GREENHOUSE CLIMATIC CHANGE AND FLOOD DAMAGES, THE IMPLICATIONS

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Abstract. Most scenarios of greenhouse climate change are obtained from general circulation models. These provide poor information on changes to extreme events. It is therefore, difficult to convert changes of flood frequency into their impact on flood damages. The procedures for estimating urban flood losses are outlined. Australian case studies illustrate the possible effects of greenhouse-induced changes in comparison to the variability under current climate; changes in urban flood losses for small and large catchments; and the implications for dam design. In all cases, relatively small increases in flood frequency would cause significant increases in loss. The policy implications are outlined, it must not be assumed that the availability of more precise data on future flood frequencies will be matched by policy response in the field of floodplain management.

1. Introduction

Most predictions and scenarios of future climate, under enhanced greenhouse gas conditions, are obtained from general circulation models (GCMs). These are extensively reviewed by the International Panel on Climate Change, see Houghton *et al.* (1990).

The scenarios for precipitation are acknowledged to be inferior to those for temperature. The majority of future precipitation scenarios relate to mean annual or seasonal estimates. For example, in Australia a widely accepted scenario is for precipitation increases of up to 50% in summer (except in southern regions) and for decreases of up to 10% in winter. Recent revisions and a background to the scenarios are given in Whetton and Pittock (1991). However, even these scenarios are open to doubt. Dr Zillman, Director of the Bureau of Meteorology, in his opening address to a Workshop on The Impacts of Climate Change on Water Resources in June 1991, stated that:

"We do not at this stage have any sound basis for saying whether particular areas of Australia will become wetter or drier, more or less subject to flood or drought than has been the case over the past century".

Information on seasonal variations is of little use for studies concerned with the impacts of future flooding. Rural or urban flood losses, certainly in Australia, are small for events below the level of the 1 in 5 year event. This is because experience of such events is sufficiently widespread that it is factored into decisions of land use regardless of the presence or absence of floodplain zoning legislation. In terms of probability, damaging floods are rare events.

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It is an open question whether any useful information on the future changes in frequency of such rare events can be obtained. Most climate modellers would agree that:

"...extreme meteorological events cannot be explicitly forecast by GCM simulations, ...in practice the quantitative estimates of possible changes in runoff extremes are as yet unavailable" (Lins *et al.*, 1990, p 4).

Most studies of climate change present information in terms of changes to the mean. Simple scenarios assume that changes to the mean will be accompanied by constant variance. In this simple case, assuming a normal distribution, increases to the mean result in major changes to extreme events. Wigley (1985) discussed this problem and showed that changes of the mean by one standard deviation, a very likely outcome for temperature and precipitation for a doubling of atmospheric carbon dioxide concentration, would result in a hundred year event ($P = 0.01$) having an nine-fold increase in expected frequency. Warrick and Barrow (1991) illustrate such effects for the United Kingdom. If this analysis is extended, the 1 in 10,000 year event is over thirty times more likely to occur. Although this represents a very rare event it is relevant to hydrology. One instance is the design criteria for hazardous dams, discussed in section 2.4. below.

The first complication that arises in the assumption that the distribution remains static under climatic change. Katz (1988) rightly suggests that the problem is more concerned with the variance of variances than with the variance of means.

Secondly, there are limitations to the capacity of GCMs to generate information on changes in variability under greenhouse scenarios. Rind *et al.* (1989) review this problem at three time scales, namely interannual, daily and diurnal variability. While acknowledging the limitations, they conclude that interannual and daily variability of precipitation would increase as mean precipitation increased.

