CLIMATE CHANGE IMPACTS ON URBAN FLOODING

S. YU. SCHREIDER[1], D. I. SMITH[2] and A. J. JAKEMAN[2]
[1]*Integrated Catchment Assessment and Management (ICAM) Centre, The Australian National University, Canberra 0200, ACT, Australia*
[2]*Centre for Resource and Environmental Studies (CRES), The Australian National University, Canberra 0200, ACT, Australia*

Abstract. This paper estimates changes in the potential damage of flood events caused by increases of CO_2 concentration in the atmosphere. It is presented in two parts: 1. the modelling of flood frequency and magnitude under global warming and associated rainfall intensities and 2. the use of greenhouse flood data to assess changes in the vulnerability of flood prone urban areas, expressing these in terms of direct losses.

Three case studies were selected: the Hawkesbury–Nepean corridor, the Queanbeyan and Upper Parramatta Rivers. All three catchments are located in southeastern Australia, near Sydney and Canberra. These were chosen because each had detailed building data bases available and the localities are situated on rivers that vary in catchment size and characteristics. All fall within a region that will experience similar climate change under the available greenhouse scenarios. The GCMs' slab model scenarios of climate change in 2030 and 2070 will cause only minor changes to urban flood damage but the double CO_2 scenarios estimated using the Stochastic Weather Generator technique will lead to significant increases in building damage.

For all the case studies, the hydrological modelling indicates that there will be increases in the magnitude and frequency of flood events under the double CO_2 conditions although these vary from place to place. However, the overall pattern of change is that for the Upper Parramatta River the 1 in 100-year flood under current conditions becomes the 1 in 44-year event, the 1 in 35-year flood for the Hawkesbury–Nepean and the 1 in 10 for Queanbeyan and Canberra. This indicates the importance of using rainfall-runoff modelling in order to estimate changes in flood frequencies in catchments with different physical characteristics.

1. Introduction

Floods that cause urban damage are rare events and this leads to uncertainty in estimating the average recurrence interval (ARI) for the more extreme floods, even under present climate conditions. These problems are amplified in any attempt to model changes for low probability flood events under double CO_2 conditions. Notwithstanding these difficulties, the aim of the study is to present information on the nature of future flooding under greenhouse climatic conditions and to assess the effects for urban flood loss.

The starting point is to use existing records to model rainfall and runoff under present day conditions. The IHACRES model, applied in this study, is a hybrid-metric, conceptual model based on the instantaneous unit hydrograph technique. The model has been used worldwide in many different hydroclimatologies

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for a range of applications including streamflow prediction under enhanced CO_2 climates (Jakeman et al., 1990; Schreider et al., 1996b).

IHACRES was first calibrated using historical records of precipitation, temperature and stream flow, and then tested by a validation or simulation run. Two different approaches were taken to use this information for the generation of future climate series. The first combines IHACRES with the IPPC/CSIRO 1996 greenhouse scenarios for Australia (CIG, 1996) for the years 2030 and 2070. Two future extremes cases are considered, these are termed the most 'wet' and most 'dry' scenarios; more detail is presented for the former since it is most pertinent to the assessment of future flood losses. Limitations to this approach have been described by Bates et al. (1994) who proposed an alternative which uses stochastic models to represent daily weather variables at the location used for the hydrological modelling, this form of analysis is known as stochastic weather generation. The hypothetical time series from the weather generator is then used as an input into the IHACRES rainfall-runoff model to produce streamflow data which, in order to assess flood losses, are then converted into flood heights. The final stage in the hydrological analysis is to estimate changes in the annual recurrence interval for a sequence of floods under climate change. These are typically for the events with an ARI of 10, 20, 50, 100, 1000 years and for the probable maximum flood (PMF).

2. Background

A comprehensive overview of Australian flood damage estimation and floodplain management is given in Smith (1996) and details of flood loss assessment methodologies used in Australia appear in Smith et al. (1990, 1996). The potential effects of climate change on urban infrastructure are addressed in Smith (1993) and Minnery and Smith (1994). They emphasise that 'for urban areas the most significant climatic impacts are likely to result from an increased frequency of extreme events, including flooding'. The basic damage assessment methodology used in those studies is followed in this project. This methodology requires three major classes of input data:

- collection of spatial data bases on locations, class definitions and ground and floor heights
- stage damage curves for each class of buildings, and
- information on flood magnitude and frequency for present and hypothesised future climate conditions.

These input data are combined to estimate the damage for specific flood events with different ARI. The results are then used to calculate the annual average direct damage.

The novelty of the present work compared with the earlier studies can be outlined as follows:

1. In earlier studies (for example Minnery and Smith, 1996; Fowler and Hennessy, 1995) changes in intensities of rainfall events were assumed to correspond to changes in flood frequency. In the present work the rainfall-runoff model IHACRES is applied to obtain direct estimates of changes in streamflow under different climatic change scenarios.
2. A revised version of the climate scenarios (CIG, 1996) at two dates in the future (2030 and 2070) is utilised.
3. A stochastic weather generator is employed to synthesise inputs to IHACRES for estimating runoff changes and hence damages under the double CO_2 conditions (the date at which these conditions occur depends on the rate of increase in greenhouse gas emissions, but roughly can be estimated as in the period 2060–2100).

Additional details of the hydrological modelling and its application to the case studies are reported in Smith et al. (1998).

3. Selection of the Modelling Tool

There are three types of rainfall-runoff models which could be used for predicting the stream discharge effects of climatic variations: empirical, physically based and conceptual. Wheater et al. (1993) discuss the advantages and limitations of each type. Basically, empirical models contain too little process description to be used to make predictions on independent periods not used for model calibration. Physically based models are too computationally demanding to be used on a catchment of more than a few square kilometres.

The IHACRES model, applied in the present study, 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 (the hydrograph of direct runoff resulting from one unit of effective rainfall generated uniformly over a catchment area with instantaneous duration) with rainfall excess or effective rainfall. It is partly metric in the sense that measured precipitation-discharge observations are used to infer the configuration and number of stores used to represent the linear convolution.

The three regions chosen for consideration here have been instrumented for many years. Streamflow, precipitation and temperature data are available for decades for the majority of gauging sites in these regions. Thus, conceptual lumped rainfall-runoff models seem to be the most adequate type of model for the streamflow analysis required in the region selected and for the particular purposes of this study. The model IHACRES falls sufficiently well within this class of models, and its number of the parameters (six) to be fitted is small compared with other conceptual models, yet its performance has been impressive across a range of hydroclimatologies (e.g., Jakeman and Hornberger, 1993; Ye et al., 1997). Another substantial argument for the use of conceptual hydrological models in the present work is that models of this type allow one to link together process components reflecting physical concepts under the presumption that model parameters have a physical interpretation. It allows one to establish their parameter values under present conditions and then to use them 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, land use, building and road structure for the urban catchments) will not change considerably.

4. Two Approaches Selected for Climate Analysis

The climate impact analysis undertaken here uses two approaches to generate inputs to the rainfall-runoff model: the climate scenarios approach and an approach based on the use of a stochastic weather generator. The first approach proposed by CIG (1992, 1996) analysed climate outputs for the Australian continent from five different General Circulation Models, thereby providing a range of possible mean changes in annual temperature and seasonal precipitation. From this approach, two extreme climate scenarios are considered: a ‘most wet’ scenario, reflecting a minimum reduction or, possibly, an increase in river discharge, and a ‘most dry’ scenario, where discharge reduction is at a maximum. These two cases can be considered as endpoints in an interval containing possible climate impacts on surface runoff. In this case the analysis was performed for two future dates (2030 and 2070), for which historical climatic time series (precipitation and temperature) were linearly transformed in order to possess the same long term means as the selected climate scenarios. There is, of course, substantial uncertainty in the magnitude, timing and spatial distribution of these scenarios.

