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# Flood Scenarios for Hydrological and Hydrodynamic Modelling

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***Abstract*****—**Future flood can be predicted using the probable maximum flood (PMF). PMF is calculated using the historical discharge or rainfall data considering the other climatic parameters remaining stationary. However climate is changing globally and the key climatic variables are temperature, evaporation, rainfall and sea level rise are likely to change. To develop scenarios to a basin or catchment scale these important climatic variables should be considered. Nowadays scenario based on climatic variables is more suitable than PMF. Six scenarios were developed for a large Fitzroy basin and presented in this paper.

***Keywords*****—**Climate change, rainfall, potential evaporation, scenario, sea level rise (SLR), sub-catchment.

## I. Introduction

AUSTRALIA has an extremely variable climate [1]-[3]. Extreme weather events like floods will become more severe and frequent due to climate change [4]. Rainfall, drought and stream flow variability in Australia is more than the rest of the world [5], [6]. Between 1910 and 2004, average maximum and minimum land surface temperatures in Australia have rose by 0.6°C and average minimum temperatures rose by 1.2°C [7], [8]. Most of the rise increase has occurred since 1950.

References [9], [10] found that the frequenvy of high sea level is increasing significantly around Australia. Sea level rise (SLR) along the Australian coastline is more rapid at present than in the past [11]-[13]. Rising sea levels will continue to rise and as a result frequency and intensity of coastal flooding, inundation, flood and storm damage, and drainage congestion will increase during the 21st century [14]. For instance, eastern Australia was extremely wet during late November and December 2010. Widespread flooding on many rivers, especially in Queensland and New South Wales, was observed due to major rain events. Extreme flooding occurred from the last week of December 2010 to first week of January 2011 in Queensland. These floods were the most significant floods in Australia since the 1970s. The Murrumbidgee and Lachlan catchments of inland New South Wales also experienced considerable flooding in December 2010. Record-breaking floods also occurred in western and north-western Victoria in January 2011. For Queensland and eastern Australia, December 2010 was the wettest December on record. Water levels in many of the affected catchments were already high due to rainfall in July to October before the heavy rainfall in late November and December 2010 [15].

Reference [16] developed a data set for severe tropical cyclones in an area extending from Cairns to 1,600 km southward. They found that the number of severe cyclones in the last 20 years was lower than the number in all other twenty-year periods since 1880. This suggests that the number of tropical cyclone events along the eastern coastline is likely to be higher in future decades. Similarly, severe tropical cyclone along the east coast of Australia was projected to increase by 56% by 2050 [17], 22% by 2050 [18] and 140% by 2070 [19]. Besides, reference [19] found an increase in intensity (Category 3-5) and duration of cyclone which will create severe flood.

The traditional approach for future flood is the probable maximum flood (PMF) which has been used in several studies [20]-[27]. PMF is the limiting value of flood that could reasonably be expected to occur. It is based on observations of extreme events in the current climate with a design period. For example, if the design period is 100 years or 500 years, then PMF can happen only once in every 100 years or once in every 500 years respectively. This PMF is calculated from measured historical data which is rarely longer than 100 years. Consequently, statistical extrapolation (i.e. extreme value distribution) is required for the calculation outside the historical measured data. The climate is considered stationary for this statistical extrapolation which seems inappropriate now a day [28]. In contrast, climate scenarios are more appropriate rather than PMF for use in studies exploring the impacts of climate change [29]-[31]. Scenarios based on climate change provide information on the chance of weather extremes. They are neither long term weather forecast nor prediction of weather on a certain day. Rather, these scenarios are consistent and plausible pictures of possible future climate. Therefore, scenarios based on climate change are viewed more suitable than the PMF to explore the impact of climate change on future flood. In this paper functional scenarios are presented based on climate change in a case study area of the Fitzroy Basin.