A recurring theme in the greenhouse climate literature is the problem of detecting if, and when, greenhouse effects become apparent in the climate record. Due to natural variability this requires the recognition of significant changes in the signal to noise ratio, see Wigley and Jones (1981). There is no doubt that this would become apparent from a shorter length of record for temperature than for precipitation. The procedures for estimating flood probabilities, certainly as used in floodplain management, are firmly based on the assumption that the historic record of events is stationary. To precisely estimate the magnitude of the one in hundred year flood requires longer runs of record than are available. As greenhouse gas concentrations have exhibited an increasing upward trend for some decades it is possible that the assumption of a stationary series is incorrect. If rainfall intensities have already changed due to greenhouse effects it is most unlikely that these could be discerned from existing records. A change of assumption to a non-stationary series of rainfall and flood records would challenge the basic methodology used in engineering hydrology to obtain data on flood frequency and magnitude Palaeoclimate methods are of value but lack the quantitative base required for flood management.

The use of palaeoflood techniques in Australia is reviewed in Gillieson *et al.* (1991).

All of these factors conspire to militate against estimating changes to future flood probabilities. The situation in Australia is even more difficult. This is because Australia exhibits a greater variability of rainfall and runoff than any other continent or sub-continent, the only exception is South Africa. The verification of this variability can be found in Finlayson and McMahon (1988).

For Australia, a further complication is that the distribution of extreme flood events may be affected more by changes to the distribution and magnitude of tropical cyclones and east coast 'lows'. These events are not easily modelled by GCMs which, at present, are concerned with larger scale phenomena. This problem is reviewed in Evans (1991).

Despite these limitations, Fowler *et al.* (See this volume) have used the CSIRO 4-level global climate model to gain an insight into the simulated changes in daily rainfall intensity under enhanced greenhouse conditions that might occur in Australia. They conclude that:

> "...it is notable that the model does simulate quite large increases in the frequency of moderately high rainfall events, such as those with return periods of one or two years ... over most of the region [Australia] the frequency of this event [rainfall events with a return period of one year] increases in the $2 \times CO_2$ run, and over large portions of the region its frequency doubles. We would expect that such a change would extend to events with a longer return period were it possible to analyse thes".

Despite these major limitations, the concensus of studies of future climatic change, certainly for Australia, is that there will be increases in the frequency of extreme floods. If, or when, scenarios become available that provide more precise information as to the changes in flood flow probabilities, it would be a relatively simple matter to combine these with the existing property data bases in order to estimate the changes in damage. The examples, discussed below, all illustrate the adverse impacts that would result. It is however, possible that frequencies could decrease. The implications of such decreases can, it is hoped, also be discerned from the case studies presented. It is essential in assessing the impacts to consider the policy implications for agencies charged with floodplain management.

An outline will be also given of the effect of changing flood probabilities on the design of hydrological structures. One such example is for the design of hazardous dams. This is of particular interest as, for reasons other than climatic change, the estimates of probable maximum precipitation (PMP) and therefore probable maximum flood (PMF) in Australia were modified in the mid-1980s. The policy response to this has significance in considering the implications of further greenhouse-induced changes to PMP and PMF.

Comparative policy studies of this kind are the social science equivalent of assessing climate change by analogue techniques. The background of this approach to such societal responses an their implications for decision making are reviewed in Glantz (1988).

2. Flood Damages

There are a number of reviews of the impact of greenhouse climate change on water resource management, for example Jacobs and Riebsame (1989) and various papers in Pearman (1988). The majority of these however, are concerned with changes to long term means of annual river discharge. Supply is the dominant issue. Few studies have seriously attempted to address the effects on flood damage that would arise from greenhouse-induced changes to flood frequencies.

2.1. *Flood Damage Assessment*

Flood damages can be classified in a variety of ways. This account will focus upon losses to buildings and their contents rather than to rural damages. It should be noted however, that the areal extent of rural flooding can be extensive. For example, in 1974 at least a third of the land mass of New South Wales was inundated. The situation in many of the other states is similar.

The methodology for the estimation of urban losses is long established and stems from the initial studies of Gilbert White (1945) in the U.S.A. There are three essential inputs:

- a building by building data base
- stage-damage curves
- flood probability

The building information includes ground and floor height, size and type of building, construction material etc. Individual properties are allocated to damage classes based on susceptibility to flood loss. These include both residential and commercial property.

