for ephemeral streams, where often one store is sufficient (Ye et al., 1997). In the two-store configuration, at time step k, quickflow, $x_k^{(q)}$, and slowflow, $x_k^{(s)}$, combine additively to yield streamflow (discharge), q_k:

$$q_k = x_k^{(q)} + x_k^{(s)} \tag{1}$$

with

$$x_k^{(q)} = -\alpha_q x_{k-1}^{(q)} + \beta_q U_k \tag{2}$$

$$x_k^{(s)} = -\alpha_s x_{k-1}^{(s)} + \beta_s U_k \, , \tag{3}$$

where U_k is the effective rainfall. The parameters α_q and α_s can be expressed as time constants for the quick and slow flow stores, respectively:

$$\tau_q = -\Delta / \ln(-\alpha_q) \tag{4}$$

$$\tau_s = -\Delta / \ln(-\alpha_s) \, , \tag{5}$$

where Δ is the time step (daily here).

Parameters expressing the relative volumes of quick and slow flow can also be calculated:

$$V_q = 1 - V_s = \frac{\beta_q}{1 + \alpha_q} = 1 - \frac{\beta_s}{1 + \alpha_s} \, . \tag{6}$$

In catchments which are modeled with only one store only Equations (2) and (4) are relevant.

The CMD-IHACRES loss module accounts for antecedent soil moisture conditions and evapotranspiration (ET) losses. This module is a water balance-based catchment moisture store accounting scheme that uses rainfall and temperature as inputs and provides ET and rainfall excess as outputs. The catchment moisture store accounting scheme calculates Catchment Moisture Deficit at time step k, CMD_k, according to

$$CMD_k = CMD_{k-1} - P_k + E_k + D_k \, , \tag{7}$$

where P is the precipitation, E is the ET loss and D is the drainage. CMD is zero when the catchment is saturated and increases as the catchment becomes progressively drier. Equation (7) is simply the lumped water balance continuity equation for a catchment.

Effective rainfall is calculated from

$$U = \begin{cases} D_k & CMD_k \geq 0 \\ D_k - CMD_k & CMD_k < 0 \end{cases} \tag{8}$$

ET and Drainage are calculated using the equations below

$$D_k = \begin{cases} \dfrac{-c_2}{c_1} CMD_k + c_2 & CMD_k < c_1 \\ 0 & CMD_k \geq c_1 \end{cases} \tag{9}$$

$$E_k = c_3 T_k \exp(-c_4 CMD_k) \, , \tag{10}$$

where c_1, c_2, c_3 and c_4 are non-negative constants, and T is the air temperature. In (10) temperature is assumed to be a proportional surrogate to potential evaporation (PE) which is attenuated according to the antecedent soil moisture conditions in terms of the CMD. It has been assumed in (9) that drainage is dependent only on the soil moisture conditions. The presence of the drainage equation allows water to escape to stream even when a moisture deficit exists within the catchment.

To measure the performance of the model estimate of streamflow, $\hat{q}_i$, two performance statistics are used: the bias (B) and the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970). These are defined as

$$B = \frac{1}{n} \sum_{i=1}^{n} (q_i - \hat{q}_i) \tag{11}$$

$$NSE = 1 - \alpha_e^2 / \alpha_q^2 \, , \tag{12}$$

where α_e^2 and α_q^2 are the variance of the model residuals $(q_i - \hat{q}_i)$ and of the observed streamflow respectively. Good model fit is indicated by a bias close to zero and NSE close to one.

2.1. TEMPERATURE AS A SURROGATE FOR PE

PE is the evaporation rate that would be achieved if the catchment surface was wet (i.e., the catchment is saturated). In the current model terminology this occurs when the CMD is zero, a condition which is met rarely in the current study area. When looking at the future hydrological impacts it is the evaporative losses which need to be modeled, in this study they are modeled as being proportional to temperature. There are several reasons for this use of this assumption.

Since precipitation and temperature are the two most commonly available meteorological variables, limiting the methods data requirements allows it to be used in relatively data sparse areas. Climate model based future scenarios generally do not include estimated changes in PE and the stochastic weather generator used naturally produces temperature as an output, not PE. This use of temperature in (10) allows the direct application of the output of the stochastic weather generator without the added complication involved in preparing scenarios for potential evaporation change which is itself fraught with uncertainty.

There currently exist a multitude of methods for calculating PE, and these methods have the potential to produce different results. While it is not clear which methods are better than others, there are several which display a proportionality with temperature. Empirically derived methods such as the Blaney-Criddle Formula and the Hargreaves method (Jensen, 1990) for example. One of the most widely accepted formulations of PE was first proposed by Penman (1948).

$$E = \frac{\Delta}{\Delta + \gamma} Q_{ne} + \frac{\gamma}{\Delta + \gamma} E_A \,, \tag{13}$$

where Q_{ne} is the available energy flux density divided by the latent heat of vaporization (L_e), $\Delta = (de^*/dT)$ is the slope of the saturation water vapor pressure curve $e^* = e^*(T)$ and is given by (7), γ is the psychrometric constant (which actually varies with temperature and pressure) is given by

$$\gamma = \frac{c_p p}{0.622 L_e} \,,$$

where c_p is the specific heat capacity for constant pressure and p is the pressure.

Also E_A, a drying power of the air, is defined by

$$E_A = f(\bar{u})(e_a^* - \bar{e}_a) \,,$$

where $\bar{e}_a$ is the mean vapor pressure in the air, T_a is the air temperature, $e_a^* = e^*(T_a)$ the corresponding saturation vapor pressure and $\bar{u}$ is the mean wind speed.

From a practical point of view, (13) requires measurements of vapor pressure deficit, wind speed, temperature, atmospheric pressure and the net incident radiation. Clearly the data required to use this formulation to produce a future climate change scenario for PE are simply unavailable. To facilitate the use of this equation outside experimental areas, Linacre (1992, p. 105) used several substitutions and simplifications to rewrite (13) as

$$PE = \left[0.015 + 4 \times 10^{-4}T + 10^{-6}z\right]\left[\frac{480(T + 0.006z)}{84 - A} - 40 + 2.3\bar{u}(T - T_d)\right], \quad (14)$$

where z and A are the elevation and latitude of the location of interest, and T_d is the dewpoint temperature. Taking our area of interest to be at sea level and at 34° latitude, (14) becomes

$$PE = [0.015 + 4 \times 10^{-4}T][9.6T - 40 + 2.3\bar{u}(T - T_d)]\,. \quad (15)$$

For temperatures around 20 °C and low wind speeds the term involving mean wind speed in (15) would be negligibly small compared to $9.6T$ and hence it can be ignored collapsing (15) further to

$$PE = [0.015 + 4 \times 10^{-4}T][9.6T - 40]\,. \quad (16)$$

The climate change scenarios used in this study differ by approximately 5 °C, taking typical values for T in two of the scenarios, say $T = 20$ °C and $T = 25$ °C, the first bracketed term in (16) gives values of 0.023 and 0.025 respectively. That is, over the estimated climatic change this term is essentially a constant and to first order we see that

$$PE \propto T\,.$$

Hence using a proportionality to temperature can provide a reasonable, first order, approximation for PE. It has been shown that using this surrogacy to estimate PE on time scales of a few days provides results at least as good as using more complicated forms of potential evaporation such as that given by Priestley and Taylor (1972) or Penman (1956) (Evans et al., 1999).

2.2. CLIMATE INVARIANCE OF RAINFALL-RUNOFF MODEL PARAMETERS

The Jamieson River (stream gauging station 405218), in the Goulburn River Basin, was selected as an example of a catchment with no significant land use changes. The catchment is dominated by state protected forest, where logging is negligibly small because this area is mostly covered by unproductive mixed tree species (DNRE, 1998). The mean annual rainfall in lower part of the catchment at the Jamieson Post Office is 1250 mm. However, the climatology of this catchment is characterized by a considerable difference in precipitation levels between its drier lower part, and headwaters located in an alpine region with 1500–1800 mm of annual precipitation.

Table I shows the calibration results for the Jamieson River catchment for years 1972, 1978 and 1985. These calibration results were obtained using precipitation

Table I
Calibration results for the Jamieson River catchment

Model number	Starting date	c_1	c_2	c_3	c_4	Model efficiency (NSE)	Model bias (m^3/s)	Mean precip. (mm)	Mean temp. (°C)
1	1 January 1972	35	3	0.28	0.01	0.856	0.57	920	13.4
2	1 January 1978	35	3	0.28	0.01	0.906	0.30	1330	13.6
3	1 January 1985	35	4	0.28	0.01	0.829	–0.28	1190	13.3

data recorded for the meteorological station at Jamieson PO (83017) and temperature from the Lake Eildon meteorological station (88023). Fits to the observed streamflow are shown in Figure 1.

An important justification that the Jamieson River catchment has not been subject to considerable land use change over the period of study is that simulation runs over the whole period of observation (∼20 years) provide a similarly high Nash-Sutcliffe efficiency: 0.753, 0.791 and 0.744 for these three models respectively. This test fails for areas with extensive land use change, where the model parameters can be expected to vary dramatically because of changes in the physical characteristics of the catchment considered. Another important result of streamflow modelling in this catchment is that the parameters of the non-linear module are very similar from one calibration period to another despite the difference in the climatic condition during these periods (Table I).

These climatic conditions are quite different for the periods of 1972, 1978 and 1985 with annual precipitation varying by ±20%. While this change in precipitation covers the potential range due to climate change the demonstrated range of annual temperature falls well short of what could be expected under enhanced greenhouse gas conditions. Unfortunately the large change in mean annual temperatures expected due to climate change fall well outside that present in historical records thus precluding a comprehensive test. However, under the limitations of the historical record, the modelling exercise in the Jamieson catchment demonstrates that the CMD-IHACRES model parameters have little climatic dependence, and hence justifies the applicability of this model for streamflow assessment under future climatic change impacts.