Limitations of the above historical scaling approach are described by Bates et al. (1994). The linear transformation of historical climate records to conform to GCM long-term averages in order to estimate possible climate impacts may be considered improper, due to the coarse resolution of GCM spatial grids and the simplified GCM representation of land surface-atmosphere-ocean interactions. The use of stochastic models representing daily weather variations at the site of the hydrological model application is an alternative approach to estimate possible climate impacts on streamflow. This approach, developed for the Australian region, is described in Bates et al. (1993, 1994) and Charles et al. (1993). The major advantage of this approach is that the correlation structure amongst the different climate variables simulated is realistic, at least in terms of historical climate which may not be the case when historical frequency distribution of climate variables such as rainfall and temperature are independently shifted.

The latter approach is applied here for the Queanbeyan and Upper Parramatta catchments. A 1000 year daily time series was generated for a period in the future when the CO_2 concentration in the atmosphere is assumed to be double the present.

The time series were then used as an input to the IHACRES model to estimate the changes in runoff. The major disadvantage of the latter approach is that it uses the output statistics of a single Global Climate Model (CSIRO9, McGregor et al., 1993). Thus, it inherits all the limitations of the CSIRO9 model and disregards the results provided by other climate models.

5. Methodological Summary

The steps in the methodology, used to provide the hydrological information needed to estimate changes to flood damage, are as follows:

1. Calibration of the conceptual rainfall-runoff model using historical records of precipitation, temperature and streamflow.
2. Testing of the model performance by a so-called validation (or simulation) run.
3. Generation of future climatic data series (here two options are used as stated in Section 4).
4. Use of the hypothetical climatic time series as inputs to the rainfall-runoff model in order to produce streamflow discharge and associated stage height data series for the future.
5. Estimation of changes in the ARI for flood events of different magnitudes; usually for the events with an ARI of 10, 20, 50, 100, 1000 years, and for the probable maximum flood (PMF).

6. The IHACRES Model Description

The lumped parameter rainfall-runoff model IHACRES used here has been tested successfully in several regions worldwide for catchments of different sizes and under different climate conditions (e.g., Jakeman et al., 1990; Jakeman and Hornberger, 1993; Ye et al., 1997; Schreider et al., 1995, 1996a; Post et al., 1996). It was first described in Jakeman et al. (1990), and its loss module was updated by Jakeman and Hornberger (1993) and subsequently by Ye et al (1997). The model has two modules. A non-linear loss module which at each timestep k (a daily timestep is used in this study) transforms measured rainfall r_k into effective rainfall u_k using temperature or pan evaporation data t_k. A linear module then describes the travel of effective rainfall to streamflow y_k on the basis of a total unit hydrograph approximation. The latter module invokes a recursive relation at time step k for modelled streamflow y_k, computed as a linear combination of its past values and current and past effective rainfall.

The linear module identified as most appropriate in this work for the Queanbeyan catchment is:

$$y_k = -a_1 y_{k-1} - a_2 y_{k-2} + b_0 u_k + b_1 u_{k-1} \qquad (1)$$

It implies that the effective rainfall is considered to travel through two parallel stores. This means that during dry periods the recession of streamflow is a superposition of two exponential decay functions, one of them being responsible for quick recession and the other for recession of the slow component. The two-reservoir structure of the linear module is selected for the relatively humid catchments where the naturally regulated baseflow component exists. The coefficients a's and b's are parameters to be optimised using the Simple Refined Instrumental Variables algorithm (Jakeman et al., 1990). The linear module accepted for the Parramatta and Hawkesbury-Nepean catchments is represented as follows:

$$y_k = -a_1 y_{k-1} + b_0 u_k \tag{2}$$

This simpler one-reservoir model is usually identified for catchments in dry regions where base flow is negligibly small, for urban catchments where the base flow is strongly affected by artificial regulations (the case of Parramatta River) or for catchments where no data about base flow is available (the case of the Hawkesbury-Nepean catchment, where only flood event records are accessible).

7. Climate Scenarios and Stochastic Weather Generators

The climate scenarios developed by the Climate Impact Group, CSIRO Division of Atmospheric Research have been described in CIG (1992), Whetton (1993) and updated in CIG (1996). The scenarios provide the changes for two main climatological variables, temperature and precipitation, for two periods in the future: 2030 and 2070. They are based on scenarios of future global warming produced by Wigley and Raper (1992) and regional results of five recent GCM equilibrium experiments (including two Australian GCMs, from CSIRO and the Bureau of Meteorology) analysed by CSIRO which provided information on possible regional climatic changes. These five GCMs considered are: BMRC (Colman et al., 1994), CSIRO9 (McGregor et al., 1993), CCC (McFarlane et al., 1992), GFDLH and UKMOH (Houghton et al., 1990). Scenarios, from IPCC (1996), indicate average global warming ranges from 0.4 to 0.8 °C by 2030 and from 0.7 to 2.1 °C by 2070. These large ranges take into account two major sources of uncertainty: the range of possible future greenhouse gas emissions (Houghton et al., 1992; IPCC, 1996); and the range in the estimated global sensitivity of climate to the concentration of greenhouse gases in the atmosphere (1.5 to 4.5 °C equilibrium warming for a doubling of CO_2).

CIG (1996) presents regional response patterns of temperature for three broad regions of Australia: Northern Coast (north of about 25° S), Southern Coast (south of about 25° S) and Inland (more than about 200 km from the coast). Respectively, these patterns, expressed *as ranges* of coefficients of local warming per degree global warming, are 0.9–1.3, 0.8–1.6 and 1.0–1.8.

TABLE I

Climate scenarios for 2030 and 2070 from GCM slab models

Scenario	Warming (°C)	Changes in precipitation (summer)	Changes in precipitation (winter)
'most dry' 2030	1.3	0%	–4%
'most wet' 2030	0.6	8%	0%
'most dry' 2070	3.4	0%	–10%
'most wet' 2070	1.7	20%	0%

The three case studies are within a single precipitation region, for which the CIG (1996) scenarios are a -5% to $+5\%$ rainfall change per degree global warming for the summer period (November to April) and –10% to 0% for the winter period. Details of the 'most dry' and 'most wet' scenarios, for both 2030 and 2070, are given in Table I. The 'most dry' is attained for the case of maximum increase in temperature and maximum reduction in precipitation. The 'most wet' is attained for the case of a maximum increase in precipitation and the least warming that can be related to this level of increased rainfall (the changes in temperature and precipitation had to be considered with regard to the trend of global warming). That this case yields the highest runoff is not obvious. The level of evaporation increases very sharply with increasing temperature. The scenarios for 2030 and 2070 with minimum warming (0.3 and 0.6 °C respectively) and with the correspondingly lower increases in rainfall were also considered and were found to provide less runoff than the scenarios with the maximum increase in precipitation. The scenarios were applied by increasing all observed daily temperatures by the appropriate scenario increment and by adjusting the rainfall by the scenario percentage on all days with rain.

The methodology used to stochastically generate synthetic series for future climates is described in Bates et al. (1993, 1994) and Charles et al. (1993). The rainfall is modelled as a 1st order, 2-state (wet/dry) Markov process with rainfall amounts fitted by the gamma distribution. The double CO_2 parameters were derived from the changes observed from the CSIRO9 Global Climate Model runs using the method of Wilks (1992).

