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Flood generation during the SW monsoon season in northern Thailand

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Abstract: This paper analyses the annual floods for the city of Chiang Mai in northern Thailand using a relatively long dataset (1921–2009) to study the mechanisms behind flood generation in this region. Four floods of different magnitudes were chosen for the empirical analysis. Daily rainfall, flow and baseflow data are analysed together with information about tropical storm occurrence–frequency and El Niño Southern Oscillation (ENSO) events to identify the occurrence and causes of floods. We found that floods are caused by a variety of factors but the most extreme floods are often caused by a combination of wet catchment conditions and heavy rainfall due to monsoonal effects or tropical storms. Tropical storms play a variable role in that their occurrence in the earlier part of the monsoon season may only wet up the catchment and have no part to play in the peak-flow generation. However, heavy rainfall due to tropical storms during the later part of the monsoon season may result in extreme floods. Typhoon Damrey (2005) is such an example as a 100 year flood event occurred after the passage of this typhoon across northern Thailand. Flood forecasting and management therefore need more high-resolution information about rainfall patterns and tropical storm activity.

Seasonal flooding is a regular feature of the monsoon climate and its occurrence signals the beginning of the rice-growing season when plentiful rains arrive. Communities living in monsoonal regions have learned to live with floods but there is now a growing perception that floods are hazards that need to be controlled (Manuta & Lebel 2005). Floods are common in north Thailand because this region experiences the highest seasonality in rainfall distribution within Thailand (Boochabun et al. 2004). In addition, the complex interactions between rainfall and large-scale climatic circulation systems, such as the El Niño Southern Oscillation (ENSO) and tropical storms, make peak-flow generation a highly variable and complex process. For instance, monsoon rainfall generally decreases during El Niño years while the opposite occurs during a La Niña year (Rasmussen & Carpenter 1983; Kripalani & Kulkarni 1997). Yet, high rainfall occurred during an El Niño year in 2002, resulting in serious flash floods in certain parts of northern Thailand (Singhrattna et al. 2005).

This paper examines floods that occur in Chiang Mai, the main city in northern Thailand and the second largest city in Thailand. Floods occur regularly in the city but have recently been causing more damage as urban development encroaches into the floodplain. The gauging record for this city is relatively long for this part of the world (1921–present) and includes flow data for many floods that occurred in the recent past. The growing importance of flooding in this city is reflected in the academic literature. Wood & Ziegler (2008) examined sedimentation patterns for a 100 year flood that caused serious flooding in the city in 2005. Duan et al. (2009) used the HEC-RAS (Hydrologic Engineering Center’s River Analysis System) model and satellite imagery to map and model the extent of flood inundation for the same event. Their analysis showed that the flood depth was up to 1.68 m in the floodplains, and that several schools, hospitals and factories were found to be located in areas that are categorized as having a high flood risk. As an attempt to contribute to the growing literature on flood studies in Thailand, this paper examines a series of Chiang Mai city floods of different magnitudes in order to understand the occurrence and causes of floods in this city through an analysis of the hydrological response behaviour and the climatic factors that drive flood generation. The case-study floods chosen are caused by different mechanisms in order to highlight the complexities surrounding the generation of floods in northern Thailand.
Study site

The Ping River flows through Chiang Mai city and flow is gauged at the P1 gauging station (18°47′09″, 99°00′29″). The catchment above the P1 station drains an area of 6355 km² (Fig. 1). The Ping River originates within the mountainous area of northern Thailand, with steep mountains that go up to an elevation of 2000 m and valleys that lie below 500 m. This river basin is underlain by older Palaeozoic gneiss and foliated granitic rocks, Palaeozoic sediments and volcanics, Mesozoic granitic rocks, and Tertiary continental basin-fill sediments (Wood & Ziegler 2008). The catchment was previously covered by subtropical forests that have been slowly converted to agricultural land use, which includes upland rice, irrigated crops, flower farms and commercial greenhouses on the hillslopes and floodplains of the catchment. The width of the river at the P1 gauging station is approximately 110 m. The floodplain is about 3 km wide, extending to about 1–1.5 km on either side of the river bank (Wood & Ziegler 2008). The annual peak stage levels at P1 show that the river overflows its bank once water levels rise above an elevation of approximately 3.7 m above sea level, which seems to be a common occurrence according to the data shown in Figure 2.