Stage-damage curves are an averaging procedure which provides damage estimates for flooding to specific overfloor depths. There are separate curves to match the damage classes recognised in the building data base, these incorporate losses to structure and contents.

The building data and stage-damage curves are combined with the flood information to obtain damage estimates for specific floods, e.g. the 1 in 20, 1 in 50 and 1 in 100 year event. Such data also enable estimates to be made of the mean annual damage. This is the simplest single statistic to measure changes in flood damage.

Computer programs are available to handle these procedures. ANUFLOOD is a commercially available package which is widely used for such purposes in Australia. It is described in Smith and Greenaway (1988).

The general form of the relationship between damage and probability is illustrated in Figure 1, mean annual damage is the integral of the area under the curve. The steep rise for the rarer events is due both to the increased lateral extent of the inundation and to increased depth and velocity of flood waters in the more flood prone areas. Climatic changes that increase the occurrence of low probability events result in comparatively large increases in damage.

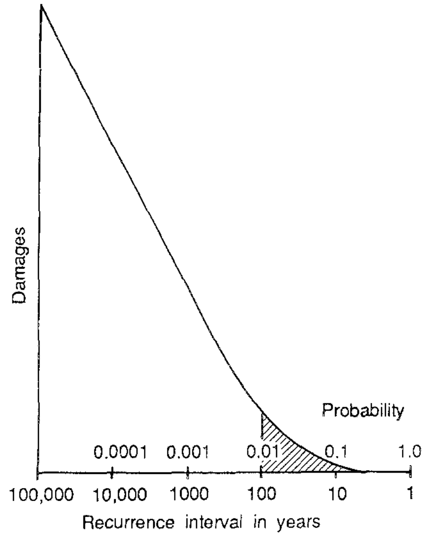

Fig. 1. The relationship of flood damage to flood probability.

The background to flooding in Australia, including the role of flood warnings and the part played by government relief and insurance in distributing the loss burden etc, is reviewed in Smith and Handmer (1986 and 1989).

2.2 *Historic Climatic Variability and Flood Damage*

The effects of variations in the historic record can be illustrated by an example based on the problems posed by using relatively short time historic flood records to obtain estimates of mean annual damage. In the late 1970's a study was undertaken to establish mean annual damage in order to assess the benefits and costs of flood mitigation options for Lismore, a flood prone town in northern New South Wales situated on the Richmond River. Flood records data from the 1870s. These are for flood heights recorded on a town gauge, flood volumes are available for a very much shorter period. There was doubt over the completeness of the records, there were very few floods in the period 1895–1930. This created problems in deciding what was the appropriate period of flood record to use to obtain the mean annual damage. The mean annual damage was therefore, separately estimated for the whole run of data, from 1875–1975, and using the post-1945 flood gauge records. The latter were known to be complete although they coincided with a widely accepted period of increased annual rainfall (Pittock, 1981). The flood probabilities for the two periods are shown graphically in Figure 2.

The initial study of Lismore was extended to other flood-prone communities in northern New South Wales. This confirmed the differences in the mean annual damage for Lismore (Richmond R.), Murwillumbah (Tweed R.) and South Grafton

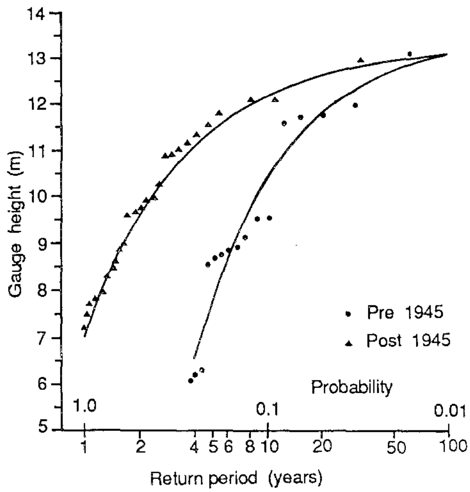

Fig. 2. Flood heights and probability for the gauge at Lismore, N.S.W., based on pre- and post-1945 records.