## II. Study Area

The study area is the Fitzroy basin, which is located in the east part of Queensland, Australia (Fig. 1). This area lies geographically between latitude 21°S and 27°S and longitude 147°E and 151°E [32]-[33]. The Fitzroy river catchment covers an area of 144,000 km$^2$ [33]. A total of 6 sub-

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catchments have been defined based on six major rivers of this basin. All of the sub-catchments and major river systems are presented in Fig. 1. Development of scenario for flood modelling of a large basin like the Fitzroy is a difficult task due to its large catchment size, the long duration flood events, the non-uniform spatial distribution of rainfall and the lack of required data for modelling. Therefore, the whole Fitzroy basin was divided into two parts. Probability based statistical analysis was carried out in the five upstream sub-catchment to upper Fitzroy sub-catchment and developed six scenarios for hydrological modelling. The climatic variables rainfall, potential evaporation, temperature and SLR were analysed to develop the scenarios in the area of interest – the lower Fitzroy sub-catchment. The scenarios developed for the lower Fitzroy basin was applied for integrated hydrological and hydrodynamic modelling. Both the area is presented in Fig. 1.

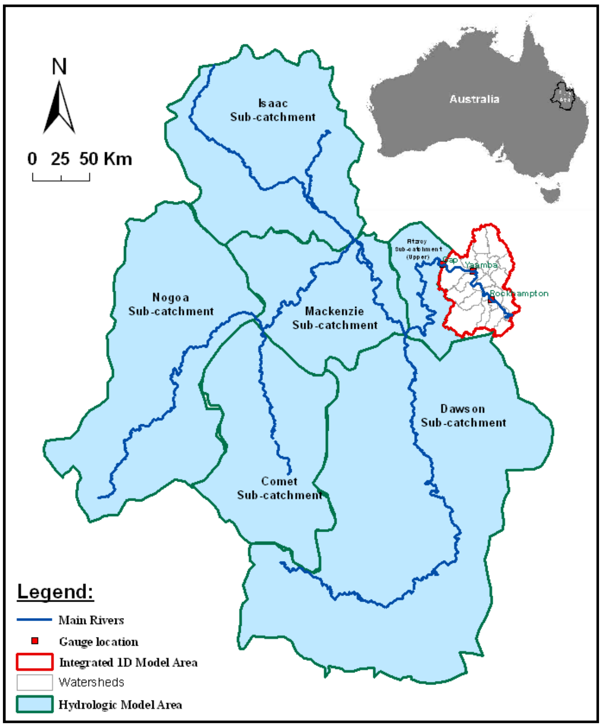

Fig. 1 Study area

## III. METHODOLOGY

Three impacts were considered to formulate the flood scenarios. These were:

i) upstream catchment flooding effect,
ii) local climatic fluctuation on rainfall, potential evaporation and temperature due to climate change, and
iii) SLR due to climate change.

### A. Impact of Flooding in Upstream Sub-Catchments

The weighted daily rainfall data of five sub-catchments were analysed for the period 1 January 1909 to 31 March 2011 to find out the probability of the syncronisation of maximum rainfalls in two or more sub-catchments using joint probability distribution. According to the Bureau of Meteorology (BOM), the Rockhampton area experiences significant moderate to major flooding if the average sub-catchment rainfall exceeds 200 mm in 2 days. As the available rainfall data is daily, the days when 100 mm or more rainfall occurred in one day were identified. A spreadsheet-based macro was used for this analysis. In the 100 years of rainfall data, a total of 274, 241, 195, 176 and 208 independent days were found in the Isaac, Nogoa, Mackenzie, Comet and Dawson sub-catchments respectively. Daily rainfall in each sub-catchment was considered as an independent event.

### B. Impact of Climatic Variables in Local Sub-Catchment

Projections calculating the impact of climate change on rainfall, potential evaporation and temperature for all over the Australia were carried out by CSIRO based on the results from 23 Global Climate Models (GCMs) [34]. Queensland Climate Change Centre for Excellence (QCCCE) has extracted the GCMs dataset to get the projection of rainfall, potential evaporation and temperature for the Central Queensland region (Rockhampton Aero station). The base period for the calculated projections was taken as 1980–1990 and three emission scenarios for 2030, 2050 and 2070 were projected. Little difference was found in the results for low, medium and high emissions scenarios for 2030 of the GCMs. Therefore, for 2030, climate change projections have been considered only for a mid-range emissions scenario. However, the 2050 and 2070 projections are based on low and high emissions scenarios because of divergence of GCM results.