There is no rigorous method to assess when the doubling of CO_2 in the atmosphere will occur, and hence the period to which the double CO_2 results apply is undateable. However, the best estimate based on prediction of greenhouse gas emission rates is that the most probable time interval is 2060–2100 (P. H. Whetton, personal communication). Nevertheless, comparison of the 2070 'most wet' scenarios with the double CO_2 stochastic weather generator experiment shows that the latter provides a much higher increase in mean annual precipitation (about 50%, with monthly fluctuations from 29% in August to 66% in January for the case of the Upper Parramatta catchment) and a higher level of warming (about 5.5 °C). This is mirrored in the results of estimation of changes in direct flood damage; the changes in the direct flood damage are considerably higher for the double CO_2 simulation than those obtained utilising the climate scenarios.

8. Assumptions and Limitations

Two important limitations of the model's applicability to the estimation of possible climate impact must be mentioned here. The methodology assumes that the parameters of the IHACRES model remain constant under different climatic conditions and are only a function of the catchment landscape characteristics, vegetation cover and level of urbanisation.

8.1. LIMITATIONS RELATED TO THE UNCERTAINTIES OF FUTURE CLIMATE PREDICTION

Limitations of the approach are also related to the high level of uncertainty in the estimated climatic patterns, mirrored in the large differences in streamflow values associated with the selected scenarios. The difference between 'most wet' and 'most dry' cases illustrates this. Another problem in the applicability of the 'scenario' methodology is that it deals with the transformation of historical records of precipitation and temperature, which are usually not very long (about several decades of continuous records). This makes it difficult to estimate the changes in the ARI for large flood events (higher than a 1 in 20 year event).

The methodology based on use of the stochastic weather generator is preferred because it generates a long term synthetic climatic series (1000 years here) for $1 \times CO_2$ as well as for $2 \times CO_2$ conditions. This allows one to estimate changes for large flood events (up to an ARI value of 1000 years). The limitation of this approach is that the hypothetical distributions of daily temperature and precipitation are also estimated with respect to a relatively short period of historical records. This can induce errors for the extrapolated long term series, related to problems appearing during the instrumental period (e.g., errors in recording, missing data, anomalously large rainfall events occurring during the short period of data recording, etc.). Another limitation of this approach, already mentioned in Section 4, is that the stochastic weather generator employs the output of a single Global Climate Model CSIRO9. However, we should emphasise that in general the stochastic weather generator methodology is much preferred for flood frequency analysis under future climatic conditions.

8.2. LIMITATIONS RELATED TO THE ESTIMATION OF FLOOD DISCHARGE AND FREQUENCY

There are limitations to the estimation of flood discharge, although these are common to most catchments and would have similar effects in any comparable location. Firstly, the rating curves reflecting the relationships between river discharge and stage heights are usually calibrated for sites remotely located from the floodplain areas. In such cases the changes in stage height frequencies are assumed to be the same as at the closest station where such information is available. Secondly, discharge records for extreme flood events lack reliability. The model was calibrated using mean daily discharge data only, whereas the peak discharge is critical for the assessment of flood damage. Attempts to calibrate the model using peak discharge data were unsuccessful. A possible solution to this problem in the future is to calibrate the model using subdaily (for instance, hourly) time steps. However, such an approach can cause additional problems in generating subdaily climatic series into the future.

9. Rainfall-Runoff Modelling – The Results

The locations of the three case study catchment is given in Figure 1. Catchment size varies considerably: the Upper Parramatta area is 104 km^2, that for the Queanbeyan River 490 km^2 and for the Hawkesbury-Nepean catchment 22,000 km^2.

Each presents its own unique set of characteristics and difficulties for hydrological analysis. There are problems with the number, location and lengths of available records for rainfall and river gauging stations and with modifications to drainage from dams and retention basins. This account outlines the characteristics and problems for each of the locations, the details are presented in Smith et al. (1998).

It is important to note that the difficulties with flow records and the influence, over time, of modifications such as dams and detention basins is not unique to the case studies. Similar problems are likely to be universally encountered in any area subject to frequent urban flooding. This is because flood-liable communities are those in which structural mitigation measures are most commonly used and these inevitably distort the historic flood record.

9.1. THE UPPER PARRAMATTA CATCHMENT

The Upper Parramatta catchment is located in the Sydney metropolitan area and includes the flood-prone suburb of Toongabbie. Two high flow events occurred during the instrumented period in the Upper Parramatta catchment: at 5.08.1986 with mean daily discharge of 207 m^3 per second (cumecs) at the Lennox Bridge station; and at 30.04.1988 with discharge of 297 cumecs. Thus, two one-year periods have been selected for model calibration in this catchment, starting on 19-5-1986

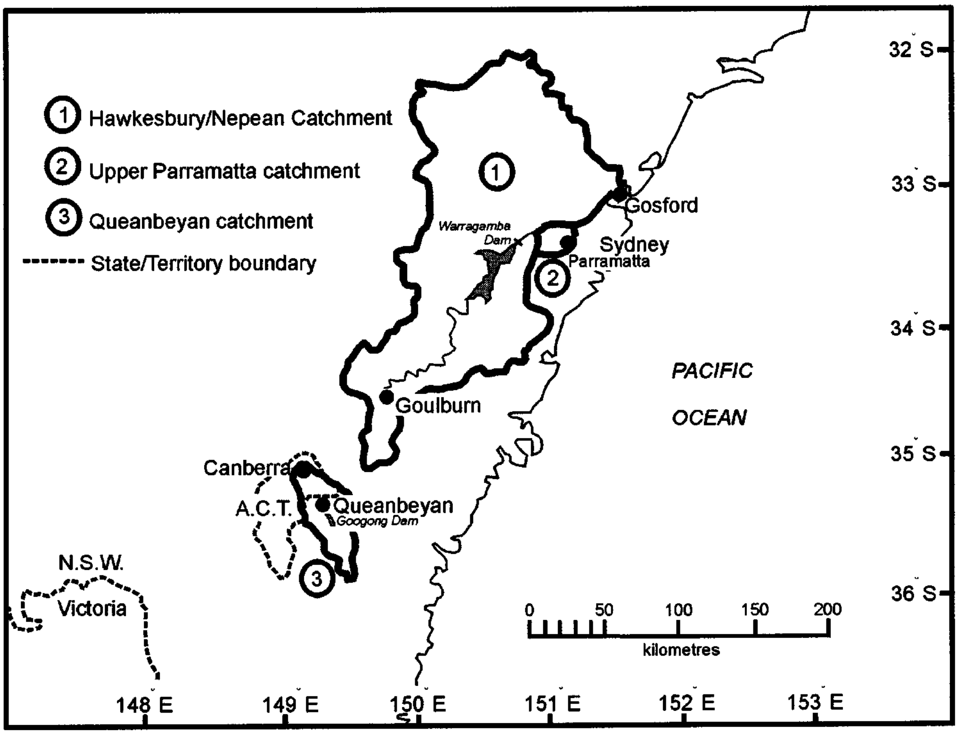

Figure 1. Upper Parramatta, Queanbeyan River and Hawkesbury-Nepean catchment locations.

and 1-10-1987, respectively. The results of calibration (in terms of Nash-Sutcliffe (1970) efficiency) are $E = 0.991$ for the first calibration period, and $E = 0.961$ for the second one. The results of the calibration for the 1986 event is presented in Figure 2. The calibration results for the 1988 event are presented in Figure 3.