The climate of the catchment is classified as tropical monsoon (Aw) according to the Köppen system. The average annual temperature ranges from 20 to 34 °C (Thanapakpawin et al. 2006). The annual long-term rainfall is approximately 1200 mm (Wood & Ziegler 2008). The rainfall distribution is highly variable on an annual and seasonal basis. This is because the region is located at the interface of two dominant regional climatic systems: the Indian SW monsoon and the ENSO system.

The SW monsoon lasts from approximately late April–early May to October–November (Matsumoto 1997). It occurs as warm air from the Indian Ocean moves towards Thailand around late April–early May. At this time the Inter-Tropical Convergence Zone (ITCZ) moves quickly from south to north Thailand, bringing fresh rains to the study area in early May. By June, the ITCZ has moved further northwards to southern China, so north Thailand is relatively dry during this period. In August, the ITCZ moves southwards again and lies over

Fig. 1. Map of the Ping River catchment area above the P1 gauging station and the rainfall stations in the catchment.
northern Thailand. Peak rainfall occurs during this month or in September. The end of the monsoon period occurs approximately in October when the ITCZ moves further south. This is followed by the winter season, which is dominated by the NE monsoon that lasts from mid-October to approximately April or early--mid May (Thai Meteorological Department 2002). Cyclones and other forms of climatic disturbances in the form of monsoon depressions and typhoons also influence rainfall activity in this catchment. Tropical cyclones originate from the east of the catchment over the western North Pacific Ocean or the South China Sea and pass through or close to north Thailand from May to October. Peak activity occurs around the months of September and October (Thai Meteorological Department 2002). Seasonal rainfall can account for as much as 92% of the annual rainfall. The hydrological regime of the Ping River reflects the seasonal rainfall distribution as 70% of annual total flow occurs during the rainy season (Thanapakpawin et al. 2006).

**Data and methods**

The empirical analysis of flood generation is based on an analysis of annual peak-flow data derived from analysing daily flow data from the P1 gauging station. Annual peak flow, $Q_p$, is used as an indicator of flooding, especially if it corresponds with overbank flow (Fig. 2). Confirmed reports of flooding are based on news sources and information from the Royal Irrigation Department office in Chiang Mai.

Daily rainfall and baseflow data are analysed together with information about tropical storm occurrence and ENSO events. Daily rainfall is the simple average of rainfall data from six stations located throughout the P1 catchment (Fig. 1). Data on tropical cyclones are obtained from the Thai Meteorological Department (TMD). Cyclone is the term given to tropical cyclones originating from the Indian Ocean and the South Pacific (west of longitude 160°), while typhoons refer to tropical cyclones originating in the Pacific Ocean. In this

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**Fig. 2.** Time-series of annual peak flows ($Q_p$) and water level at the P1 gauging station, 1921–2009. Threshold level of 3.7 m indicates bankful conditions. Bars with hashing and numbers 1, 2 and 3 indicate the top three ENSO events in terms of their severity. (Source of data: Royal Irrigation Department.)
paper, tropical cyclone is used as a generic term to refer to either typhoons or cyclones; however, the terminology adopted by the TMD is used to refer to specific events in relation to the floods. The ENSO events (El Niño or La Niña) are identified using the method developed by the Japan Meteorological Agency (JMA). The Southern Oscillation Index (SOI) was not used because it is relatively noisy (Bove et al. 1998). The JMA Index is a 5 month running mean of spatially averaged sea-surface temperature anomalies over the tropical Pacific in the region 4°S–4°N, 150°W–90°W (ftp://www.coaps.fsu.edu/pub/JMA_SST_Index/). An El Niño or La Niña event occurs when the JMA Index is greater than 5°C or at least 5°C below average for at least six consecutive months (including October, November and December), respectively.

