Strengthening Financial Resilience to Disasters in Asia

Catastrophe Risk Modeling and Live Hazard Data for Parametric Risk Financing in Asia

Summary Technical Report

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Disaster Risk Financing & Insurance Program
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All the work related to this project can be found at www.financialprotectionforum.org/asiaregional

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Executive Summary

This report summarises the work carried out under World Bank contract number 7179802. The remit was to scope catastrophe risk live data and models for disaster risk finance in Asia with the aim of evaluating available catastrophe data suitable to support the design and implementation of parametric disaster risk financing mechanisms in selected Asian countries.

The countries of interest were Afghanistan, Bangladesh, Cambodia, India, Indonesia, Lao PDR, Malaysia, Myanmar, Nepal, Pakistan, Philippines, Sri Lanka, Thailand and Viet Nam. The perils of interest were flood, tropical cyclone, earthquake and drought.

The scope of the project gave particular focus to selected perils in Bangladesh, Indonesia, Pakistan, Sri Lanka and Viet Nam.

Live data sources were catalogued both at overall global / regional level and at local level for the aforementioned five countries of focus. Each dataset was categorised as "low", "medium" or "high", according to its potential utility for parametric disaster risk financing. Catalogues were developed through desktop / internet research, and through contacting people known to the consortium or the World Bank. For local sources in particular, personal contact was important in gathering the required information. Full details of the datasets are provided in Appendix A and summarised in Sections 2 and 3 of this report. Suitable live datasets were discovered for contract settlement for each of the four perils.

In general, the **tropical cyclone** peril is the best served in terms of appropriate live data for contract settlement: nine high-rated global / regional sources were identified including sources based on Earth Observation (EO) instruments and assimilation products. In general, the EO products providing storm location, wind speed, radius and rainfall information provide a good basis for a hazard footprint. Station-based observations, although not rated high, provide the ability to ‘ground-truth’ or calibrate the EO products for the specific locations. However, the extreme wind speeds of tropical cyclones can cause damage to weather stations and lead to loss of data. Assimilation products essentially use numerical weather prediction models to interpolate station data in a physically consistent way, and so the spatial irregularity of station data is mitigated. However, the resolution of assimilation-based products is often insufficient to fully resolve tropical cyclones, and there is a danger of smoothing real extremes in hazard intensity through the interpolation process, implying that these products should also be used as supplementary sources of live data for tropical cyclone.

Flood inundation footprints with depth information are difficult to develop due to the high resolution nature of this peril: flood varies over small spatial scales. Seven high-rated global / regional sources were identified, all of which are EO based. These and other, lower-rated, data sources provide estimates of rainfall rate, river flow, flood depth and flood extent. Of all the perils considered in this study, flood is perhaps the most difficult to define a high quality event footprint suitable for running through a catastrophe model shortly after an event has taken place, because of the weaknesses of each live data source described in Section 2.3.1. A combined approach using: (i) rainfall rate propagated through a model to describe the overall flood extent, (ii) river flow data to establish the return period of the event, and (iii) flood depth and flood extent to validate the final footprint is likely the best approach.

Five high-rated sources of global / regional **earthquake** information were identified, all of which are derived from station-based instruments (seismometers). EO data sources were also identified, but not rated ‘high’. The sources identified can be classified as providing either: (i) information about parameters that define the underlying earthquake, (ii) information about the level of ground motion caused by the earthquake, (iii) estimation of economic damage and fatalities and (iv) ‘before and after’ images from EO sources to identify damage. Sources that provide information about the level of ground motion are perhaps the most accessible and easily understandable. However, sources that provide information about the underlying event parameters are the most useful in terms of parametric contract settlement. These sources can be employed to define an event footprint within the same catastrophe models used to design the contracts, thus leading to stronger consistency between contract design and contract settlement. Sources that provide estimation of economic damage and fatalities may not be consistent with catastrophe models used in the contract structuring. EO ‘before and after’ sources also may suffer from a lack of consistency with catastrophe models and can have issues in terms of the necessary high resolution image capture at precisely the right before- and after-event time points. The global / regional network of seismometers is fairly sparse in the Asia region, and in developing live data for this region it is essential that global / regional data are supplemented with data from local seismometer networks in order to provide more accurate ground shaking maps.

Only two high-rated global / regional sources were identified for **drought**, however, this information does show potential in terms of being appropriate for contract settlement.

Prototypes for parametric disaster risk financing indices were developed, considering both the live data and the catastrophe models available. These are described in Appendix C.

Scoping for **catastrophe models** (defined as probabilistic models including stochastic event sets) was carried out by contacting the catastrophe model vendors directly, where possible. Twenty vendors, who make models available for commercial or general use, were contacted. We are aware that risk carriers in the region / internationally may have internal models that are not documented here. Catastrophe risk models suitable for structuring and placing parametric risk financing instruments, or with the potential to be developed further to fit this function, were considered within scope. Full details of the catastrophe models discovered for this region are given in Appendix B and summarised in Sections 2 and 3 of this report. Catastrophe models are available for this region, but gaps do exist:

- No full **flood** models were discovered for nine countries; however, flood hazard components, or partial models, or imminently available models, are available for eight of the nine countries. Flood hazard can be considered prevalent for every country in this region.
- No full **tropical cyclone** models were discovered for four countries in the region exposed to tropical cyclone hazard; however tropical cyclone hazard components are available for three of these countries.
- No full **earthquake** models were discovered for five countries in the region exposed to earthquake hazard.
- No catastrophe models were found for the **drought** peril.

Given the availability of live data and catastrophe models, **priorities** for future work are suggested in Section 4 of this report. These include the following:

- **Filling** probabilistic **catastrophe** risk **model gaps**, in particular (see Section 4.2):
    - **Flood** models for Cambodia, Bangladesh, Lao PDR, Pakistan, Myanmar, the Philippines, Nepal, Afghanistan and Indonesia.
    - **Tropical cyclone** models for Myanmar, Lao PDR, Sri Lanka and Cambodia.
    - **Earthquake** models for Nepal, Afghanistan, Myanmar, Bangladesh and Lao PDR.
- **Developing regional or sub-regional models** and an over-arching model framework (see Sections 4.3 and 4.4).
- **Improving live data**, in particular:
    - Research into the best method to derive and validate a post event flood footprint using the different live data sources for rainfall, river flow and inundation extent (see Section 4.6.1).
    - Incorporating local seismometer network information to supplement the global networks when defining ground motion footprints (see Section 4.6.1).
    - Extrapolating spatial time series of drought indexes into stochastic events such that they can be used for preliminary parametric risk financing structuring and settlement (see Section 4.6.1).
    - Improving the capacity of local agencies to record and report hazard occurrence from instrumentation networks for specific countries (see Section 4.6.2).

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Abbreviations

AAL	Average Annual Loss
Ass	Assimilation-based data
CCRIF	Caribbean Catastrophe Risk Insurance Facility
DRFIP	Disaster Risk Financing and Insurance Program
DEM	Digital Elevation Model
DTM	Digital Terrain Model
EO	Earth Observation based data
EQ	Earthquake
FL	Flood
GAR	Global Assessment Report
GMPE	Ground Motion Prediction Equation
GFDRR	Global Facility for Disaster Reduction and Recovery
PGA	Peak Ground Acceleration
SAR	Synthetic Aperture Radar
SA	Spectral Acceleration
Sta	Station-based data
TC	Tropical Cyclone
WB	World Bank

1 Context and regional overview

1.1 Context

This report summarises a project to scope catastrophe risk data for disaster risk finance in Asia, and is a World Bank (WB) – Global Facility for Disaster Reduction and Recovery (GFDRR) Disaster Risk Financing and Insurance Program (DRFIP) project (ref 7179802).

The overall aim of this project is to "evaluate available catastrophe data suitable to support the design and implementation of disaster risk financing mechanisms in selected Asian countries". Task 1 involved the cataloguing and evaluation of live data sources; task 2 involved the cataloguing of catastrophe models. The focus of this report is to summarise the findings of task 1 and task 2 and, given these findings, to identify priorities for high-impact investment in catastrophe risk modelling in the region in order to improve capabilities for disaster risk financing.

The countries within the scope of this project are shown in Table 1-1; the overall region of interest is shown in Figure 1-1. The region comprises a significant spatial scope: from Afghanistan in the North West to Indonesia in the South East and includes two ocean basins: the Indian Ocean and the Pacific Ocean. There are 14 countries of interest and five focus countries (chosen according to the World Bank priorities and recognising the existence of other projects in this region).

The perils of interest are earthquake, flood, tropical cyclone, and drought, although the importance of these varies by country as discussed in Section 1.2. The focus in terms of perils was specified within the project scope and is also shown in Table 1-1.

The availability of catastrophe models and region-wide live data sources are captured for all 14 countries; these are described in Section 0. The exercise focused on data and models to support parametric disaster risk financing. Details on local data sources and enhanced detail on catastrophe models and their components are provided for the five focus countries; these are described in Section 3. Priorities for investment are described in Section 4.