(Clarence R.) based on the whole run of record (approximately 100 years) and for the post-1945 period differed by a factor of approximately two. Such differences substantially change the assessment of costs and benefits for flood mitigation schemes. The study is reported in Smith and Greenaway (1983). Table I is reproduced from that publication.

This case study illustrates two points:

- climatic variations (assumed to be pre-greenhouse) can cause variations in flood damage.
- such variations in flood damage can be substantial.

TABLE I: Mean annual poential residential direct damages with differing flood probability estimates

	Mean Annual Direct Damages ($)		
	Whole run of record	Post-1945 Probabilities	Increase (%) using Post-1945 data
Lismore			
Total	143,100	269,400	88.3%
Per dwelling	76	142	
Murwillumbah			
Total	552,800	1,010,000	82.7%
Per dwelling	1,142	2,087	
South Grafton			
Total	117,200	268,200	128.8%
Per dwelling	356	815	

The values are in mid-1980s dollars, since that date flood mitigation measures have modified the damage values.

It is also worth noting that the householders in Lismore responded to periods of frequent flooding by 'lifting' their houses, often by as much as three or more metres. The majority of the houses are of detached weatherboard construction and raising floor levels in this way is practical. Penning-Rowsell and Smith (1987) have shown that these householder decisions can be regarded as favourable in cost-benefit terms. Over 90% of the 2,000 floodprone weatherboard houses in Lismore have been adapted in this way. The majority well before any form of government assistance was available to promote such mitigation measures. This could therefore be regarded as an individual response, i.e. non-government, to an 'increased' flood frequency. This too, has relevance in assessing possible future response to change.

2.3. *Extreme Events and Flood Damage*

Typically, international regulations for urban floodplain management only apply within the limits of the 1 in 100 year flood line. For convenience, floods with a lower probability than this will be referred to in this account as 'extreme floods'. It is unusual for hydrological information to be available for extreme floods. Thus, as was the case for the Lismore study outlined above, the mean annual damage is limited to the area that experiences the 1 in 100 year flood, shaded in Figure 1. However, it is important to incorporate the extreme floods in order to obtain the true value for the mean annual damage (see Figure 1) and because increases in flood probability would modify the position ascribed to the 'original' 1 in 100 year flood level.

There is an additional factor. This concerns the potential for building structures to collapse when the combination of depth and velocity exceed critical limits. Such limits vary with the form of construction, however adequate information is available for differing types of building. These are reviewed in Smith (1991). The problem has been to obtain reasonable estimates of velocity for water flowing over the floodplain in order to apply these techniques, especially for extreme events. Published case studies on urban losses from extreme floods that allow for the velocity effects on building collapse are very few.

Recent studies in Australia have incorporated the effects of velocity and extreme floods (rarer than the 1 in 100 year event) into urban damage studies, see for example Smith (1990) and Smith *et al.* (1990). The results, for the Georges River in Sydney and for Queanbeyan in New South Wales, are taken from those studies and will be used to illustrate the effects on flood damage, see Table II. The significance of both studies is that the mean annual damage for events greater than the 1 in 100 year flood is approximately equal to that for events below that limit. A major factor responsible for this is that increased depths and velocity associated with the rarer events can cause building collapse.

The losses in Table II are restricted to direct flood damage. These result from the contact of floodwaters and sediment with building and contents. The increases to indirect damage from extreme floods e.g. loss of trade, costs of alternative accom-

TABLE II: Estimates of mean annual direct damage for floods below and above the 1 in 100 year event.

	Georges River		Queanbeyan	
	Res.	Com.	Res.	Com.
Up to 1 in 100 year	$0.49	$6.22	$0.12	$0.21
1 in 100 year to PMF	$0.39	$7.29	$0.24	$0.22
Total	$0.88	$13.51	$0.36	$0.47
	$14.39		$0.83	

Damages are in $ millions at 1986 values.

modation, disruption of traffic networks etc, would be proportionately much greater than for direct damage. In addition, the risks to life are much enhanced if building collapse is involved.

