Urban Flooding - Greenhouse Climate Modelling, Flood Hydrology And Damages

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Abstract The literature on the impacts of extreme events under greenhouse-induced climates draws attention to the potential of increased urban flood damages. However, few studies have attempted to model the changes to flood hydrology and to convert these to changes in flood damages. Modelling methodologies are outlined for both aspects of the problem. For flood hydrology the preferred combination is to use an established conceptual rain-runoff model, IHACRES, with a stochastic weather generator to provide the inputs for future greenhouse precipitation. Results are presented for three flood prone urban communities in south-eastern Australia. Detailed attention is given to the 'most wet' option for the year 2070; analysis of the 'most dry' case indicates little change from present day conditions.

The flood frequencies for the worst case ('most wet') option are used with a computer package, ANUFLOOD, to assess the changes to urban flood damage for the case study sites. The estimates are based on building data bases for all the case study areas that contain information for all buildings (residential, commercial and industrial) at risk to the level of the highest flood under double CO_2 conditions, ie. for the year 2070. ANUFLOOD also incorporates the enhanced damages due to building failure from extreme floods.

The results are presented as changes to the number of buildings at risk, to changes in direct flood damage (separately for the residential , commercial and industrial sectors) and as increases to the liability for building failure. For the ('most wet') option there are large increases to direct losses to building structure and contents. For the year 2070, these are estimated to increase average annual damage, for the case study sites, by factors of between 2.5 and 9.8. For the 'most dry' option the damages would be comparable to, or slightly less than, those experienced under present day conditions of flood frequency and magnitude. The results are subject to considerable uncertainty but the methodology is considered to represent the best available. An outline is given of the problems the results pose for floodplain management and policy

1. INTRODUCTION

Many natural hazards are closely related to the frequency of occurrence of extreme meteorological and climatic events. If such frequencies were to increase under greenhouse-induced climates there would be an increase not only in hazard risk but, for many areas, in vulnerability and losses. Riverine flooding, and especially increased risk to existing flood prone urban developments, are often cited as examples of potentially major adverse effects of future greenhouse-induced climates. However, there is a paucity of studies that provide quantitative or descriptive estimates of the magnitude of losses, tangible or intangible, that would result from such climate change. The IPCC review of the economic and social dimensions of postulated greenhouse succinctly comments that, for river flooding, '...little information is currently available regarding the socioeconomic impacts of changes in the frequency and intensity of river floods'[Bruce *et al.*, p.202, 1996].

There are two obstacles to the assessment of the possible changes to urban flood damage under greenhouse conditions. These are:

- how to convert greenhouse climate scenarios into the effects on flood hydrology;
- how to convert changes in flood hydrology to estimates of tangible and intangible losses.

Both present challenges for modelling. This account outlines approaches used to provide methodologies to assess the potential impact of climate change for four Australian case studies. These are for Toongabbie in the Upper Parramatta catchment, Queanbeyan and Canberra in the Molonglo catchment, and the urban developments along the Hawkesbury-Nepean in western Sydney. A more detailed account is available in Smith *et al.* [1997]. A major obstacle to progress is that damaging urban floods are statistically low probability events. It is unusual for urban damage to be of significance for a flood with annual recurrence interval (ARI) of less than 1 in 5 years, ie an annual probability of 0.05. It is the very rare events, with ARIs of 1 in 100 years or worse, that have the potential to produce catastrophic losses.

2 FLOOD HYDROLOGY AND GREENHOUSE CHANGE

2.1 Scenarios and Assumptions

The greenhouse climate scenarios employed are those provided by CSIRO for Australia [CIG, 1996], a summary of these applicable to the region in which all of the case studies are located is given in Table 1. These are based on the latest IPCC [1996] information which are an amalgam of the results from five global climate models (GCMs). Scenarios are presented for two future dates, 2030 and 2070, the latter of which is assumed to be the year when atmospheric carbon dioxide concentrations will have doubled. All such greenhouse scenarios are subject to substantial uncertainty and to assist with the interpretation of the results two cases are considered, the 'most wet' and 'most dry' cases.