Country (ISO code)	Short-list country perils
Afghanistan (AF)	
Bangladesh (BD)	**Flood, Tropical Cyclone, Earthquake**
Cambodia (KH)	
India (IN)	
Indonesia (ID)	**Flood, Earthquake**
Lao PDR (LA)	
Malaysia (MY)	
Myanmar (MM)	
Nepal (NP)	
Pakistan (PK)	**Flood, Earthquake**
Philippines (PH)	
Sri Lanka (LK)	**Flood, Tropical Cyclone**
Thailand (TH)	
Viet Nam (VN)	**Flood, Tropical Cyclone, Drought**

Table 1-1: Countries in the region of interest and 'focus' country-perils (shown in bold)

Figure 1-1: Overall region of interest

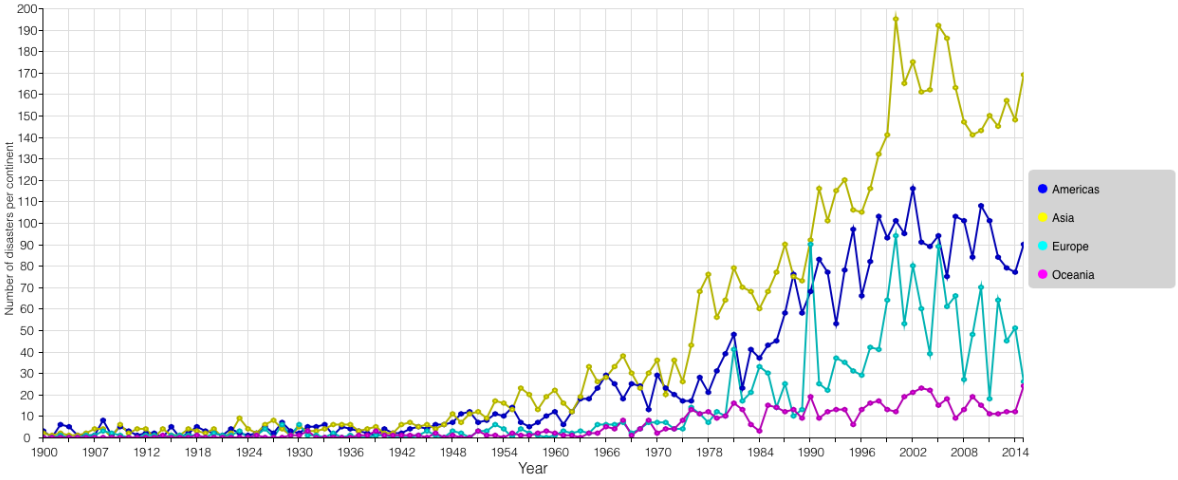
The prevalence of perils and the economic scale of the countries varies across the region as described in Section 1.2.

1.2 Regional overview of perils

Asia is a region that is exposed to a variety of natural hazards leading to a significant number of natural hazard events. EMDAT (http://www.emdat.be) catalogues worldwide natural disasters according to at least one of the following criteria:

- 10 or more people dead
- 100 or more people affected
- The declaration of a state of emergency
- A call for international assistance

Figure 1-2 shows the number of reported natural disasters between 1900 and 2015 by region. It is clear that a significant number stem from the Asia region.



EM-DAT: The OFDA/CRED International Disaster Database - www.emdat.be - Universite Catholique de Louvain, Brussels - Belgium

Figure 1-2: Total number of reported natural disasters between 1900 and 2015 by region (source: EMDAT)

The main perils within the scope of this project are flood, tropical cyclone, earthquake and drought. These are discussed in the context of the Asia region.

1.2.1 Exposure

Figure 1-3 shows the economic stock exposure density for the region. It is clear that the exposure is not homogeneous across the region but is concentrated in particular regions. Although the map shows economic stock, this also serves as a reasonable proxy for population density.

Figure 1-3: Exposed economic stock, darker colours representing increased economic exposure density (source: GAR 2015 Risk Data Platform)

1.2.2 Flood

Flood is a very geographically sensitive peril; however, all countries within the scope of this proposal are subject to flood risk. Figure 1-4 shows the 200-year flood depth. Although all countries are exposed to the risk of inland flooding, those with exposure to tropical cyclone risk will be exposed to the risk of flooding at the same time as wind damage caused by tropical cyclones. They may also be exposed to the risk of flooding due to coastal flooding from storm surges caused by the reduced pressure and driving winds associated with tropical cyclones. Note that the sources of flooding investigated here are focused on inland flooding including fluvial (flooding from rivers) and pluvial (surface water flooding), but not coastal flooding.

Figure 1-4: 200-year return period flood (source: GAR 2015 Risk Data Platform). Darker blue denotes higher flood depth.

1.2.3 Tropical Cyclone

Figure 1-5 represents the tropical cyclone risk within the region. Tropical cyclones are formed both in the Pacific Ocean (including the South China Sea) and the Indian Ocean (including the Bay of Bengal and the Arabian Sea).

The risk is heterogeneous across the region with Afghanistan and Nepal not being exposed to this risk due to their inland location and Malaysia and a significant part of Indonesia only being exposed to a small extent due to their location near the equator (where tropical cyclones rarely form and rarely progress due to the lack of Coriolis force; a force due to the earth's rotation that is necessary for tropical cyclones and is zero at the equator).

The Philippines is potentially the country most exposed to hurricane risk in this region, although countries such as Viet Nam, India and Sri Lanka are also exposed to significant risk.

Tropical cyclones bring risk through wind damage, but also through damage via inland and coastal flooding; discussed in Section 2.2.2.

Figure 1-5: Tropical cyclone risk (source GAR Risk Data Platform). The 250-year return period wind speed (light green = low wind speed, dark green = high wind speed) is displayed along with cyclone tracks from 1969 to 2009.

1.2.4 Earthquake

Figure 1-6 shows a representation of the earthquake hazard for the region. It is clear that earthquake hazard is prominent in the region due to its proximity to the Ring of Fire. While all countries in the region are exposed to some level of earthquake hazard, certain countries border tectonic subduction zones, and thus have higher hazard. For example, the Sunda Trench off the coast of Indonesia and the Philippine Trench to the east of the Philippines pose greater risk to these countries. Across the region, the Philippines, Indonesia, Myanmar, Bangladesh, Nepal, Pakistan and Afghanistan have higher earthquake hazard coinciding with high areas of exposure, whereas Malaysia, Cambodia and Viet Nam are less exposed to this risk. Although ground shaking is the most significant component of earthquake risk, damage from earthquake-induced tsunamis should also be considered for countries with low lying coastal exposures.

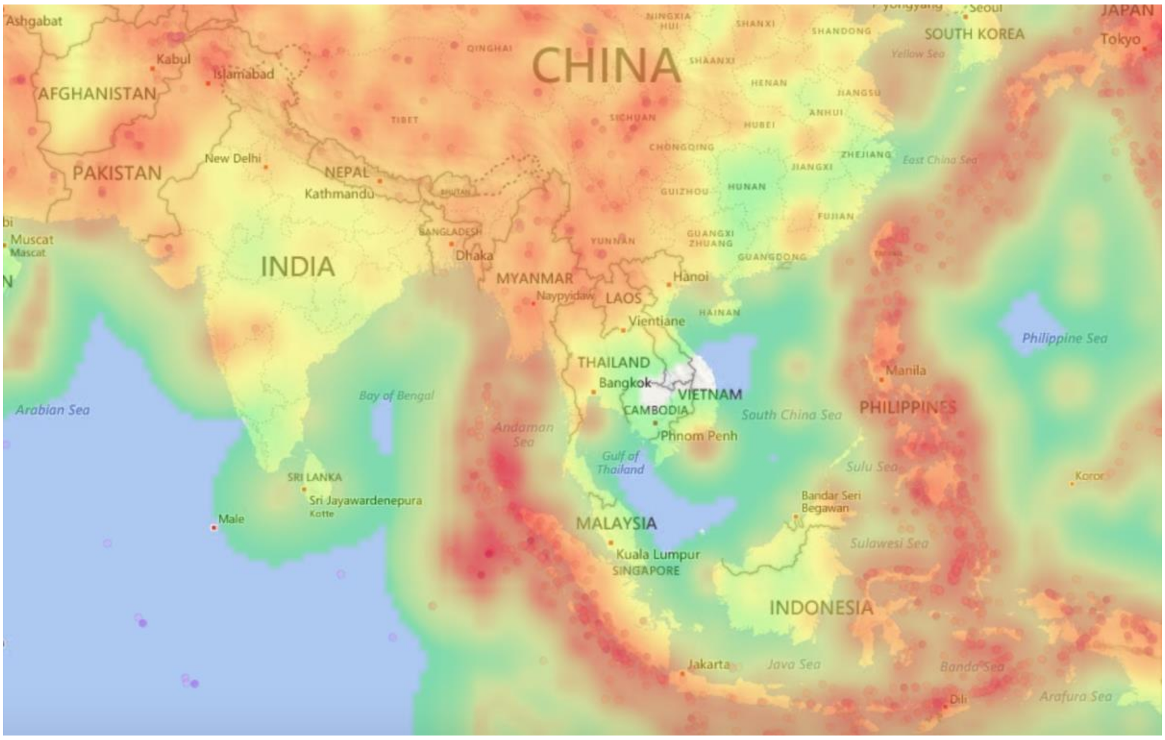


Figure 1-6: Peak ground acceleration (PGA) at 475-year return period (source: GAR 2015 Risk Data Platform). Colours represent the intensity of the PGA from green (low) to red (high). Circles represent the epicentres of earthquakes above magnitude 6.0 between 1970 and 2014.

1.2.5 Drought

Droughts take a high human toll in terms of hunger, poverty and the perpetuation of under-development. They are associated with widespread agricultural failures, loss of livestock, water shortages and outbreaks of epidemic diseases. Some droughts last for years, causing extensive and long-term economic impacts, as well as displacing large sections of the population. Droughts are caused by a period of abnormally dry weather sufficiently prolonged for the lack of water to cause a serious hydrologic imbalance across the affected area. Drought severity depends upon the degree of moisture deficiency, the duration, the timing with respect to the growing seasons, and (to a lesser extent) the size of the affected area. In general, the term should be reserved for periods of moisture deficiency that are relatively extensive in both space and time. All countries within the scope of this proposal are subject to drought, although India, Thailand, and Bangladesh had the highest number of total affected population; and India, Viet Nam, and Thailand the highest total damage associated with droughts between 1900 and 2015 (EMDAT).

Figure 1-7: This map shows the areas affected by drought events (source: IRI Columbia University). Darker brown denotes higher highly unusual dry period conditions.

1.3 Country peril focus

Section 1.2 focuses on describing the perils across the whole region; we now focus on the individual countries. Two sources are used to identify potential risk by peril for each country: historic event data from EMDAT and a prospective calculation of the average annual loss (AAL) for each peril from the GAR.

Metrics from these sources are summarised in Table 1-2.