Figure 3 shows the relationship between flood probabilities and direct flood damage for Queanbeyan and Canberra. The damages incorporate losses due to building collapse. This is one of the few studies for which hydrological information, including flood velocities, is available to the level of the PMF. The damage estimates are restricted to buildings and their contents. The overall totals were obtained from data for each of the 3,200 residential and commercial properties at risk.

The Queanbeyan and Canberra studies are among the few available with detailed information on the limit of the PMF. If a change of one standard deviation in the frequency of floods is applied, see section 1, the mean annual direct damage for Queanbeyan would increase by a factor of about eight, from about $850,000 to in excess of $7 million. This does not include any increase in the number of properties affected by an upward revision of the PFM. The assumptions are many but there is little doubt that the losses from such a scenario of increased flood frequency would be very large.

2.4. *Dam Failure*

At a simplistic level the effects of damages from dam failure flooding are similar to those from extreme floods. The salient problem is the enhanced effects of depth and velocity causing building (and infrastructure) failure. Immediately downstream of dams the effects far exceed those of PMF river flooding but progressively downstream the effects attenuate and eventually become less severe than extreme river flooding.

The key issue is that 'hazardous' dams are normally built to design specifications based on the ability of the spillway to pass the PMF. These standards are those of the International Committee on Large Dams (ICOLD, described in U.S. National Research Council, 1985) and the Australian National Committee on Large Dams

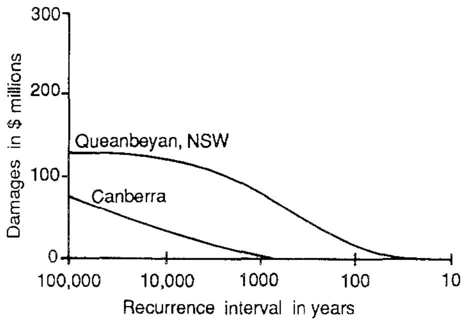

Fig. 3. Estimates of direct flood damage for Queanbeyan, N.S.W., and Canberra, A.C.T.

(ANCOLD, 1986). A 'hazardous' dam is one which is upstream of habitation and presents potential risk to life.

The Bureau of Meteorology (1985) revised national data for the PMP for short duration storms. These data were converted by the appropriate agencies to give the PMF for the catchments upstream of major dams. In much of Australia the PMP and PMF values increased and therefore the safety of spillways of many hazardous dams fell below the accepted standard. Although the problem has national implications, New South Wales was the first state to respond and to publicise the associated changes to dam safety. In part, this is because it is the only state which has a Dam Safety Committee directly answerable to stage Parliament.

The major concern in NSW is with Warragamba Dam, to the west of Sydney. The revised spillway capacity was the equivalent of the 1 in 500 year event. Interim works were completed in 1990, at a cost in excess of $20 million, to upgrade the spillway capacity to accommodate the 1 in 1,000 year flood. The dam was completed in 1960, has a height of 142 m and supplies two-thirds of metropolitan Sydney's water. A dam failure would inundate some 20,000 properties many of which would be completed destroyed. Understandably, the problems of upgrading the structure to PMF standard have major political implications. Enlarging the spillway would cost between $50 and $100 million dollars and the alternative of constructing a new dam, with the facility to reduce extreme natural flooding downstream, several hundred million dollars. An environmental impact study has been in preparation for some three years.

The revised PMF estimates, which have caused this reappraissal of dam safety, are *not* directly related to climate change. They are due to a change of method in the calculation, following more closely international practice, and reflect the longer run of record than was previously available. The record, in some areas, has upward revisions of PMP. The interest is that the revision gives an indication of the policy response that might be expected if further upward revision was to occur due to climatic change.

