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CLIMATE AND LAND SURFACE CHANGES IN HYDROLOGY

Impacts of climate and land-use changes on floods in an urban catchment in southeast Queensland, Australia

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Abstract Over the coming decades, the projected land-use change, when coupled with climate change, could potentially lead to an increased risk of flooding in urban catchments. This research aims to examine impacts of climate and land-use changes on floods in southeast Queensland, Australia. A rainfall–runoff routing model, RORB, was first calibrated and validated using observed flood hydrographs for an urbanised catchment, the Bulimba Creek catchment, for the period 1961–1990. The validated flood model was then used to generate flood hydrographs using projected rainfall based on a global climate model, GFDL, and a regional climate model, CCAM, for 2016–2045. Projected daily precipitations for the two contrasting periods were used to derive adjustment factors for a given frequency of occurrence. Two scenarios of land-use change were considered to evaluate the likely impact of land-use change. Results showed that future flood magnitudes are unlikely to increase for large flood events for the urban catchment. Further, land-use change would not significantly affect flood magnitudes for a given frequency of occurrence in the urbanised catchment.

Key words climate change; land-use change; floods; Queensland, Australia

INTRODUCTION

Projected rapid land-use changes when coupled with climate change, could potentially lead to increased flood risk which may have a deleterious impact on infrastructure (Ewen & Parkin, 1996). The precise effects of such changes are difficult to predict. For example, the current once in 100-year flood may become once in 20- or 50-year flood events in some areas, while the one in 20-year event may become one in 100-year in others (Leander *et al*., 2008). Consequently, the current infrastructure and storm drainage systems may be inadequate in the future. Whilst stakeholders are aware of this possibility in general terms, there are as yet no strategies to mitigate the impact of the shifts in flood risk in the future.

It is widely known that changes in land-use, such as conversion of forest land into cropland or grazing land, and urbanization, can increase surface runoff and flooding (Chow *et al*., 1988). The influence of land-use change on surface runoff has been investigated in many studies (Lahmer *et al*., 2001; Bathurst *et al*., 2004). Urbanisation leads to an increase in the impervious area, and, as a result, an increase in the magnitude and frequency of occurrence of floods (Tollan, 2002). The effect of land-use change on flood behaviour is likely to occur for moderate storms, and this effect is reduced during extreme rainfall events (Sriwongsitanon & Taesombat, 2011). Only a few studies have considered a combination of climate and land-use change scenarios for flood impact assessment (Chang & Franczyk, 2008). Notter *et al*. (2007) found that the influence of climate change on floods was greater than that of land-use change, and changes in climate could significantly affect flood peaks and frequencies.

The objective here is to evaluate the combined impacts of climate and land-use changes on flooding in an urban catchment. For this research, outputs from two climate models and two land-use change scenarios were considered to compare flood hydrographs using a calibrated rainfall–runoff model for an urban catchment in southeast Queensland (SEQ), Australia.

DATA AND METHODOLOGY

Study area and the observations

An urban catchment in the Brisbane region was selected for this study: the Bulimba Creek catchment (128 km^2). Mean annual rainfall is approximately 1100 mm in the area. The creek is a major tributary of the lower Brisbane River. It flows through undulating hills down into a wide, flat floodplain and drains from south to north into the Brisbane River (Brisbane City Council, 1992). The impervious area of the catchment has gradually increased due to the construction of roads, footpaths and buildings over the years.

The land-use map for 1999 was available as a baseline for this study (Queensland Department of Natural Resources and Mines, 1999). Figure 1 shows the location of the Bulimba Creek catchment, gauging stations and land-use types in 1999. The impervious fractions were estimated from land-use types and their corresponding impervious fractions in a nearby Norman Creek catchment (Trevithick & Yu, 2010). On average, the fraction impervious was 0.36 in the upper part of the catchment (upstream from the gauging station), and most of the remaining catchment consisted of grass, farm and forested lands in the headwater area and along the creek, and recreational use or reserves, based on the 1999 land-use map.