3. Site Description

A schematic of the study area, along with catchment boundaries and gauging sites, is given in Figure 2. All the catchments studied drain into the Swan River, which subsequently flows through the city of Perth itself. The area is dominated by winter

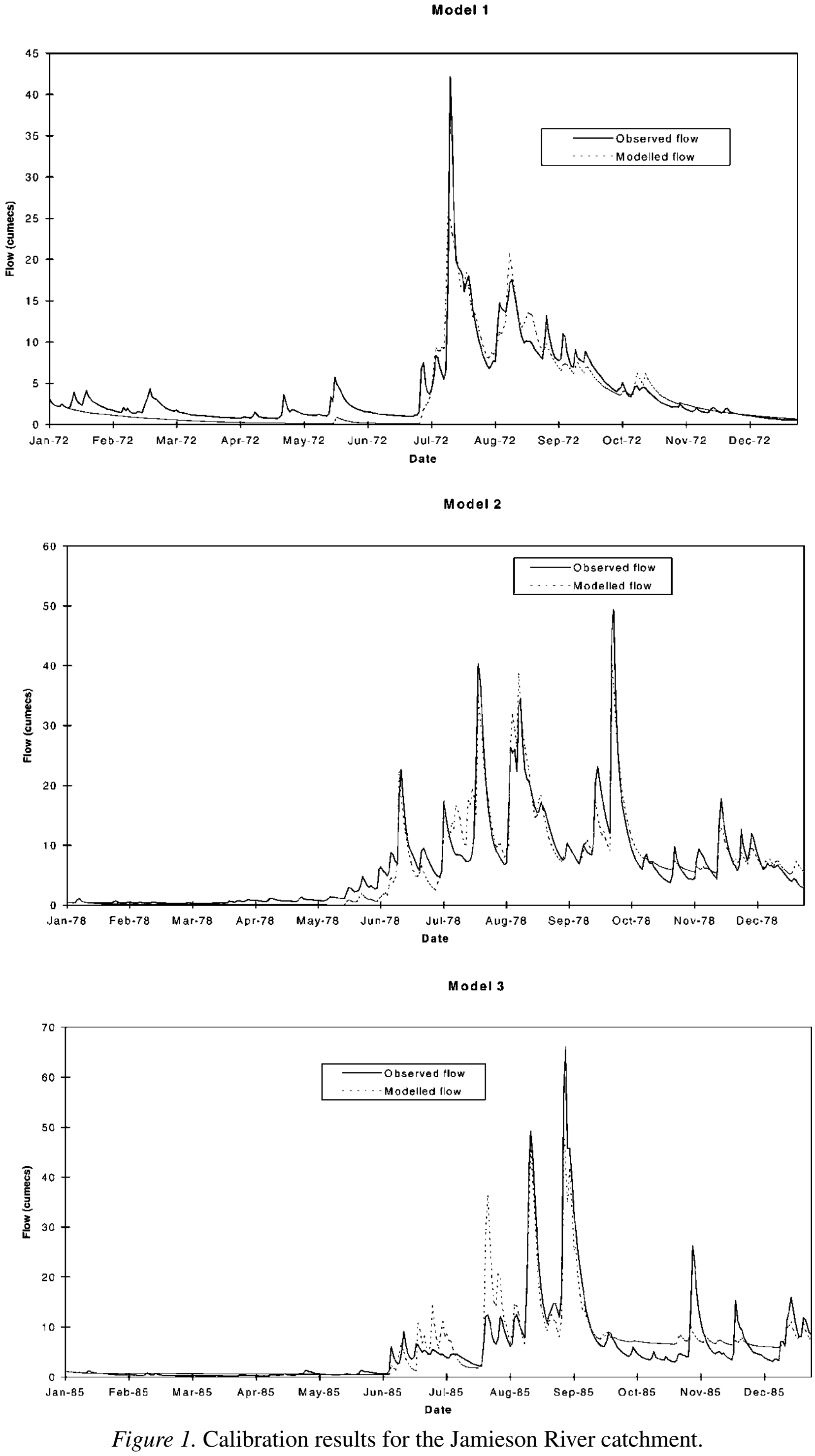


Figure 1. Calibration results for the Jamieson River catchment.

rainfall, and the streams are ephemeral in nature. Some Descriptors of the studied catchments are given in Table II. Clearly the Avon River catchment covers an extremely large area and extends much further from the coast than the other catchments. The majority of the inland parts of this catchment do not contribute flow to the Avon River itself except during large flow events. During 'normal' conditions a series of inland lakes store the streamflow from the eastern part of the catchment.

4. Modeling

Using streamflow data provided for each of the streamflow gauges shown in Table II, and rainfall data from Belmont, CMD-IHACRES was calibrated and the results are shown in Table III. Rainfall from just one station was used since it was the station for which the stochastic weather generator was run, producing 1000 years of climate data under $1 \times CO_2$, $1.5 \times CO_2$ and $2 \times CO_2$ conditions. The methodology used to stochastically generate synthetic series for future climates is described in Bates (1993,; 1994) and Charles (1993). The altered climate scenarios were derived from the CSIRO9 Mark 1 GCM runs (circa 1992) which used a slab ocean configuration. The changes in mean temperature and precipitation given by this scenario are increases of just under 5 °C and just over 10% respectively.

More recent scenarios constructed using coupled GCMs suggest that the slab model above has overestimated the potential climate change. For this reason, we have included a '$1.5 \times CO_2$' scenario. This scenario was derived by interpolating the stochastic weather generator parameters to produce around half the climate change estimated by the slab model.

Rainfall records from one rainfall station are unlikely to capture the actual rainfall over a catchment, especially if the rainfall station lies outside the catchment boundary and/or the catchment is large. This reliance on a single rainfall station would be expected to cause significant problems in reproducing the current streamflow regime using a rainfall-runoff model. This problem is not as severe as it may seem for two reasons: first, the model appears to be robust enough to perform well even with just one rainfall station (see Table III); and secondly, we are concerned with the changes that occur rather than the accuracy with which we can reproduce current streamflows. We analyze changes in the average recurrence intervals (ARI) of flood events up to an ARI of 1000 years by using the simulations from the stochastic weather generator.

The Avon River presents a particular challenge since it is extremely large in areal extent. It extends well beyond the coastal region for which rainfall data has been provided, and it contains several lakes within the catchment boundaries. It does however, represent a significant proportion of the total volume of streamflow reaching the Swan River and hence is important for any urban flooding study of Perth. The Helena River presents a unique challenge in terms of streamflow pre-

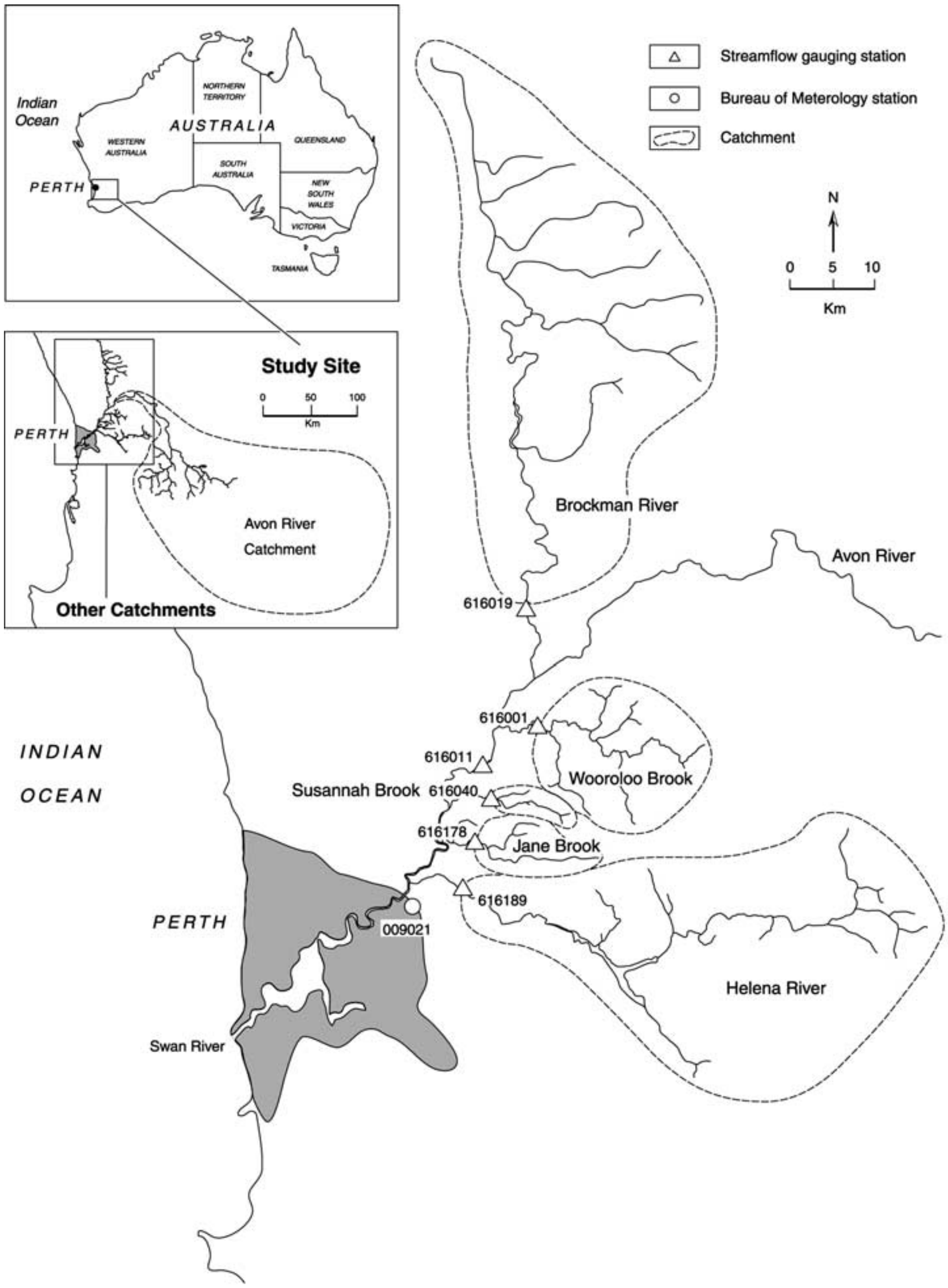


Figure 2. Schematic of study area.