Emphasis is given to the worst case (ie the 'most wet') scenario and the projected effects for the year 2070.

Table 1: Climate scenarios for 2030 and 2070 from CIG [1996]

PRECIPITATION		
	2030	2070
Winter	-8 to 0%	-20% to 0%
Summer	-4 to 4%	-10% to +10%

The analysis is subject to all the caveats and assumptions that surround all greenhouse scenarios, magnified by the necessity to extend the hydrological effects to changes in very rare events, ie. to the 1 in 10,000 ARI event, and the assumption that catchment conditions (ie. type and nature of land cover) will remain constant to the year 2070.

2.2 Hydrological Modelling

The structure of the methodology follows the steps outlined below.

1. Calibration of the rainfall-runoff model using historical records of precipitation, temperature and stream discharge.
2. Testing of the model by validation or simulation runs. The model parameters estimated for the calibration period are applied to a separate validation period without changing their values. The validation period precipitation time series then becomes the input to the model and the modelled streamflow is then compared with the measured values for the period.
3. Generation of future climatic data series. Two approaches have been used; one transforms the present climatic time series according to the scenarios presented in CIG [1996], the other uses the output from a stochastic weather generator.
4. Use of the hypothetical time series as an input into the model to produce streamflow data for the future.
5. Estimation of changes in the ARI for flood events of different magnitudes.

There are three types of model that could be used to for the rainfall-runoff modelling in Step 1. These can be termed empirical, physically-based or conceptual, the relative merits and limitations of each are reviewed in Wheater *et al.* [1993]. 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. IHACRES was selected. This can be described as a hybrid metric-conceptual model based on the use of the instantaneous unit hydrograph. The model and a selection of applications are described in Jakeman *et al* [1990] and Jakeman and Hornberger [1993]. It is partly metric because measured precipitation-discharge observations are used to infer the configuration and number of stores used to route effective rainfall to stream flow. Such conceptual lumped rainfall-runoff models are considered to be the most adequate for streamflow analysis for the regions and purposes of this study. The number of parameters (six) is small compared to other conceptual models, yet its performance is impressive across a range of hydro-climatologies [see Jakeman and Hornberger, 1993].

Step 2 applies the model parameters estimated for the calibration period to another period without changing their values and then, the modelled streamflow is compared to the measured values of streamflow for this period.

Two different methodologies were used for the modelling involved in Step 3 of the analysis. The first was based on the CIG [1996] scenarios and the climate time series for precipitation and temperature were transformed according to the relevant climate scenario ('most wet' in our case because of its greater relevance to the study). However, Bates *et al.* [1993 and 1994] and Charles *et al.* [1993] have drawn attention to the limitations of this approach. The direct scaling of historical climate records using GCM outputs to estimate possible climate impacts may be considered improper due to the coarse resolution of the GCM spatial grids and the simplified GCM representation of the land surface-atmosphere-ocean interactions. They recommend the use of stochastic weather generators as an alternative method to estimate possible climate impacts on streamflow. Bates and Charles undertook such analysis for the Queanbeyan (and Canberra) and Upper Parramatta catchments reported here. A 1000 year daily weather time series was generated for a future with double present CO_2 concentrations.

The results from the weather generator were used, in Step 4, as an input into IHACRES to estimate the corresponding future changes in runoff. The disadvantage of this approach is that the stochastic weather generator is related to a single GCM, namely CSIRO9, described in McGregor *et al.*, [1993].

Step 5 converts the future streamflow data into frequencies that correspond to ARIs, usually for 10, 20, 50, 100, 1000 years and for the probable maximum flood, assumed to be the equivalent of the 1 in 10,000 year event. These data are required to estimate depth of inundation and are therefore converted from discharge units into stage heights.

2.3 Flood hydrology - the results

There are wide variations between the results for the 'most dry' and 'most wet' scenarios.

'Most wet' scenarios. The changes can be summarised as:

- a marked decrease in the ARIs, ie increase in flood probability, at all the localities studied
- the size of the decrease varies between the three sites
- there are indications that the decreases in ARI are less in the period from present to 2030 than between 2030 and 2070.
- a possibility that decreases in ARI are greater for drier, and therefore generally inland locations, than for more humid coastal regions.

