The 2011 Thailand flood: climate causes and return periods[1†]

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Thailand is one of the wealthiest and most developed countries in southeast Asia. However, its tropical location and the influence of seasonal monsoon rains and local topography make it prone to floods. The floods in 2011 were especially severe, causing estimated losses of US $30 billion (economic; Swiss Re, 2012) and US $12 billion (insured; Swiss Re, 2012). The insured loss ranks easily as the highest-ever worldwide from a freshwater flood disaster (Swiss Re, 2012). The primary reason for the floods was record rainfall: over Thailand as a whole, annual rainfall in 2011 was the highest in the country's 61-year precipitation record (Thai Meteorological Department, 2011). In this article we first review the nature, impacts and historical ranking of the 2011 Thailand floods. We then examine the 2011 rainfall totals and anomalies across Thailand and use these with other data to discuss the climate causes for the exceptional rainfall. We then estimate the rainfall return period for this flooding event and compare this with satellite-derived return periods for the 2011 river flow. Finally, we bring together the different estimated return periods to provide a firmer assessment of how likely it is that a flood of the magnitude of 2011 will happen again.

Thailand flooding and 2011 flood overview and ranking

The climate of Thailand is monsoonal, with 80% of the normal annual rainfall occurring between May and October from the summer southwest monsoon (Thai Meteorological Department, 2012). During the wettest months of August and September rivers carry high runoffs and can overflow, leading to flooding. In extreme rainfall years the flooding may spread along Thailand's main water artery, the Chao Phraya River basin, towards Bangkok, the country's capital, before emptying into the sea. The Chao Phraya River basin is home to about 20 million people (30% of the total population) (DHI, 2012) and to much of Thailand's manufacturing industry (Swiss Re, 2012). The basin's relatively flat topography (a gradient of just 1.5m per 100km (DHI, 2012)) means that floodwaters drain away slowly and that floods have long durations. Due to its tropical location Thailand also experiences the remnants of northwest Pacific tropical cyclones, which bring additional heavy rainfall that can also initiate or exacerbate flooding during the monsoon season.

In 2011, the southwest monsoon started early, and Thailand experienced record rainfall in March and April (Swiss Re, 2012). Above-average rainfall continued throughout the six-month summer monsoon season. This, together with heavy rainfall from four tropical storm remnants crossing the north of the country, led to rivers bursting their banks. Insufficient management of the main dams in Thailand led to overtopping and to the release of yet more water, further exacerbating the flooding which caused extensive damage (Figure 1(a)) to homes, sites of historical interest and to industrial estates run by large multi-national companies (including Sony, Honda and Toyota) (Aon Benfield, 2012). An area of about 30 000km^2 was inundated with floodwater (Figure 1(b)). In total, 65 out of 77 provinces in the country were affected by flooding to some extent (Aon Benfield, 2012).

How does the 2011 flood rank in comparison to other historical Thailand floods? Table 1 shows the ten largest Thailand flood events for the period 1985–2012 as documented by the Dartmouth Flood Observatory (Brakenridge, 2012). In terms of ranking by flood magnitude this event is only fifth, but if ranked by duration it would (at 158 days) be first. The flood in 1995, which ranks highest in terms of magnitude and area affected, was an important event as it led to changes in how flooding was managed in the country. It was unusual in that it affected a large proportion (approximately 87%) of the country, but rainfall totals in 1995 were lower than in 2011: the explanation for this difference appears to be the lack of flood mitigation schemes in 1995 as compared with 2011. After 1995 measures, such as better drainage systems and improved reservoir operations, were brought in to reduce the risk of flooding (Hungspreug *et al*., 2000).

Table 1 may be used to estimate the return period of the 2011 flood. Since five events of equal or greater magnitude have

(a) (b)

Figure 1. (a) Bangkok, the Thailand capital, suffered extensive flooding as seen in this aerial survey on 24 October 2011. (b) Map showing the extent (in blue) of the 2011 flood in Thailand, with Switzerland shown for area-comparison. (Images courtesy of Cpl. Robert J. Maurer, U.S. Marine Corps (a) and Swiss Re, sigma No.2/2012 (b).)

