

THE IMPACTS OF CLIMATE CHANGE ON URBAN FLOODING IN THE MELBOURNE AREA USING EXISTING FLOOD MODELS

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ABSTRACT

Our cities, until recently, have been developed under the assumption that climate is relatively stable. Recent observations suggest that this is not the case and this has been reflected in legislative changes across Australia. For these reasons it will be necessary to adapt and plan for these challenges. This paper focuses on future flooding using existing tools and models coupled with recent predictions in future rainfall.

This paper has taken recent research into future rainfall intensity by the CSIRO (Abbs & Rafter, 2008) and applied them to existing flood models in the Melbourne area. The 2030 and 2070 rainfall intensities derived from the CSIRO paper were used to produce design storms and design hydrographs for each catchment.

Peak flows were determined at catchment outlets for design events based on the existing conditions and future conditions for 2030 and 2070. To evaluate changes in the Annual Recurrence Intervals (ARI) relative to current design standards quantile relationships for the Generalised Extreme Value (GEV) distribution were numerically solved for the GEV parameters. The resulting GEV relationship was used to determine the return period of these future design events using current conditions. While results varied from catchment to catchment typical results from this analysis indicated the 2070 1 in 5 year design ARI event was equivalent to the present 1 in 10 year ARI event and the 2070 1 in 100 year ARI event was equivalent to the 1 in 300 year ARI event. In addition to providing information on return periods the hydraulic model showed increases in the extents of inundation.

The results have important implications on future planning, management and infrastructure. They suggest we may need to revise our infrastructure design standards and some areas currently considered appropriate for development may be vulnerable in the future.

Introduction

Our cities and infrastructure, until recently, have been developed under the assumption that climate is relatively stable or stationary. Recent observations indicated that climate is changing, for instance the Bureau of Meteorology (2010) *State of the Environment Report: 2010 Update* notes an average increase of 0.6°C in temperature across Australia since 1960. Furthermore this has been reflected in legislative changes across Australia with requirements to consider the impacts of climate change in terms of Coastal Hazard

and Flood Risk in many States. Individually both of these factors would provide an impetus to plan for the future impacts of climate change and development of adaptive strategies to manage these impacts.

The aim of this paper is to investigate the future flooding in 5 urban catchments in Melbourne using existing tools and models coupled with recent predictions in future rainfall. The future rainfall estimates have been taken from recent research by the CSIRO (Abbs & Rafter, 2008) and applied to existing flood models in the Melbourne area. The CSIRO results are based on dynamical downscaling which involves using a hierarchy of climate models to increase the level of detail and hence modelled resolution.

Background

The exact quantum of climate change for various climatic variables at present remains uncertain. There is however, strong evidence to suggest the direction and magnitude of climate change. Given this increasing body of evidence there is a need to respond and plan for adaptation. At present there are a variety of methods to investigate the quantum of climate change including Global Climate Models (GCM). There is general agreement between GCM on future temperature and some consensus on annual rainfall totals, however, at shorter temporal scales this consensus is not reached and there remains a large degree of uncertainty.

Rainfall intensities

GCM by their nature cover large areas with individual cells sizes of several hundred square kilometres, within which there can be significant climatic variation. However, dynamical downscaling can be used to obtain information at a finer resolution. This technique involves the nesting of progressively finer scale models to focus on an area of interest. Abbs and Rafter (2008) employed this technique to investigate extreme rainfall in the Melbourne area. The results of that study have been used as the basis for the rainfall intensities used in this paper.

In the Abbs and Rafter study a fine scale model (Regional Atmospheric Modelling System (RAMS)) was nested in CSIRO's Conformal Cubic Atmospheric Model (CCAM). The CCAM was forced by outputs from CSIRO's Mark 3 Atmospheric-Ocean Global Climatic Model (GCM). The GCM was used to simulate climate under the IPCC SRES A2 emissions scenario (which is the second most extreme emission scenario).