Baseflow represents an integrated measure of catchment wetness. Baseflow data for the P1 gauging station was obtained using the Baseflow Index Program (BFI) version 4.15 available on the World Wide Web (http://www.usbr.gov/pmts/hydraulics_lab/twahl/bfi/). Baseflow separation is based on the Institute of Hydrology (UK) Standard method of baseflow separation (Institute of Hydrology 1980).

Flood frequency analysis was conducted on the 89 year-flow dataset to identify the return periods of various flood events (Fig. 3). (The return period of the flood events in this study was calculated using the Weibull formula, which is the most commonly used method to calculate return periods; see Brutsaert 2005, p. 515 for a fuller explanation. The return period, \( T(x) \), is calculated as \( T(x) = (n+1)/m \), where \( n \) is the number of years of record and \( m \) is the rank of an individual flood event. The largest event in an annual maximum flow series will have a rank of 1 (i.e. \( m = 1 \)).) A range of different floods that occurred in Chiang Mai city (in 1952, 1973, 2005 and 2006) were identified. These floods represent events of different magnitudes and were also caused by different mechanisms. The 2005 flood is the largest flood recorded within the 89 year period. The second largest flood on record occurred in 1973. The 1952 flood is included because local accounts stated that large parts of Chiang Mai city were inundated. Finally, the 2006 flood is included as a comparative example against the 2005 flood, as floods occurred in both years but may have been caused by different mechanisms. Their close temporal proximity reduces the impact of land-use change or changes in channel capacity in influencing flood generation and subsequent flood behaviour.

To examine the interactions between rainfall, flow and baseflow (i.e. catchment wetness) in causing floods, the normalized cumulative flow, baseflow and rainfall values for each day of any month are plotted together to show the relative increase in each of these three variables over the course of a month. The normalized cumulative value for each day is obtained by dividing the daily value of a particular variable by its cumulative value observed for each month. The following indices for peak flows for the selected years could be obtained.

- \( Q_p \) – annual peak-flow value.
- \( Q_p/Q_{p\text{ longmean}} \) – represents the annual peak flow as a function of the long-term average for the 89 year period.

![Fig. 3. Flood frequency graph for the P1 gauging station, 1921–2009. The floods analysed are highlighted. (Source of data: Royal Irrigation Department.)](image-url)
API-7 – the 7 day antecedent rainfall prior to each flow peak; it provides an indication of recent rainfall activity prior to the peak flow.

RF
p – refers to the maximum daily rainfall occurring within the API-7. It provides an indication of the rainfall intensity in relation to the daily flow.

BF at Q
p – refers to the baseflow value when Q
p occurs.

BF/BF
p – refers to the ratio of baseflow when Q
p occurs to the annual peak baseflow value. It provides an indication of how wet the catchment is when Q
p occurs.

BF/Q
p – ratio of baseflow to Q
p. This value provides an indication of whether baseflow or quickflow processes dominate in the production of Q
p (following Hibbert & Cunningham’s 1967 definition of baseflow and quickflow, see Gregory & Walling 1973). (According to Hibbert & Cunningham 1967, a storm hydrograph can be separated by a line into a quickflow and a delayed flow component. The quickflow component generally represents rapid runoff, while the delayed flow generally represents runoff from slow sources or from baseflow (Gregory & Walling 1973)).

Results

When will it flood?

Rainfall patterns show a bimodal distribution. Higher rainfall is observed around the month of May and peaks in September following the movement of the ITCZ over northern Thailand (Fig. 4). Baseflow is highest in September owing to the continuous rainfall in the previous months. Peak flows and, therefore, floods are likely to occur in late August or September when heavy rainfall falls on a wet catchment. Furthermore, the increased frequency distribution of tropical cyclone activity in September implies that heavy rainfall associated with this storm activity results in favourable conditions for flooding to occur (Fig. 5).