There are undoubtedly caveats with the metrics in Table 1-2; in particular, the prospective AAL figures by peril will be reliant on the effectiveness of the underlying hazard, exposure and vulnerability models used to assess the AAL. The historical economic losses are unlikely to be complete for every country back to 1900. Normalising the historical economic losses by dividing by the 2014 capital stock is unlikely to be appropriate as the underlying exposure will have changed significantly over the period of capture (1900 – 2015). However, these data are fit for the usage within this report of providing a rough indication of the relative hazard propensity for each country normalised by an exposure measure.

Country Summary	AF	BD	KH	IN	ID	LA	MY	MM	NP	PK	PH	LK	TH	VN
Population (m, 2013)	31	157	15	1252	250	7	30	53	28	182	98	20	67	90
Pop. density (people / km^2, 2013)	46.8	1203	85.7	421.1	137.9	29.3	90.4	81.5	193.9	236.3	330	326.6	131.2	289.3
GDP (m USD, 2013)	20,725	129,857	15,250	1,876,797	868,346	11,141	312,435		19,294	236,625	272,017	67,182	387,252	171,392
Capital stock (m USD, 2014)	60,188	381,432	27,390	5,769,372	2,827,835	21,926	1,170,979	195,390	53,997	502,334	566,949	208,274	1,378,999	487,574
Average Annual Losses (m USD)														
Earthquake	146.8	126.5	0.0	446.6	1,116.0	5.0	10.5	35.6	29.5	272.1	703.5	0.8	32.6	4.0
Tsunami	0.0	5.5	0.0	19.1	48.2	0.0	5.5	3.3	0.0	0.2	30.6	1.8	0.5	0.7
Tropical cyclone wind	0.0	465.9	0.0	1160.4	0.5	0.4	0.0	41.8	0.0	7.5	4071.5	1.7	0.0	35.1
Storm surge	0.0	23.4	0.0	726.9	37.9	0.0	0.5	40.6	0.0	18.1	2541.6	18.6	0.1	40.9
Flood	92.2	2,463.2	251.2	7,471.8	2,372.5	219.5	1,271.1	1,956.7	143.3	1,029.8	545.4	143.8	2,586.2	2,295.4
Economic loss 1900 to 2015 (m USD)														
Earthquake	54	0	0	4,200	7,189	0	0	5	5,480	5,330	583	0	62	0
Tsunami	0	500	0	1,023	4,507	0	500	500	0	0	0	1,317	1,000	0
Tropical cyclone	0	4,806	0	16,872	0	104	53	4,079	0	1,715	21,096	194	764	6,207
Flood	399	12,238	1,419	56,549	6,657	171	1,360	256	406	20,969	3,794	981	45,390	3,960
Drought	142	0	138	2,441	160	1	0	0	10	247	149	25	424	1,262
Average Annual Loss x 1000 / capital stock														
Earthquake	2.4	0.3	0.0	0.1	0.4	0.2	0.0	0.2	0.5	0.5	1.2	0.0	0.0	0.0
Tropical cyclone	0.0	1.2	0.0	0.2	0.0	0.0	0.0	0.2	0.0	0.0	7.2	0.0	0.0	0.1
Flood + storm surge	1.5	6.5	9.2	1.4	0.9	10.0	1.1	10.2	2.7	2.1	5.4	0.8	1.9	4.8
Historical loss x 1000 / capital stock														
Earthquake	0.9	0.0	0.0	0.7	2.5	0.0	0.0	0.0	101.5	10.6	1.0	0.0	0.0	0.0
Tropical cyclone	0.0	12.6	0.0	2.9	0.0	4.7	0.0	20.9	0.0	3.4	37.2	0.9	0.6	12.7
Flood	6.6	32.1	51.8	9.8	2.4	7.8	1.2	1.3	7.5	41.7	6.7	4.7	32.9	8.1

Table 1-2: Metrics by country showing economic indicators, prospective average annual loss by peril and historical economic loss. Economic metrics and prospective AAL (not available for drought) sourced from 2015 GAR. Historical economic losses sourced from EMDAT (extracted 10 August 2016). Focus countries are shown in red.

The data in Table 1-2 largely support the conclusions drawn when observing maps of the overall region shown in Section 1.2. In particular, these are as follows:

- All countries are exposed to flood risk; every country has some level of historical economic loss and prospective AAL. From a historical loss perspective Cambodia, Pakistan and Thailand have the largest ratios of economic loss to capital stock. From an AAL to capital stock ratio perspective Lao PDR, Myanmar and Cambodia have the highest values.
- Afghanistan, Nepal, and Cambodia have little exposure to tropical cyclone wind risk according to the metrics in Table 1-2. Figure 1-5 shows that Cambodia should have some level of tropical cyclone risk; however, its sheltered position in the Gulf of Thailand coupled with the shielding effect of Viet Nam mitigates the risk. Malaysia and Indonesia also have relatively low levels of tropical cyclone risk. The Philippines has the highest ratios of both AAL and historical loss to capital stock. Viet Nam and Bangladesh also have relatively high tropical cyclone metric values. Note that tropical cyclones also give rise to flood risk, be this from storm surge or from rain-induced flooding. AALs and historical losses due to these effects are included under the "flood" category for this analysis.
- Cambodia is the only country to have zero earthquake shaking AAL and zero historical economic loss, though this does not rule out the possibility of an earthquake occurring in the future. Malaysia, Thailand, Sri Lanka and Viet Nam also have low ratios of AAL and economic loss to capital stock. Note that these four countries do, however, have exposure to earthquake-induced tsunami risk. Afghanistan and the Philippines have the highest values of earthquake AAL to capital stock whereas Nepal and Pakistan have the highest values of historical economic loss to capital stock.
- Although AAL figures for drought are not provided in the GAR, economic loss figures are provided by EMDAT. This shows India and Viet Nam to have the highest absolute values of economic loss due to drought over the period 1900 to 2015. Viet Nam has the highest ratio of economic loss per head of population due to drought.

The ranks for each country (within the 14 countries in the region) of each of the ratios of AAL to capital stock and historic economic loss to capital stock were calculated for each peril of earthquake, tropical cyclone and flood. The AAL and historical loss country ranks were then averaged, and the ranks of these averages calculated to obtain an overall ranking for each country by peril (in case of an equal ranking the ratio of AAL to capital stock was used to differentiate). These rankings are shown in Table 1-3.

Rank	Flood	Tropical Cyclone	Earthquake
1	Cambodia	Philippines	Nepal
2	Bangladesh	Myanmar	Afghanistan
3	Lao PDR	Bangladesh	Philippines
4	Pakistan	Viet Nam	Pakistan
5	Viet Nam	India	Indonesia
6	Thailand	Lao PDR	India
7	Myanmar	Pakistan	Myanmar
8	Philippines	Sri Lanka	Thailand
9	Nepal	Cambodia	Bangladesh
10	India	Thailand	Lao PDR
11	Afghanistan	Indonesia	Malaysia
12	Indonesia	Malaysia	Viet Nam
13	Sri Lanka	Nepal	Sri Lanka
14	Malaysia	Afghanistan	Cambodia

Table 1-3: Rankings of country by peril from prospective AAL (source: GAR 2015) and historic economic loss (source: EMDAT) ratio to capital stock (source: GAR 2015). Grey font represents those countries where the peril is not significant enough to warrant further examination.

Once again, it should be emphasised that flood is prevalent across the region: even Sri Lanka and Malaysia (ranked last in this list for flood) will have material flood exposure. Whereas for tropical cyclone and earthquake the lowest ranked countries will generally have limited risk.

The ten largest economic events from the perspective of economic losses and number of people affected are shown in the subsequent sections for each of the five focus countries of Bangladesh, Indonesia, Pakistan, Sri Lanka and Viet Nam. Note that the largest number of deaths in Indonesia, Pakistan, and Sri Lanka are due to earthquake events in 2004 and 2005.

1.3.1 Bangladesh largest historical events

Table 1-4 and

Table 1-5 show the ten largest natural disasters in Bangladesh, recorded in the EMDAT database, by economic loss and by number of deaths.

Flood events dominate the economic losses while storm events are the most frequent source of a significant number of deaths. A drought event and an epidemic are the two most severe individual events from the perspective of loss of life. An earthquake event is listed as the 10th largest economic loss.

These figures tend to support the peril ranking developed in Section 1.3 that indicates Bangladesh should be reasonably highly ranked within the region for flood and tropical cyclone and mid-ranked in terms of earthquake risk.

A. Table 1-4: Bangladesh ten largest natural disasters by economic loss (source: EMDAT)

Date	Peril	Economic loss ('000s USD)
5 July 1998	Flood	4,300,000
15 November 2007	Storm	2,300,000
20 June 2004	Flood	2,200,000
June 1988	Flood	2,137,000
29 April 1991	Storm	1,780,000
15 May 1995	Storm	800,000
August 1987	Flood	727,500
July 1974	Flood	579,200
September 2000	Flood	500,000
26 December 2004	Earthquake	500,000

Date	Peril	Deaths
1943	Drought	1,900,000
1918	Epidemic	393,000
12 November 1970	Storm	300,000
29 April 1991	Storm	138,866
October 1942	Storm	61,000
11 May 1965	Storm	36,000
July 1974	Flood	28,700
28 May 1963	Storm	22,000
24 May 1985	Storm	15,000
June 1965	Storm	12,047

Table 1-5: Bangladesh ten largest natural disasters by number of deaths (source: EMDAT)

1.3.2 Indonesia largest historical events

Table 1-6 and Table 1-7 show the ten largest natural disasters in Indonesia, recorded in the EMDAT database, by economic loss and by number of deaths.

Earthquake, flood and wildfire events dominate the economic losses while earthquake, drought and volcanic activity cause the most deaths. The earthquake / tsunami event in December 2004 is the single largest event individual event from the perspective of loss of life. A storm event is listed as causing the eighth-largest loss of life.

These figures tend to support the peril ranking developed in Section 1.3 that indicates Indonesia should be reasonably highly-ranked within the region for earthquake and lower-ranked in terms of storm and flood risk.