The changes to the ARIs are illustrated in Figures 3 to 6. These indicate that by the year 2070, the present 1 in 100 year ARI for the Upper Parramatta River would have changed to the 1 in 44 year, to the 1 in 10 year for Queanbeyan and Canberra and the 1 in 35 year for the Hawkesbury-Nepean corridor. At each site the degree of change varies with flood frequency. If these variations are integrated over the whole frequency range, a single statistic can be obtained to indicate overall change in flood risk. These average annual changes, by the year 2070, increase by factors of 2.5, 3.8 and 3.8 for the Upper Parramatta catchment, the Hawkesbury-Nepean and Queanbeyan (and Canberra) respectively.

'Most dry' scenario. In contrast, for the 'most dry' case the changes in ARI are small and by the year 2070 are likely to remain similar to those under present climatic conditions or for the ARIs to have slightly increased. This is the reason for the concentration in this account upon the worst case scenario.

The CIG [1996] climate scenarios for 2030 and 2070 were also used with IHACRES alone, ie. without the use of a weather generator, to provide estimates of future flood discharges. In this case, long term means of the climate series (precipitation and temperature) were scaled according to the climate scenarios. The results give more optimistic estimates of changes, almost no change at 2030 and about a 10% increase at 2070 for all the sites considered. However, there is need for caution in interpreting these results as the historical records available for the three sites are limited to 24 years for Queanbeyan and 13 years for the Upper Parramatta and Hawkesbury-Nepean. Such limitations are not unique to the sites studied. Major changes to catchment conditions, dams, water off-takes, urbanisation etc all limit the available data especially for established urban locations.

The future changes in flood frequency used to assess the implications for urban flood damage and policy are illustrated in Figures 3 to 6. These are based upon the use of IHACRES, a conceptual rainfall-runoff model, to obtain runoff estimates combined with the use of a stochastic weather generator to provide the rainfall input from the greenhouse scenarios. This combination is considered to provide the best methodology for converting greenhouse scenarios into estimates of future flood frequencies. Discussion of the considerable difference in climate change using the climate scenarios and the stochastic weather generator are outside the scope of this presentation.

3 FLOOD DAMAGES

3.1 The background

The basic methodology for the estimation of urban flood losses was established some fifty years ago in the USA, see White [1945]. Three classes of input are required: a data base for all flood prone buildings, stage-damage curves and the frequency and magnitude of flooding.

The building data base includes ground and floor height, building material, size etc. and is geo-coded for location; slightly different procedures are used for the residential, commercial and industrial sectors. Stage-damage curves are an averaging procedure that estimate the flood damage that would occur for different levels of overfloor inundation for different classes of buildings. For example, residential buildings may be divided into differing categories depending on construction material, commercial and industrial stage-damage curves are based on type of activity and size, eg. type of retail outlets, large storage concerns etc. To obtain the flood damages for a single flood event, eg. the 1 in 20 year, the height and slope of the flood surface are combined with the building data base and stage-damage curves. Such analysis is normally undertaken using a computer package, in this case ANUFLOOD a commercially available program widely used for such purposes since the early 1980s and described in Smith and Greenaway [1988]. The damage estimates from a range of individual flood heights are combined to give a single statistic, average annual damage (AAD) which integrates the flood losses and probability. AAD can be considered as equivalent to the annual insurance premium to cover all potential flood losses for the whole urban community (without the addition of administrative costs, profit etc).

It is theoretically a relatively simple matter to assess the changes to flood damages under greenhouse conditions - the only change is to the component of the package that relates to flood frequency and magnitude. Such procedures are routinely used to evaluate the changes to AAD for a range of flood mitigation measures, for instance construction upstream of a flood retention dam. There are however, a number of assumptions and cautions to such a simple application for climate change. The first is that the building stock, and its use, remains unaltered and a number of other limitations on how AAD values are normally estimated. Secondly, stage damage curves only assess direct flood losses to building structure and contents. The assessment of indirect damages, such as loss of trade and alternative accommodation, or of intangible effects that range from loss of building confidence to adverse health effects and to death. For simplicity, in this account quantitative results will be limited to direct losses. Technically the AAD values presented are for average annual direct damages (AADD).