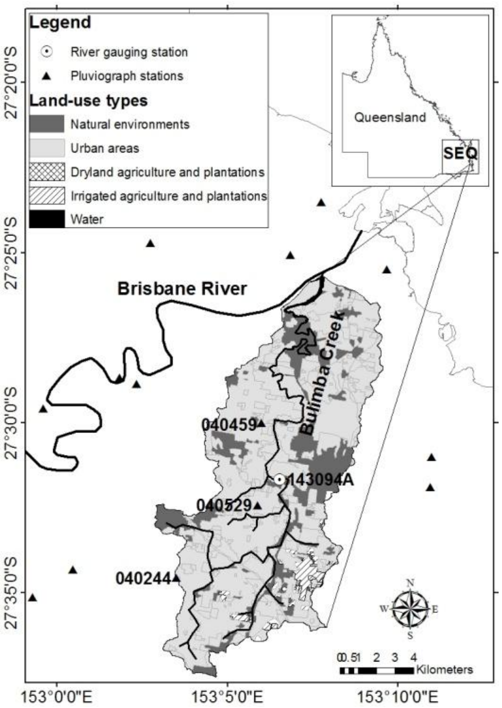

Fig. 1 Details of the study area.

The flow data were available from 1971 to 1996 and 12 major flood events were recorded during this period. Daily and 6-min rainfall data from the Australian Bureau of Meteorology (BOM) were used. Since a 30-year time frame is often used as a standard period for climate classification and assessment, rainfall data for 1961–1990 were collated herein and used as the baseline for rainfall–runoff modelling.

The projected future climate and land-use scenarios

The projected future climate for this research was based on a global climate model (GCM) and a regional climate model (RCM) with the IPCC A2 scenario (Nakicenovic *et al*., 2000). The advantage of using one GCM and one RCM was to provide an acceptable range of future climate change scenarios. The GFDL CM2.1, at a resolution of 2–2.5 deg., was widely used for climate change impact analyses (Tuleya *et al*., 2007). A higher resolution (i.e. 0.15 deg.) of RCM, CCAM, which is a downscaled model from the Australian CSIRO MK 3.0 GCM (Chiew *et al*., 2010) was also used for comparison purposes. Outputs from these two models were tested and results showed broad agreement with observations for the baseline period of 1961–1990 for SEQ (Kent *et al*., 2012).

Outputs from these two models were available at a daily time scale for the reference period 1961–1990 and future period 2016–2045. Results from evaluating the mean annual maximum daily rainfall showed that GFDL CM2.1 and CCAM, respectively, gave 7 and 36% discrepancies when compared with observations for the baseline period (Chen *et al*., 2012). As daily output cannot be used directly for sub-daily flood simulations, a temporal downscaling method was needed. Downscaling methods have been previously developed and used for hydrological modelling (Chen *et al*., 2011). The methods from Chen *et al*. (2011) were tested and showed that the peak intensities would be under-estimated for the Bulimba Creek catchment. A new method based on the historical observations and GCM-predicted daily precipitation was developed for this study. This method is based on the assumption that historical observations may be adjusted to simulate future flood-producing storms as predicted by climate models for the same frequency of occurrence. For a given frequency of occurrence, changes in daily precipitation amounts were calculated as ratios between the two 30-year periods. These ratios, called adjustment factors, were then applied to historical data for the same frequency of occurrence in terms of total rainfall depth. Two methods were used to empirically determine the frequency of occurrence. Method 1 considered all the daily precipitation amounts for the 30-year period. Method 2 only considered the annual maximum daily rainfall amount. Figure 2 illustrates the rainfall adjustment factors for both methods.

Development of future land-use scenarios for hydrological impact analysis is a complex task as it involves the actual urban planning for specific regions and various economic factors. For the purpose of this study, two scenarios were developed following suggestions from Lahmer *et al*. (2001). The first scenario was a moderate but realistic urban development which was a conversion of all farms to urban land, roughly representing an increase of 9% to an impervious fraction of 0.39 from 0.36 in the upper part of the catchment. The second scenario was the worst case development scenario with a conversion of all the remaining farm and forested lands to urban areas in the catchment, giving an average impervious fraction of 0.48.

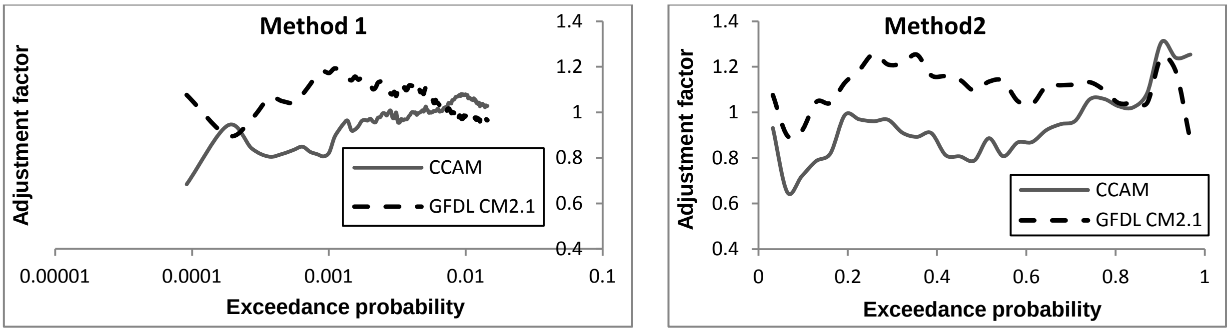

Fig. 2 The adjustment factors using Method 1 and Method 2.