Table II
Description of catchments used in this study

Catchment	Description	Area (km^2)	Land uses	Streamflow data
Avon River	Terminated at Beverly as not much streamflow above that point (1). Drains the wheatbelt area and then cuts through the escarpment	Including above Northam 120,000 km^2	Going up the Avon there is 30–40 km of forest, then it emerges onto the wheat belt. Low intensity grazing and cropping (1)	616011
Brockman River	No significant water extractions. North-East of the study area. OUTFLOWS to this river (which then joins the Avon outside the study area)	1512 km^2 (1)	Some forest, then sheep grazing (1).	616019
Wooroolo Brook	No significant water extractions	525 km^2 (1)	Pasture, forest, mixed farming (1)	616001
Susannah Brook	No significant water extractions	25 km^2 (1)	Pasture, forest, not much cropping (1)	616040
Jane Brook	No significant water extractions	73 km^2 (1)	Urban, pasture, not much cropping	616178
Helena River	Forms lower boundary of study area. Heavily regulated by Mundaring Weir	1600 km^2 (1)	Urban, forest, pasture below Mundaring Weir; mostly forest above the weir	616189

Table III
Calibration results

Catchment	Period	NSE	B cumecs/d	Linear module structure	Model parameters						
					c_1	c_2	c_3	c_4	τ_q	τ_s	V_s
Avon River	1/1/76–31/12/79	0.71	1.90	1 store	10	1	0.63	0.12	7.6		
Brockman River	1/1/84–31/12/87	0.74	0.00	1 store	18	1	0.68	0.10	24.1		
Wooroolo Brook	1/1/79–31/12/82	0.74	0.00	2 stores in parallel	13	7	0.46	0.03	1.3	35.9	0.77
Susannah Brook	1/1/82–31/12/85	0.78	–0.01	2 stores in parallel	13	8	0.36	0.04	1.0	34.6	0.72
Jane Brook	1/1/80–31/12/83	0.78	–0.02	2 stores in parallel	23	13	0.32	0.02	1.2	39.3	0.70
Helena River	1/1/78–31/12/81	0.67	0.07	1 store	25	1	0.37	0.07	1.6		

diction since it is heavily regulated by Mundaring Weir. The weir is a moderately large water supply reservoir that infrequently overflows.

Streamflow entering the Perth urban area from the studied catchments represents some 90% of the total flow of the Swan River. As such, this is a fairly comprehensive study of the likely impacts on the urban flooding regime for Perth.

4.1. RAINFALL-RUNOFF MODEL CALIBRATIONS

Each of the six catchments was calibrated over a four year period of the historical record. The calibration results can be seen in Table III and Figure 3. The Avon River, Brockman River and Helena River were all modeled with a one store linear module structure, while the rest used two stores in parallel. The one store structure reflects the lack of an identifiable base flow component in the data, and reduces the number of model parameters from seven to five.

Figure 3 shows the modeled streamflow and the observed streamflow for each of the six catchments calibration periods. In general, the modeled flow agrees quite well with the observed, even with the problems associated with the use of a single rainfall station. Note that in Figure 3a the modeled flow is generally underestimated when compared with the observed flow. This is quantified in Table III where the Avon River has significant bias. This bias of 1.90 cumecs per day, while large compared to the other catchments modeled, is still only a small fraction of the total flow from the Avon River. Figure 3 shows the Avon River producing around ten times as much streamflow as the other catchments.

Helena River is strongly regulated by Mundaring Weir, since the model fails to capture most of the small releases from the weir. It does get the timing of the large releases correct though their magnitude may be understated. This error is not of paramount importance since the bulk of the study is focused on the comparative performance under different CO_2 conditions rather than absolute values.

Results of the validation of the model on independent periods for each catchment are presented in Table IV. The performance of the models in terms of the NSE is not as good as during the calibration period, particularly for the Avon River catchment. Much of this decrease in performance can be explained by the changing land uses occurring in the catchments (the model assumes static land use) as well as the use of only one rainfall station as discussed previously, which is particularly important for the Avon River catchment. Clearly the model performance suggests that a reasonably high level of uncertainty is associated with the streamflow predictions and as such caution must be taken when interpreting the results in any operational sense.

Figure 4 shows how evapotranspiration changes with CMD given a unit temperature for each of the six catchments. The differences between these relationships can be explained principally in terms of vegetation and its distribution within the catchment, as well as catchment size. Two of the largest catchments, the Avon and Brockman Rivers, produce very little ET once the CMD has reached 50–60 mm

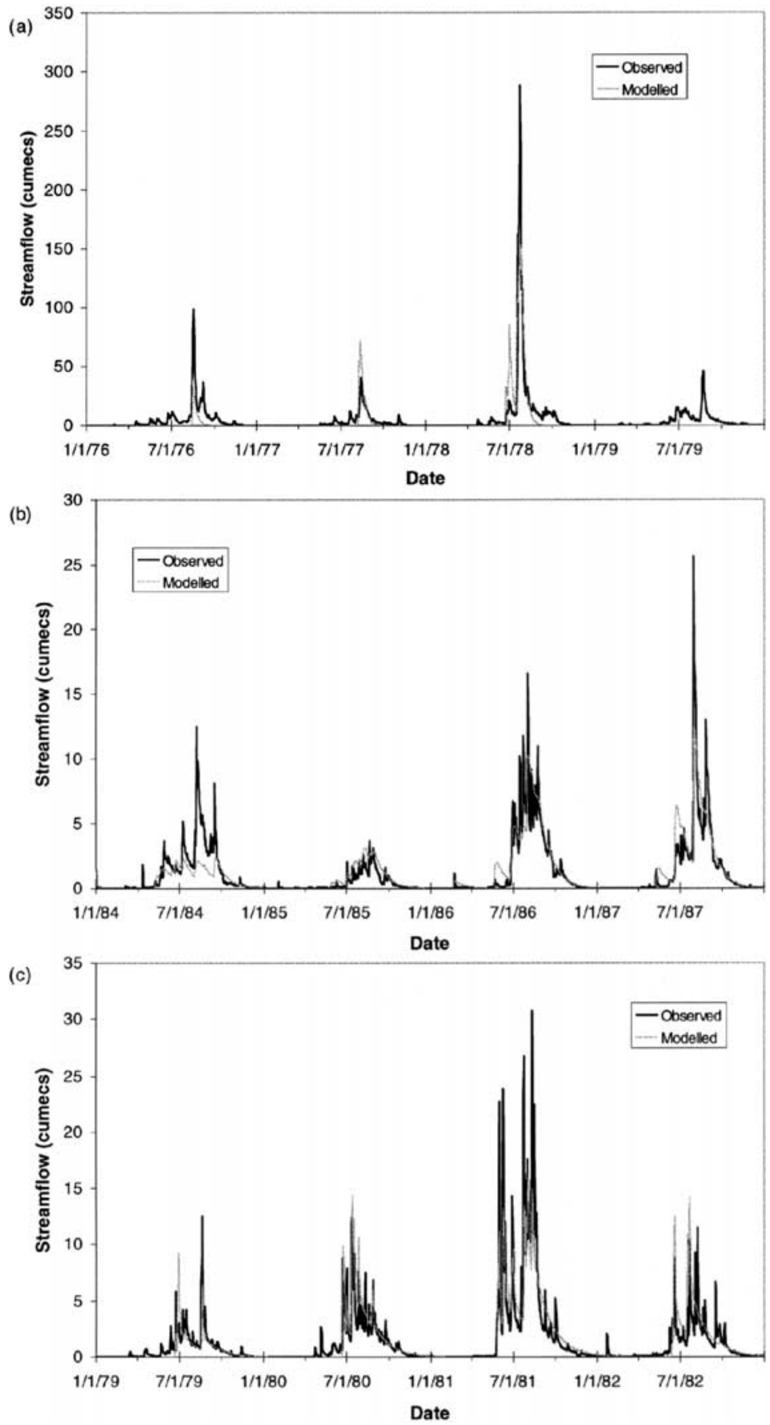

(a)
Observed
Modelled
Streamflow (cumecs)
Date
1/1/76
7/1/76
1/1/77
7/1/77
1/1/78
7/1/78
1/1/79
7/1/79
(b)
Observed
Modelled
Streamflow (cumecs)
Date
1/1/84
7/1/84
1/1/85
7/1/85
1/1/86
7/1/86
1/1/87
7/1/87
(c)
Observed
Modelled
Streamflow (cumecs)
Date
1/1/79
7/1/79
1/1/80
7/1/80
1/1/81
7/1/81
1/1/82
7/1/82

Figure 3a.