A validation or simulation test of the calibrated models was also implemented: the model calibrated for the 1986 event was applied without changes in parameters to the second calibration period and vice-versa. The simulation results are $E = 0.553$ for the 1988 model applied on the 1986 period and $E = 0.786$ for the 1986 model applied on the 1988 period. Thus, the 1986 model parameters were selected as the better ones and are used later for the simulation of runoff using the future climatic data as input.

9.2. THE QUEANBEYAN RIVER CATCHMENT

The gauging station used for modelling the Queanbeyan River catchment is located upstream of Googong Dam which was completed in the mid-1970s. The station has continuous daily streamflow data from 1966. The IHACRES model was applied in this catchment by Schreider et al. (1995) using the rainfall data interpolated over the catchment area using point data from five different stations. The model was recalibrated for the present project using the single station data for the convenience

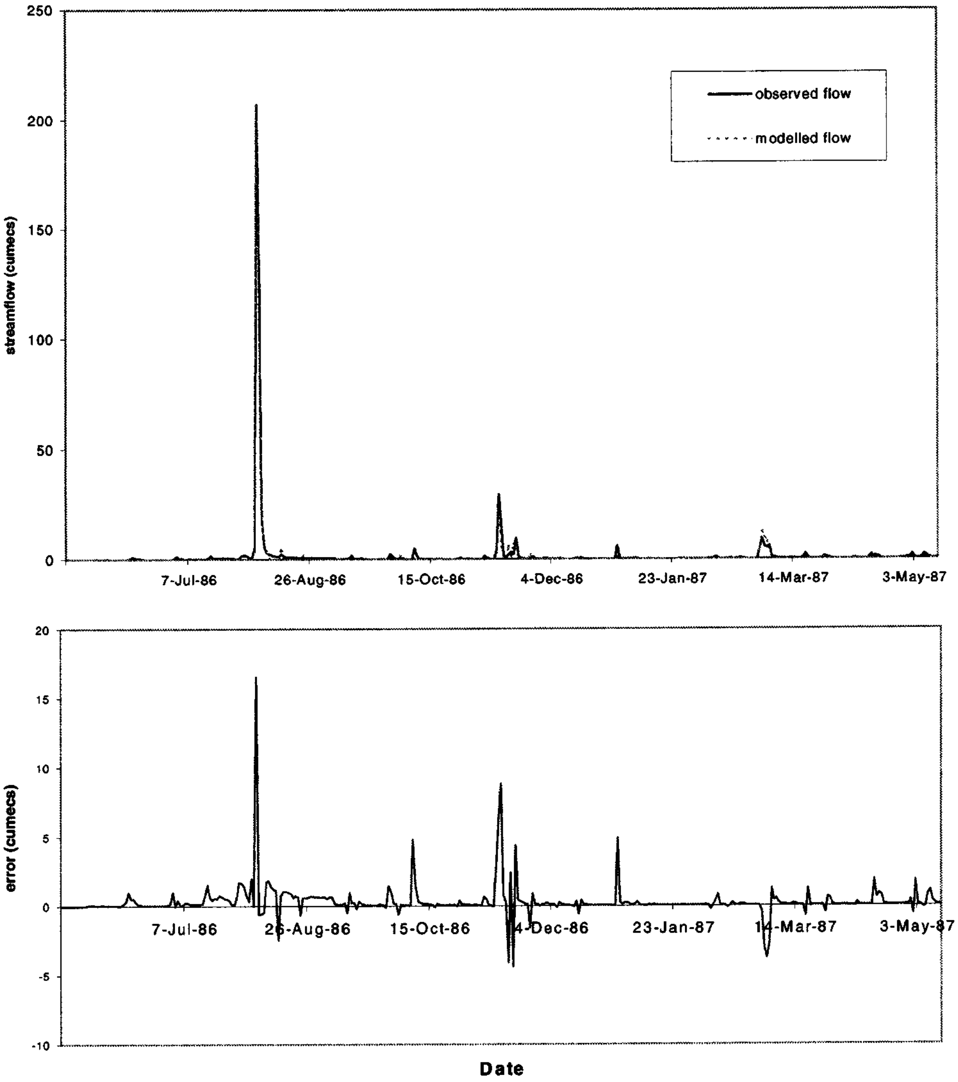

Figure 2. IHACRES calibration results for the Upper Parramatta River for the 1986 flood.

of utilising the stochastic weather generator methodology. The Queanbeyan River catchment is the only one among the three regions considered where the two-reservoir structure of the model has been applied. The largest streamflow event during the instrumented period occurred on 21-3-1978 and has a discharge value of 247 cumecs. Correspondingly, the calibration period was selected so that this event is included, it is a two year period starting on 17-7-1977. The calibration efficiency obtained is E = 0.724 and the result of calibration is presented in Figure 4. The simulation test for this model was implemented over the whole period where the

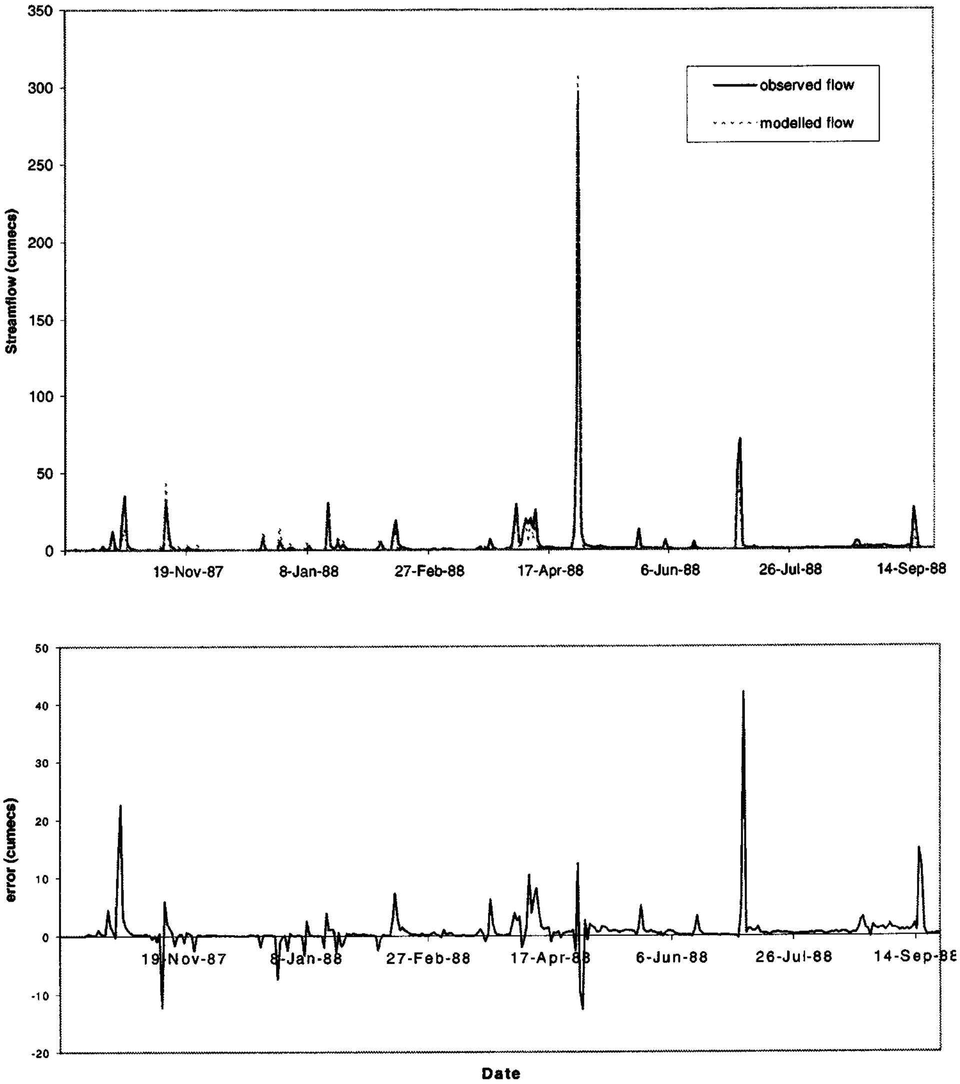

Figure 3. IHACRES calibration results for the Upper Parramatta River for the 1988 flood.

flow data are available, from 1966–1992. The simulation efficiency obtained is E = 0.619.