2.5. *Other Forms of Flooding*

Urban flood damage estimates are, worldwide, restricted to mainstream overbank flooding, and then usually to the standard design flood level of 1 in 100 years. This poses limitations to the assessment of future changes to flood probability. Two other forms of urban flooding are generally excluded from such studies. These can be referred to as:

- small urban catchments
- storm drainage surcharge

The first category comprises fully urbanised catchments, typically less than ten square kilometres. They have usually been omitted from flood damage studies, in part due to the problems of applying normal hydrological techniques to such small areas. Currently the Sydney Water Board is undertaking a study of some 40 such catchments in the built-up area of the city. Some individual catchments encompass well over 3,000 buildings (residential and commercial) at risk under PMF conditions. The total number of floodprone buildings for Sydney in this category is in excess of the numbers at risk from mainstream overbank flooding. Urban drainage systems, smaller in area than the catchments described above, are normally designed for the 1 in 10 year event. The importance of flood damage from such urban catchments is very real but is impossible to realistically assess. This is complicated because such systems do not always perform to standard. Often in times of flood urban drains become blocked with debris, e.g. cars, trees etc.

Robinson (1988) undertook a scenario approach for greenhouse changes for flooding relevant for the smaller urban catchments. He assumed that hydrological 'losses' and the rainfall frequency distribution remain constant. He then applied the standard Australian urban design guidelines and rainfall statistics as presented in *Australian Rainfall and Runoff* (IEA, 1987). The resulting changes in the hydrologic capacity of urban drainage systems for increases of 25% and 50% in half-hour rainfall intensities for Hobart, Sydney and Darwin are given in Table III. For instance, a 25% increase in half hour rainfall intensities for Sydney would reduce a channel with a current design capacity of 1 in 100 year to 1 in 31 years.

Due to the uncertainities of the scenarios for changed greenhouse frequencies the author is reluctant to present specific examples of the impacts on flood damage. However, if Robinson's 25% increase in half-hour rainfall intensities is applied to a small urban catchment (in Sydney), for which there is a property data base, the magnitude of the change in damages can be illustrated. The residential and commercial flood damages for such a catchment are given in Table IV, the losses from building collapse are included. There are over 2,000 residential and some 200 commercial/industrial properties within the limit of the PMF. A comparison of Tables III and IV indicates the changes to direct flood damage in response to changes in rainfall intensity. Within the context of urban floodplain management the magnitude of the increases in damage for specific flood events is of very considerable significance. There are insufficient data however, to realistically assess the

TABLE III: Reduction in hydrologic capacity due to increase in half-hour storm intensity (from Robinson, 1988)

	Design capacity ARI in years	**Capacity with increase of 25% ½ hr storm intensity**
Hobart	100	31
	50	17
	20	7
	10	4
Sydney	100	17
	50	10
	20	5
	10	3
Darwin	100	39
	50	21
	20	9
	10	5

ARI is the annual recurrence interval.

changes to mean annual damage but this would increase by a factor of at least two, probably much more.

3. Implications of the Impacts

Some guidance to the impact on flood damages can be obtained by varying the flood probability data that are one of the inputs into the assessment of mean annual flood damage. From the analysis presented above, it is clear that relatively small increases in probability can cause very large increases in damage. For mainstream flooding this can be easily assessed by analysing existing property data bases with revised flood frequencies. However, it is important that new estimates are not limited to mainstream flooding but incorporate small urban catchments and urban drainage systems.

TABLE IV: Residential and commercial potential direct event damages for a small urban catchment in Sydney

Event	**Residential**	**Commercial**
1 in 5 year	$0.18	$0.01
1 in 10	$0.24	$0.16
1 in 20	$0.29	$0.27
1 in 100	$0.46	$0.55
PMF	$21.78	$51.88

Damages are in $ millions at 1991 values

However, the availability of revised hydrological data accompanied by revised mean annual damage estimates does not mean that there will be a corresponding policy response. Urban floodplain management is an excellent example of the lack of response of communities and governments to the availability of additional information on risk.