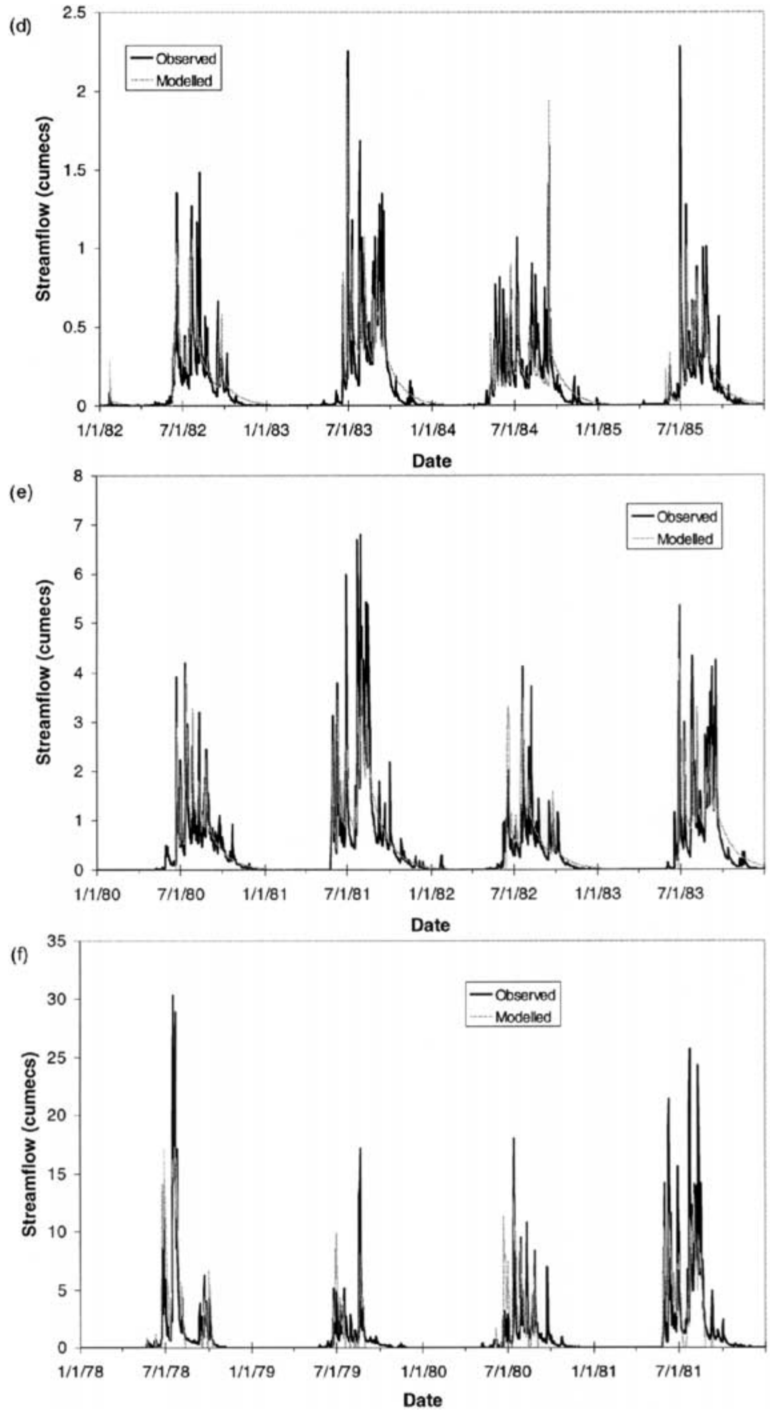


Figure 3b.

Figure 3. Observed and modeled streamflow for the calibration period for the: (a) Avon River; (b) Brockman River; (c) Wooroolo Brook; (d) Susannah Brook; (e) Jane Brook; and (f) Helena River.

Table IV
Validation results

Catchment	Period	NSE	Bias cumecs/d
Avon River	1/1/80–31/12/83	0.44	–0.22
Brockman River	1/1/77–31/12/80	0.61	–0.11
Wooroolo Brook	1/1/83–31/12/84	0.58	0.32
Susannah Brook	1/1/88–31/12/91	0.64	–0.01
Jane Brook	1/1/84–31/12/85	0.64	–0.06
Helena River	1/1/83–31/12/86	0.52	0.16

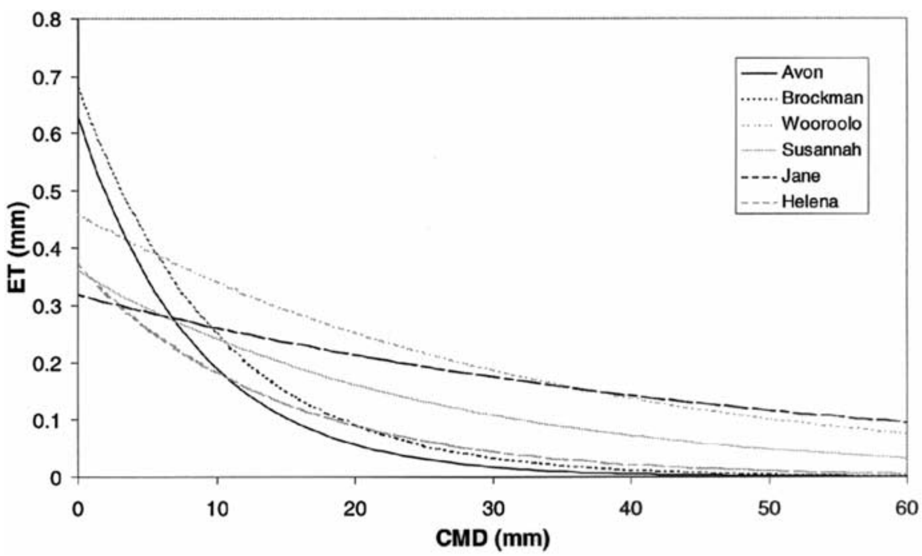


Figure 4. Variation in ET with Catchment Moisture Deficit given a unit temperature input.

while for low CMD they display a high gradient and high saturation ET. This is fairly typical of catchments dominated by farming with forest remaining along the highest parts of the catchment. It has been well established that forests transpire at a significantly greater rate than grasslands (Holmes and Sinclair, 1986). In Figure 4, the forest dominates the ET at first but since the forest only exists in the catchment highlands it is the first area to dry out, subsequently the lowland grassed areas begin to be the dominant ET source and a sharp fall occurs in the total ET.

The three smaller catchments display a similar but less pronounced change in ET. This is to be expected in these smaller catchments, since the horizontal gradient in soil moisture would be considerably less than in the large catchments, making the transition from forest dominated ET to grassland dominated ET less severe. The

ET for Jane Brook displays the smallest gradient for low catchment moisture; this is due to the relatively uniform land cover in the catchment as shown in Table II. In particular there is no forest present and hence no transition from forest dominated to grass dominated ET. In fact the ET displays an almost linear fall with increasing CMD.

As it was stated above, the Helena River streamflow is strongly affected by the presence of Mundaring Weir. Despite being a large catchment with forest dominated uplands and crop dominated lowlands the catchment displays a much smaller gradient difference between high and low CMD than is seen in the Avon or Brockman. This can be largely attributed to the presence of the reservoir above the weir which evaporates water at a fairly consistent rate regardless of the CMD.

5. Results

The models given in Table III were then used, in conjunction with the supplied 1000 year precipitation and temperature records, to produce 1000 years of streamflow data under $1 \times CO_2$, $1.5 \times CO_2$ and $2 \times CO_2$ conditions.

Figures 5 and 6 display properties of the temperature and precipitation time series under different CO_2 conditions. Clearly seen in Figure 5 is a fairly uniform increase in temperature with increasing CO_2. In isolation, this increase in temperature would be expected to lead to an increase in evaporation, and hence a decrease in streamflow. Figure 6a shows a slight increase in precipitation with increasing CO_2 across the broad range of precipitation occurrence. Figure 6b shows significant increases in the precipitation of the few largest events, i.e., events with very large ARIs. In isolation, this change in precipitation would be expected to have little effect on the streamflow except for the few largest events when significant increases in streamflow could be expected.

Figure 7 shows flow duration curves for each catchment under the three CO_2 scenarios. In general, the potential impacts outlined above have occurred, with flow decreasing as CO_2 increases. The $1.5 \times CO_2$ scenario streamflow is consistently lower then present streamflow conditions, while the $2 \times CO_2$ scenario streamflow commonly produces even less streamflow. Deviations from this general outcome occur in Wooroolo Brook where Figure 7c shows an increase in some of the lowest flows with increasing CO_2.

In Figure 8 are shown ARI curves for all six catchments starting with events possessing an ARI of five years. For these most common events (i.e., smallest ARI) the trend seen in Figure 7 is borne out with the $1.5 \times CO_2$ scenario producing smaller flood events than under present day conditions while the $2 \times CO_2$ scenario floods are smaller again. The high ARI events demonstrate significantly more variation among the catchments. The magnitude of the rarest flood events under $1.5 \times CO_2$ conditions is generally below those under $2 \times CO_2$ conditions and almost always lower than present day conditions. For the Avon, Brockman and

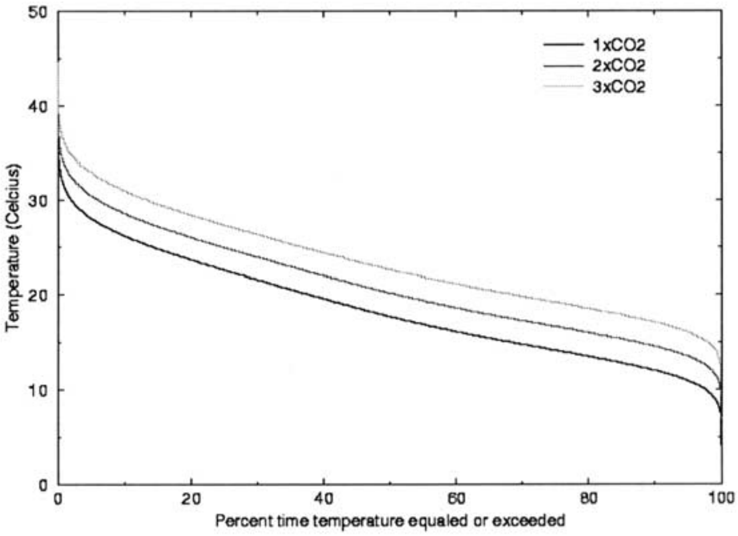


Figure 5. Temperature duration curves for $1 \times CO_2$, $1.5 \times CO_2$ and $2 \times CO_2$ conditions.