The RAMS was initialised with conditions from the CCAM that lead to extreme rainfall events in simulations. Results were documented for various duration events, including the 2, 12 and 72 hour events. While these results are based on a single GCM and emission scenario they have been run a number of times with realisations in 40 year blocks centered on 2030 and 2070. Results were therefore available for 2030 and 2070.

Study Catchments

Five urban catchments in the Melbourne area were selected for investigation. The study catchments were all part of the Melbourne Water Floodplain Mapping and Mitigation program.

The 5 catchments are clustered in 2 locations; in the north-western and eastern suburbs of Melbourne. The two north-western catchments discharge to a tributary of the Maribyrnong River. The three eastern catchments discharge to Port Phillip. Key characteristics of the 5 catchments are listed in Table 1.

Tab.1: Key catchment characteristics for the selected catchments

Catchment	Area (km ²)	Fraction Impervious	Length MW Assets (km)	50 year 1 hour (mm/hr)
A	0.86	0.61	0.6	43.4
B	3.1	0.58	2.2	43.4
C	8.5	0.58	7.0	39.6
D	0.87	0.58	1.5	39.6
E	4.2	0.57	5.8	40.1

Methodology

This paper examines the impacts of climate change on urban flooding in the Melbourne area using estimates of increased extreme rainfall intensities as inputs to existing flood models. This was completed for 5 urban catchments in the Melbourne area.

To achieve estimates of future extreme rainfall intensity, results were taken from Abbs and Rafter (2008) who table fractional increases in rainfall intensity. These fractional increases were used to factor current Australian Rainfall and Runoff (AR&R) (Institution of Engineers Australia, 1999) Intensity Frequency Duration (IFD) rainfall intensity parameters. The resulting design rainfall estimates for 2030 and 2070 were then applied to existing RORB hydrological models, producing runoff throughout the catchments. The resulting hydrographs were applied to 1D-2D linked hydraulic TUFLOW models of each study area. As well as these future estimates of rainfall, current AR&R design rainfall events were also applied to the hydrological and hydraulic models. The resulting flows in both the hydrological and hydraulic models were analysed and compared.

Rainfall IFD factors

The results of the CSIRO paper tabled future fractional increases in rainfall intensities for 2030 and 2070 relative to 1960-1999 observations for the 2 hour, 24 hour and 72 hour rainfall events. These results varied spatially, as well as temporally, across the Melbourne region.

Fractional increases in rainfall to the nearest 5% for each catchment were determined at 2030 and 2070 for the three storm durations. Given the spatial and temporal variation, the fractional increase for each catchment, duration and future scenario could be different. Future rainfall intensities were determined by applying the fractional changes to current AR&R rainfall intensities of the same durations for each of the catchments.

The fractional increases were only available for the selected storm durations noted above and it was desirable to examine a boarder range of storm durations. This was achieved by creating a set of IFD curves using the method outlined in AR&R, Book 2 Section 1.3. A set of IFD curves gives information about rainfall intensity for a given frequency (return period) and duration. To establish a set of IFD curves for each catchment using the AR&R method required information on the 1 hour, 12 hour and 72 hour rainfall intensities together with 2 geographic factors and a value for skew. In order to estimate the 1 hour and 12 hour rainfall intensities a log-log relationship was determined between the future rainfall depths and event duration. From this relationship rainfall intensities for the 1 hour and 12 hour storms were determined.

The new set of IFD intensity parameters for each catchment was combined with the existing skew and geographic factors to create sets of IFD curves for each catchment for each scenario. These new IFD sets of curves were used as input to the hydrological model.

Hydrological Model

The existing and future IFD curves were used as inputs to established RORB hydrological models to produce design event hydrographs throughout the catchment. Design events are theoretical events for a given frequency (or probability). For instance, the 1 in 100 year design event is an event that occurs on average once every 100 years and has a probability of 1% annually. The RORB models were developed in accordance with the Melbourne Water Technical Specification (Melbourne Water Corporation, 2009).