The projected change of rainfall, potential evaporation and temperature is shown in Table I for the summer season of the Rockhampton region for the year 2030, 2050 and 2070. The numbers presented in Table I indicate the range of the results from the GCMs. As the study was intended to generate the extreme flood events from cyclones which normally occur during the summer season, the projected increase to rainfall, potential evaporation and temperature during the summer season were used for the development of the scenarios.

TABLE I
PROJECTED CHANGES OF RAINFALL, POTENTIAL EVAPORATION AND TEMPERATURE FOR THE ROCKHAMPTON STATION FOR DIFFERENT EMISSION SCENARIOS

| Variable | 2030 (Medium Range) | 2050 | | 2070 | |
|---|---|---|---|---|---|
| | | Low | High | Low | High |
| Rainfall | -12 to +8 | -14 to +10 | -23 to +16 | -19 to +13 | -34 to +26 |
| Potential Evaporation | +2 to +5 | +2 to +4 | +3 to +10 | +3 to +8 | +5 to +15 |
| Temperature | +0.6 to +1.4 | +0.8 to +1.8 | +1.3 to +2.9 | +1.0 to 2.4 | +2.0 to +4.7 |

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### C. Impact of SLR

CSIRO developed global SLR projections for 2030-2100 for the three emission scenarios (low: B1, medium: A1F1 and high-end: AR4) which are presented in Table II. Table II shows global sea level rises (SLRs) of 0.5 m, 0.8 m and 1.1 m in 2100 for low, medium and high scenarios respectively.

TABLE II
GLOBAL SLR SCENARIOS BETWEEN 2030-2100 (METRES)

| Year | Low scenario (B1) | Medium scenario (A1F1) | High-end scenario (AR4) |
|---|---|---|---|
| 2030 | 0.13 | 0.15 | 0.20 |
| 2070 | 0.30 | 0.50 | 0.70 |
| 2100 | 0.50 | 0.80 | 1.10 |

Projected regional SLRs vary from the global mean trend due to several effects including meteorological, oceanographic, and geological influences [35]. Besides, global mean sea level reconstruction is based on satellite radar altimeters which is theoretically less effective [14]. Therefore it is important to use the regional projections of SLRs for simulating the hydrodynamic model to obtain appropriate predictions of future extreme events.

Reference [14] estimated relative sea level trends for 47 tide gauges around Australia which have more than 25 years of recorded data. To the best of our knowledge, this is the most up-to-date and accurate study of sea level trends for this study area. Therefore for this study a 1.95 mm/year projected SLR has been taken for the simulation of climate change scenarios according to the recommendation of reference [14].

## IV. RESULTS

### A. Upstream Catchment Flooding Effect

To calculate the probability of two or more sub-catchments experiencing maximum rainfall simultaneously, all possible combinations of sub-catchments were analysed. The results of the analysis are presented in the Table III. This table shows the probability of synchronisation for two, three, four and five sub-catchments. The first ten rows represent the different combinations of synchronisation of maximum rainfalls in two sub-catchments. From the 26 combinations, four combinations were selected for four scenarios.

The mean rainfalls of the sub-catchments were analysed for the historical flood events of 1918, 1928, 1954, 1988, 1991, 2008 and 2011. This analysis is presented in Table IV. This analysis was carried out to identify the synchronisation of two or more sub-catchments during the flood events, and to select the scenarios.

Table III shows that the Mackenzie and the Comet sub-catchments have the greatest probability of synchronisation. However, the Isaac and the Nogoa sub-catchments were synchronised during the historic flood events of 1988. Therefore the combination of the Isaac and the Nogoa sub-catchments was selected as a scenario due to this historical flood event. Similarly, the three sub-catchments: Isaac, Mackenzie and Comet were selected for a scenario although the maximum probability was not found for the combination of these three sub-catchments. Another scenario was selected for maximum rainfall in four sub-catchments: Isaac, Nogoa, Mackenzie and Comet which is similar with the the 1918 flood event. It is evident from the historical data that the five upstream sub-catchment flows have never synchronised. Though the possibility of occurrence such a situation is very low, it is felt that the impact of such a situation should be assessed.