Date	Peril	Economic loss ('000s USD)
September 1997	Wildfire	8,000,000
26 December 2004	Earthquake	4,451,600
27 May 2006	Earthquake	3,100,000
17 January 2013	Flood	3,000,000
30 September 2009	Earthquake	2,200,000
March 1998	Wildfire	1,300,000
September 2015	Wildfire	1,000,000
31 January 2007	Flood	971,000
8 January 2014	Flood	600,000
12 September 2007	Earthquake	500,000

Table 1-6: Indonesia ten largest natural disasters by economic loss

Date	Peril	Deaths
26 December 2004	Earthquake	165,708
21 January 1917	Earthquake	15,000
January 1966	Drought	8,000
27 May 2006	Earthquake	5,778
1909	Volcanic activity	5,500
May 1919	Volcanic activity	5,000
12 December 1992	Earthquake	2,500
June 1973	Storm	1,650
3 January 1963	Volcanic activity	1,584
1930	Volcanic activity	1,369

Table 1-7: Indonesia ten largest natural disasters by number of deaths

1.3.3 Pakistan largest historical events

Table 1-8 and Table 1-9 show the ten largest natural disasters in Pakistan, recorded in the EMDAT database, by economic loss and by number of deaths.

Flood events dominate the economic losses although the 2005 earthquake was a significant individual event. Earthquakes, and floods cause the most deaths. The earthquake event in October 2005 is the single largest event individual event from the perspective of loss of life. A storm event in 1965 is listed as causing the third-largest number of deaths, and a separate event in 2007 the sixth-largest economic loss.

These figures tend to support the peril ranking developed in Section 1.3 that indicates Pakistan should be reasonably highly ranked within the region for flood and earthquake and mid-ranked in terms of storm risk.

Date	Peril	Economic loss ('000s USD)
28 July 2010	Flood	9,500,000
8 October 2005	Earthquake	5,200,000
August 2012	Flood	2,500,000
12 August 2011	Flood	2,500,000
1 September 2014	Flood	2,000,000
26 June 2007	Storm	1,620,000
7 August 2013	Flood	1,500,000
8 September 1992	Flood	1,000,000
August 1973	Flood	661,500
2 August 1976	Flood	505,000

Table 1-8: Pakistan ten largest natural disasters by economic loss

Date	Peril	Deaths
8 October 2005	Earthquake	73,338
31 May 1935	Earthquake	60,000
15 December 1965	Storm	10,000
28 December 1974	Earthquake	4,700
27 November 1945	Earthquake	4,000
1950	Flood	2,900
28 July 2010	Flood	1,985
8 September 1992	Flood	1,334
18 June 2015	Extreme temperature	1,229
2 March 1998	Flood	1,000

Table 1-9: Pakistan ten largest natural disasters by number of deaths

1.3.4 Sri Lanka largest historical events

Table 1-10 and Table 1-11 show the ten largest natural disasters in Sri Lanka, recorded in the EMDAT database, by economic loss and by number of deaths.

Flood events dominate the economic losses although the 2004 earthquake was a significant individual event. Earthquakes, storms and floods cause the most deaths. The earthquake-induced tsunami event in December 2004 is the single largest event individual event from the perspective of loss of life.

Despite being low ranked for flood, the figures demonstrate that flood is a hazard prevalent throughout the region for low and high ranked countries. Sri Lanka is mid-ranked for storm and the figures tend to support this. Although Sri-Lanka is low ranked for earthquake risk – which these figures seem to contradict, it should be noted that the loss of life and economic loss caused by the December 2004 event was largely due to the earthquake-induced tsunami. Sri Lanka itself is at relatively low risk of damage from ground shaking.

Date	Peril	Economic loss ('000s USD)
14 May 2016	Flood	2,000,000
26 December 2004	Earthquake	1,316,500
1 February 2011	Flood	300,000
5 June 1992	Flood	250,000
5 January 2011	Flood	200,000
14 May 2010	Flood	105,000
24 November 1978	Storm	100,000
29 October 2012	Storm	57,000
22 December 1964	Storm	37,300
30 May1989	Flood	35,000

Table 1-10: Sri Lanka ten largest natural disasters by economic loss

Date	Peril	Deaths
26 December 2004	Earthquake	35,399
24 November 1978	Storm	740
January 2009	Epidemic	346
30 May 1989	Flood	325
14 May 2016	Flood	245
17 May 2003	Flood	235
22 December 1964	Storm	206
25 December 1957	Storm	200
29 October 2014	Landslide	196
January 2011	Epidemic	167

Table 1-11: Sri Lanka ten largest natural disasters by number of deaths

1.3.5 Viet Nam largest historical events

Table 1-12 and Table 1-13 show the ten largest natural disasters in Viet Nam, recorded in the EMDAT database, by economic loss and by number of deaths.

Storm events dominate the economic losses although drought and flood events also feature in the top ten. Storm events also cause the most deaths although floods and an epidemic also feature in the top ten. The storm event in September 1964 is the single largest event from the perspective of loss of life.

These figures tend to support the peril ranking developed in Section 1.3 that indicates Viet Nam should be low ranked for earthquake risk, relatively highly ranked for tropical cyclone risk, and mid ranked for flood risk.

Date	Peril	Economic loss (‘000s USD)
28 September 2009	Storm	785,000
11 November 2013	Storm	734,000
30 September 2013	Storm	663,230
27 September 2006	Storm	624,000
December 2015	Drought	613,000
27 October 2008	Flood	479,000
2 November 1997	Storm	470,000
30 November 2006	Storm	456,000
December 1997	Drought	407,000
24 July 1996	Storm	362,000

Table 1-12: Viet Nam ten largest natural disasters by economic loss

Date	Peril	Deaths
September 1964	Storm	7,000
2 November 1997	Storm	3,682
26 September 1953	Storm	1,000
23 October 1985	Storm	798
25 May 1989	Storm	751
25 October 1999	Flood	622
1 January 1964	Epidemic	598
24 July 1996	Storm	585
September 1983	Storm	578
July 2000	Flood	460

Table 1-13: Viet Nam ten largest natural disasters by number of deaths

2 Regional catastrophe models and live data

2.1 Overview

A key purpose of this project is to establish which catastrophe models and live data are available in the region described in Section 1.1. The focus is on the use of these data and models for parametric disaster risk financing, and so the cataloguing and evaluation focuses on the usability of the sources for this purpose.

Three different categories of parametric contract structure are described for the purposes of this report:

- **First generation**: "Cat in a box" structure where a contract pays out if a single parameter, or combination of simple single parameters representing an event, exceed a certain threshold within a certain geographical region. For example, an earthquake exceeding a certain moment magnitude within a specified region. These are the least complex structures and have the most basis risk.
- **Second generation**: A more complex index than first generation, typically comprising substantial additional geographic information on hazard variability for the event. For example, a weighted average of anemometer gust data, where the weights are derived from exposure information.
- **Third generation**: A contract that pays out based on modelled loss, whereby parameters are used in combination with a catastrophe risk model to construct a footprint. The most complex structure but the least basis risk assuming the model is adequate.

"Live" data are needed for all three types of parametric structure given the need to establish that an event has occurred shortly after the time of occurrence (typically within a matter of weeks).

Catastrophe models are primarily used within parametric disaster risk financing to 1) price and structure first, second and third generation parametric contracts and 2) for contract settlement of third generation parametric contracts following an event, given a source of live ‘footprint’ data for the event that can be entered into the model.

In this context, and for the remainder of this report, **catastrophe models** are defined as models that contain a stochastic event set, enabling contract structuring and pricing. Given this definition the following are not defined as catastrophe models, and are therefore not catalogued as models:

- Hazard maps: these can be an output of catastrophe models but are not, by themselves, useful for structuring or pricing contracts given the lack of definition of event.
- Scenarios: These represent an event, but are not useful for structuring or pricing contracts given the lack of probability (or frequency) associated with a given scenario.

The methodology for collecting and cataloguing information about potentially suitable live data and catastrophe models is described in Sections 2.2 and 0 respectively.

2.2 Regional catastrophe models

In order to collect details of the catastrophe models available in the region, known catastrophe model providers were contacted and a desktop / internet based search was performed. Table 2-1 shows the model providers contacted by the consortium. Responses were received from all but one of the catastrophe model providers; for ICRM publicly available information was relied upon. Additional models may exist in the form of proprietary in-house models developed and used by risk carriers. However, only models made available to third parties (commercially or otherwise) were catalogued for this exercise.

A list of catastrophe models for the 14 countries in the region is shown in Appendix B and Table 2-2, Table 2-3 and Table 2-4. Catastrophe models were included in this list if they are probabilistic models, containing a stochastic hazard event set that represents a period of synthetic history long enough to structure and price parametric contracts (say >1000 years).

For drought no catastrophe models were discovered. However, an ensemble dataset by The UK Met Office (UKMO) was included that may be useful for this peril (but needs further work to define a drought hazard index from the underlying meteorological metrics). This is not shown in Tables 2-2 to 2-4, but is included in Appendix B. The possibilities in-lieu of catastrophe models for drought are discussed further in Section 4.6.1.

Detail on the models is captured within a standardised template for specific perils in the five focus countries of Bangladesh, Indonesia, Pakistan, Sri Lanka and Viet Nam. This detail is provided in Appendix B. Note that Viet Nam earthquake is a peril beyond the scope of this project, however specific detail was captured for some Viet Nam earthquake models (and is shown in Appendix B) as it was submitted by some of the providers together with information about other (in scope) country earthquake models.