Flood-generating mechanisms

The analysis of floods that occurred in two consecutive years, in 2005 and 2006, show the different mechanisms influencing flood generation of this catchment (Figs 6 & 7).

Three floods occurred in 2005 (Figs 3 & 7). This is a 100 year event. Two of the three floods are related to tropical storm activity. The earliest flood was due to a tropical depression (14–16 August) (Table 1); Tropical Cyclone Vicente (20–22 September) and Typhoon Damrey (30 September) caused the subsequent two floods. Typhoon Damrey, in particular, caused massive flooding as it swept westwards across the IndoChina peninsula as a tropical depression around 27 September (Wood & Ziegler 2008). The annual peak flow for 2005 was the highest annual peak flow (867 m³ s⁻¹) recorded for the 89 year data record.

The normalized cumulative flow, baseflow and rainfall plots for August showed flows increasing significantly in response to heavy rainfall on 12 August 2005 (106 mm) (Fig. 8a, b). By contrast, the annual peak flow observed on 30 September was caused by continuous rainfall due to Tropical Cyclone Vicente (19 September, 26.2 mm) and Typhoon Damrey (27 September, 39.6 mm). Both flow and baseflow increased gradually throughout September in response to continuous rainfall (Fig. 8c). This corresponded to a period of rapid increase in flow and catchment wetness conditions (Fig. 8a). In fact, Typhoon Damrey occurred at a time when the P1 catchment was very wet, as the baseflow to annual baseflow peak (BF/BF
p) was

Fig. 4. Long-term monthly distribution of annual peak flow, rainfall and baseflow, P1 gauging station, 1921–2009.
relatively high compared to the baseflow during the August high flow (Table 2). The relatively low API 7-day value (107.2 mm) also showed that this flood was not caused by a single heavy rainfall event (Table 2). The main 2005 flood was, therefore, caused by continuous typhoon-bearing rainfall occurring over a wet catchment that was already previously wetted up by another tropical cyclone and heavy monsoon rainfall.

The 2006 event is ranked ninth on the list of annual peak flows and has a 10 year return period (Fig. 3). In this case, monsoon rainfall appears to have been the sole cause of the floods in 2006, unlike the main 2005 flood. The annual peak flow occurred earlier in the monsoon season compared to its 2005 counterpart; 1 August 2006. Subsequent high flows were recorded on 2 September, 23 September and 10 October. The cumulative graphs showed that the 1 August and 2 September flow peaks were a result of heavy rainfall approximately 2 days prior to the recorded $Q_p$ (43.7 mm on 30 July and 34.8 mm on 31 August) (Fig. 9). The subsequent peaks in late September and October were a result of continuous rainfall during the period prior to each recorded peak flow (Fig. 9d). The annual peak flow on 1 August occurred when the catchment was about 65% wet ($BF/BF_p = 0.65$; Table 2). The peak was therefore caused by 2 days of relatively heavy rainfall on 30 and 31 July, which resulted in an annual peak flow that was 1.5 times that of the long-term average (Fig. 9b, Table 2).

Role of tropical cyclones

The role of tropical cyclones in causing floods is examined in this subsection using the floods that occurred in 1952 and 1973 as examples. Tropical cyclones occurred in both years but their effect on the annual peak flow and flood generation was quite different.
In 1952, two typhoons (Typhoon Louise and Typhoon Nora) made landfall near the Ping River catchment (Table 1). These typhoons did not result in the annual peak flow for the year (Tables 1 & 2, Fig. 10). The annual peak flow was, in fact, caused by high rainfall (62.1 mm on 19 September) that was not related to any tropical cyclones. The resulting annual peak flow was 1.2 times the long-term average and is ranked 21 in the 89 year period. Historical accounts tell of extensive flooding of the city of Chiang Mai. Flow and baseflow increased gradually over the course of August and September, even though there were certain days that experienced more rainfall owing to the effects of the two typhoons, Louise and Nora (Fig. 10c, d). The role of the two typhoons appears to have been to wet up the catchment, given the high BF/BFp value when the impacts of Typhoon Nora were felt by the P1 catchment (BF/BFp = 0.99; Table 2). The annual peak flow on 22 September was then caused by a single heavy rainfall event (19 September) on already wet catchment soils (Fig. 10d).