A reason for the selection of the case study sites was that suitable building data bases already existed for Queanbeyan, Canberra and the Hawkesbury-Nepean corridor. In all three cases these were collected in the late 1980s in order to assess studies of potential losses from dam failure; a summary of the results is presented in Smith [1990]. Because of the enhanced flood depths of dam failure inundation the data bases extended well above the level of the probable maximum flood, the worst case natural flood that could occur under present climatic conditions. The data bases have not been updated but all the loss estimates are converted to mid-1996 values.

3.2 Extreme floods

It is common practice in flood damage studies to only consider damages to the level of a specified design flood event, usually the 1 in 100 year ARI flood line. Thus, AADD is calculated using only a portion of the flood damage/probability relationship, illustrated diagrammatically in Figure 1. The errors involved are compounded by the likelihood, for some urban communities, that under extreme conditions there is a risk of building failure for lightweight structures, of which single storey weatherboard dwellings are an example. Smith [1991] presents a detailed review of building failure and its significance for flood damage assessment. Figure 2 illustrates the critical combination of flood height and floodwater velocity for different types of building structure. The information from Figure 2 is incorporated into the ANUFLOOD program which estimates the additional losses due to such failure and the loss of all contents, ie for failure the stage-damage curve approach is over-ridden. All the flood damage estimates in this account incorporate these additional failure losses. The addition of failure losses can greatly increase the AADD, has the potential to cause dramatic increases in intangible losses (often with the possibility of widespread fatalities) and is a key factor in assessing worst case greenhouse climate-induced flood effects.

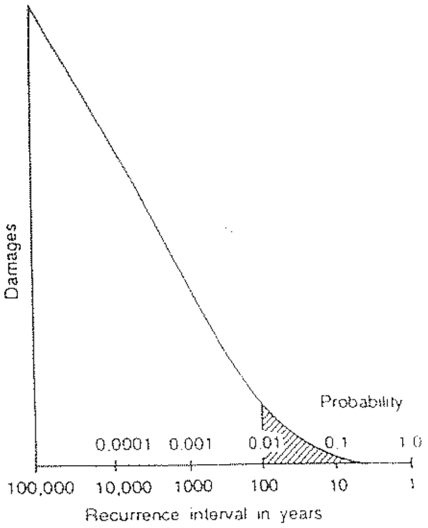

Figure 1: Damage against probability, ADD is obtained by integrating the area under the curve

3.3 FLOOD DAMAGES THE RESULTS

The effects on urban building damage for the 2070, worst case ('most wet') scenario, described in Section 2, are given in Figures 3 to 6. These have been selected to illustrate the changes to the number of buildings at risk (confined to those liable to overfloor inundation), to the direct damages to the residential and commercial sectors and to the number of expected building failures in the residential sector.

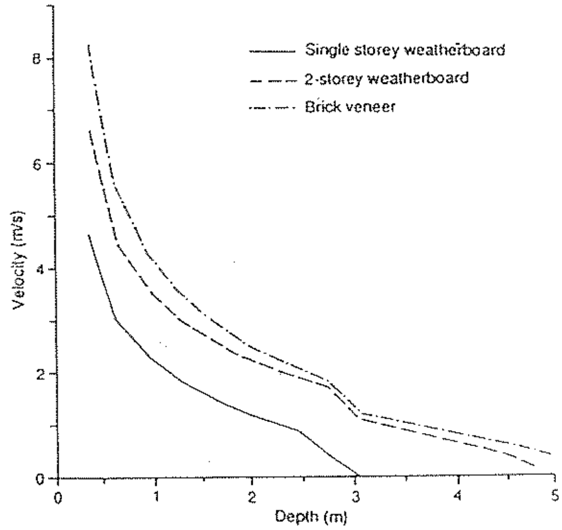

Figure 2: Critical flood velocity and depth for residential building failure, based on Black (1975)