These hydrological models were designed to provide inflows to the 1D-2D linked TUFLOW hydraulic model and as such they did not include any catchment storages or model diversions. As no calibration data existed for any of the catchments the peak flow at the model outlet was adjusted to match a peak flow calculated using the Rational Method by altering the model parameters. This was completed for existing conditions and the determined model parameters were used for future case model runs.

The RORB model was then run for a series of ARI storms from the 5 year to the 100 year and durations ranging from the 10 minute storm to the 24 hour storm. All storms were filtered to ensure lower probability shorter duration rainfall bursts were not embedded within the design storm. Given the modest size of the catchments no areal reduction factors were applied.

Both the routed (total) and local (rainfall excess) hydrographs were stored for further analysis and application to the hydraulic model as appropriate.

Hydraulic model

The hydraulic models used in this paper have been constructed as part of the Melbourne Water Floodplain Mapping and Mitigation programme by BMT WBM. At this stage all results presented are to be considered draft. These hydraulic models have been constructed in accordance with the Melbourne Water Technical Specification (Melbourne Water Corporation, 2009).

Specific details of the hydraulic models are contained within Hydraulic and Flood Mapping Reports issued to Melbourne Water. These hydraulic models are linked 1D-2D TUFLOW models where the overland flow paths and storages were modelled in the 2D domain and underground drainage structures were represented as 1D elements dynamically linked to the 2D domain. These models were designed to cover the area at risk of flooding from Melbourne Water (MW) assets and were extended to include minor drainage as appropriate.

Inflow boundaries were distributed throughout the models to ensure a ‘realistic’ distribution of rainfall throughout the study area. External boundaries were applied upstream of the MW assets when the entire catchment was not incorporated into the hydraulic model. For those sub-areas within the 2D domain the inflow hydrographs were distributed to the manholes (or inflow points). The downstream boundaries for the TUFLOW models were set to an appropriate fixed water level such as Port Phillip or the watercourse to which the MW drains outlets. Both, the watercourse and the Port Phillip levels were set to the 1 in 10 year water level as outlined in the Melbourne Water Technical Specification. In addition an allowance for sea level rise was also included in the bay levels. The additional amount for sea level rise was derived from the Victorian Coastal Strategy with the value taken from Figure 4: Project sea level rise of the 21st century (Victorian Coastal Council, 2008). As noted above, the extreme rainfall realisations were grouped together in 40 year blocks and to ensure a conservative approach the estimates of sea level rise were taken from the later extremity of these blocks, that is, 2050 and 2090.

Flood Frequency Analysis

To evaluate changes in the Annual Recurrence Intervals (ARI) of future events to current design standards, and vice versa, Flood Frequency Analysis was undertaken. To achieve this, quantile relationships (see Equation 1 and 2 (Coles, 2001)) for the Generalised Extreme Value (GEV) distribution were solved, using the design event results, for the GEV parameters.

$$\tilde{z}_p = \hat{\mu} - \frac{\hat{\sigma}}{\hat{\zeta}} [\mathbf{1} - y_p^{-\zeta}] \quad \text{Equation 1}$$

$$y_p = -\ln(\mathbf{1} - p) \quad \text{Equation 2}$$

where \tilde{z}_p is the return discharge for probability p , $\hat{\mu}$ is the estimated location parameter of the GEV distribution, $\hat{\sigma}$ is the estimated scale parameter and $\hat{\zeta}$ is the estimated shape parameter.

Given the quantile values for given probabilities were known *a priori* it was not necessary to resort to parameter estimation techniques such as Maximum Likelihood, Probability Weighted Moments (L-Moments, LH-Moments, etc) or Bayesian Parameter Estimation. Rather a set of simultaneous equations were set up using the modelling results for each for the five ARIs modelled. As there are 3 parameters in the quantile relationships the problem was over determined and numeric techniques were used to solve for the parameters.