The 1973 flood is, by contrast, more severe than the one that occurred in 1952, being ranked second in magnitude over the 89 year record based on the annual peak-flow data (45 year return period).

### Table 1. List of tropical cyclones and peak-flow characteristics for the four floods studied

<table>
<thead>
<tr>
<th>Type of storm</th>
<th>Name</th>
<th>Date</th>
<th>Where it landed</th>
<th>Date of $Q_p$ occurrence</th>
<th>$Q_p$ (m$^3$ s$^{-1}$)</th>
<th>API-7* (mm)</th>
<th>$Q_p$ rank†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typhoon Louise</td>
<td>29 August 1952</td>
<td>Nan</td>
<td>1 September 1952</td>
<td>396</td>
<td>83</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Typhoon Nora</td>
<td>8 September 1952</td>
<td>Chiang Rai</td>
<td>10 September 1952</td>
<td>450</td>
<td>110.6</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Typhoon Anita</td>
<td>9 July 1973</td>
<td>Nan</td>
<td>13 July 1973</td>
<td>308</td>
<td>83.9</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Tropical cyclone Jones</td>
<td>23 August 1973</td>
<td>Nan</td>
<td>25 August 1973</td>
<td>726</td>
<td>117.7</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Tropical cyclone Vicente</td>
<td>19 September 2005</td>
<td>Nan/Chiang Rai</td>
<td>21 September 2005</td>
<td>679.5</td>
<td>122</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Tropical cyclone Damrey</td>
<td>27 September 2005</td>
<td>Nan</td>
<td>30 September 2005</td>
<td>867.2</td>
<td>64.1</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Note that the criterion for inclusion into the table is that the date of $Q_p$ occurrence must be within 5 days of the date of the tropical storm entering Thailand.

*API-7 is the amount of rainfall recorded during the week prior to $Q_p$ occurring. It is calculated as the weekly sum of rainfall starting from the date that the tropical storm arrived at Thailand.

†The ranking is given only if the tropical cyclone was the cause of the annual peak for a year.
Fig. 8. (a) Cumulative plots of rainfall, flow and baseflow, and normalized cumulative plots of rainfall, flow and baseflow for (b) August and (c) September 2005, Ping River at P1 gauging station. The red diamonds in (a) refer to the days when a spike in flow occurs.
Typhoon Anita and Tropical Cyclone Jones crossed near to the Ping River catchment in 1952 (Table 1). Their landfall resulted in a significant increase in river flow (Fig. 11c, d). Tropical Cyclone Jones resulted in 1 day of heavy rainfall over the catchment (114.3 mm on 23 August) that led to the annual peak flow for the year (Fig. 11d). The limited impact of Typhoon Anita ($Q_p/Q_{pl longmean} = 0.8$) is related possibly to its early occurrence in the monsoon season when the catchment was still relatively dry ($BF/BF_p = 0.19$; Table 2). However, the catchment had become relatively wetter by the time Tropical Cyclone Jones occurred, such that heavy rainfall resulted in an extreme annual peak (1.8 times the long-term average) (Table 2). In this case, it would seem that both heavy rainfall and wet catchment conditions played a role in flood generation, although the former seemed to have a greater role.