Catastrophe model provider	Abbreviation	Notes
AgRisk	AGR	Hazard event set in region
AIR Worldwide	AIR	Models in region
Ambiental Technical Solutions		No models in region, but considering development
Aon Benfield Impact Forecasting	IF	Models in region
Applied Research Associates	ARA	Hazard event set in region
Catalytics	CAT	Models in region
CatRisk Solutions		No models in region
CoreLogic	CL	Models in region
ERN		No models in region
GEM		No models in region
GNS Science		No models in region but current project to produce EQ models in the region
Guy Carpenter	GC	Model in region
Institute of Catastrophe Risk Management	ICRM	Relied on publicly-available information
Imperial College	IMP	Hazard event set in region
JBA Risk Management	JBA	Models in region, hazard event set in region
KatRisk	KR	Models in region
Risk Frontiers		No models in region, but considering development
RMS	RMS	Models in region
SSBN		No models in region
UK Met Office	UKMO	Ensemble that may be suitable for drought in region
Willis Towers Watson		No models openly available in region

Table 2-1: Catastrophe model vendors contacted during this project

Country	Rank	Full catastrophe model	Hazard only
Afghanistan	11		
Bangladesh	**2**		**JBA**
Cambodia	1	CAT	JBA
India	10	GC, JBA	
Indonesia	**12**	CAT, **ICRM, IF**	**JBA**
Lao PDR	3		JBA
Malaysia	14	IF, JBA	IMP
Myanmar	7	CAT	JBA
Nepal	9		JBA
Pakistan	**4**		**JBA**
Philippines	8	CAT	JBA
Sri Lanka	**13**	**JBA**	
Thailand	6	CAT, IF, JBA	
Viet Nam	**5**	CAT, IF, JBA	

Table 2 -2: Summary of flood catastrophe model vendors and country ranking. Focus countries are highlighted in bold. Hazard models require work to enable production usage. Grey font denotes models not yet released but anticipated within a year at the time of writing.

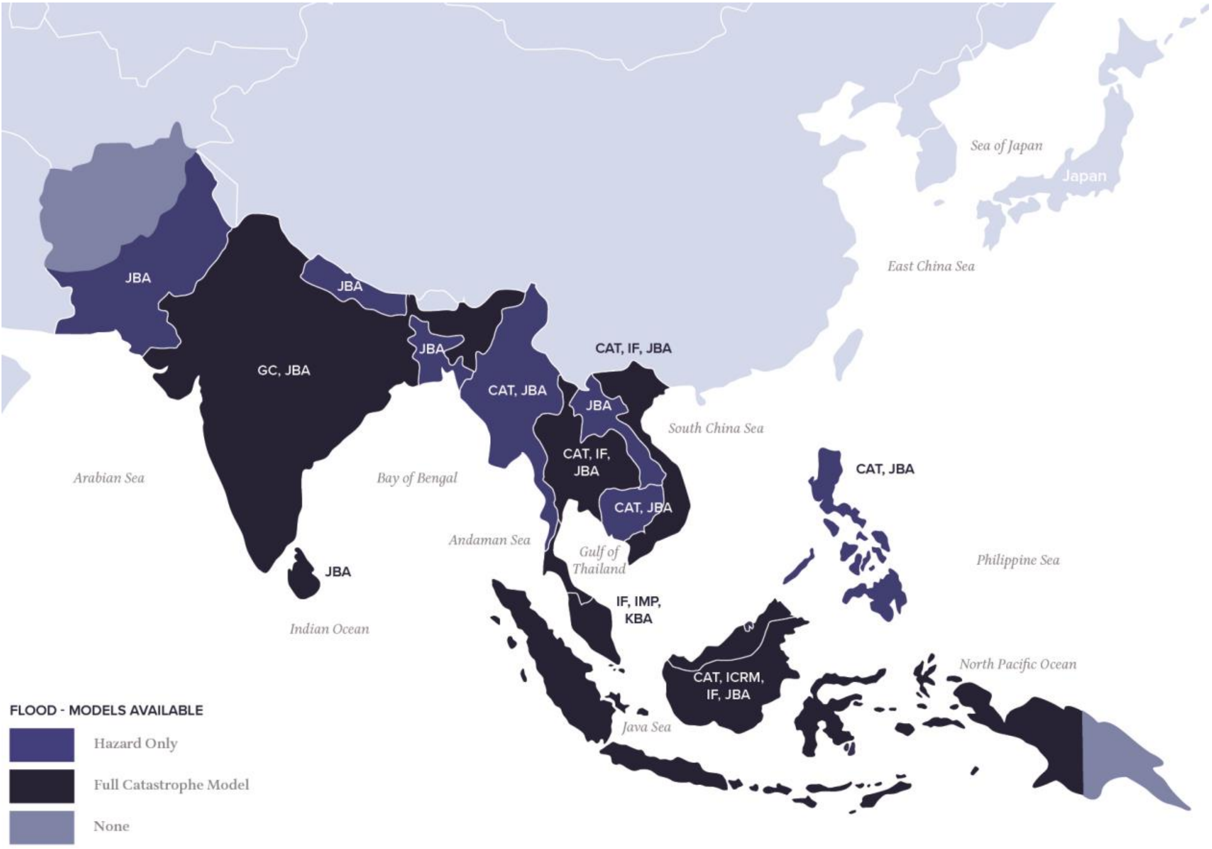


Figure 2-1: Type of flood models and the vendors available. Focus countries shown with a bold outline.

Country	Rank	Full catastrophe model	Hazard
Afghanistan	14		
Bangladesh	**3**	**AIR**	**ARA**
Cambodia	9		ARA
India	5	AIR, CL, IF	AGR, ARA
Indonesia	11	KR	
Lao PDR	6		
Malaysia	12	CL, IF	ARA
Myanmar	2		ARA
Nepal	13		
Pakistan	7	CL	ARA
Philippines	1	AIR, CAT, CL, IF	ARA, IMP
Sri Lanka	**8**		**ARA**
Thailand	10	CL, IF	ARA
Viet Nam	**4**	**AIR,** CAT**, IF, KR**	**ARA, IMP**

Table 2-3: Summary of tropical cyclone catastrophe model vendors and country ranking. Focus countries are highlighted in bold. Hazard models require work to enable production usage. Grey font denotes models not yet released but anticipated within a year at the time of writing.

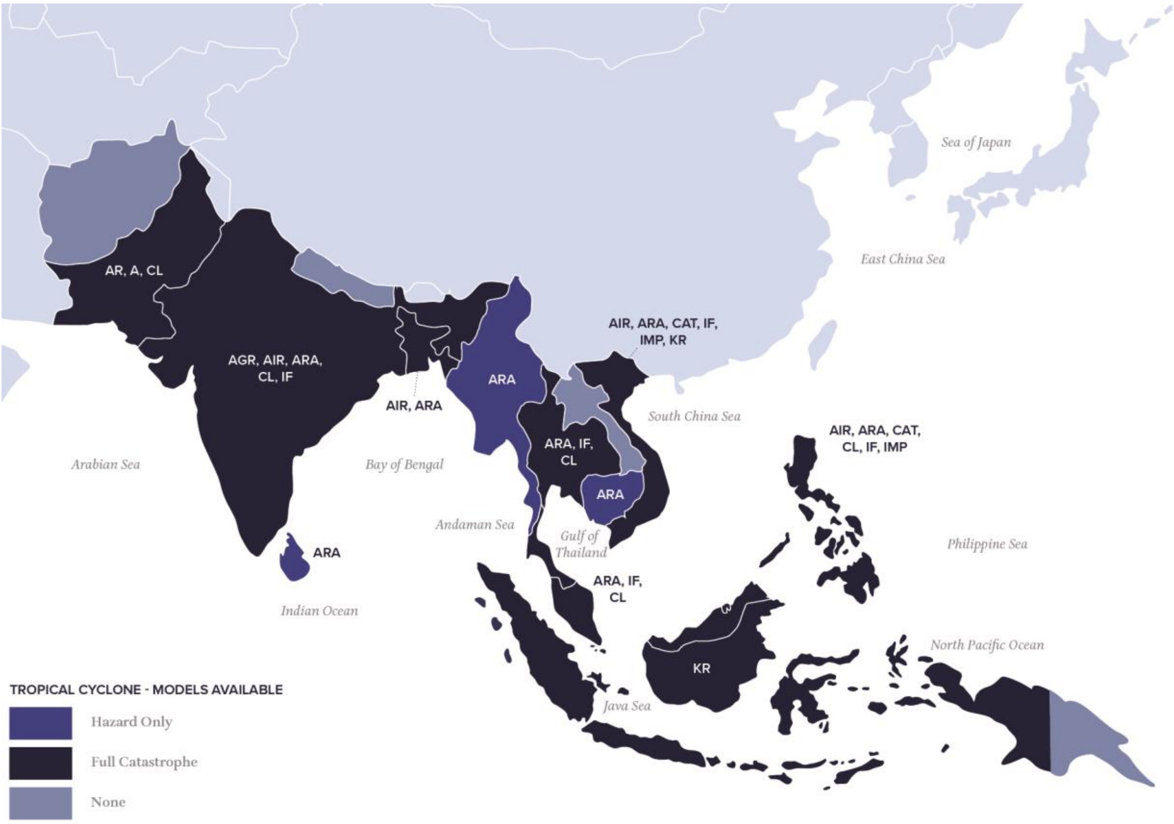


Figure 2-2: Type of tropical cyclone models and the vendors available. Focus countries shown with a bold outline.

Country	Rank	Full catastrophe model
Afghanistan	2	
Bangladesh	**9**	
Cambodia	14	
India	6	AIR, CL, RMS
Indonesia	**5**	**AIR, CAT, CL, RMS**
Lao PDR	10	
Malaysia	11	AIR, CAT, CL, RMS
Myanmar	7	
Nepal	1	
Pakistan	**4**	**CL**
Philippines	3	AIR, CAT, CL, RMS
Sri Lanka	13	
Thailand	8	AIR, CAT, CL, RMS
Viet Nam	12	AIR, CAT, IF, RMS

Table 2 -4: Summary of earthquake catastrophe model vendors and country ranking. Focus countries are highlighted in bold. Grey font denotes models not yet released but anticipated within a year at the time of writing.