Flood modelling

A commonly used non-linear rainfall–runoff model, RORB, was used to simulate future flood hydrographs. In RORB, a catchment is divided into sub-areas and each is represented by a lumped hydrologic unit (Laurenson *et al*., 2010). Rainfall excess is estimated with a simple infiltration model consisting of initial loss amount (*IL*) and constant loss rate (*CL*) for each sub-area, and the rainfall excess is then routed through the catchment using a storage–discharge relationship to produce runoff hydrographs (Laurenson *et al*., 2010). For calibration purposes, *IL* needs to be specified, while *CL* is calculated automatically based on mass balance. The storage for each sub-area is represented as follows:

$$S = kQ^m \tag{1}$$

where S is the storage, k is the empirical coefficient, Q is the outflow discharge and m is an exponent. The coefficient k is decomposed into:

$$k = k_c \times k_r \tag{2}$$

in which k_c is the coefficient related to the size of the catchment and k_r is a dimensionless ratio related to the delay time for each sub-area, and k_r does not require calibration.

Twelve flood events were available to calibrate and validate the RORB model for the Bulimba Creek catchment. The first six events were used to calibrate the k_c and m values. The calibration was undertaken by giving a set of *m* values ranging from 0.7 to 0.9 and a fixed initial infiltration amount of 0 mm. The value of k_c was then altered to match the observed peak discharge.

For calibration runs, *CL* was automatically calculated to allow for impervious areas to simulate the effect of urbanisation (Laurenson *et al*., 2010):

$$CL_i = (1 - F_i) \times CL_{perv} \tag{3}$$

where CL_{perv} is the baseline rate of infiltration for non-urbanized areas and F_i is the fraction of the impervious area for the sub-area, *i*. Future infiltration parameters were estimated using the equations below:

$$CL_{perv} = CL_{current} / (1 - F_{current,areal\ average}) \tag{4}$$

$$CL_{future} = (1 - F_{future}) \times CL_{perv} \tag{5}$$

where *CL* is the continuing loss rate (mm/h) for the *i*th sub-area, *F* is the imperviousness fraction and CL_{perv} is the continuing loss rate (mm/h) in the previous area. For validation, average *CL* values were calculated separately for all the events, and those in the wet (November–April) and dry (May–October) seasons. For validation, the calibrated k_c, m and the overall and seasonal averages of *CL* were applied.

RESULTS

Calibrate and validation

A fixed *m* value of 0.8 was adopted because the k_c values converged to a fixed value when *m* was close to 0.8 for the calibration events (results not shown), as reported in the literature (Weeks, 1986). In order to determine the best k_c value for the catchment, the mean k_c value and its standard deviation were calculated at the *m* value of 0.8. The mean k_c value for the six calibration events was 5.65 with a standard deviation of 0.24. The overall average *CL* value for all calibration events was 1.51 mm/h with a standard deviation of 0.52. For floods in the wet half of the year (Nov–Apr), the mean *CL* value (1.13 mm/h) was slightly lower than the mean *CL* value (1.89mm/h) in the dry season (May–Oct).

The mean k_c and *CL* values were used for the six validation events (Table 1). As all the validated events occurred in the wet season (Nov–Apr), the average *CL* value and that for the wet season were used for validation purposes (Table 1). It appeared that using the mean *CL* value for the wet season would lead to better validation results, especially in terms of the surface runoff volume; it was decided to use the mean k_c value of 5.65, constant *m* value of 0.8, and the mean *CL* value depending on the season for all simulation of flood hydrographs to assess the effect of climate and land-use change for the urbanized catchment.

Table 1 Errors in simulated runoff volumes (Vol) and peak discharge (Qp) using *m* value of 0.8, k_c value of 5.65, and a continuing loss rate of 1.13 mm/h (row 2) and 1.51 mm/h (row 3) for six validation events.