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Table 1

Top ten Thailand flood events for the period 1985–2012. The data are taken from the Dartmouth Flood Observatory Global Active Archive of Large Flood Events (Brakenridge, 2012). Ranking is by flood magnitude.

Year	*Dates*	*Flood magnitude*	*Duration (days)*	*Area affected (km²)*
1995	1 Aug–9 Nov	7.9	101	444 000
2002	18 Aug–26 Nov	7.9	101	372 000
2006	20 Aug–13 Dec	7.7	116	213 000
2004	6 Aug–3 Oct	7.6	59	378 000
2011/2012	5 Aug–9 Jan	7.5	158	97 000
2007	5 Sep–10 Nov	7.3	67	300 000
1994	3 Sep–18 Dec	7.1	107	65 000
2005	13 Aug–26 Sep	7.1	45	134 000
2003	12 Sep–12 Oct	7.0	31	315 000
1996	18 Jul–21 Aug	7.0	35	314 000

Flood magnitude = log (Duration × Severity × Area Affected).
'Severity' depends on the estimated recurrence interval of floods in the region affected and is defined on a scale between 1 and 2.

occurred in the last 28 years, one may deduce a return period for the 2011 flood of 5.6 years. However, this estimate is likely to be low due to the improvements in flood protection that have occurred since 1995. These improvements mean that the flood magnitudes in Table 1 are not normalized to current conditions.

Climate causes

Interannual variability in Thailand rainfall is caused by year-to-year changes in the strength of the southeast Asian monsoon (Singhrattna *et al*., 2005a) and by year-to-year changes in the number of remnant tropical storms crossing the country. The contribution of these two causes to the record-breaking annual rainfall in 2011 is examined below. First, we assess the 2011 precipitation totals and anomalies across the country.

Precipitation in 2011

The Thailand precipitation data used in this study were obtained from the Thai Meteorological Department and comprise daily precipitation totals from 100 weather stations for the 20-year period 1 January 1992 to 31 December 2011. The completeness of these data is high with 95 stations having at least 99% complete records over the 20 years. For the few cases where data are missing, precipitation records from the UK Met Office Integrated Data Archive System (MIDAS: UK Meteorological Office, 2012) are employed. Figure 2 shows that the highest rainfall totals (over 3200mm) in 2011 occurred in southern Thailand, while in northern Thailand precipitation was between 1400mm and 1800mm. Taking the country as a whole rainfall was 23% above normal in 2011; the largest positive anomalies (up to 1800mm) occurred in the south. Precipitation totalled 2073mm (530mm above normal) in Bangkok, and 1330mm (255mm above normal) in Chiang Mai.

Southeast Asian monsoon

We can examine the contribution of the summer southeast Asian monsoon to the record 2011 rainfall by considering time series (1992–2011) for the May–October period (MJJASO) mean sea level pressure (MSLP) anomaly (Figure 3(a)), and the MJJASO precipitation anomaly (Figure 3(b)). The MJJASO MSLP anomalies are calculated using NCEP/NCAR data (Kalnay *et al*., 1996) averaged over the area 12.0–20.6°N, 97.2–105.8°E, which comprises most of Thailand. The precipitation anomalies are computed for stations north of 12°N.

The MSLP anomalies are a proxy for summer monsoon strength: positive anomalies indicate a weaker monsoon, negative anomalies a stronger one. As expected, a negative correlation exists between the MJJASO MSLP and the precipitation anomalies. Figure 3 shows that in 2011 the MJJASO precipitation anomaly (+246.1mm) was by far the highest in the last 20 years, and that the MSLP anomaly was the second most negative (but comparable to that in three other years) for the same period. This suggests that the summer monsoon was a significant, but not the only, factor in the Thailand rainfall in 2011 being so high.