9.3. THE HAWKESBURY–NEPEAN CATCHMENT

The upper catchment of the Hawkesbury–Nepean comprises two major tributaries, the Nepean and Warragamba Rivers, which join to form the main Hawkesbury River. This lower section of the river, locally termed the Hawkesbury–Nepean, is a major growth area for Sydney but also has a major risk from river flooding. The

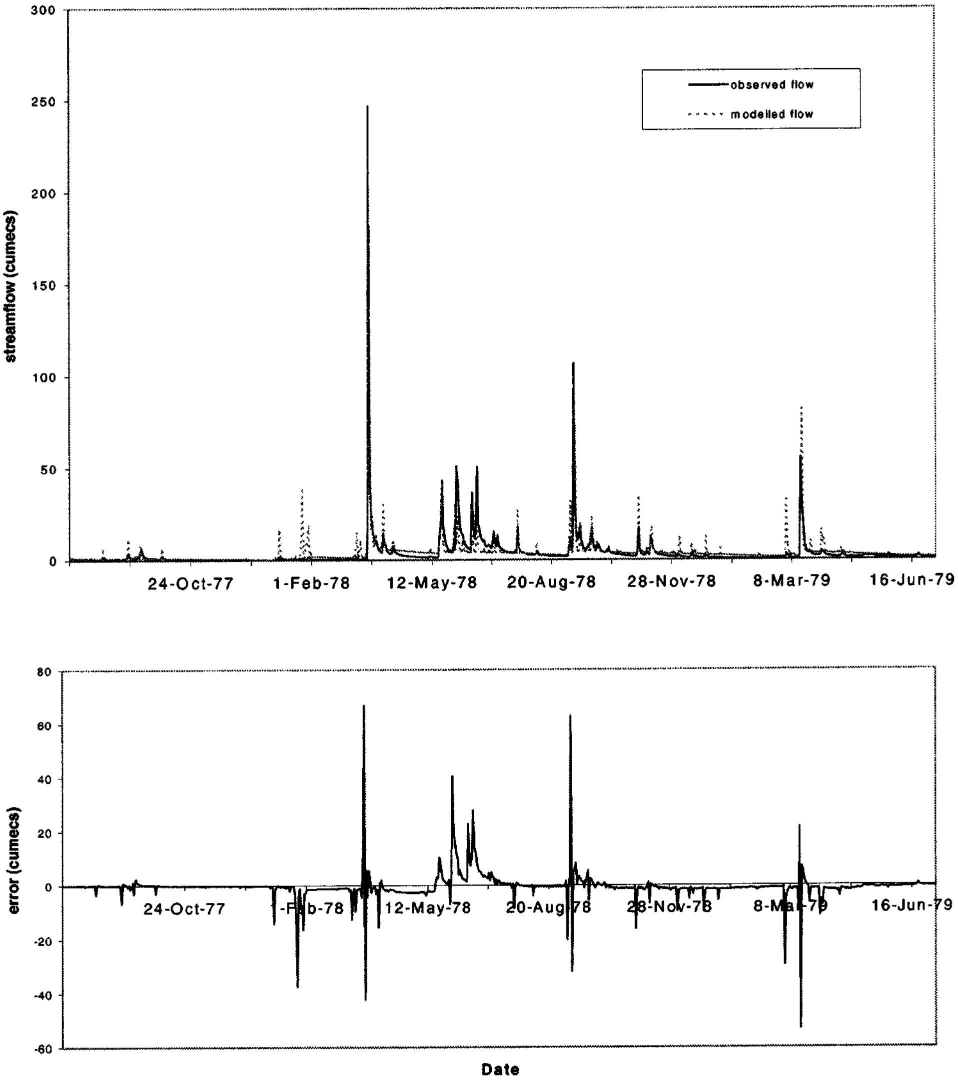

Figure 4. The IHACRES calibration results for the Queanbeyan River catchment for the period 1977–1979.

main difficulty of streamflow modelling in this basin is that the flow regime here is strongly affected by artificial regulation: firstly, by the Warragamba Dam which forms the Lake Burragorang storage reservoir and, secondly, by a series of smaller dams in the headwaters of the Nepean River and its tributaries: the Avon, Cordeaux and Cataract Rivers (SWB, 1994). In addition, the climatology in the basin is very heterogeneous. It is relatively dry in its southern part, whereas in the northwest a wet oceanic climate prevails.

The streamflow data for the model calibration are taken from the Warragamba Dam outlet. These were recorded for nine major flood events since 1964 with an hourly time step, over periods of two to three days for each flood event. The hourly rainfall data for each flood event were collected for a set of meteorological stations within the catchment. There were difficulties in obtaining suitable rainfall records for time series modelling from within the catchment used for runoff analysis. The strategy adopted was to use data, for precipitation and temperature, from stations some 50 km distant from Warragamba.

The streamflow data for calibration were aggregated from an hourly time step to the daily one. The gaps between flood events were arbitrarily assumed as having zero values of baseflow. Therefore, only a one store structure for the linear module of the IHACRES model was applied in this case. The advantage of this approach is that the model is calibrated against continuous climatic time series. This makes it possible to apply both methodologies (the stochastic weather generator and climate scenarios) for generating climatic inputs to the runoff model. The two highest flow events occurred on almost the same days as in those used in the Upper Parramatta catchment. The flood on 6 August 1986 had a mean daily discharge of 28.21 cumecs at the Warragamba Dam outlet and on 1 May 1988 a discharge of 37.67 cumecs. The one day delay compared with the Upper Parramatta catchment is related to the much larger size of the Hawkesbury–Nepean catchment. A one-year calibration period was selected for model calibration in this catchment, starting on 1 October 1987. The results of calibration in terms of the Nash-Sutcliffe efficiency is $E = 0.726$. A simulation test using the model calibrated for the 1988 event was applied to the one-year period starting on 19 May 1986. The simulation results are $E = 0.551$ for the 1988 model applied on the 1986 period.