Helena Rivers, flood events under $2 \times CO_2$ are always smaller than those under present day conditions. Wooroolo Brook and Jane Brook have only the rarest flood events under $2 \times CO_2$ conditions being greater than those under current conditions, while Susannah Brook has larger flood events under $2 \times CO_2$ conditions for ARIs greater than 113 years. Figure 9 presents the ARI curves for the total flow entering the Swan River from these tributaries.

6. Discussion and Conclusions

Under the $1.5 \times CO_2$ and $2 \times CO_2$ scenarios, the mean streamflow entering the Swan River from these tributaries decreases by approximately 12% and 24% respectively. This outcome may be typical of relatively dry areas where current catchment moisture is rarely high enough to allow evaporation at the potential rate. Under globally warmed conditions any increase in precipitation will allow evaporation to reach this potential rate more often. It should also be noted that an increase in potential evaporation is associated with global warming. To account for this increase in evaporative demand precipitation would have to increase substantially. In the current study the mean precipitation does not increase by a substantial enough factor and mean streamflow levels decrease.

However, when investigating the flood regime it is the outliers rather than the means that are of interest. How much water from a single large precipitation event is converted to streamflow depends to a large extent on what the antecedent moisture conditions in the catchment are. These antecedent conditions are affected by various catchment characteristics such as soil type and depth, and vegetation, which

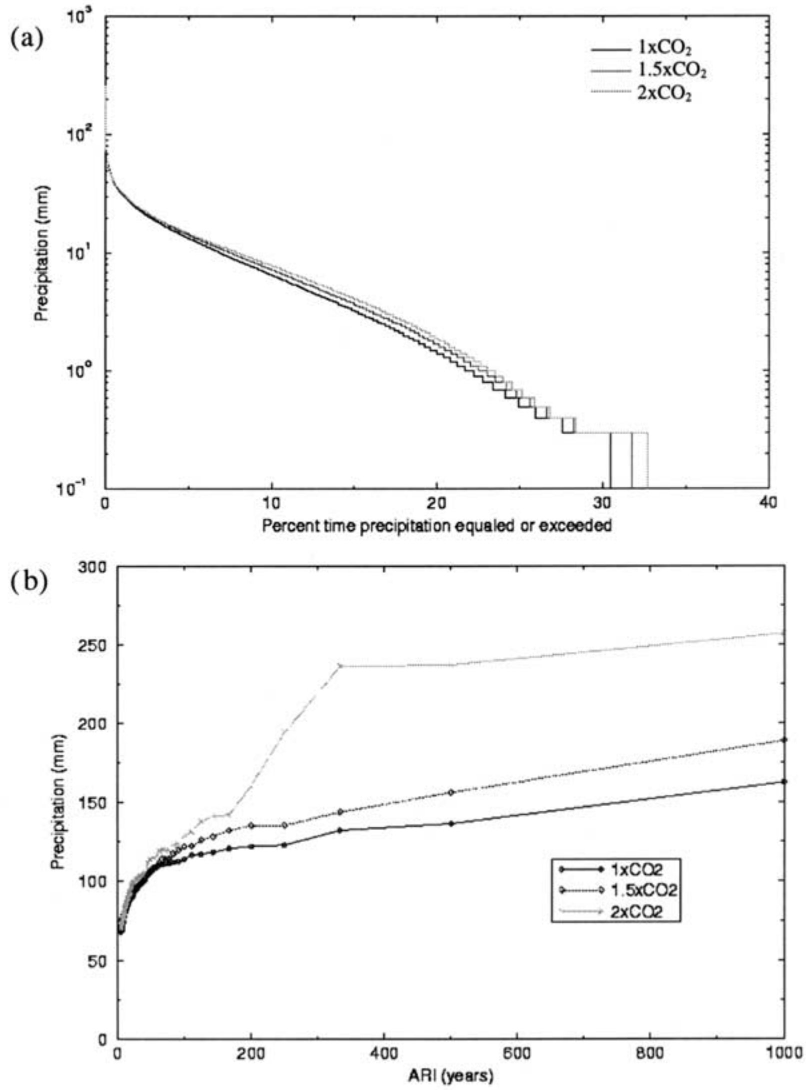


Figure 6. Precipitation under $1 \times CO_2$, $1.5 \times CO_2$ and $2 \times CO_2$ conditions. (a) Precipitation duration curve; (b) average recurrence interval.

determine the movement of water through the catchment as well as the evaporative losses. Figure 8 provides the most insight into the changing flood regime with increasing CO_2 levels in the atmosphere. It demonstrates the influence of catchment characteristics on the streamflow response changes with a significantly different response to global warming for each catchment.

It is of interest to note that the change in extreme events is often larger in the $1.5 \times CO_2$ scenario than the $2 \times CO_2$ and in the cases of Wooroolo Brook, Susannah

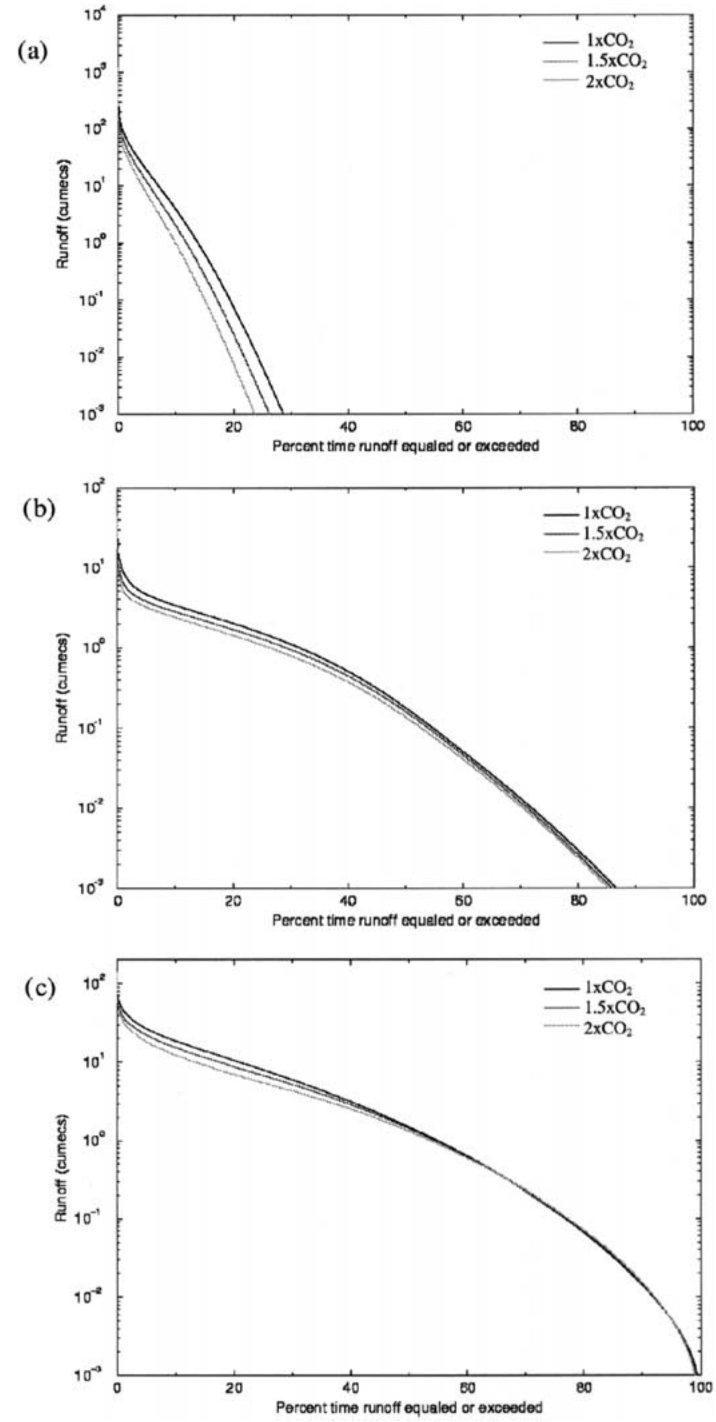

(a)
1xCO2
1.5xCO2
2xCO2
Runoff (cumecs)
Percent time runoff equaled or exceeded
(b)
1xCO2
1.5xCO2
2xCO2
Runoff (cumecs)
Percent time runoff equaled or exceeded
(c)
1xCO2
1.5xCO2
2xCO2
Runoff (cumecs)
Percent time runoff equaled or exceeded

Figure 7a.