Extrapolation of the results for urban flood damage to other Australian locations are problematic because each flood prone community has a unique combination of hydrology and buildings at risk. However, Figures 3 to 6 show a similar form for all three locations. Under current flood regimes the numbers of buildings at risk and, therefore all forms of flood damage, show a steep rise above the level of the 1 in 100 ARI event. In part, this is due to the controls placed on new developments in flood prone areas, generally defined as the area at risk from the 1 in 100 ARI flood. In this respect, Queanbeyan and the Hawkesbury-Nepean corridor could be atypical of the national picture because both are located in New South Wales which has had exemplary floodplain management and controls for some twenty years. There are no matching State restrictions in Queensland which has a comparable number of flood prone buildings to New South Wales; together they comprise some 85% of the total number of flood prone buildings in Australia. Canberra is unique in that the ACT administration owns all the land and has enforced 1 in 100 years ARI floodplain controls since its inception some eighty years ago. A recent review of the numbers of buildings at risk from flooding in Australia and a background to policy is given in Smith [1996].

Under worst case conditions the buildings clustered close to the designated (planning) flood line become exposed to more frequent flooding with adverse effects for all forms of flood damage. The pattern in Figures 3 to 6 is analogous to a step function.

The annual average direct damages values for the combined residential, commercial and industrial sectors for Queanbeyan, Canberra and the Hawkesbury-Nepean under present conditions are $1.25m, $0.01m and $6.10m respectively, under the 'most wet' 2070 scenario these become $12.15, $0.07m and $23.20m (all at mid-1996 values). The increased risk of residential failure for the Hawkesbury-Nepean corridor, illustrated in Figure 6, is of particular concern and is not acceptable on grounds of safety and potential for fatalities. There the current 1 in 100 ARI flood is estimated to cause the collapse of some 70 dwellings, the equivalent number for the most wet 2070 scenario is some 1200. It is stressed however, that the flood height range at that location is exceptionally large and comparable risk of building failure for most flood prone communities is very much less.

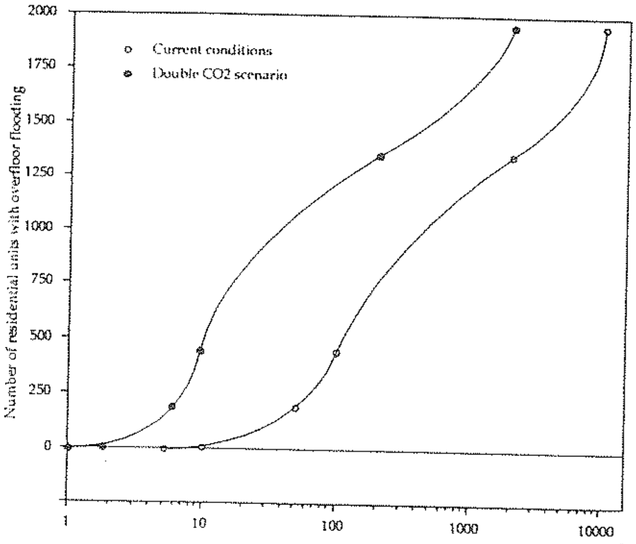

Figure 3: Number of residential units at risk from flooding in Queanbeyan under current conditions and for the most wet 2070 scenario.

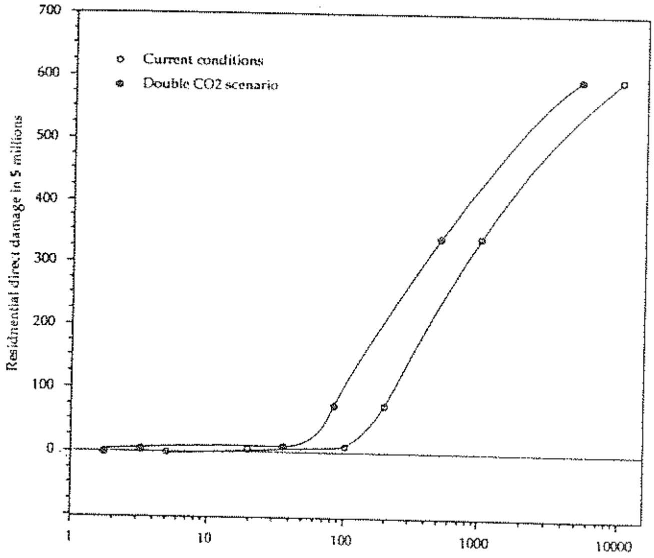

Figure 4: Direct residential flood damage for the Hawkesbury-Nepean for current flood frequencies are for the most wet 2070 scenario.