**Discussion**

The empirical analysis of flood events that occurred in Chiang Mai highlights that the flood generation mechanisms vary on an annual basis. Here, we used the annual peak-flow data as an indicator of the magnitude of floods. The 1952, 1973 and 2005 floods were all influenced by tropical storm activity, whilst this influence was lacking in the 2006 floods. The most extreme floods experienced in this catchment were caused by a combination of common mechanisms of flood generation in this region; wet catchment conditions due to continuous monsoon rainfall or tropical storm activity (e.g. 1952) in addition to heavy rainfall from tropical storm activity (see Hirschboeck 1988). We see this happening in the case of the 1973 and 2005 floods. Additionally, the P1 catchment exhibits a fast response time to rainfall that is an approximate 2 day delay period between rainfall and $Q_p$ for the four floods examined in this paper (Table 1). This could be a reflection of the mountainous topography and suggests that high-resolution data collection is necessary for the flood-monitoring programme of this catchment area.

Typhoon Anita was an influence on catchment conditions in 1952 (Table 1). Their landfall resulted in a significant increase in river flow (Fig. 11c, d). Tropical Cyclone Jones resulted in 1 day of heavy rainfall over the catchment (114.3 mm on 23 August) that led to the annual peak flow for the year (Fig. 11d). The limited impact of Typhoon Anita ($Q_p/Q_{pl longmean} = 0.8$) is related possibly to its early occurrence in the monsoon season when the catchment was still relatively dry ($BF/BF_p = 0.19$; Table 2). However, the catchment had become relatively wetter by the time Tropical Cyclone Jones occurred, such that heavy rainfall resulted in an extreme annual peak (1.8 times the long-term average) (Table 2). In this case, it would seem that both heavy rainfall and wet catchment conditions played a role in flood generation, although the former seemed to have a greater role.

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The role of tropical cyclones in flood generation is highly variable and complex for the P1 catchment. Analysis of the four floods showed that the effect of tropical cyclones was to: (a) wet up the catchment, especially if they occur in the earlier part of the monsoon season (e.g. the 1952 flood); or (b) to act as a trigger for peak-flow generation as high rainfall associated with these storm events tend to magnify the effects of other rainfall-generating mechanisms during the monsoon season (e.g. rainfall associated with southwesterly winds, tropical depressions). Previous studies showed that the formation of tropical cyclones is dependent on factors such as the occurrence and location of sea-surface temperature anomalies that are associated with ENSO events. For instance, cyclone formation...
Fig. 9. (a) Cumulative plots of rainfall, flow and baseflow, and normalized cumulative plots of rainfall, flow and baseflow for (b) July, (c) August and (d) September 2006, Ping River at P1 gauging station. The red diamonds in (a) refer to the days when a spike in flow occurs.
Fig. 10. (a) Time-series of rainfall, flow and baseflow. (b) Cumulative rainfall, flow and baseflow, and normalized cumulative plots of rainfall, flow and baseflow for (c) August and (d) September 1952, Ping River at P1 gauging station. The red diamonds in (b) refer to the days when a spike in flow occurs.
Fig. 11. (a) Time-series of daily rainfall, flow and baseflow. (b) Cumulative daily rainfall flow and baseflow, and normalized cumulative plots of rainfall, flow and baseflow for (c) July, (d) August and (e) September 1973, Ping River at P1 gauging station. The red diamonds in (b) refer to the days when a spike in flow occurs.
was found to decrease between the months of September and November during an El Niño year (Elsner & Liu 2003; Wu et al. 2004). A further study of the relative role and impacts of tropical cyclone activity on flood generation in this catchment requires a closer examination of cyclone tracks landfalling in northern Thailand. In addition, the amount of rainfall associated with each tropical storm, its characteristics and timing of its landfall within the monsoon season as well as ENSO occurrence will provide more specific information on the relative role of tropical cyclones in flood generation for this catchment. In particular, the role of the mountainous terrain of this catchment may enhance the impact of tropical storms, especially through orographical rainfall enhancement – as shown elsewhere in Puerto Rico (see Smith et al. 2005).