With regard to the cause of the strong summer monsoon over Thailand in 2011, Singhrattna *et al*. (2005b) examined the link between summer (August–October (ASO)) Thai rainfall and large-scale climate indices. A statistically significant positive correlation between the contemporaneous Southern Oscillation Index (SOI) (Troup, 1965) and Thai summer monsoon rainfall was found after 1980 but not in earlier years. Interestingly, a significant link between the SOI and Indian summer monsoon rainfall

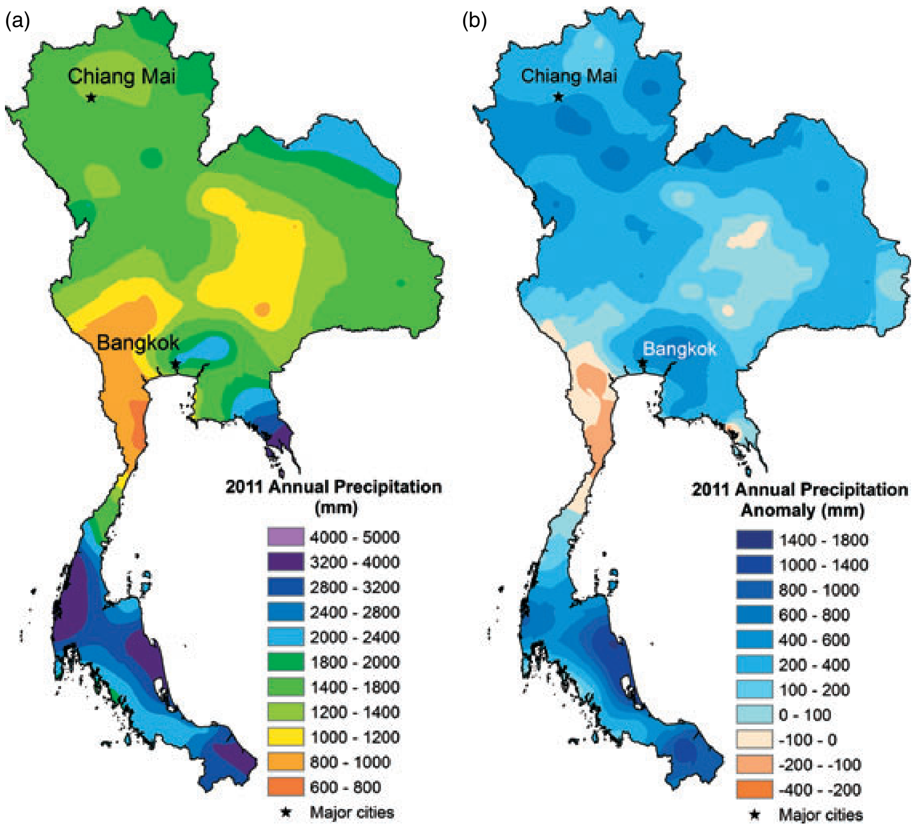

Figure 2. (a) Annual precipitation and (b) precipitation anomaly (cf 1992–2011 mean), for Thailand in 2011. The kriging technique (Webster and Oliver, 2007) is used for spatial interpolation.