The sum of squares of the difference between the modelled ARI results (from the hydrological and hydraulic models) and GEV quantiles was minimised using a Simplex Technique to determine the optimal parameter set. A variety of initial values were tested to ensure the final parameter set comprised realistic parameter estimates and in this way equifinality (for a discussion see Beven, 2001) of parameter sets was addressed. Given the nature of flooding it was assumed that the GEV distributions were not upper bound and the shape parameter was constrained to be greater than or equal to 0, that is, $\hat{\zeta} \geq 0$.

Parameter sets were determined for each of the catchments for both the hydrological and hydraulic models for the present day, 2030 and 2070 conditions, that is, 30 parameter sets in all. The GEV quantile relationship, Equation 1, was inverted to solve for probability and thus return period. It was then possible to determine the return period of future events under present day conditions, and also the frequency of present day events under future conditions.

Results

The results for the future rainfall intensities, the hydrological and hydraulic modelling, flood frequency analysis (both hydrological and hydraulic modelling) and flood extents are presented below. In general averages together with the range for key variables are presented and the results are also illustrated using specific figures and tables for selected catchments.

Rainfall intensities

The average factorial rainfall intensity increases across all 5 catchments are presented in Table 2 below. This table illustrates that there is a consistent response in the predicted increases across the catchments investigated for a given duration at 2030 and 2070 as illustrated by the ranges in Table 2.

Tab.2: Average fractional rainfall intensity increases with storm duration derived from Abbs & Rafter (2008) for 2030 and 2070

	2030			2070		
Strom Event	2 hour	24 hour	72 hour	2 hour	24 hour	72 hour
Factional Increase	1.3	1.2	1.1	1.3	1.4	1.3
Range	1.4-1.25	1.2-1.1	1.1-1.1	1.35-1.3	1.4-1.2	1.3-1.25

The results in Table 2 indicate that the fractional changes for 2030 are expected to vary with duration, with the shorter duration storms experiencing larger fractional increases than the longer duration storms. The expected increases are more consistent for the 2070 results where all storm durations are expected to increase by similar fractional increases. There is close agreement between the expected 2030 and 2070 2 hours storms although this agreement does not occur for longer duration storms.

The results of the analysis for Catchment C are presented in Figure 1. This figure illustrates that, for both the 2 year ARI and the 50 year ARI the gradient of 2070 results is approximately parallel to the present day results whereas for the 2030 results the

gradients diverge with larger fractional increases for the shorter duration storms and smaller fractional increases for the longer duration storms.

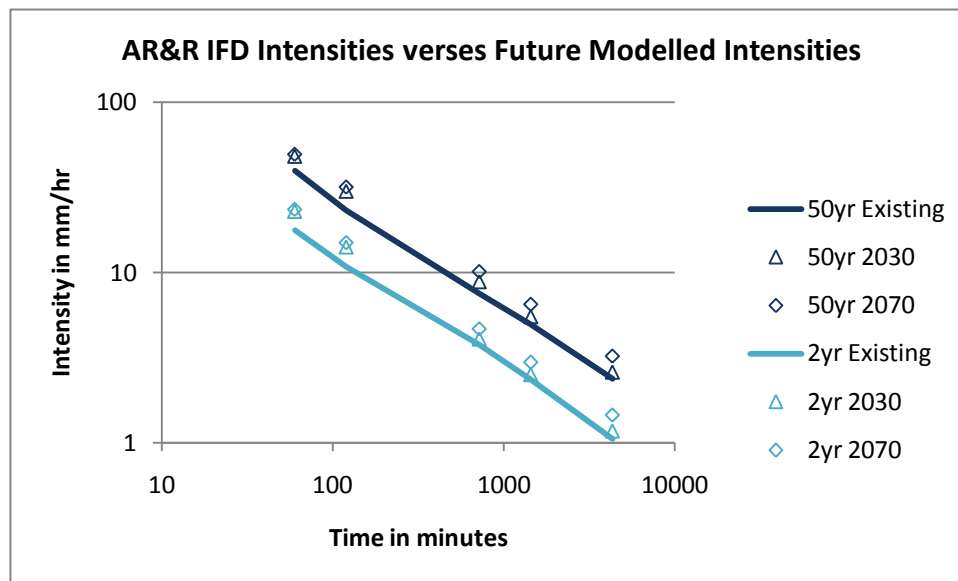


Fig. 1: Intensity-Frequency-Duration plots for the Catchment C for present and future modelled conditions