Event	Apr 1989	Feb 1990	Dec 1991	Mar 1992	Jan 1994	Dec 1995
Errors in Vol (%)	–2	–8	–1	4	2	–3
Errors in Qp (%)	–4	1	–5	–1	3	4
Errors in Vol (%)	–11	–12	–7	0	–2	–8
Errors in Qp (%)	–3	–2	–8	–3	1	1

The impact of climate change on flood frequency

Figure 3 illustrates a sample hydrograph and changes to peak discharge as a function of return periods using GFDL CM2.1. For this event, the rainfall adjustment factor was 1.06 for Method 1 and 1.2 for Method 2, and the respective increases in peak discharge were 6% and 21%. In general, peak discharge would increase in future years using outputs from GFDL CM2.1 and the increase is more pronounced for smaller return periods (Fig. 3). Figure 4 shows the same sample hydrograph and changes to peak discharge as a function of return periods using CCAM outputs. For this event, the rainfall adjustment factor was 0.81 for Method 1 and 0.79 for Method 2, and the respective decreases in peak discharge were 19% and 28%. Peak discharge would in general decrease in future years using outputs from CCAM, although an increase in peak discharge is noted when the return period is less than about 2 years (Fig. 4). The difference between Methods 1 and 2 is smaller than that between GFDL CM2.1 and CCAM for the urban catchment tested. On average, GFDL suggests a 7–10% increase in the peak discharge between 1961–1990 and 2016–2045, while CCAM suggests a 7% to 11% decrease for the same two contrasting periods (Table 2).

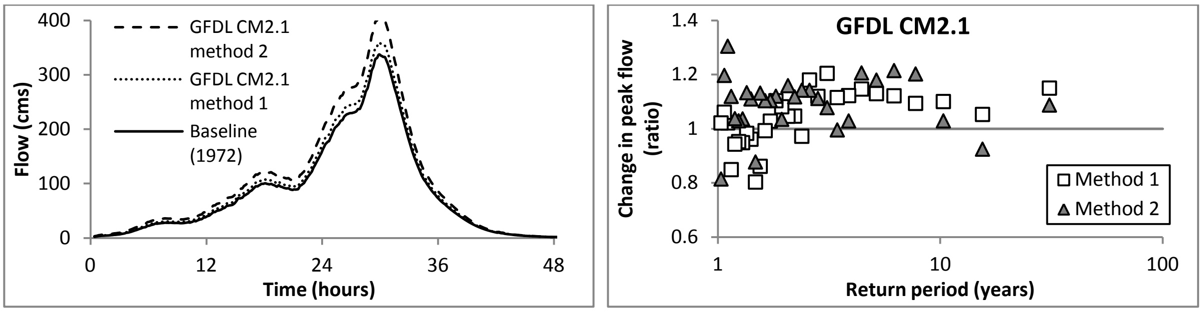

Fig. 3 Flood hydrographs for a sample event in February 1972 and changes to peak discharge as a function of return periods using GFDL CM2.1 rainfall.

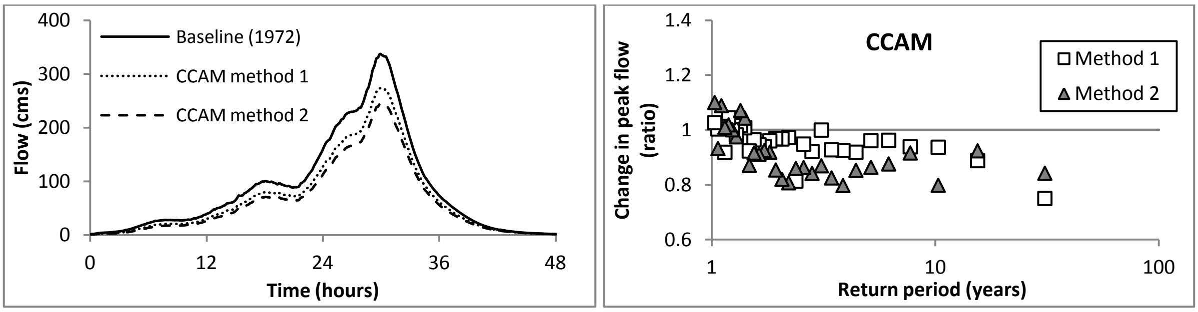

Fig. 4 Flood hydrographs for a sample event of February 1972 and changes to peak discharge as a function of return periods using CCAM rainfall.