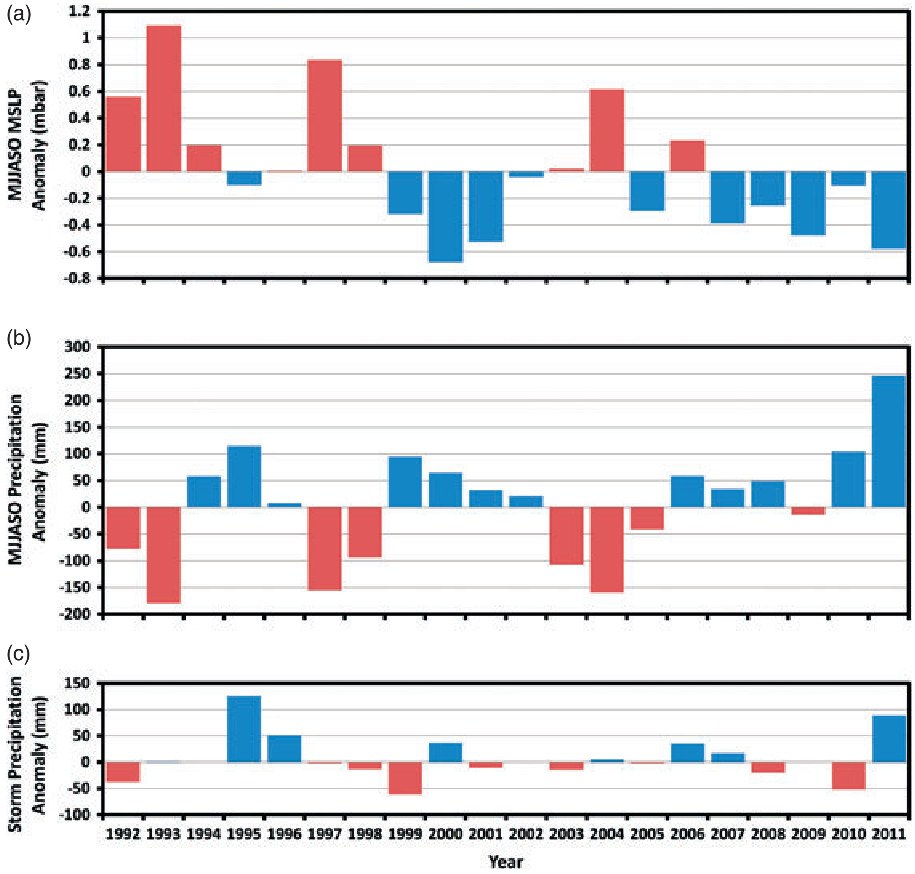

Figure 3. Time series (1992–2011) for the Thailand area north of the Kra Isthmus at 12°N for (a) summer monsoon strength (proxy): anomaly in May–October (MJJASO) mean sea-level pressure (MSLP) anomaly. (b) Summer monsoon rainfall: anomaly in MJJASO precipitation, and (c) tropical storm rainfall only: anomaly in storm precipitation. Red and blue in (a) denote respectively high and low pressure anomalies. Red and blue in (b) and (c) denote respectively positive and negative precipitation anomalies.

existed before 1980 but weakened after 1980. These changed links are consistent with an SOI-related circulation change around 1980. The SOI was positive throughout 2011 and had a moderately high value of +7.0 for ASO (Australian Bureau of Meteorology, 2012), typical of La Niña conditions. This suggests that the sign and strength of the Southern Oscillation may have contributed to the Thai flooding in 2011. Singhrattna *et al*. (2005b) also found a statistically significant negative correlation between Thailand ASO rainfall and the prior March–May (MAM) Dipole Mode Index (DMI). The DMI is a measure of the sign and strength of the Indian Ocean Dipole – a coupled ocean-atmosphere phenomenon in the Indian Ocean (Saji *et al*., 1999). The DMI value for MAM in 2011 was +0.19 degC (JAMSTEC, 2012): this weakly positive value suggests that the Indian Ocean Dipole did not contribute to the Thailand floods in 2011.

Tropical storms

The contribution of tropical storms to the Thailand 2011 record rainfall may be examined by comparing Figure 3(c), which displays the anomaly in annual Thai rainfall from tropical storms only, with Figure 3(b). The tropical storm remnants that cross Thailand originate from storms that form in the northwest Pacific basin – the most active basin for tropical storm formation worldwide (Xue and Neumann, 1984); they affect the country between May and December, with peak incidence in September, October and November. Using best-track data from the Joint Typhoon Warning Center (JTWC) (Chu *et al*., 2002), we find that 52 tropical storms (or their remnants) crossed Thailand between 1992 and 2011: an average of 2.6 storms per year. The number of storms affecting the country ranged from nil in 2002 and 2009 to six in 1995. The rainfall from individual storms affects a smaller area than does summer monsoon rainfall. The 'storm' rainfall for each of the 52 tropical storms was computed using daily rainfall data from the 100 Thai weather stations and the dates that each storm was over Thailand (given by the JTWC best-track data).