Hydrological and Hydraulic modelling results

Peak flows and hydrographs from both the RORB model and TUFLOW model were extracted at key locations throughout the catchments, including the catchment outlet, for further analysis. This was repeated for each of the design events for each catchment for the three scenarios; present conditions; 2030; and 2070.

Initially the critical event (the event that produces the largest discharge) at the catchment outlet was determined for each catchment from the hydrological model results. Hydrological model results were preferred to determine the critical event due to difference in the model run times; the hydrological model can run all required ARIs and storm durations in a matter of minutes whereas a single run in the hydraulic model takes several hours. The results indicated that the 2 hour event was critical in most catchments. Given this, the 2 hour event was selected to be modelled for all catchments which had the benefit of reducing the number of model runs and ensuring direct comparison between results.

In addition to its ability to produce hydrographs the TUFLOW model produces information about the depth, extent and timing of flow throughout the catchment for a given event. Information on the changes in extent of flooding for each of the catchments was determined and is presented below.

Flood frequency analysis

A GEV distribution was fitted to each of the subject catchments for both the hydrological and the hydraulic results. All fitted distributions were confined to GEV Type I and GEV Type II distributions. The fitted distributions all had excellent fits with Nash Sutcliffe Efficiencies (NSE) (Nash and Sutcliffe, 1970) greater than 97% for all results. In fact, for all results, except for Catchment C in the Existing Case and 2030 hydraulic model results,

a NSE of greater than 99% was achieved. A strong agreement between these results was expected given the modelled events have been based on design rainfall events which in turn were derived from an extreme value distribution. In general the hydrological model results had superior fits to GEV distributions than the hydraulic models results, although these improvements were marginal.

The determined GEV distributions were used to calculate the ARI of the modelled future events under present day conditions and the ARI of present day events using future conditions. These results are presented in Table 3 for the hydrological model results and Table 4 for the Hydraulic model. Figure 2 and Figure 3 illustrate the flood frequency curves from the hydrological and hydraulic models for Catchment B.

Tab.3: Average ARI Hydrological model results

Hydrology										
	<i>Average ARI of future events based on present day conditions</i>									
	<i>1 in 100</i>	<i>Range</i>	<i>1 in 50</i>	<i>Range</i>	<i>1 in 20</i>	<i>Range</i>	<i>1 in 10</i>	<i>Range</i>	<i>1 in 5</i>	<i>Range</i>
2030	300	530-144	140	234-76	50	77-32	25	32-17	10	13-8
2070	250	358-153	120	156-81	45	51-35	20	22-18	10	10-9
	<i>Average ARI of existing events in the future</i>									
	<i>1 in 100</i>	<i>Range</i>	<i>1 in 50</i>	<i>Range</i>	<i>1 in 20</i>	<i>Range</i>	<i>1 in 10</i>	<i>Range</i>	<i>1 in 5</i>	<i>Range</i>
2030	45	67-25	20	32-14	10	12-7	5	6-4	3	3-3
2070	45	63-34	25	30-20	10	11-9	5	6-5	3	3-3