10. Possible Change in Flood Frequencies under the Double CO_2 Conditions and Climate Scenarios for 2030 and 2070

Comparison of the ARI estimated for the resultant synthetic discharge time series for $1 \times CO_2$ with the results of a partial series flood frequency analysis of the historical streamflow data (DWR, 1989) was undertaken. These results are summarised in Table II. Some level of uncertainty in the right column exists since there were no streamflow events with the same magnitude of discharge in the simulated streamflow series. Despite the fact that only two substantial flood events have been recorded during the instrumented period, the results presented in Table II show that the synthetic data series produced by the stochastic weather generator and the rainfall-runoff model corresponds well to the historical data. The results of the changes to flood frequency in the Toongabbie area, Queanbeyan and the Hawkesbury-Nepean corridor for double CO_2 conditions are presented in Table III. The changes for Canberra, the Australian national capital, are assumed to match

TABLE II

Results of a partial series flood frequency analysis of historical data for the Upper Parramatta catchment and the ARI estimated for a 100 year 1 × CO_2 synthetic times series of discharge produced by the stochastic weather generator IHACRES

Flood	ARI estimated by partial series flood frequency analysis of historical data	ARI estimated from 1 × CO_2 series produced by stochastic weather generator
1986	22 years	31–32 years
1988	63 years	62–66 years

TABLE III

Comparison of present flood frequency and that for the double CO_2 conditions estimated using the stochastic weather generator and IHACRES

ARI	The Upper Parramatta catchment		The Queanbeyan catchment		The Hawkesbury-Nepean corridor	
(years)	Discharge value for the present, cumecs	Change in frequency (ARI under 2 × CO_2) for the flow events of this magnitude (years)	Discharge value for the present, cumecs	Change in frequency (ARI under 2 × CO_2) for the flow events of this magnitude (years)	Discharge value for the present, cumecs	Change in frequency (ARI under 2 × CO_2) for the flow events of this magnitude (years)
5	86.2	2	83.4	1	16.9	1.7
10	118.2	3.3	104.8	1.8	n/a	n/a
20	n/a	n/a	n/a	n/a	23.9	3.2
50	252	17	158.2	5.8	n/a	n/a
100	362	44	182.2	9.4	68.3	35.7
1000	1134	400	361.4	100	242.3	500

those for Queanbeyan. This is because Canberra is only about 10 km downstream of Queanbeyan.

Some additional comments relating to Table III should be made. A 1 in 5-year flood event is arbitrarily selected as a threshold where no flood damage occurs. Thus, the estimation for future changes in damage caused by events of such magnitude is not calculated. The changes in PMF cannot be estimated using the methodology applied in the present work. PMF is plotted as a 1 in 10,000 years flood event.

Table IV illustrates how the recurrence intervals for high flow events change under the ‘most wet’ and ‘most dry’ climate scenarios at 2030 and 2070 in the Queanbeyan, Upper Parramatta and Hawkesbury-Nepean catchments. The results say little about changes in the ARI of flood events, because the instrumental periods

TABLE IV

Changes in the streamflow discharge corresponding to the different recurrence intervals under the DAR CSIRO 'most wet' and 'most-dry' climate scenarios for 2030 and 2070

Recurrence Interval (years)	Discharge value (cumecs) corresponding to this Recurrence Interval				
	Present	'Most wet' scenarios 2030	'Most wet' scenarios 2070	'Most dry' scenarios 2030	'Most dry' scenarios 2070
The Upper Parramatta catchment					
4.3	158.7	185.0	207.2	158.6	158.5
6.5	177.3	204.2	228.0	172.7	166.2
13.0	208.0	207.7	246.8	191.1	167.2
The Queanbeyan River catchment					
4.8	172.6	199.2	244.3	168.8	162.9
6.0	239.5	276.8	294.7	234.8	227.1
8.0	298.2	296.1	325.8	270.7	232.2
12.0	330.1	327.5	339.7	299.1	256.1
24.0	344.9	343.4	342.5	314.9	272.7
The Hawkesbury-Nepean corridor					
4.3	29.6	31.4	38.8	27.2	26.9
6.5	35.4	41.0	44.5	34.9	34.2
13.0	44.6	44.6	50.0	41.0	36.0

are very short in the region considered; only 13 years in the Upper Parramatta and Hawkesbury-Nepean catchments, and 24 years in the Queanbeyan River catchment. However, these Tables show that the changes in recurrence intervals, of the order of about 10–20 years, are insignificant for 2030.

11. Vulnerability and Flood Damage

The aim of this Section is to provide estimates of the changes to urban flood damages under climates associated with an atmosphere containing double the present CO_2, estimated using the SWG technique (see Section 4). The detailed direct damage estimates for the double CO_2 scenario are presented in 1996 Australian dollars *($AU)*, for three major flood prone urban locations: Queanbeyan, Canberra and the Hawkesbury-Nepean corridor. Consideration is also given to the 'best' case option (the 'dry' GCM scenarios from Table I).

The Toongabbie Creek area of the Upper Parramatta River was not considered in this part of this study because of the lack of detailed residential and commercial property data in this catchment. It was, however, included in the hydrological analysis because it is an example of a small, highly urbanised catchment. Flooding in such catchments is of key importance to the overall analysis of urban flood loss and the Upper Parramatta catchment is unusual in that the quality of the hydrological data, although of limited time duration, is exceptionally good.

The procedure followed in this study is to use the original (year 1996) damage estimates, updated for inflation to mid-1996[⋆] and then to increase these using the changes in magnitude and frequency for the greenhouse climate changes. The original estimates are based on information recorded in the field for every individual building (residential, commercial and industrial) at risk. The original surveys are unique in that the building data base extends beyond the limits of the contemporary estimates for probable maximum flood, which can be considered as the largest flood that could be expected under the prevailing climate conditions. The reason for the extended building data base was that the initial studies were designed to assess the impacts that could be expected not only from riverine inundation but for the much more severe case of upstream dam failure. A review of the original studies and their implications for flood damage, dam design and warning systems is given in Smith (1990). The significance of this is that the building data base extends beyond the height that would be attained by the current 1 in 100 years flood event. Therefore, the building data bases can be used to assess increases in flood magnitude that may result from the effects of a doubling in atmospheric CO_2. It should be noted that the normal practice in flood damage estimation, worldwide, is to only record information for buildings to the level of the 1 in 100 year event. The availability of these pre-existing data bases played a major role in the selection of the study sites for the present work. It should also be noted that no additional information was collected on changes to the number or uses of buildings since the original surveys undertaken in the late 1980s. The implications of this are only of minor significance to the conclusions. The original (present) direct damage, estimated for Queanbeyan, Canberra and the Hawkesbury-Nepean corridor, is compared with that for the double CO_2 climate in Section 11.2.

11.1. DIRECT DAMAGE – DEFINITIONS AND METHODS

Before discussing the estimation of changes in direct damage for the case study sites, it is necessary to provide background on the definition of flooding, the effects of building failure and the estimation of average annual damage (AAD).

11.1.1. *Definition of Flooding*

Compared to most other natural hazards, there is little debate on what constitutes a flood event and how to estimate magnitude and frequency. However, in order to estimate building damage there is a major difference between a property where inundation is limited solely to overground inundation as opposed to overfloor flood-

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[⋆] The annual inflation in Australia in mid-1996 was 3.1%. This value is considered to be a more realistic estimate for future extrapolation than the abnormally low annual inflation of 1.6% at present.

ing. Although the former results in damage to gardens and grounds (i.e., garages, swimming pools etc), it causes much less damage than when flooding exceeds floor level. Normally, the stage damage curves used to estimate damage to differing classes of building are only applicable to overfloor inundation. This relates direct damage to contents and structure (including walls, built-in furniture, etc.) to the depth of overfloor flooding. The description of use of stage damage curves is given in Smith (1994).

The ANUFLOOD program (Smith and Greenway, 1988), employed for the direct flood damage estimates in the present study, provides a separate routine that estimates losses for flooding restricted to overground inundation, i.e., for floods that do not exceed floor level. For buildings with overfloor damage the ANUFLOOD program adds the overground losses to those for overfloor flooding obtained from the appropriate stage damage curve. This procedure can be especially important in evaluating residential losses because, in some instances, floor level can be significantly higher than ground level. However, the estimates for direct event damage (1 in 20, 1 in 100 years, etc.), given in this paper, incorporate both overground and overfloor components. In the case study descriptions, the numbers of flood affected residential properties are presented solely in terms of overfloor flooding. The reason for this is that overfloor inundation is much more significant in the assessment of all forms of flood loss.