The impact of land-use change on flood frequency

Figure 5 illustrates the flood hydrographs derived from observed rainfall in 1972 and two land-use scenarios for the Bulimba Creek catchment. The peak flows based on land-use scenarios 1 and 2 are 0.5% and 1.4%, respectively, higher than the observed peak flow in 1972. The effects of land-use change on flood frequency are presented in Fig. 5. There is a slight increase in the flood frequency curves based on the projected moderate and extreme land-use scenarios. The difference between the extreme land-use change scenario and the moderate land-use change, however, is not statistically significant. Changes in the peak flow are greater for shorter return periods. In other words, the increase in peak discharge is reduced for larger but rarer flood events.

Table 2 shows the mean peak discharge and the standard deviation for a number of different scenarios. On average, GFDL CM2.1 suggests an increase in peak discharge, while CCAM suggests a decrease. The difference between the two methods of rainfall adjustment is smaller than that between different climate models. The worst case scenario from this study, a combination of extreme land-use change and GFDL CM2.1 Method 2, shows a 13% increase on average for the urbanized catchment investigated (Table 2).

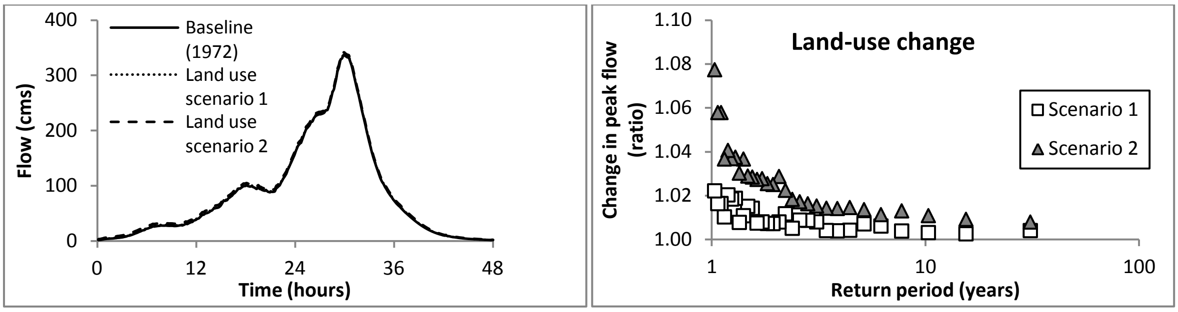

Fig. 5 Current and future flood frequency curves derived from observed rainfall (solid line) with moderate land-use change (dotted line) and extreme land-use change (dashes) and change in peak flows.

Table 2 Mean peak discharge (Qp in $m^3.s^{-1}$) and the standard deviation for different climate and land-use scenarios.

Scenarios	Mean Qp	Std	Change in Qp from baseline
Baseline	218	124	–
GFDL CM2.1 Method 1	234	145	7%
GFDL CM2.1 Method 2	240	134	10%
CCAM Method 1	203	104	–7%
CCAM Method 2	194	102	–11%
Moderate land-use change	220	124	1%
Extreme land-use change	223	124	2%
GFDL Method 2 + Extreme land-use change	246	134	13%

DISCUSSION AND CONCLUSION

Outputs from two climate models and land-use change scenarios were used to assess likely changes to flooding in an urban catchment in SEQ, Australia. A rainfall–runoff model, RORB, was first calibrated and then validated using observed rainfall and runoff data for 12 flood events. We found that fixed parameter values for runoff routing are adequate for both calibration and validation events for the catchment. In contrast, the parameter values for the continuing loss rate are different for different seasons of the year. Two distinct values, one for the dry season and one for the wet were found to be adequate for simulation purposes.

To predict future floods, output from two climate models, GFDL CM 2.1 and CCAM, were used to adjust historical rainfall intensity data to simulate likely changes to rainfall and peak discharge in this study. Overall, results show that the increase in peak discharge for urban catchments in SEQ would not be significant, noting that, the increase is likely to be associated with relatively small recurrence intervals. This observation was in particular supported by outputs from high resolution CCAM. For the same frequency of occurrence, peak discharges for 2016–2045, derived from GFDL CM 2.1 projected rainfall, were higher than those from CCAM projected rainfall. Two land–use scenarios were considered and applied to simulate the effect of land-use change. Based on the 1999 land-use map, the Bulimba Creek catchment was already an extensively urbanized catchment. Therefore, the change in pervious area was structurally limited, and the land-use change had an insignificant effect on flooding, when compared with climate change.

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