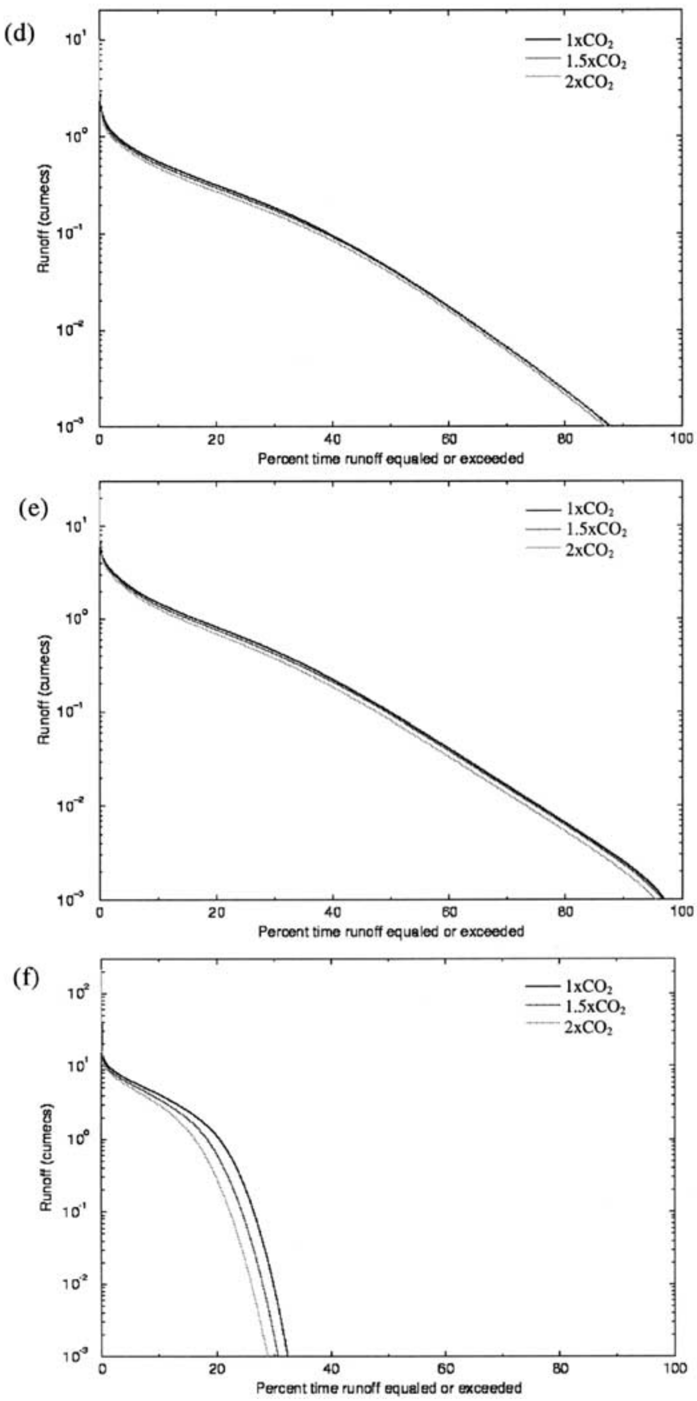
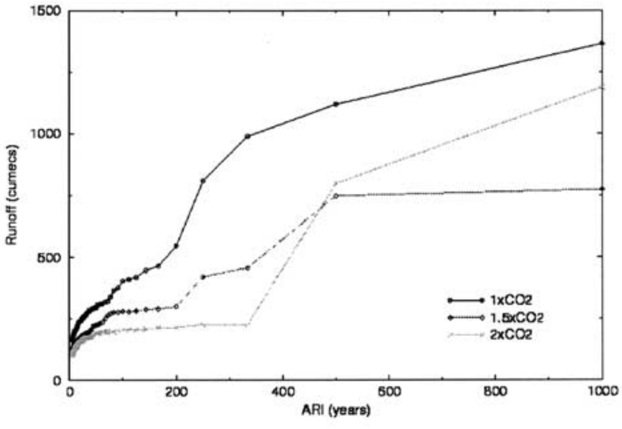


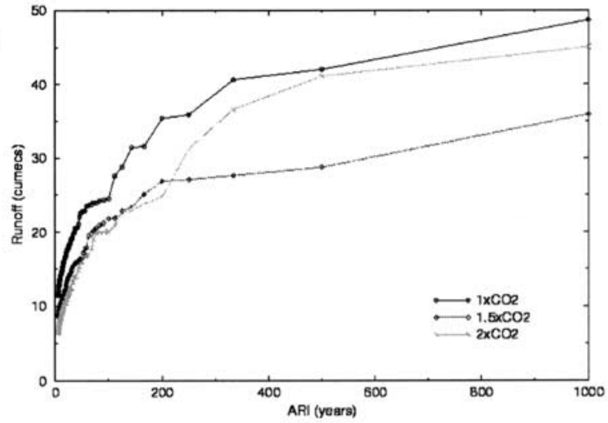
Figure 7b.

Figure 7. Flow duration curves the three CO_2 scenarios: (a) Avon River; (b) Brockman River; (c) Wooroolo Brook; (d) Susannah Brook; (e) Jane Brook; and (f) Helena River.

(a)



(b)



(c)

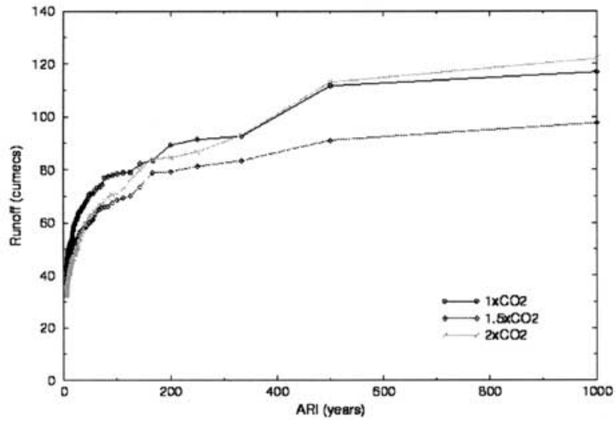


Figure 8a.

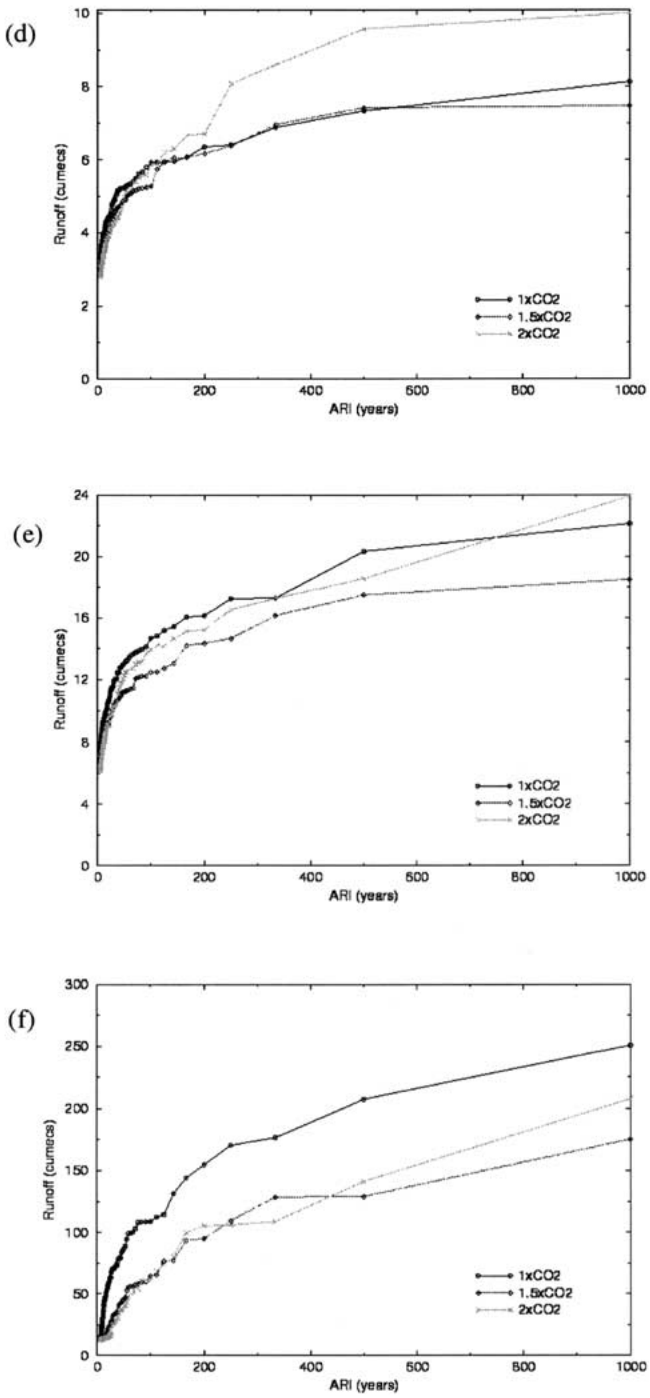


Figure 8b.

Figure 8. ARI curves for: (a) Avon River; (b) Brockman River; (c) Wooroolo Brook; (d) Susannah Brook; (e) Jane Brook; and (f) Helena River.

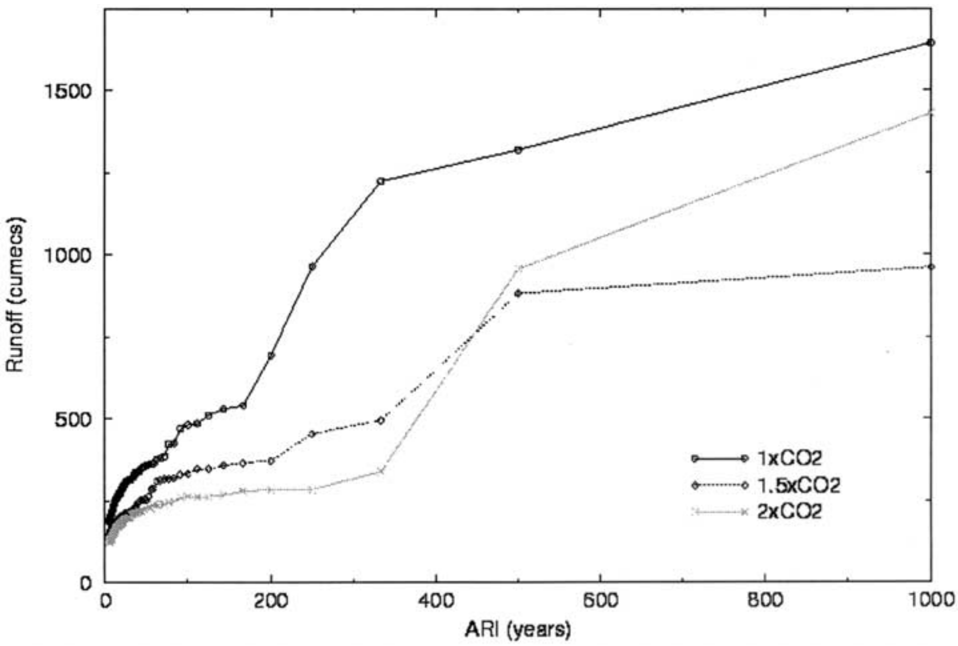


Figure 9. Average recurrence interval for flood events in the upper Swan River.