Typically, an established floodprone urban community will lobby for structural mitigation solutions such as levees and flood storage dams. The first step in addressing the problem is for the relevant government agencies to assess flood frequencies and to produce a 'flood map'. Normally this shows the limits of the 1 in 100 year flood event, sometimes accompanied by the 1 in 50 and 1 in 20 year flood lines. The planning approach is then to assess the costs of possible structural accompanied by various non-structural mitigation measures. The most usual of these is for zoning regulations to be applied to the 'flood prone' area, nearly always the area within the limits of the 1 in 100 year flood. Without exception, the zoning regulations cause a vehement community backlash. They distort the existing property market, new developments are not allowed in the zoned area and existing property owners perceive, often wrongly, that their properties have become devalued. There is no question that nonstructural measures are the best strategy to halt urban flood losses by severely restricting further encroachment into known flood prone locations. This has the advantage of reducing the evergrowing amounts of government flood relief. However, the problem of existing buildings is the stumbling block. Most 'new' nonstructural schemes can only be 'sold' to existing flood prone communities by offering some form of subsidy. For example, flood zoning controls were only introduced into the U.S.A. by the federal government offering subsidised insurance to existing residential property and small businesses. Various forms of federal assistance were withdrawn from locations that did not produce approved flood maps and enact local zoning regulations. Urban flooding is a flash point for local and state politics. The widespread use of the 1 in 100 year flood limit as the 'design' flood is far from ideal, in some locations the occurrence of high flood velocities poses a threat to life and property. However, politically it is too difficult to change legislation from the accepted use of the 1 in 100 year event.

Now imagine the scenario that proposes that what has been the reluctantly accepted 1 in 100 year zoning line be suddenly changed. In the example from Robinson, a 25% increase in half hour rainfall intensities for Sydney changed the 1 in 100 year line to the 1 in 17 year line. The new maps would therefore, require vast extensions of the zoning rules. In addition, the level of protection afforded by existing stuctural measures would be greatly reduced. Those unfortunate enough to live in very flood prone locations, say within the current 1 in 20 year limit, could well be exposed to building failure and face life threatening situations in flood.

The situation for hazardous dams is not dissimilar. Upward revision of PMFs reduces the capacity of spillways to pass extreme floods. Existing dams require retro-fitting at very considerable expense. The decision has to be made as to whether to divert finance from other publically funded projects. This is complicated by the legal situation where dam owners are likely to be liable for any damages caused by failure of their structures. The current situation with revised PMFs for Australian dams is very similar to this greenhouse scenario. At present owners of hazardous dams in New South Wales, mainly government and quasi-government agencies, are actively contemplating upgrading and have informed the downstream communities of the increased risk. Other states, equally aware of the problem, have differing legislation and the problem has not been so widely discussed. The response of the bureaucracy to a further major upgrade, say in twenty years time, is not difficult to forecast.

The response of governments to changes in hazard risk is commonly only taken after a major disaster has occurred. Often widespread loss of life and property is required to trigger such a response. The dam design guidelines, described above, stem in large part from a sequence of dam disasters with accompanying loss of life in the U.S.A. If the scientific community provides evidence of increased frequency of flooding it is to be hoped that this will be accepted without need to wait for the occurrence of major disasters.

3.1. *The Responses?*

Atmospheric scientists should guard against the assumption that scientifically agreed futures for climate change will lead to a corresponding rational approach to planning. This question is discussed in Handmer (1990). He usefully lists the possible responses as:

- *Adjustment* – this will vary from country to country and region to region.
- *Institutional* – at best likely to be incremental rather than dramatic.
- *Individual* – will education produce the desired effects, can individuals afford the measures suggested?
- *Emergency Action* – this incorporates warnings and well designed emergency systems. These are likely to be the major short term response and are all too frequencly underfunded.
- *Planning and control Strategies* – For successful implementation these require political will and legal power. Such changes are not easily achieved.

Harris (1990) concludes a discussion of international aspects of greenhouse climatic change with the phrase "...solutions to the problem of climatic change are economic and political". To the extent that 'economic' and 'political' include 'social' – this is undoubtedly true.

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