Tab.4: Average ARI Hydraulic model results

Hydraulics										
	<i>Average ARI of future events based on present day conditions</i>									
	<i>1 in 100</i>	<i>Range</i>	<i>1 in 50</i>	<i>Range</i>	<i>1 in 20</i>	<i>Range</i>	<i>1 in 10</i>	<i>Range</i>	<i>1 in 5</i>	<i>Range</i>
2030	400	1009-152	160	314-85	55	80-36	25	33-17	10	14-7
2070	300	548-168	130	183-94	50	54-40	20	24-19	10	11-7
	<i>Average ARI of existing events in the future</i>									
	<i>1 in 100</i>	<i>Range</i>	<i>1 in 50</i>	<i>Range</i>	<i>1 in 20</i>	<i>Range</i>	<i>1 in 10</i>	<i>Range</i>	<i>1 in 5</i>	<i>Range</i>
2030	45	61-23	20	28-14	10	11-7	5	6-4	3	4-2
2070	40	53-33	20	25-19	10	11-8	5	6-4	3	4-2

Table 3 and 4 both indicate that the magnitude of future events for a given ARI will increase, with the future ARI of events approximately doubling and larger increases for rarer events. For instance the hydrological modelling results (Table 3) indicate, on average across the 5 catchments, the future 2030 1 in 100 year event will be approximately equivalent to the present day 1 in 300 year event. That is if an event of the same magnitude as the calculated 2030 1 in 100 year event occurred today it would be considered a 1 in 300 year event. For the 2030 1 in 100 year event there was a range

of results across the catchments from the 1 in 150 year event to the 1 in 550 year event. Conversely the ARI of present day events will approximately halve in the future. For example the hydrological modelling results suggest the present day 1 in 5 year event would occur on average at least once every 3 years.