Brook and Jane Brook the change in these extreme events can even differ in sign between the two scenarios. To elucidate the causes of this difference in model response, closer examination of these extreme events was conducted and will here be discussed with particular attention on the largest events at Jane Brook and Helena River as presented in Figure 10. These events display characteristics which broadly appear for the extreme events in all of the catchments and are indicative of the two model responses mentioned above.

Figure 10 shows the 6 days leading up to and 3 days following the event in question for all three scenarios. We note that given similar precipitation inputs for the two catchments results in significantly different peak runoff outputs from the catchments. The order of largest to smallest runoff peaks in Jane Brook is the $2 \times CO_2$ scenario, $1 \times CO_2$ scenario and $1.5 \times CO_2$ scenario, while for the Helena River the order is $1 \times CO_2$, $2 \times CO_2$ and $1.5 \times CO_2$. This difference in runoff response can be attributed to the difference in catchment physical characteristics as embodied in the parameters of CMD-IHACRES.

The precipitation which causes the largest runoff event for each scenario demonstrates significantly different characteristics and it should be noted that this precipitation event is not the largest precipitation event for any of the scenarios. For the $1 \times CO_2$ scenario precipitation falls for several days increasing towards the peak precipitation which is only around half that of the peak $2 \times CO_2$ precipitation. The $2 \times CO_2$ scenario on the other hand, has almost no precipitation falling other then the peak which is relatively huge. The $1.5 \times CO_2$ scenario precipitation falls

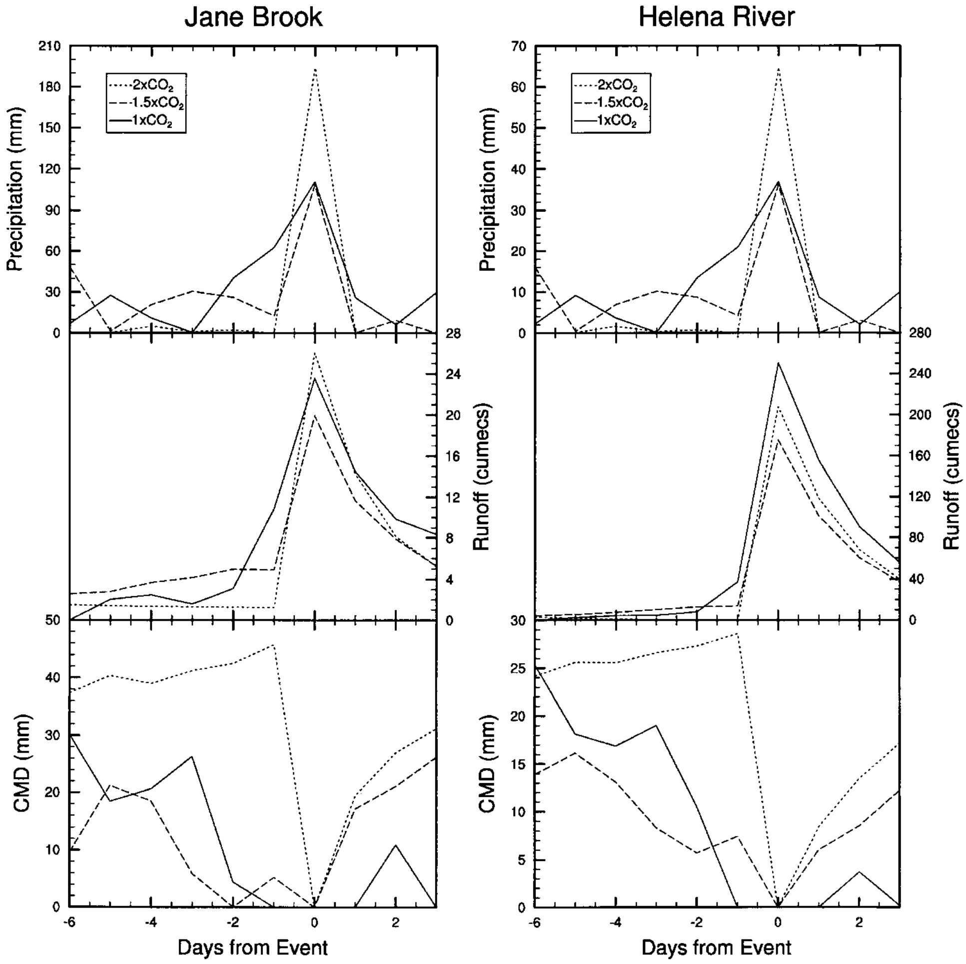


Figure 10. Precipitation, runoff and catchment moisture deficit (CMD) for the largest runoff event in Jane Brook and Helena River.

somewhere in between the other scenarios. This is fairly typical of these climate change scenarios which have increases in both the peak precipitation amounts and also the length of the interstorm/dry down periods (i.e., variability) with increasing CO_2.

The interplay between the precipitation and the antecedent catchment moisture conditions, as embodied in the CMD, then determines the height of the runoff peak. For the $1 \times CO_2$ scenario precipitation in the days preceding the peak bring the catchment to saturation (CMD = 0) thus allowing the precipitation that fell that day (minus any ET) to contribute directly to the runoff. For the $1.5 \times CO_2$ scenario the catchment is not quite saturated thus some of the precipitation that falls is used to saturate the catchment before the rest contributes to runoff. Hence despite having similar amounts of precipitation fall the $1.5 \times CO_2$ scenario produces a smaller peak than the $1 \times CO_2$ scenario. The $2 \times CO_2$ scenario has little to no precipitation prior to the actual event, thus just prior to the event the CMD is significantly higher than in the previous cases and a substantial proportion of the precipitation that falls must be used to bring the catchment to saturation before contributing directly to the runoff. In Jane Brook less than a quarter of the incident precipitation is required to bring the catchment to saturation, resulting in a runoff peak above that of the $1 \times CO_2$ scenario. For the Helena River almost half the precipitation is required to bring the catchment to saturation, resulting in a runoff peak below that of the $1 \times CO_2$ scenario but above the $1.5 \times CO_2$ scenario. This difference in catchment response demonstrates the complex interplay between precipitation, catchment moisture and runoff.

It should be emphasized that these extreme runoff events are associated with a change in the nature of the precipitation events as CO_2 increases. Under $1 \times CO_2$ conditions several days of moderate to large precipitation in a row are required to produce extreme flood conditions. Under $2 \times CO_2$ conditions, the most extreme flood events are driven by isolated but massive precipitation events. Under $1.5 \times CO_2$ conditions the consistency of precipitation required to produce extreme floods under $1 \times CO_2$ conditions is much less evident and individual precipitation events do not reach the massive levels of those under $2 \times CO_2$ conditions. Thus, in general, the $1.5 \times CO_2$ conditions produce smaller extreme flood events than either of the other scenarios. This suggests that, assuming the climate changes as the climate models predict, the study area would likely see a decrease in the magnitude of extreme floods followed by an increase. Of course, since changes in the level of CO_2 explored here are likely to be reached within a century these changes to flood events with high ARI could be considered a mute point.

Of particular interest then is the importance not just of estimating the changes in peak precipitation amounts but changes in the distributions of these events, in the length of both storm (consecutive days with precipitation) and interstorm periods (dry down). Accurate predictions of the changes in the nature of precipitation (not just the amounts) are vital before any confidence can be placed in estimates of changes in the flooding regime.

The two increased CO_2 scenarios, while not encapsulating the full range of global climate model estimates, provide some measure of the uncertainty in the global warming prediction. When combined with the uncertainties associated with the hydrological modeling and vegetation response to increased CO_2 in the atmosphere, these types of studies can provide little more than an indication of a possible range of potential future flooding regimes. As found by Lins et al. (1997) these uncertainties preclude the use of such forecasts operationally.

More recent scenarios have been constructed using GCMs coupled to dynamic ocean models (circa 1996). Some doubts about the reliability of scenarios from the coupled models currently exist (Whetton et al., 1996). These include the observed latitudinal gradient of warming in the southern hemisphere (IPCC, 1996), which is more like that in the slab ocean GCMs, and the simulated rainfall decreases in summer over Australia, given by the coupled models, which are contrary to the observed small increases this century. In a comparison of the simulation results of five coupled models, Whetton et al. (1996) found that half the models simulated a decrease in total precipitation during summer and all-but-one simulated a decrease in total precipitation during winter for our study area. The implications of these changes to the results of a study such as this could be profound. One would expect that the general decrease in runoff with increasing CO_2 seen in Figure 7 would be further exacerbated and probably accompanied by a decrease in the peaks of the extreme events. However without further information concerning the change in the nature of the precipitation, rather than simply the total, it is difficult to estimate what change to the flooding regime these coupled simulations would imply. In a region such as this, where much of the area of interest could be considered semi-arid, the implications of a general decrease in the precipitation and runoff would likely be a much more sever problem for the ecology and management of the area than any likely change in the flooding regime.

It is of interest to note however, that despite the prediction of a significant reduction in the mean streamflow it is still possible to obtain increases in the magnitudes of floods at the 100 year ARI level (Figure 8d), which is the level focused on by urban storm water planning in Australia (ACT government, 1994). Thus, in order for future global warming scenarios to provide useful information for water resource management it may be vital to include estimates of the change in variance of the precipitation along with changes in the mean. It also serves to emphasis the need for a reduction in the uncertainty associated with the global warming predictions before much confidence can be placed in long term water resource planning.

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References

ACT government: 1994, *Urban Stormwater. Edition 1: Standard Engineering Practices*, Australian Capital Territory Government, Woden, Australia, ISBN 0644332743.

Bates, B. C., Charles, S. P., and Fleming, P. M.: 1993, 'Simulation of Daily Climatic Series for the Assessment of Climate Change Impacts on Water Resources', in Kuo, C. Y. (ed.), *Engineering Hydrology. Amer. Soc. Civ. Eng.*, New York, pp. 67–72.