TABLE III
PROBABILITY OF SYNCHRONISATION OF MAXIMUM RAINFALL IN TWO OR MORE SUB-CATCHMENTS

| Sl. | Combination of sub-catchment* | Probability | Return period |
|---|---|---|---|
| 1 | I and N | 0.034 | 29 |
| 2 | I and M | 0.068 | 15 |
| 3 | I and C | 0.034 | 29 |
| 4 | I and D | 0.024 | 41 |
| 5 | N and M | 0.049 | 20 |
| 6 | N and C | 0.103 | 10 |
| 7 | N and D | 0.049 | 20 |
| **8** | **M and C** | **0.112** | **9** |
| 9 | M and D | 0.054 | 19 |
| 10 | C and D | 0.054 | 19 |
| 11 | I, N and M | 0.010 | 102 |
| 12 | I, N and C | 0.015 | 68 |
| 13 | I, N and D | 0.005 | 205 |
| 14 | I, M and C | 0.029 | 34 |
| 15 | I, M and D | 0.005 | 205 |
| 16 | I, C and D | 0.005 | 205 |
| 17 | N, M and C | 0.039 | 26 |
| 18 | N, M and D | 0.015 | 68 |
| 19 | N, C and D | 0.024 | 41 |
| 20 | M, C and D | 0.020 | 51 |
| 21 | I, N, M and C | 0.010 | 102 |
| 22 | I, N, M and D | 0.005 | 205 |
| 23 | I, N, C and D | 0.005 | 205 |
| 24 | I, M, C and D | 0.005 | 205 |
| 25 | N, M, C and D | 0.010 | 102 |
| 26 | I, N, M, C and D | 0.000 | - |

* I, N, M, C and D denote Isaac, Nogoa, Mackenzie, Comet and Dawson respectively.

TABLE IV
SYNCHRONISATION OF MAXIMUM RAINFALL OCCURRENCE IN TWO OR MORE SUB-CATCHMENTS

| Historical flood events | Peak water level at Rockhampton | Synchronised sub-catchments |
|---|---|---|
| 1918 | 10.11 | Isaac, Nogoa, Mackenzie and Comet |
| 1988 | 8.4 | Isaac, Nogoa |
| 2011 | 9.2 | Isaac, Mackenzie and Comet |

### B. Scenario Design

Considering above three important factors, six scenarios were formulated to evaluate the impacts of flooding in Rockhampton area. It was important to calculate normal flow year for the development of baseline scenario (Scenario-1). For that reason, a flood frequency analysis was carried out using yearly maximum discharge time series data for the last 50 years. HYMOS [36], a hydrological data management and processing tool developed by Delft Hydraulics, was applied to analyses the data. Log Pearson III distribution was used for

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frequency analysis because this method is recommended for catchments in Australia [37]. Gumbel distribution was carried out to validate the results of the Log Pearson III distribution. The yearly maximum peak discharge data from the Gap station were used for the frequency analysis. These data are presented in Fig. 2. The maximum peak discharges were 14,549 $m^3/s$ and 13,274 $m^3/s$ in the years 1991 and 2011 respectively. The results of frequency analysis for the Gumbel and the Log Pearson III distribution are shown in Figs. 3 and 4 respectively. The flow event which has a frequency of occurrence 2.33 years is considered as a normal flow year [38]. It can be seen from Figs. 3 and 4 that discharges values greater than 3,500 $m^3/s$ and less than 4,000 $m^3/s$ correspond a normal flow year. It was found from Fig. 2 that this discharge value was similar to that for the years 1977, 1997, 1998, and 2003. Therefore, years 1997 and 1998 were considered as normal flow years. The chosen simulation period was two years from 1 January 1997 to 31 December 1998 for this study in order to overcome the instability error involved in using short duration simulation. Scenarios 2 to 4 were chosen similar to three historical flood events. Though historical data shows that five upstream sub-catchments have never synchronised, the impact of such a situation was assessed in Scenario-5. According to reference [17], the frequency of severe tropical cyclones is projected to increase 56% in future decades. Therefore, in Scenario-6 rainfall was increased by 56% in all sub-catchments.