11.1.2. *Building Failure*

The use of stage damage curves for different classes of buildings represents the standard approach for the assessment of urban flood damage. However, for extreme floods there is the additional possibility of severe losses due to failure of the building structure. This is more likely to effect lightweight single storey buildings and is potentially a problem in those parts of Australia where the older housing stock is often dominated by detached single storey weatherboard (wooden) dwellings. Structural failure is most likely with a combination of high overfloor flood depth (stage) and high flood flow velocities. Information on the critical combinations of depth and velocity for failure in relation to differing building styles are available from studies undertaken in the U.S.A. during the mid-1970s, for example Black (1975). A detailed review of building failure under extreme flood conditions in Australia is given in Smith (1991).

In order to apply the data summarised by Black (1975), reliable estimates of over-floodplain flood velocities are required. Generally these are not available but Queanbeyan, Canberra and the Hawkesbury–Nepean corridor are exceptions. The reason for this is that building failure is accepted as an important consequence in assessing potential losses from upstream dam failure and estimates of over-floodplain velocities for extreme events were available in the background hydrological studies. Apart from these studies, data on the velocities of flood flows in Australia, and elsewhere, are sparse.

Provided that the appropriate flood velocities are available, routines to estimate flood losses due to building failure are incorporated into the ANUFLOOD program. The direct damage for failure assumes the total loss of all contents, with structural building loss assessed as rebuilding costs based on estimates available from the insurance industry.

The differences in flood damage for extreme events (i.e., exceeding that of the 1 in 100 year event) due to building failure, compared to those that ignore this factor, can be large. For instance, for Queanbeyan the direct damages for all building sectors for the 1 in 1,000 event is between three and four times larger with the inclusion of failure losses (see Smith, 1991). The flood damage estimates, under present conditions and with enhanced CO_2, presented in this account incorporate the additional losses due to building failure.

11.1.3. *Average Annual Damage*

It is accepted practice in flood damage assessment to report flood losses in terms of average annual damage (AAD). This consolidates the effects of magnitude and frequency of events into a single statistic. The AAD for an urban location can be regarded as the annual premium (without allowance for profit, etc.) to insure the total building stock and contents against flood loss. In this work all estimates of AAD, for flood damage both under present conditions and for a doubling of carbon dioxide, are based on the assumption that the probable maximum flood is the equivalent of the 1 in 10,000 year flood event. The AAD reported for direct flood damage includes losses to contents and structures due to building failure.

11.2. DIRECT DAMAGES UNDER CLIMATE CHANGE CONDITIONS

The direct damages under current and greenhouse climatic conditions depend on the number of buildings at risk and upon their distribution in relation to flood height. The GCM slab model scenarios (see Table I) at all three sites indicate only minor changes in flood frequencies (see Table III) and represent a ‘no change’ situation in terms of possible policy response. The results for the double CO_2 scenario, obtained using the SWG technique (see Section 4), are presented in Figures 5 and 6, first for numbers of buildings and then in terms of direct flood damage.

11.2.1. *Number of Buildings*

The numbers of residential buildings at risk from flooding, expressed in terms of overfloor inundation, for Queanbeyan, Canberra and the Hawkesbury–Nepean corridor, are shown in Figure 5. It is clear that, in all cases, there is a major increase in the number of buildings at risk from flooding for the double CO_2 scenario. For example at Queanbeyan, with the largest increase in flood frequency under greenhouse conditions, the total number of buildings at risk for a 1 in 100 total year event increases from 450 to 1200, the corresponding numbers for the Hawkesbury–Nepean are 1750 to 6500.

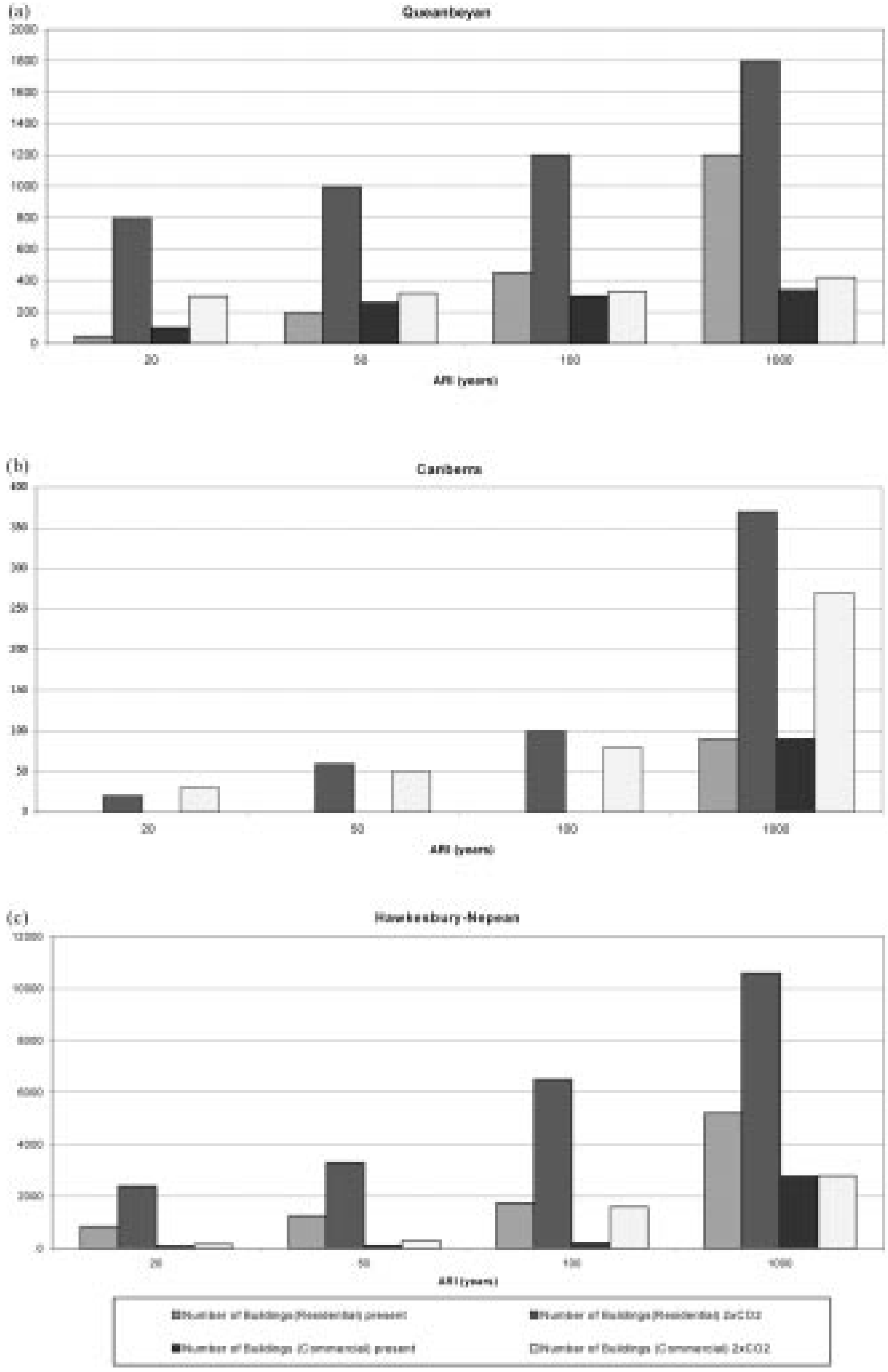

Figure 5. Numbers of residential and commercial/industrial buildings liable to overfloor flooding under present and double CO_2 climate conditions.