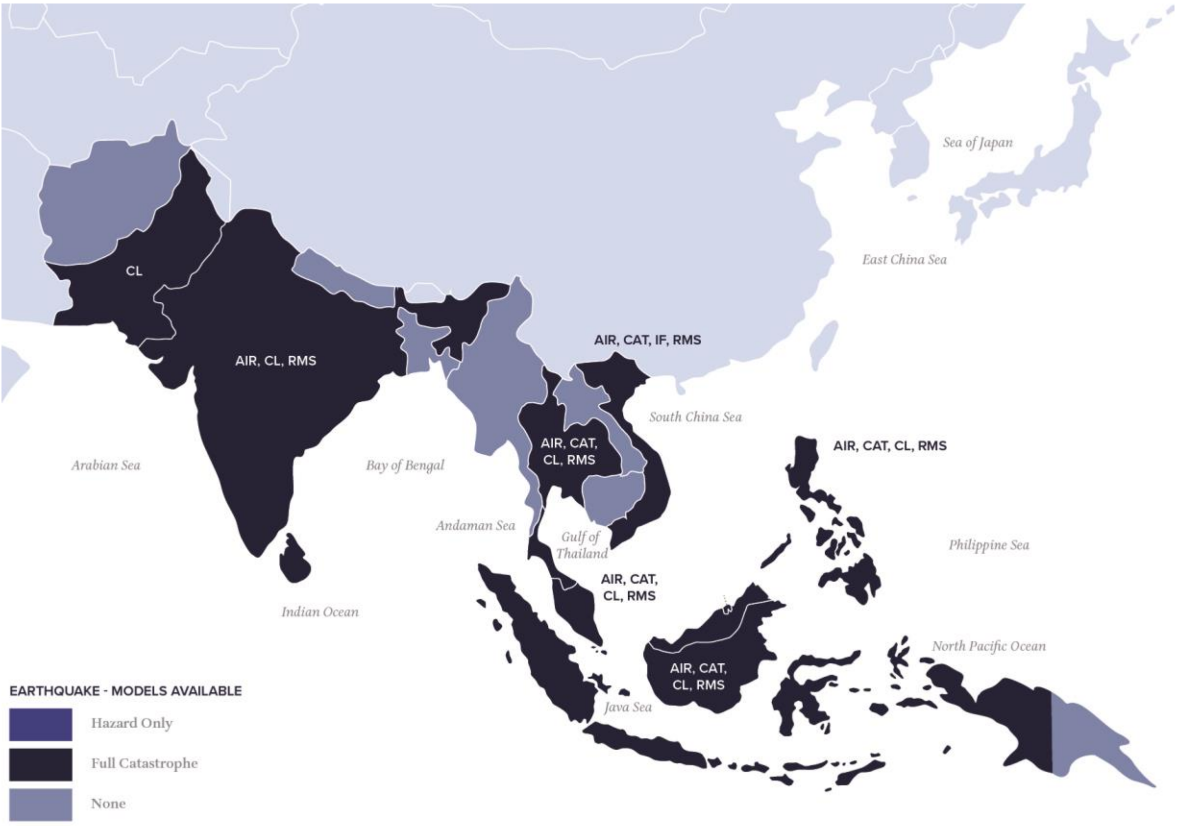


Figure 2-3: Type of earthquake models and the vendors available. Focus countries shown with a bold outline.

It is clear from Tables 2-2 to 2-4 and the maps above that a fully regional catastrophe model does not exist for any peril. Development of catastrophe models over time has traditionally been in countries with more established insurance markets and/or very high hazard.

Full **tropical cyclone models** are available for eight out of 14 countries. Tropical cyclone hazard components are available for ten countries including three where no full model exists.

Full **earthquake models** are available for seven out of 14 countries.

Full **flood models** are available for six out of 14 countries. Flood hazard components are available for eight countries including seven where no full model exists.

Although drought is a peril of interest, no probabilistic **drought models** were discovered in this project, and so methodologies other than full probabilistic catastrophe models would need to be used to structure and price parametric contracts for drought until there is further investment in this area. Some potential datasets and methods for this purpose are discussed in Sections 2.3.4 and 4.6.1.

When considering regional coverage, it important to consider cross-border consistency. There is often diversification benefit from pooling risk (a fundamental principle of insurance) and so contracts which operate on a region-wide basis are likely to offer better value for money for any individual country than country specific contracts. However, if the underlying catastrophe models for each country are produced using different methodologies, then there will be a lack of consistency between models, potentially leading to inequity between countries in the pricing and settlement of the contracts. Models produced by the same vendor, in the same region, at a similar time to each other are much more likely to be consistent than models developed by different vendors or models developed by the same vendor at significantly different times. This implies that a region-wide, or multi-country, facility for disaster risk financing would benefit from underlying models built at a similar time in a similar manner, rather than by using individual disparate models.

Peril-specific details and aspects are discussed further in the subsequent peril-specific sections.

2.2.1 Flood

JBA and Impact Forecasting have the most complete model coverage in this region, with four and three probabilistic flood models available respectively. The Viet Nam models for both of these companies are not released at the time of writing this report but are scheduled for release late in 2016 and will take the number of flood models available in the region from JBA and Impact Forecasting to five and four respectively. The JBA model for India only covers 23 cities. The IF model for Indonesia covers only Jakarta DKI.

In addition to the JBA and Impact Forecasting models, Guy Carpenter has a model for ten key urban regions in India, ICRM has a model for Indonesia (covering Jakarta DKI only), and Catalytics has a flood model for Thailand. Catalytics is also developing a further five flood models in the region, all planned for release in 2017.

JBA has a hazard model covering eight countries in the region (including seven where no full models exist), but further work is required to develop vulnerability components in order to produce modelled loss. Imperial College London has a rain hazard event set for Malaysia which would also require further development in order to produce a flood model.

The most prominent gaps from a flood model perspective are Cambodia, Bangladesh, Lao PDR and Pakistan. These countries are ranked from 1 to 4 in terms of the potential economic loss per unit of economic stock from flood (see Section 1.3), and yet no current probabilistic flood models exist for these countries. Given the prevalence of flood throughout the region, Myanmar, Philippines, Nepal and Afghanistan can also be considered gaps in terms of probabilistic flood model coverage.

Given the hydrological characteristics of this region it would make sense to consider the following groups of countries as sub-regions when considering this peril (see Figure 2-4):

- A Mekong river basin group would include Laos, Cambodia, Viet Nam, Thailand, and south China.
- The Ganges and Brahmaputra rivers span India and Bangladesh, with some of the upper catchment tributaries in Nepal, Bhutan and parts of China.

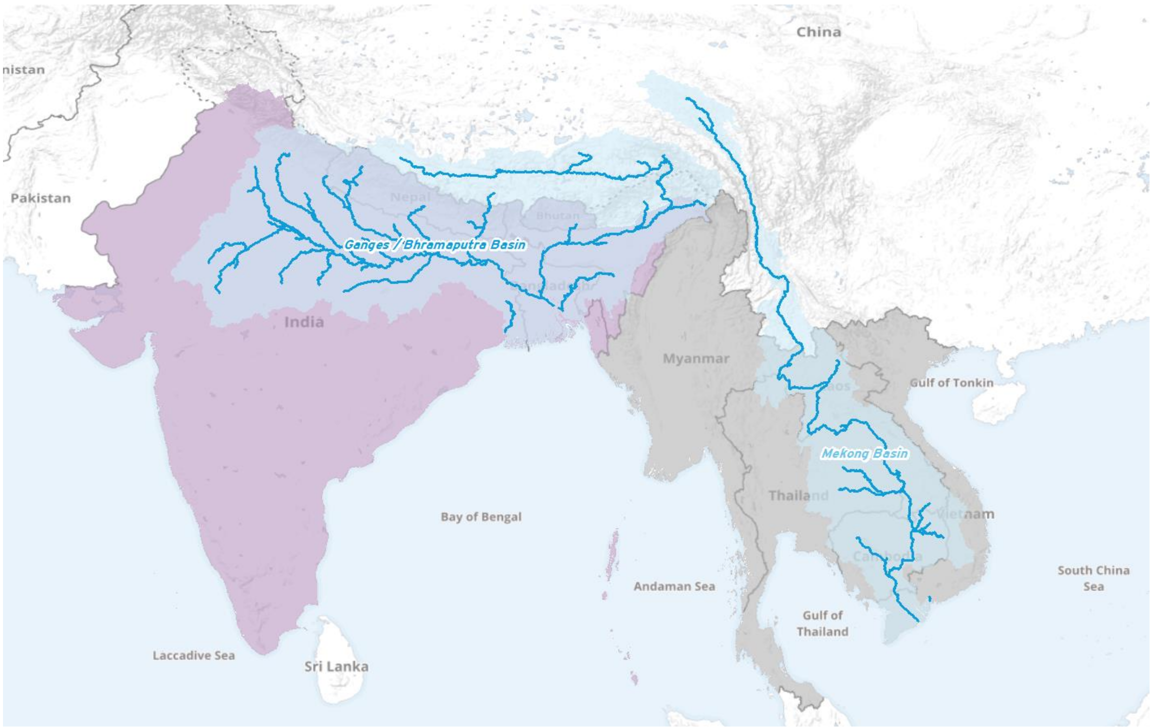


Figure 2-4: Map indicating potential countries which could be grouped based on hydrological characteristics.

The flood peril in these models generally includes fluvial (flooding from rivers) and pluvial (surface water flooding), but not coastal flooding. Coastal flooding is often correlated with tropical cyclone risk and so is sometimes included in these models (see Section 2.2.2). The predominant source of river and surface water flooding in many of the countries in this region can also be tropical cyclones. The available flood models usually capture this source of risk as the rainfall rates or river flow rates used to build the models include the rain / flow generated by tropical cyclones.

In terms of live data usage for contract evaluation, the probabilistic models would ideally take river flow as input for the fluvial peril and rainfall as input for the surface water peril. Where these datasets are unavailable, remotely sensed footprints could potentially be used. A discussion of some of the issues when considering such live data is given in the subsequent sections.

2.2.1.1 Flow data

River gauging stations can either provide flow information or river level information. River flow (m^3/s) is the preferred input to the models, but if water levels are available (generally many gauges only provide water level), they can be converted to river flows using rating curves; where rating curves are available. The issue with flow data is that on a region wide basis these data are not readily available (see Section 2.3.1) and so local sources must be utilised. However, the spatial distribution and coverage of gauging stations varies considerably between countries. Where available, measurements from gauging stations tend to consist only of data for a small number of points. It is recommended that data accessibility contracts are set up before the events in order to get these data shortly after the event if they are not publicly available on the Met-Hydro offices websites. The availability of local sources for Bangladesh, Indonesia, Pakistan, Sri Lanka and Viet Nam is discussed in Sections 3.2 to 3.6.