In 2011, the remnants of four tropical storms caused significant Thailand rainfall: they only affected northern Thailand and occurred in late June, late July, late September and early October. Figure 3(c) shows the storm precipitation anomaly in 2011 was +89.3mm. The only year since 1992 with a storm precipitation anomaly higher than in 2011 was 1995, when it exceeded the MJJASO precipitation anomaly - which means this anomaly would have been negative had it not been for the six storms that struck Thailand that year. Figures 3(b) and (c) show that tropical storms contributed one-third of the anomalous high Thailand rainfall in 2011.

Summary

The 2011 Thailand floods were caused by a combination of a strong southeast Asian summer monsoon that brought high rainfall across the country between May and October, and the remnants of four tropical storms that brought high rainfall to northern Thailand between June and October. The tropical storms contributed one third of the excess monsoonal rainfall north of 16°N. During the monsoon season the Southern Oscillation Index (SOI) was moderately positive and, as a result, is likely to have contributed to the high monsoonal rains. The SOI enhancement of Thai monsoonal rains probably arises because the ascending branch of the Walker Circulation over the Pacific Ocean and southeast Asia shifts westward towards Thailand during positive SOI conditions.

Return periods for 2011 rainfall and riverflow

The 2011 Thailand flood return period may also be estimated from pan-Thailand historical annual rainfall data and from satellite-derived riverflows in the Chao Phraya river basin. The computation of these return periods is described below.

Data and methodology for rainfall analysis

The rainfall return-period analysis employs raingauge data for the 20-year period 1992–2011. The return periods for 2011 annual total rainfall and annual tropical storm rainfall were computed for each of the 100 weather stations in Thailand using the standard method (NOAA National Hurricane Center, 1987). This method divides the number of years with complete rainfall data by the number of years where the annual (or storm) rainfall total is greater than or equal to the observed total in 2011. For example, in Bangkok the annual total precipitation in 2011 was 2073mm. As there are two occurrences of an annual total precipitation greater than or equal to 2073mm in Bangkok between 1992 and 2011, the return period for 2011 rainfall in Bangkok is 10 years. In this basic method the return period is sensitive to the number of years of available rainfall data so, in this case, the longest return period that may be computed is 20 years. As a result, return periods may be underestimated. Although Thailand has a 61-year precipitation record (Thai Meteorological Department, 2011), precipitation data prior to 1992 were not available from the Thai Meteorological Department. After completion of this study, precipitation data for 3 stations in northern Thailand with records extending back between 66 and 84 years were discovered (courtesy of Andrew Walker and the Thai Royal Irrigation Department). The return periods for 2011 rainfall calculated using the extended records from these three stations match well the return periods computed using the 1992–2011 data.

The spatial interpolation of return periods between stations is achieved using the kriging geostatistical technique (kriging was also used to produce the precipitation maps in Figure 2). The technique employs observed values of a field to interpolate to points where there are no field observations (Webster and Oliver, 2007; ESRI, 2012). The influence of other variables - not examined here - such as elevation (Goovaerts, 2000) can improve the accuracy of the interpolation process (Phillips *et al.*, 1992; Diadato, 2005) for rainfall. Also the kriging output has sensitivity to internal settings such as the 'search radius'.