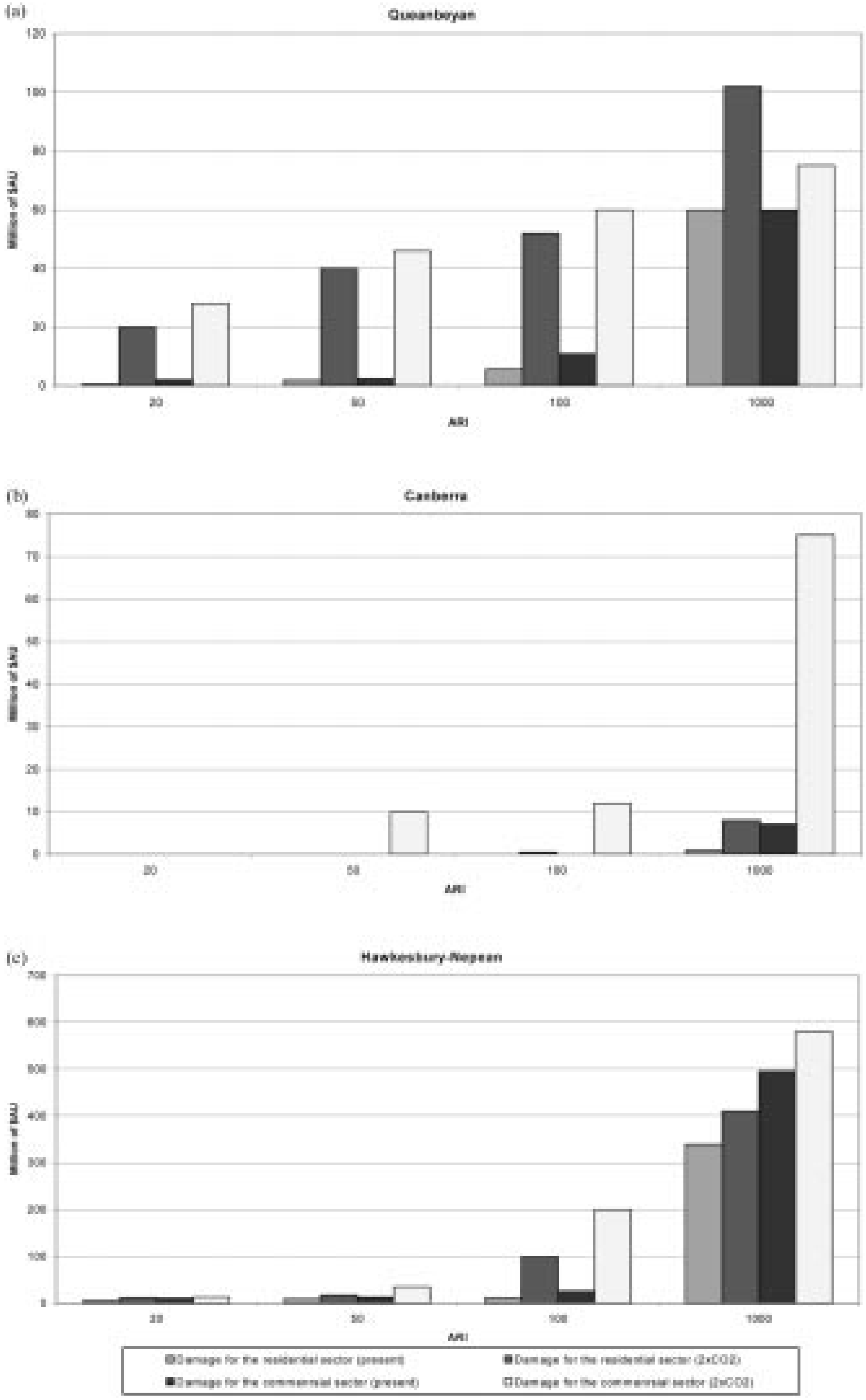

Figure 6. Direct flood damages for the residential and commercial/industrial sectors under present and double CO_2 climate conditions.

TABLE V

The average annual direct flood damage for Queanbeyan, Canberra and the Hawkesbury–Nepean corridor under present day and double CO_2 climates

Catchment	Residential	Commercial	Total	Residential	Commercial	Total
Queanbeyan	0.55	0.69	1.24	5.40	6.75	12.15
Canberra	<0.001	0.007	0.007	0.001	0.07	0.07
Hawkesbury–Nepean	3.76	2.34	6.10	14.29	8.91	13.20

All values in million $AU at mid-1996 prices.

11.2.2. *Direct Urban Damage*

Direct damage for the residential sector under current and the double CO_2 scenario for Queanbeyan, Canberra and the Hawkesbury–Nepean corridor are given in Figure 6. This Figure gives quantitative estimates for the increases in direct flood damage to buildings and their contents and incorporates the effects of any building failure. The increases under the double CO_2 scenarios are substantial and, for comparative purposes are best presented as in terms of average annual direct damage, which are given in Table V.

The AAD under the double CO_2 conditions for Queanbeyan and Canberra increase by a factor of 9.8 and for the Hawkesbury–Nepean corridor by 3.8. Although quantitative estimates for the Toongabbie area are not available, the increase in damages would be a factor of about 2.5.

A salient feature in all cases is the significant increase in the numbers of buildings at risk and in flood damages above the level of the current 1 in 100 year flood. This is due to the cumulative effects, over many years, of land use regulations that limited building development below this level.

12. Discussion and Conclusions

An estimation of changes in flood frequency under future climate conditions has been undertaken using a rainfall-runoff model with two approaches for generating daily climatic inputs to the model: a stochastic weather generator applied to estimate the changes in climate under double CO_2 conditions, and the climate scenarios provided by the DAR CSIRO for two dates in the future: 2030 and 2070. A useful simple single statistic, widely used to summarise flood damage, is average annual damage (AAD). Essentially it integrates flood frequency and damage across the whole range of flood probabilities. Using the hydrology for the double CO_2 conditions, the AAD for the Hawkesbury–Nepean and Queanbeyan (and Canberra) increase by factors of 3.8 and 9.8 respectively.

The DAR CSIRO climate scenarios for 2030 and 2070 yield lower estimates of increases in flood damage: small changes at 2030 and about a 10% increase at

2070 for all three regions considered. However, these results should be interpreted cautiously because only short historical records (24 years for Queanbeyan and 13 years for Upper Parramatta and Hawkesbury–Nepean) have been transformed for these scenarios in order to evaluate future changes in flood damage. A discussion of the considerable difference in climate change produced between the climate scenarios and the stochastic weather generator methodology is not within the scope of this study.

One conclusion that can be obtained from our results is the importance of the use of a conceptual rainfall-runoff model for estimating the direct changes in runoff under different climatic conditions. This can be illustrated by the example of the Upper Parramatta and Hawkesbury–Nepean catchments. Despite the fact that both catchment models are calibrated using the same historical climatic time series of precipitation and temperature as inputs, the estimated changes in flood hydrology, and therefore in direct flood damage, are different in the two areas. This is explained by the difference in their geomorphological and land use characteristics mirrored in the different values of the model parameters (catchment response dynamics) for these areas. Indeed, despite all its assumptions, the study demonstrates that changes in flood losses due to greenhouse climate change can be expected to vary from place to place reflecting the uniqueness of both the hydrological setting and the development of flood-prone structures.

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