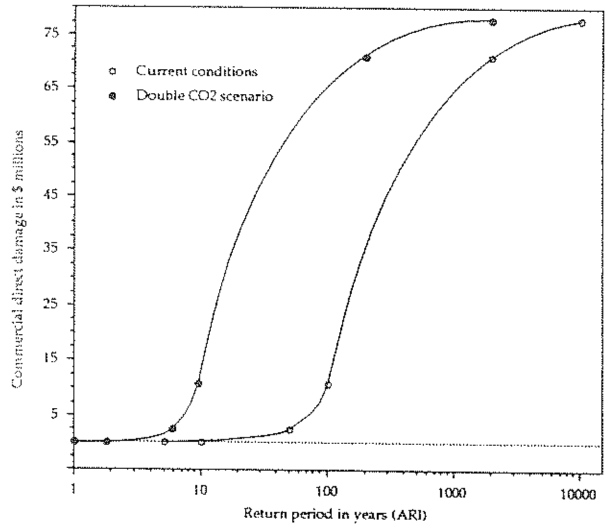

Figure 5: Direct commercial industrial damage for Queanbeyan for current flood frequencies and for the most wet 2070 scenario.

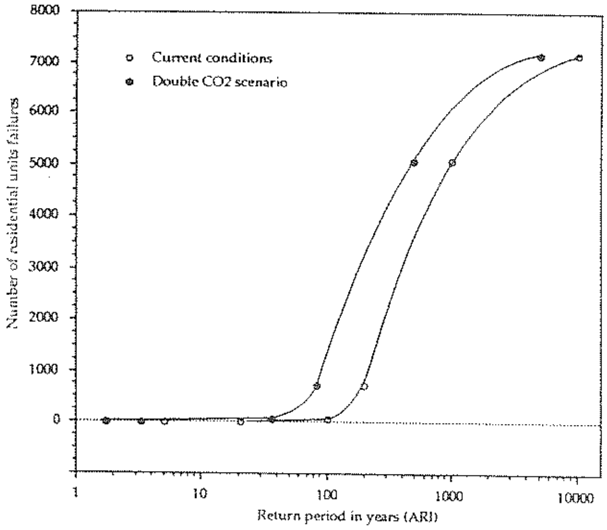

Figure 6: Residential building failure for the Hawkesbury-Nepean for current flood frequencies and for the most wet 2070 scenario.

4. RECOMMENDATIONS AND CONCLUSIONS

The methodology used for the estimation of flood hydrology under greenhouse conditions is considered to be the best available. The outputs, in terms of ARIs as flood stage height, become the inputs from which to model changes to urban damage. The damage modelling should include the effects of extreme floods and the potential effects of building failure.

The only comparable study in the literature, of which we are aware, is for the town of Limburg on the River Meuse in the Netherlands [see Penning-Rowsell *et al.*, 1996]. This indicates a four-fold increase in annual average damage by the year 2070 but the authors do not report the results for best and worst case scenarios.

For those responsible for urban floodplain management and policy at local and State government level the degree of uncertainty surrounding greenhouse effects for flooding is much too great to expect prompt action. A judicious application of policies with features of 'no regrets' and conducive to 'the precautionary principle' is recommended [see Bruce *et al.*, 1996]. The problem of potential building failure at some locations is an example. Attention to this is needed under present flood regimes, its potential benefits under future worst case conditions would be a bonus!

This account is restricted to the effects of possible changes to flood prone buildings. The potential for effects on other forms of flooding, such as urban drainage surcharge and rural inundation are also potentially severe. The most serious concern of all could well be the possible need to retrofit major hazardous dams so that they continue to meet national and international safety standards which are related to the magnitude of the probable maximum flood.

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