2.2.1.2 Rainfall data

In the absence of gauged river flow data, flows can be derived from rainfall data using a rainfall-runoff modelling approach. This approach requires consideration of antecedent conditions and catchment characteristics in order to give accurate event representation and can vary in sophistication according to the available data. In general, it is likely that model vendors will have the capacity to perform this conversion.

For models which include surface water (pluvial) flooding as a secondary peril, rainfall data described at compatible gauging stations is required as an input dataset.

2.2.1.3 Derived flood extent and depths

Where gauged observations are not available, remote sensing-derived observation of flood extent can be obtained using (1) optical sensors, (2) passive microwave instruments, or (3) active microwave imagery from synthetic aperture radars (SAR). Some limitations common to these products are if the flood is too short-lived to be seen, and if flood extent is too small to be detected; these will depend on the satellite resolution and revisit frequency. Acquisition of flood extent with optical sensors is the most straightforward, however the monitoring of specific events is hampered by their daylight-only applications and their inability to map flooding beneath clouds (often present during flooding) and vegetation, and in mountainous and volcanic areas. A factor that may lead to errors of flood omission using optical sensors is in sediment-rich areas of water that camouflage the flood event as land. Conversely, false positives may occur where reflective surfaces mistakenly appear as flood water. The potential for using passive microwave imagery for flood monitoring is limited to very large catchments due to the low resolution of the products. SAR images are the most reliable source of information for monitoring floods on rivers less than 1 km in width due to the high (1-2m) to medium (10-25m) resolution images but they usually have longer revisit times than the lower resolution products from optical or passive microwaves sensors. The strong inverse relationship between spatial resolution and revisit time for satellites makes monitoring floods from space in near real-time currently only possible through either low-resolution SAR imagery (~100m wide swath mode and ~ 3 days' revisit time) or satellite constellations. In smaller basins with shorter flood wave travel times, the probability of imaging a flood at its peak decreases and the available acquisitions from coarse, medium or fine resolutions become increasingly opportunistic. In addition, when monitoring urban areas, very fine spatial resolution imagery (finer than 5m) is necessary for accurate results (Grimaldi, et al., 2016).

As flood depth is the typical metric used to associate hazard intensity and monetary loss within a flood catastrophe model, flood extents require conversion to flood depth. The indirect retrieval of water levels from remote sensing data can be performed by the intersection of remote sensing-derived inundation (flood) extent with digital terrain models (DTM). This has been tested with optical products such as the MODIS flood maps. However, SAR data is currently the most viable technique of observing flood extent, yet the retrieval of flood information from SAR imagery is not straightforward, and interpretation errors and inaccuracies impact the outcomes of the flood monitoring and modelling exercise (Grimaldi et al. 2016). The interpretation protocol is mainly composed of:

1. Pre-processing (geo-referencing, ortho-rectification, and speckle removal)
2. Image classification (quality control of 'false positive' flood extent and production of a map with dry and flooded pixels); ideally fully automatic in an operational crisis management context, however a final visual control might be needed.
3. Retrieval of water levels from classified images and a DTM
    a. Image processing to extract flood extent limits
    b. Estimation of water levels by merging the flood extent limits in a DTM
    c. Application of constraining protocol to guarantee the hydraulic coherence of the data set from remote sensing-derived water levels
4. Comparison with auxiliary data (when available)

The accuracy of the water level dataset highly depends on the quality of the remote sensing derived flooded area and the accuracy and resolution of the DTM. A review by Di Baldasarre et al. (2011) showed that the differences in water levels between the remote sensing derived products and measurements at river gauges ranged from below 0.2m to 2m. Large under- and over-estimations of water levels may have an important effect on the estimated impacted assets. Therefore, it is recommended to use the most accurate satellite products available for each event to derive flood extent and related water level products.

2.2.2 Tropical cyclone

CoreLogic, Impact Forecasting and AIR have the most complete full model coverage for the region with five, five, and four models available respectively. KatRisk has a tropical cyclone model that covers Indonesia and Viet Nam. Catalytics is developing models for Philippines and Viet Nam.

ARA has a hazard model covering ten countries in the region, but further work is required to develop vulnerability components for this model in order to produce modelled loss. Similarly, Imperial College London has a hazard model for the Philippines and Viet Nam, and AgRisk has information for India, both of which would require further work in order to produce modelled loss.

The most prominent gaps from a tropical cyclone perspective are Myanmar (number 2 rank, no full-model coverage) and Lao PDR (number 6 rank, no model coverage). Cambodia has no model coverage, yet some TC risk exists. Nepal and Afghanistan have no model coverage but can be considered to have very little risk from TC so this does not constitute a gap.

The meteorological characteristics of this region are such that it would be most appropriate to consider the following groups of countries as sub-regions when considering this peril: Lao PDR, Cambodia and Thailand could be grouped with Viet Nam as one sub-region; Bangladesh and Myanmar as another. It may also make sense to combine India and Sri Lanka together, although the four Bay of Bengal countries could also be one sub-region.

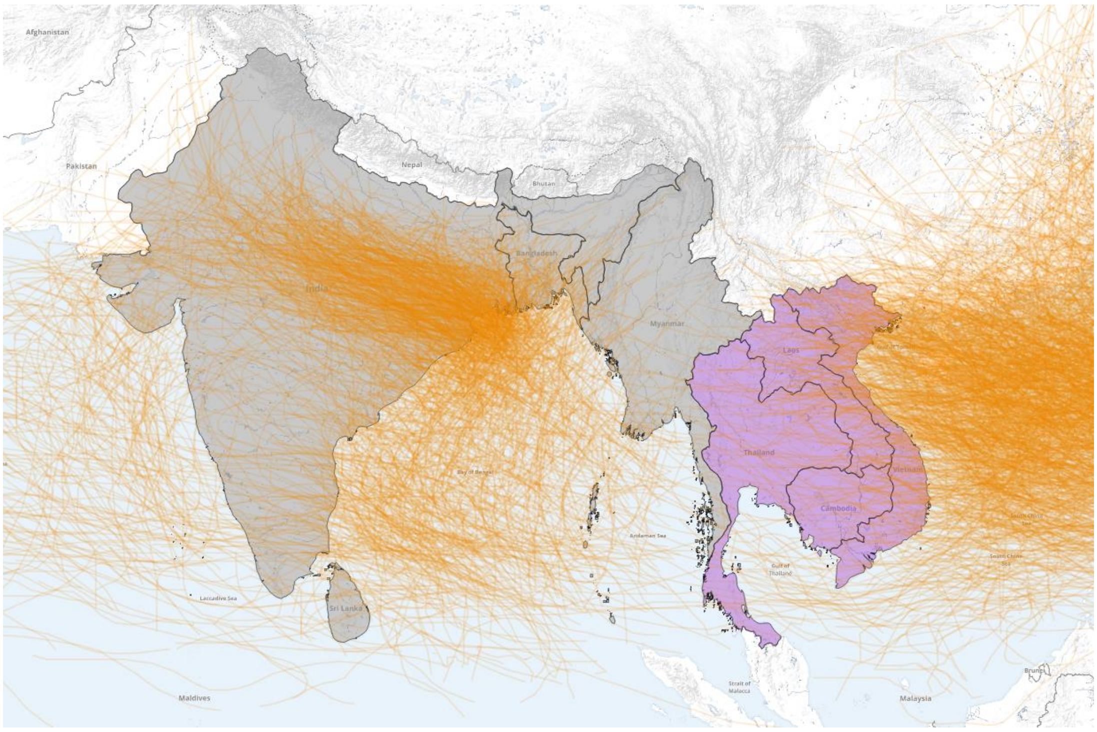


Figure 2-5: Map indicating potential countries which could be grouped based on tropical cyclone characteristics.

Although wind damage is often the most significant component of loss from tropical cyclones, in this region, precipitation-induced flooding and coastal flooding can also form a significant component of any loss. All full TC models listed include wind damage in their loss estimation, and the majority also include damage from precipitation induced flooding. However, most models do not include damage from the coastal flooding associated with tropical cyclones. In seeking to minimise basis risk, these loss sources should be included, although for contract settlement they do not necessarily have to reside in the same model. For example, the wind and coastal flood loss estimates could come from the same TC model, whereas the component of loss from precipitation-induced flooding could come from a flood model. However, if separate models are used then complications and higher costs could arise when structuring and pricing parametric contracts. If the overall modelled loss (from wind and flood components) is used as the basis for the index there will need to be some way of correlating the TC losses with the flood losses when working with separately derived models for the two perils. If the flood loss index is considered separately to the wind loss index within the contract, then the structuring and pricing becomes more straightforward. The simplest solution is a single model comprising both the wind and tropical cyclone-related flood components within a single stochastic event set.

In terms of live data for contract settlement, most TC models will take as input information about the storm at landfall, specifically landfall location, landfall direction, central pressure, forward wind speed and radius to maximum wind. If the model includes precipitation-induced flooding, then precipitation rate and precipitation radius are desirable. For coastal flooding, the tropical cyclone storm track with pressure and maximum wind speed is needed.

2.2.3 Earthquake

In respect of earthquake coverage, AIR and CoreLogic have coverage for six countries in the region, whereas Catalytics has coverage for five countries. RMS currently has coverage for three countries, but three new country models are due for release within a year, which will take the total RMS country coverage to six. Impact Forecasting have one model due for release within a year.

In terms of "gaps", Nepal and Afghanistan can be considered the main gaps as they are ranked 1 and 2 respectively in terms of potential economic damage and yet probabilistic earthquake models are not available for these countries. Myanmar (rank 7), Bangladesh (rank 9) and Lao PDR (rank 10) can also be considered gaps. Sri Lanka (rank 13) and Cambodia (rank 14) have no probabilistic earthquake models but are relatively low risk.