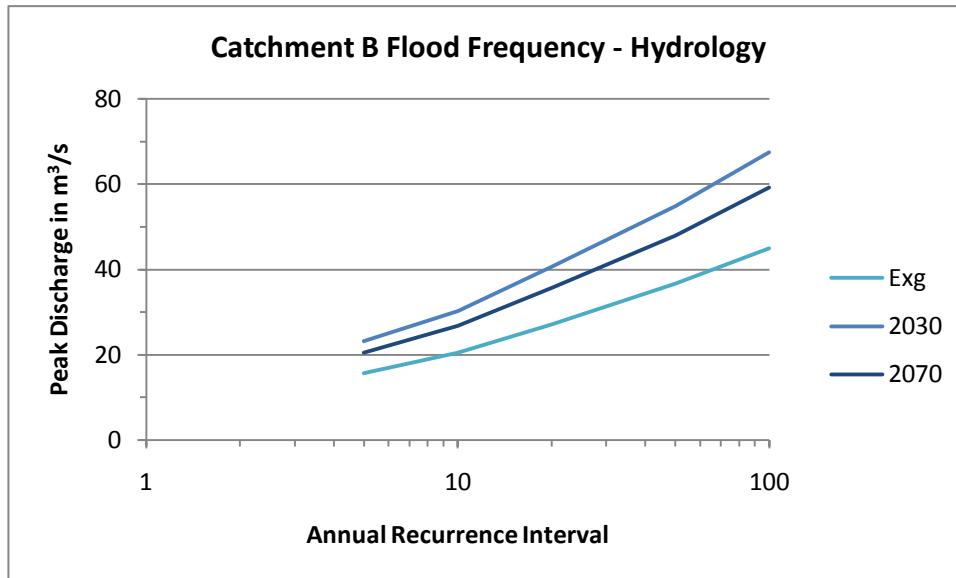


Fig. 2: Flood frequency analysis for Catchment B: Hydrological model results

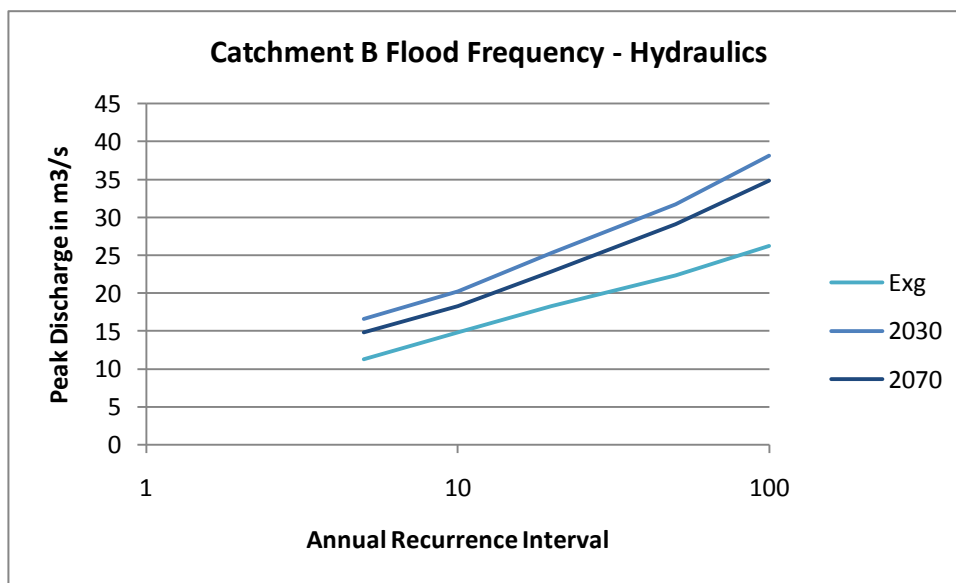


Fig. 3: Flood frequency analysis for Catchment B: Hydraulic model results

Table 3 and 4 also indicate there is a consistency between the estimate of ARIs from the hydrological model results and the hydraulic model results. However, the actual values of peak discharges associated with each ARI are significantly different with the hydraulic model results consistently being lower. For instance the peak discharge for the 1 in 100 year event determined by the hydrological model for Catchment B for the existing conditions was $48\text{m}^3/\text{s}$ compared to the hydraulic model result of $29\text{m}^3/\text{s}$ as illustrated in Figure 2 and Figure 3. This trend was found in all catchments. This

difference in peak flows reflects the influence of storage and the dynamic partitioning of flow between underground pipe networks and overland flow as discussed below.

Flood extents

As well as providing information regarding discharge with time throughout the catchment the TUFLOW model provides information about the extent of flooding. Analysis of these results indicates flood extents increase under future scenarios with the 1 in 5 year event extents increasing on average by approximately 25% and the 1 in 100 year event increasing on average by approximately 15% as illustrated in Table 5.

Tab.5: Changes in modelled flood extents for the 2030 and 2070 2 hour 1 in 100 year events compared to the existing conditions

ARI	Future Scenario	A	B	C	D	E	Average	Range
1 in 5 year	2030	55%	37%	13%	10%	20%	27%	10% - 55%
	2070	42%	27%	16%	14%	23%	25%	14% - 42%
1 in 100 year	2030	36%	13%	12%	6%	16%	17%	6% - 36%
	2070	26%	10%	15%	8%	20%	16%	8% - 26%

Discussion

The results presented here broadly indicate a 30% increase in rainfall intensities by 2030 and also for 2070 across all catchments for the critical storm. The catchments investigated were all small urban catchments clustered in 2 locations in Melbourne which were predicted to have similar responses to rainfall by Abbs and Rafter (2008). Other locations across Melbourne are predicted to have a different response to rainfall particularly to the West of Melbourne where rainfall intensities are predicted to decrease slightly by 2030 before increasing to 2070. Regardless, for the 5 catchments investigated there was consistency in terms of the rainfall increases for each of the future scenarios. For these small urban catchments where the critical storms tend to be short duration storms the predicted increase is approximately 30%, with 2030 having a slightly larger increase than 2070 on average. For these types of catchments it appears climate enters a period of pseudo-stationarity in terms of extreme rainfall events.

The results indicate that future rainfall intensities for longer duration storms do not display the consistency of shorter duration storms. It is therefore not expected that larger catchments, or catchments with long critical storm durations, would enter into this stationary period.