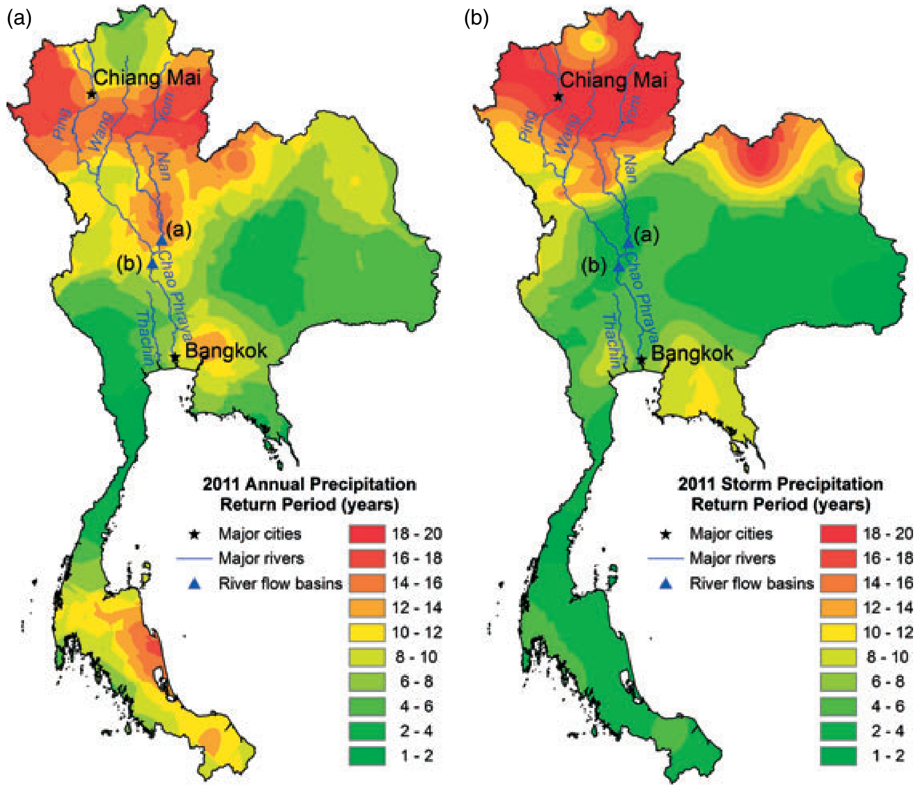

Figure 4. Return periods for 2011 Thailand rainfall displayed spatially across the country. (a) shows the return period in years for 2011 annual precipitation, and (b) displays the return period in years for 2011 tropical storm precipitation. The major rivers in the Chao Phraya River basin are included together with the two sites for which satellite-derived river discharge data are shown in Figure 5.

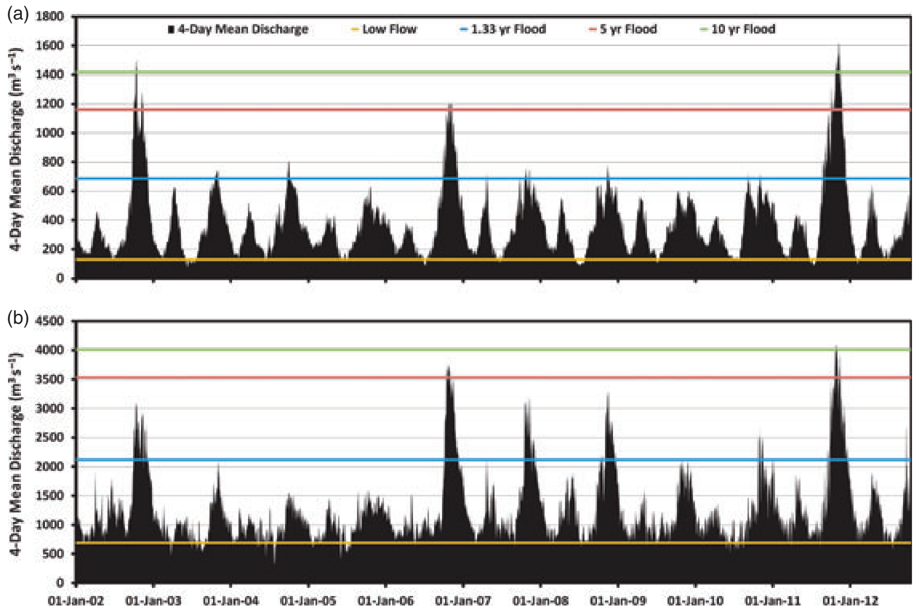

Figure 5. Satellite-derived discharge data for two locations on the Chao Phraya River basin 2002–2012. The 4-day mean river discharge records are displayed for the sites labelled (a) and (b) in Figure 4. Yellow, blue, red and green lines represent the low flow, 1.33-year, 5-year and 10-year flood amounts respectively. Location (b) has higher discharges as it is sited further downstream. (Adapted from Brakenridge et al., 2012a).