Bates, B. C., Charles, S. P., and Hughes, J. P.: 1998, 'Stochastic Downscaling of Numerical Climate Model Simulations', *Environ. Model. Software* **13**, 325–331.

Busby, J. R.: 1988, 'Potential Impacts of Climate Change on Australia's Flora and Fauna', in Pearman, G. I. (ed.), *Greenhouse: Planning for Climate Change*, E. J. Brill, New York, pp. 387–398.

Charles, S. P., Fleming, P. M., and Bates, B. C.: 1993, 'Problems of Simulation of Daily Precipitation and Other Input Time Series for Hydrological Climate Change Models', *Hydrology and Water Resources Symposium*, Institute of Engineers, Australia, pp. 469–477.

Chiew, F. H. S., Whetton, P. H., McMahon, T. A., and Pittock, A. B.: 1995, 'Simulation of the Impact of Climate Change on Runoff and Soil Moisture in Australian Catchments', *J. Hydrol.* **167**, 121–147.

Close, A. F.: 1988, 'Potential Impact of Greenhouse Effect on the Water Resources of the River Murray', in Pearman, G. I. (ed.), *Greenhouse: Planning for Climate Change*, E. J. Brill, New York, pp. 312–323.

DNRE: 1998, *North East Victoria: Comprehensive Regional Assessment*, Department of Natural Resources and Environment, Victoria.

Evans, J. P. and Jakeman, A. J.: 1998, 'Development of a Simple, Catchment-Scale, Rainfall-Evapotranspiration-Runoff Model', *Environ. Model. Software* **13**, 385–393.

Evans, J. P., Oglesby, R. J., and Jakeman, A. J.: 1999, 'A New Method Improving the Simulation of Streamflow in Climate Models', in Oxley, L., Scrimgeour, F., and Jakeman, A. J. (eds.), *International Congress on Modelling and Simulation, MODSIM99*, University of Waikato, New Zealand, pp. 611–616.

Feddema, J. J.: 1999, 'Future African Water Resources: Interactions between Soil Degradation and Global Warming', *Clim. Change* **42**, 561–596.

Giorgi, F., Brodeur, C. S., and Bates, G. T.: 1994, 'Regional Climate Change Scenarios over the United States Produced with a Nested Regional Climate Model', *J. Climate* **7**, 375–399.

Holmes, J. W. and Sinclair, J. A.: 1986, 'Water Yield from Some Afforested Catchments in Victoria', in *Hydrology and Water Resources Symposium*, Griffith University, Brisbane, pp. 214–218.

Houghton, J. T., Callander, B. A., and Varney, S. K. (eds.): 1992, *Climate Change 1992. The Supplementary Report to the IPCC Scientific Assessment*, Cambridge University Press, Cambridge.

Houghton, J. T., Jenkins, G. J., and Ephraums, J. J. (eds.): 1990, *Climate Change, the IPCC Scientific Assessment*, Cambridge University Press, Cambridge.

Hughes, J. P.: 1993, *A Class of Stochastic Models for Relating Synoptic Atmospheric Patterns to Local Hydrologic Phenomena*, Ph.D. Thesis, Univ. Washington, Seattle.

Hughes, J. P. and Guttorp, P.: 1994, 'A Class of Stochastic Models for Relating Synoptic Atmospheric Patterns to Regional Hydrologic Phenomena', *Water Resour. Res.* **30**, 1535–1546.

IPCC: 1996, Houghton, J. T., Filho, L. G. M., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K. (eds.), *Climate Change 1995. The Science of Climate Change*, Intergovernmental Panel on Climate Change, Cambridge, p. 572.

Jakeman, A. J. et al.: 1993, 'Assessing Uncertainties in Hydrological Response to Climate at Large Scale', in Wilkinson, W. B. (ed.), *Macroscale Modelling of the Hydrosphere*, IAHS, Yokohama, pp. 37–47.

Jakeman, A. J. and Hornberger, G. M.: 1993, 'How Much Complexity is Warranted in a Rainfall-Runoff Model?', *Water Resour. Res.* **29**, 2637–2649.

Jakeman, A. J., Littlewood, I. G., and Whitehead, P. G.: 1990, 'Computation of the Instantaneous Unit Hydrograph and Identifiable Component Flows with Application to Two Small Upland Catchments', *J. Hydrol.* **117**, 275–300.

Jensen, M. E., Burman, R. D., and Allen, R. G.: 1990, 'Evapotranspiration and Irrigation Water Requirements', in *ASCE Manual on Engineering Practice*, ASCE, New York, p. 332.

Kristiansen, G.: 1993, *Biological Effects of Climate Change. An Introduction to the Field and Survey of Current Research*, Center for International Climate and Energy Research (CICERO), Global Change and Terrestrial Ecosystems (GCTE), International Geosphere-Biosphere Programme (IGBP), Oslo.

Leavesley, G. H.: 1994, 'Modelling the Effects of Climate Change on Water Resources – a Review', *Clim. Change* **28**, 159–177.

Linacre, E.: 1992, *Climate, Data and Resources. A Reference and Guide*, Routledge, London, p. 366.

Lins, H. F., Wolock, D. M. and McCabe, G. J.: 1997, 'Scale and Modeling Issues in Water Resources Planning', *Clim. Change* **37**, 63–88.

McGregor, J. L., Gordon, H. B., Watterson, I. G., Rotstayn, M. R., and Rotstayn, L. D.: 1993, 'The CSIRO 9-Level Atmospheric General Circulation Model. 25', CSIRO Division of Atmospheric Research, Melbourne.

McGregor, J. L. and Walsh, K.: 1993, 'Nested Simulations of Perpetual January Climate over the Australian Region', *J. Geograph. Res.* **98**, 23,283–23,290.

Mehrotra, R.: 1999, 'Sensitivity of Runoff, Soil Moisture and Reservoir Design to Climate Change in Central Indian River Basins', *Clim. Change* **42**, 725–757.

Monserud, R. A., Tchebakova, N. M., and Leeemans, R.: 1993, 'Global Vegetation Change Predicted by the Modified Budyko Model', *Clim. Change* **25**, 59–83.

Nash, J. E. and Sutcliffe, J. V.: 1970, 'River Flow Forecasting through Conceptual Models, Part I – A Discussion of Principles', *J Hydrol.* **10**, 282–290.

Nathan, J. E., McMahon, T. A., and Finlayson, B. A.: 1988, 'The Impact of the Greenhouse Effect on Catchment Hydrology and Storage-Yield Relationships in Both Winter and Summer Rainfall Zones', in Pearman, G. I. (ed.), *Greenhouse: Planning for Climate Change*, E. J. Brill, New York, pp. 273–295.

Nemec, J. and Schaake, J.: 1982, 'Sensitivity of Water Resource Systems to Climate Variation', *J. Hydrol. Sci.* **27**, 327–343.

Penman, H. L.: 1948, 'Natural Evaporation from Open Water, Bare Soil and Grass', *Proc. Roy. Soc. London* **A193**, 116–140.

Pittock, A. B.: 1988, 'Actual and Anticipated Changes in Australia's Climate', in Pearman, G. I. (ed.), *Greenhouse: Planning for Climate Change*, E. J. Brill, New York, pp. 35–51.

Pittock, A. B.: 1993, 'Climate Scenario Development', in Jakeman, A. J., Beck, M. B., and McAleer, M. J. (eds.), *Modelling Change in Environmental Systems*, John Wiley and Sons, Chichester, pp. 481–504.

Post, D. A. and Jakeman, A. J.: 1996, 'Relationships between Catchment Attributes and Hydrological Response Characteristics in Small Australian Mountain Ash Catchments', *Hydrol. Proc.* **10**, 877–892.

Richardson, C. W. and Wright, D. A.: 1984, 'WGEN: A Model for Generating Daily Weather Variables', ARS-8, U.S. Dept. of Agriculture, Agricultural Res. Service.

Schreider, S. Y., Jakeman, A. J., Whetton, P. H., and Pittock, A. B.: 1997, 'Estimation of Climate Impact on Water Availability and Extreme Events for Snow-Free and Snow-Affected Catchments of the Murray-Darling Basin', *Aust. J. Water Resour.* **2**, 35–46.

Schreider, S. Y., Smith, D. I., and Jakeman, A. J.: 2000, 'Climate Change Impact on Urban Flooding', *Clim. Change* **47**, 91–115.

Semenov, M. A. and Barrow, E. M.: 1997, 'Use of a Stochastic Weather Generator in the Development of Climate Change Scenarios', *Clim. Change* **35**, pp. 397–414.

Tucker, G. B.: 1988, 'Climate Modelling: How Does It Work?', in Pearman, G. I. (ed.), *Greenhouse: Planning for Climate Change*, E. J. Brill, New York, pp. 22–34.

Wheater, H. S., Jakeman, A. J., and Beven, K. J.: 1993, 'Progress and Directions in Rainfall-Runoff Modelling', in Jakeman, A. J., Beck, M. B., and McAleer, M. J. (eds.), *Modelling Change in Environmental Systems*, John Wiley and Sons Ltd., p. 584.

Whetton, P. H., Fowler, A. M., Haylock, M. R., and Pittock, A. B.: 1993, 'Implications of Climate Change due to the Enhanced Greenhouse Effect on Floods and Droughts in Australia', *Clim. Change* **25**, 289–317.

Whetton, P. H., Rayner, P. J., Pittock, A. B., and Haylock, M. R.: 1994, 'An Assessment of Possible Climate Change in the Australian Region Based on an Intercomparison of General Circulation Model Results', *J. Climate* **7**, 441–463.

Wilks, D. S.: 1992, 'Adapting Stochastic Weather Generation Algorithms for Climate Change Studies', *Clim. Change* **22**, 67–84.

Ye, W., Bates, B. C., Viney, N. R., Sivapalan, M., and Jakeman, A. J.: 1997, 'Performance of Conceptual Rainfall-Runoff Models in Low-Yielding Catchments', *Water Resour. Res.* **33**, 153–166.

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