Scenarios (2 to 6) were simulated by replacing the summer (December 1997 to February 1998) rainfall with the corresponding maximum historical rainfall. After the simulation of six scenarios, discharge at the Gap station was used as the upstream model boundary for the integrated model. Hydrologic model of 21 watersheds were linked with the integrated model. The weight for rainfall, evaporation and temperature of these watersheds were increased according to projected rainfall, evaporation and temperature changes projected to occur by 2070 for different emission scenarios during the summer season only, as floods normally happen during this season. A constant SLR of 1.404 m was used as the downstream model boundary. The six scenarios are presented in Table IV.

## V. CONCLUSION AND DISCUSSION

Rockhampton city is renowned as the beef capital of Australia and famous for its position on the tropic of Capricorn. It is located downstream of the Fitzroy Basin and has a long history of flooding. During the severe flood event all upstream flood water passes through the Fitzroy River in Rockhampton. Functional scenarios based on the combined impacts of climate change and synchronization of severe rainfall on upstream sub-catchments is presented in this paper to explore the impact of climate change on future flood. The whole Fitzroy basin was divided into two parts. A probability based scenarios were developed in the upstream part. In the downstream part the climatic variable rainfall, potential evaporation, temperature and SLR were considered. These scenarios were applied in the hydrological and hydrodynamic modelling to predict the future extreme flood in Rockhampton and surrounding areas.

The methodology proposed here is a case study and can be applied in any other catchment. Development of climate scenarios can be applied to other catchments which have the impact from upstream catchment and SLR. However, scenarios will vary due to different hydrological and meteorological condition and different climate change impacts.

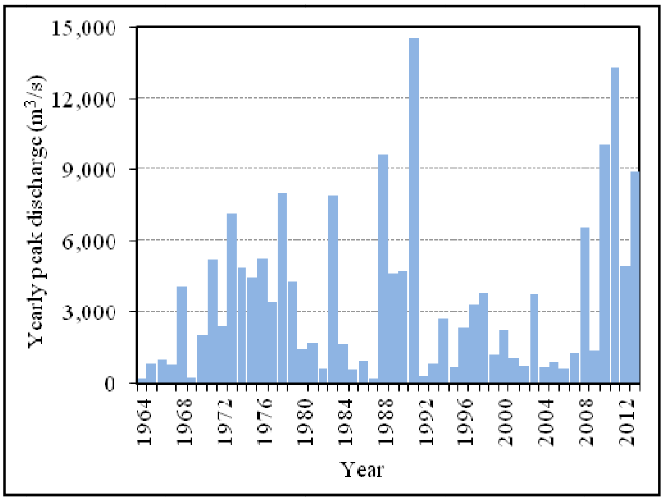

Fig. 2 Yearly peak discharge at Gap station

TABLE V
GENERATION OF DIFFERENT SCENARIOS

| Scenarios | Similarity with historical flood event | Probability | Hydrological model considerations | | HD model considerations | | |
|---|---|---|---|---|---|---|---|
| | | | Rainfall pattern in sub-catchment(s) | | Increase in lower Fitzroy sub-catchment | | |
| | | | Normal flow year | Historical maximum | Rainfall (%) | Potential Evaporation (%) | Temperature (°C) |
| Scenario-1 (Normal flow) | - | - | all upstream five sub-catchments | - | - | - | - |
| Scenario-2 (Low flow) | 1988 | 0.034 | Mackenzie, Comet and Dawson | Isaac, Nogoa | 13 | 3.0 | 1.00 |
| Scenario-3 (Medium flow) | 2011 | 0.029 | Nogoa and Dawson | Isaac, Mackenzie and Comet | 15 | 3.5 | 1.25 |
| Scenario-4 (High flow) | 1918 | 0.010 | Dawson | Isaac, Nogoa, Mackenzie and Comet | 20 | 4.0 | 1.50 |
| Scenario-5 (Very high flow) | - | - | - | all upstream five sub-catchments | 26 | 5.0 | 2.00 |
| Scenario-6 (Extreme high flow) | - | - | - | 1.56 times in all upstream five sub-catchments | 26 | 5.0 | 2.00 |