Rainfall return periods

Figure 4 displays the return periods for 2011 annual precipitation and 2011 tropical storm precipitation across Thailand derived with kriging. The Thailand hill country in the north and the Kra Isthmus in the south exhibit the highest rainfall return periods of between 8 and 20 years. A comparison of the two maps shows that the high rainfall return periods in the north are linked to excess tropical storm precipitation, while those in the south are linked to excess summer monsoon rainfall. Averaging across the country, the return period for annual precipitation in 2011 is estimated to be between six and ten years. For the three stations in northern Thailand with around 75 years of rainfall data, the return period for annual precipitation in 2011 ranges between 6 and 13 years.

Riverflow return periods

Satellite-derived river flows in the Chao Phraya River basin – the Thai region most heavily flooded in 2011 - were obtained from the Dartmouth Flood Observatory online repository of global river discharge data (Brakenridge *et al.*, 2012a). Riverflows are computed from satellite passive microwave observations and calibrated using global hydrological modelling (Brakenridge *et al.*, 2012b). Riverflows obtained with this satellite method agree well with flow estimates from ground-based discharge gauges (Brakenridge, 2012b).

Figure 5 displays time series, from January 2002 to mid-October 2012, of the 4-day mean river discharge for the two Chao Phraya River sites marked on Figure 4. The seasonal variation in the river discharge is apparent with the main peak occurring in the latter part of each year. The peak discharge in 2011 was the highest since January 2002 at both sites with the northern site showing a flood return period of

10–20 years and the southern site a flood return period of about 10 years.

Summary

The likelihood that a Thai flood of the magnitude of 2011 will happen again has been estimated in three different ways. First, the Dartmouth Flood Observatory Global Active Archive of Large Flood Events ranks the event's magnitude fifth highest for the 1985–2012 period, suggesting a return period of five to six years. However, recent improvements to the Thai flood defences may bias this estimate low. Secondly, satellite-derived river flows at two locations on the Chao Phraya River suggest a return period of 10–20 years, with the northerly site having the longer return period. Thirdly, pan-Thailand historical weather station rainfall data suggest a return period for annual precipitation which varies from 8 to 20 years in the north and south of the country to 1–8 years in the east and centre of the country. However, since the available precipitation records limit this technique to identifying return periods of up to 20 years, the 8–20 year values may be biased low. Bringing these different return period estimates together leads to a 'consensus' return period for the 2011 Thai flood of 10–20 years. However, as noted above, this value may be biased low.

Conclusions

The 2011 Thailand flood ranks as the country's most damaging flood to date. The flooding was caused by unusually high monsoonal rainfall between May and October 2011 (linked to a positive correlation with the Southern Oscillation Index) and to anomalously high rainfall from four tropical storm remnants that crossed the north of the country. These factors combined to produce the highest annual rainfall in Thailand's 61-year precipitation record. Thailand's central water artery, the Chao Phraya River, could not cope with the volume of water runoff from the country's elevated north, and burst, inundating an area of about 30 000km^2. As this river basin is home to 30% of the Thai population and to most of Thailand's manufacturing industry, economic and insured losses were severe.

A consensus of three different estimates suggests a return period for the 2011 Thailand flood of 10–20 years. However, these estimates may be biased low due to the limited 20–30 year extent of the historical data used for model building. Nevertheless one may reasonably expect that another Thailand flood as devastating as in 2011 will occur within the next two to three decades unless flood defences and flood management practices are improved.

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