The four flood events also allowed an analysis of the influence of ENSO activity on flood generation. No ENSO activity was reported for 1952 and 2005. The 1973 flood occurred during a La Niña year and the 2006 flood occurred during an El Niño year. In fact, the 1973 flood is located within a period in the early 1970s when there was an unusual persistence of La Niña conditions (Fig. 2). Monsoon rainfall in Thailand shows a generally negative correlation during El Niño years, while the opposite occurs during a La Niña year (Rasmussen & Carpenter 1983; Kripalani & Kulkarni 1997). Kripalani & Kulkarni (1997) claimed that rainfall exhibited distinct sequences of above and below normal rainfall, lasting 30 years in the case of Thailand, that are not forced by ENSO events. The impact of a La Niña event will be magnified if it occurs during a period of above-normal rainfall (i.e. these two forcings are phase-locked). According to these authors, above-normal rainfall occurred between approximately the mid-1930s until the end of the 1960s. The early 1970s occurrence of La Niña fell outside of this high rainfall period but, nonetheless, the persistence of several La Niña events over a short period of time in the early 1970s meant that the P1 catchment may well have been generally wetter compared to other years during the 89 year period. In fact, Table 2 shows that the BF/Qp values for 1973 high flows are generally higher (ranging between 0.23 and 0.50) for the same periods of time within the monsoon season compared to other years, such as 2005 and 2006, when the BF/Qp ratio is at a maximum of 0.29 (in 2005) (Table 2). The relatively higher BF/Qp values for the 1973 and, in addition, the 1952 high flows also suggest that baseflow formed a more significant component of peak-flow composition than in 2005 or 2006 when quickflow sources of runoff would have been more significant contributors to peak flows (following the definitions of quickflow and baseflow adopted by Hibbert & Cunningham 1967 in Gregory & Walling 1973) (Table 2).

Floods can also occur owing to heavy monsoon rainfall even during an El Niño year (i.e. 2006). In 2002, flash floods were reported for some areas near the P1 catchment when monsoon rainfall coupled with heavy rainfall due to Tropical Cyclone Usagi occurred. This unexpected heavy monsoon rainfall during an El Niño year was attributed to the unusual shift in the location of sea surface temperature (SST) anomalies over the Pacific Ocean. In 2002, ENSO activity was centred over the date line rather than the eastern Pacific Ocean. This led to above-normal rainfall over Thailand (Singhratna et al. 2005). The influence of ENSO activity on flood generation is therefore highly complicated owing to complexities within the ENSO system, such as the location of SSTs and the relationship between ENSO and rainfall.

Conclusion

The empirical study of four different flood events of different magnitudes in Chiang Mai city gave us the opportunity to analyse the different mechanisms of flood generation in northern Thailand using the Ping River catchment at the P1 gauging station as a case study. Floods occur regularly but the mechanisms behind their formation vary on an annual basis. Floods that affect the city can occur even during El Niño years when monsoon rainfall is generally expected to be lower. However, the most extreme floods experienced in this catchment are caused by a combination of factors that work together. The 2005 and 1973 floods are a result of heavy rainfall often due to tropical storms making landfall near the catchment area, especially when the catchment is already wetted up by monsoonal rainfall or prior tropical storms. As such, a complex interaction is observed between monsoonal rainfall and the number, timing and occurrence of tropical storms in causing more extreme floods at this site using just four examples of floods. Whilst climatic controls are important in flood generation, land-cover/land-use changes also feature as a potentially important force in flood generation given the rapid changes in land cover/land use in SE Asia (e.g. Schmidt-Vogt et al. 2009). Future work for this site looks at investigating trends in annual peak flows and the climatic variables that affect rainfall in northern Thailand, as well as an analysis of land-cover/land-use changes over time to identify the relative effects of these two forces on peak flow and flood generation. On a more practical basis, the fast response time of this relatively large catchment area implies that the continued monitoring of storm tracks by the Royal Meteorological Office is necessary.
Department, and more detailed temporal and spatial monitoring of rainfall and flow patterns, are necessary for the successful flood monitoring and management for this catchment. This is especially true in the case of flash-flood monitoring and the development of warning systems using telemetry to convey real-time data to government agencies for flood monitoring and warning.

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