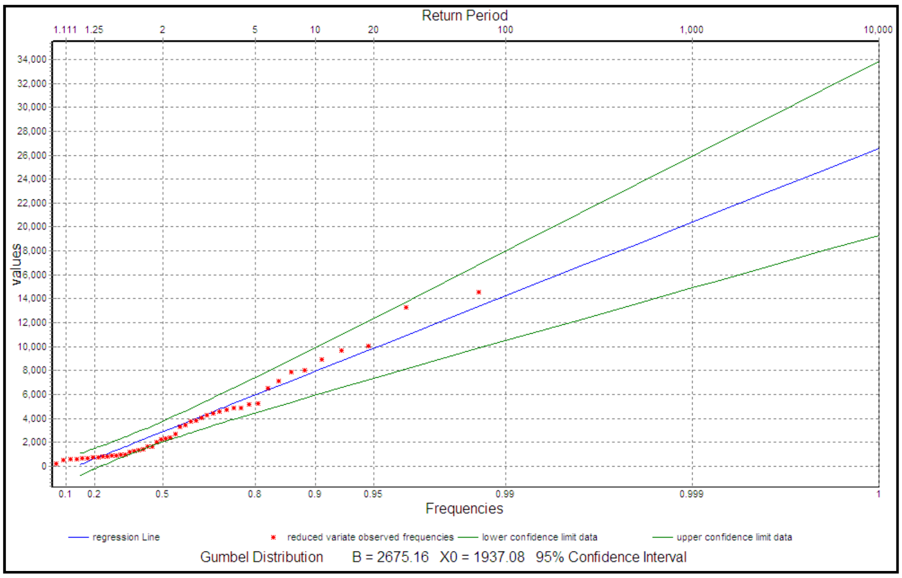

Fig. 3 Frequency analysis using Gumbel distribution for Gap station

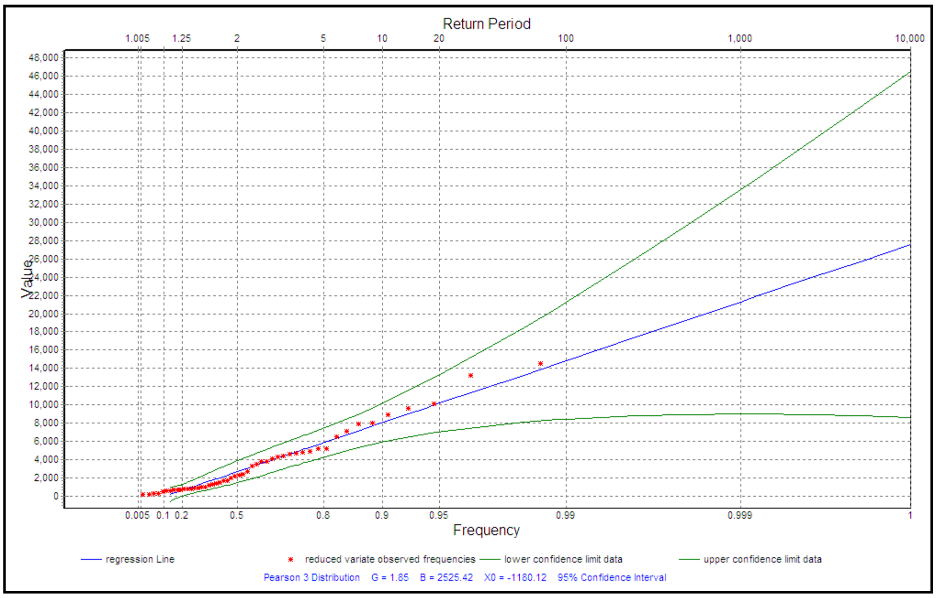

Fig. 4 Frequency analysis using Log Pearson III distribution for Gap station

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