An alternative methodology for investigating the increase in extreme rainfall due to climate change is based on the Clausius Claperyon theory. The application of this theory to future flood risk is currently being investigated by researchers in Queensland (Fairweather *et al*, 2010). The Clausius Claperyon theory indicates for each 1°C increase in temperature, the amount of water vapour a parcel of air can hold increases by approximately 7% (e.g. Allen and Ingram, 2002).

Using this theory and information on projected temperature increase, an estimate of future extreme rainfall increases can be obtained. The CSIRO publication *Climate Change in Australia* (CSIRO, 2007) indicates that temperatures in Melbourne will increase by between 2.0 – 4.5°C in summer (using the A1F1 Scenario) by 2070. Using the Clausius Claperyon theory this equates to a 14% to 32% increase in extreme rainfall, the upper end of which corresponds to the values presented here of 30%. The 30% presented here also compares well with the Rainfall Intensity Scenario of 32% adopted by MW as an indication of what may occur by the year 2100.

While the 2 hour storm duration has been reported here, other durations from the 15 minute storm to the 24 hour storm have also been investigated using the hydrological model. In all catchments storm durations of 2 hours and less were critical. The results from these shorter duration storms followed the same trends as outlined above, that is, peak discharges increased significantly. However, for larger catchments where the critical duration storm was longer, it is expected that the trends found here would change.

In all circumstances the 2030 and 2070 peak discharges increased significantly compared to existing conditions with both the hydrological and hydraulic models showing return periods of present day events are typically halved in the future. When future peak discharges are expressed in present day ARIs these events approximately double with even larger differences found for rarer events. While there is consistency between return periods calculated from hydrological and hydraulic models, there were significant differences in the magnitudes with the hydrological model results being significantly larger.

It is worthwhile considering the differences in the results from the hydrological model and the hydraulic model. The hydraulic models consistently have lower peak flows than the hydrological model. This difference in hydrological and hydraulic modelling results reflects the influence of storage and the dynamic partitioning of flow between underground pipe networks and overland flow. There are features in RORB that can incorporate these effects. However, the hydrological models used in this assessment have not been designed to account for additional system storage or the partitioning of flow into formalised drainage systems and overland flow. This was not considered appropriate as these aspects are modelled explicitly in the hydraulic model. Given this, lower peak flows are expected in the hydraulic model.

The hydraulic model results provided an extent of inundation, and analysis indicated that flood extents increased in the future, as expected. However, there were proportionally larger increases in more frequent events. The extents of the 1 in 100 year event increased on average by 15% while the corresponding increase in the 1 in 5 year event was 25%. The larger increases in the 5 year results are a consequence of the majority of flow being conveyed in the drainage system under present conditions with only a small amount of overland flow and hence a small extent. Thus a small increase in overland flow leads to a larger proportional extent in the 5 year event.

CONCLUSIONS

The purpose of this paper was to investigate future projections of extreme rainfall on flooding in urban catchments in the Melbourne area. The results also indicate that short duration rainfall events increase by approximately 30% by 2030 and enter into a period of pseudo-stationarity with the results from 2030 being similar to the results from 2070. The analysis of the ARI of future results found these doubled while the ARI of present day events in the future halved.

This change in rainfall intensities may have significant implications on future planning management and infrastructure. For instance drainage infrastructure designed to the 1 in 5 year standard may be overwhelmed on average at least once every 3 years by 2030 in smaller urban catchments. These results also suggest that the typical “safe” design standard of the 1 in 100 year ARI event may be halved by 2070. As a result, areas currently considered appropriate for development may be at higher risk of flooding in the future than currently acceptable.

By using these types of methodologies and incorporating consideration of climate change it is possible to adapt future planning, works and development to the expected impacts. While this is possible for future works, retrofitting adaptive strategies is more difficult and planners and managers will need to address these issues informed by studies taking into account future climate change projections.

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