The seismological characteristics of the region are such that it would be most appropriate to consider the following groups of countries as sub-regions when considering this peril: Afghanistan, Pakistan, India, Nepal, and Bangladesh (see Figure 2-6 below).

Given Indonesia's location, high hazard, and its relatively dense network of sensors to capture ground motion, it can be considered its own independent region.

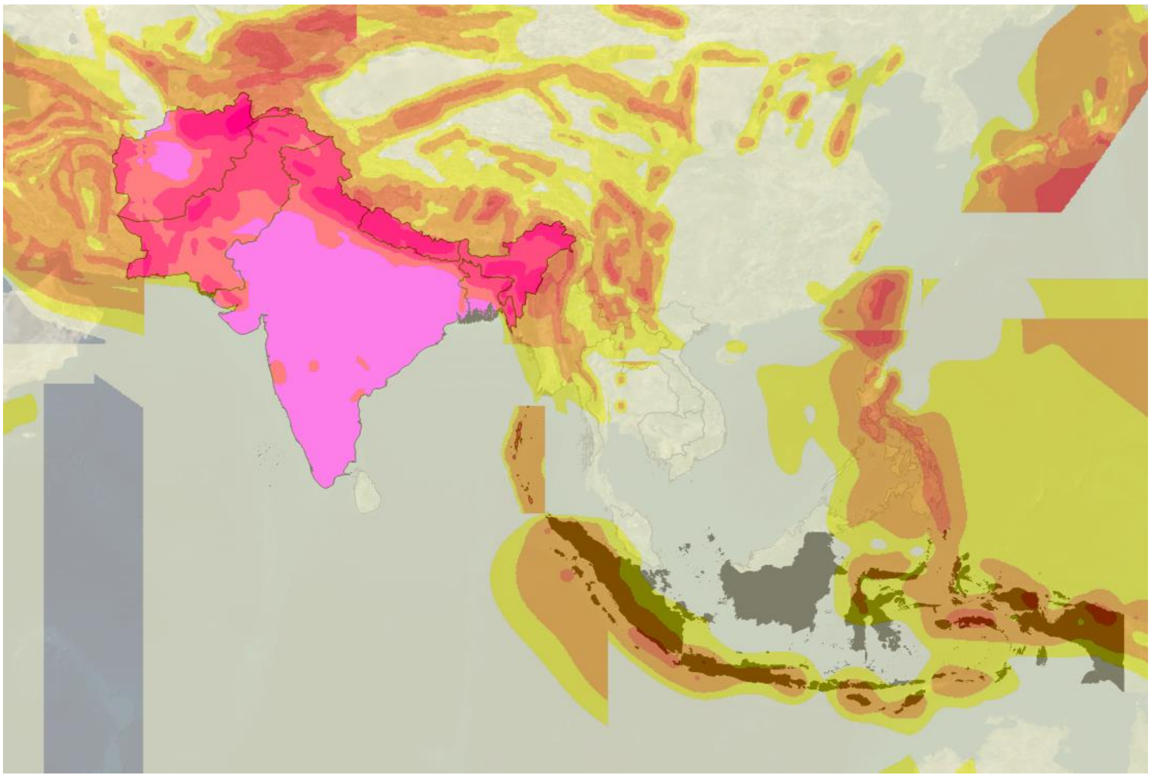


Figure 2-6: Map indicating potential countries which could be grouped based on seismic characteristics.

In terms of live hazard data for contract settlement, catastrophe models will usually need live information about the earthquake's magnitude and location (epicentre or hypocentre depth), rupture type (focal mechanism), as well as slip distribution models (e.g. finite fault). Together with the use of appropriate empirical ground motion prediction equations (GMPEs) and site characterization (e.g. soil class), catastrophe models can create a synthetic ground motion footprint. The actual ground motions, however, can still differ dramatically from the predicted values from catastrophe models for individual events, due to the complex source rupture dynamics, heterogeneous medium of the Earth's crust along the wave propagation path and local geology and topology. Including the live ground motion data from local seismometer networks can significantly improve the ground motion footprint from two perspectives:

1. Improving the accuracy of the footprint at or near places where ground motion recordings are available
2. Removing the overall bias in the predicted footprint with GMPEs, provided a sufficient number of recordings are available from local seismometer networks post-event.

The denser the network of seismometers the more accurate the ground motion map. Catastrophe models can then utilize this improved ground motion footprint, along with appropriate exposure and vulnerability assumptions, to generate more accurate modelled loss.

2.2.4 Drought

The hazard footprints of areas affected by droughts are typically larger than those for other hazards, which are usually constrained to floodplains, coastal regions, storm tracks or fault zones. Perhaps no other hazard lends itself quite so well to monitoring, because the slow onset of droughts allows time to observe changes in precipitation, temperature and the overall status of surface water and groundwater supplies in a region. Drought indicators or indices are often used to help track droughts, and these tools vary depending on the region and the season. Droughts can arise from a range of hydro-meteorological processes that supress precipitation and/or limit surface water or groundwater availability, creating conditions that are significantly drier than normal or otherwise limiting moisture availability to a potentially damaging extent. Drought impacts are significant and widespread, affecting many economic sectors and people at any one time. Therefore, the type of impacts relevant in a particular drought monitoring and early warning context is often a crucial consideration in determining the selection of drought indicators.

No probabilistic catastrophe models were found in the countries examined for the drought peril. This means that the only available option currently for parametric contract structuring and pricing is to make use of the available time series data such as indicators (individual variables or parameters) or indices (multiple indicators). For example, the NOAA GVH data (DR; see Section 2.3.4 and Appendix A) has been produced since 1981 and so a 30+ year time series exists. This alone is insufficient to structure and price a contract; however, statistical techniques could be used to extend this (or other) time series while preserving key spatio-temporal correlation characteristics. Both Exeter University and Imperial College London are developing such techniques. For example, see Youngman and Stephenson (2016). The validation of any such time series of indicators against actual experience on the ground would be a critical component of any such exercise. Reported data on food security responses, crop and livestock statistics, or acute water shortages are examples of datasets that could be used for ground-truthing.

An alternative approach to the statistical extrapolation of indices based on available parameters is to extrapolate data using a physical basis. For example, the UK Met Office have underlying metrics (temperature, precipitation) which could be used to calculate a drought index using their hindcast ensemble. This would provide the equivalent of a circa 2000-year stochastic history; albeit at 60km resolution. Details of this dataset are provided in Appendix B. Another example is the global hindcast dataset used by GlobalAgRisk- Global Parametrics. This dataset is based on daily climatology and simulated data where several variables (e.g. total rainfall, maximum wind speed, min/max temperature and average soil moisture) are generated. The climatology data record spans from 1979-2015 based on four different reanalysis datasets using the Morrigu™ modelling system. The information will be provided for the first level administrative units for 24 low and middle-income countries (not published at the time of this report) as open data on the GlobalAgRisk website as it was developed with support from the Rockefeller Foundation.

2.3 Regional live data

The approach for identifying and cataloguing live data sources involved a combination of internet search and contacting sources known to the consortium. For drought we considered a limited subset of available data, such that work was not done to examine direct in-country sources such as crop yield statistics; instead the focus was on satellite and other international/cross-border sources. However, we are aware that these other drought sources exist. A template for capturing information about each dataset was defined and populated for each source of information and is shown in Appendix A.

For live data to be useful for parametric disaster risk financing contract settlement it must be

- credible;
- transparent;
- independent;
- reported frequently (with short time-lag after an event);
- consistent; and
- stable.

Each dataset was assigned a high / medium / low category in terms of its potential utility as a live data source for parametric contract settlement, bearing in mind the desirable characteristics above. Table 2-5 summarises the number of regional datasets identified by peril and by potential utility.

Peril	Total Number	Number Low	Number Medium	Number High
Flood	17	5	5	7
Tropical Cyclone	13	0	4	9
Earthquake	23	9	8	5
Drought	8	2	4	2

Table 2-2: Number of global/regional datasets by potential utility

The medium- and high-rated datasets are summarised for each peril in Sections 2.3.1 to 2.3.4. Full detail on all the datasets is provided in Appendix A. Examples of how these datasets could be used together with catastrophe models for contract settlement are given in the prototypes in Appendix C.

2.3.1 Flood

Table 2-6 shows the flood global / regional live data sources identified by the consortium and rated either medium or high.

Ref	Name	Rating	Type	Hazard Parameter(s)	Notes
FL2	Sentinel Asia	H	EO	Flood extent: 2.5–30m resolution	Possible aggregator but post-processing needed
FL3	EC Copernicus Emergency Management Service (EMS)	H	EO	Flood extent: 3-20m resolution	Use of several SAR images to provide flood extent
FL4	EarthLab Luxembourg FloodWatch®	H	EO	Flood extent: 5–30m resolution	Use of several SAR images to provide flood extent. Data not provided by Copernicus has an associated cost
FL5	MDA FloodWatch	H	EO	Flood extent: 1-100m resolution	Main RADARSAT provider but all data has an associated cost
FL14	JAXA Global Rainfall Watch - Global Rainfall Map in Near-Real-Time (GSMaP_NRT)	H	EO	Rainfall rate (mm / hour) at 0.1 degree (~11km) resolution	This needs to be paired with other sources to derive index / footprint
FL7	Global Flood Monitoring System (GFMS)	M	EO	Flood depth at 0.125 degree (~12km) resolution	Flood depth derived using the TRMM/GPM precipitation data coupled to a land surface model.
FL6	UNOSAT flood portal	M	EO	Flood extent: 3-20m resolution	UNOSAT satellite processed maps are useful as a quality checked flood extent product. However, it is also available for all events. Further addition of flood events and/or methodology used will require future investigation for collaboration.
FL9	Global Flood Detection System (GFDS)	M	EO	Flood extent at 0.09 degree (9km) resolution	For regional analysis due to resolution, experimental but 18 years of outputs available.
FL13	River Watch (Version 3) - Experimental Satellite-Based River flow Measurements	M	EO	River flow (m^3 / sec) – satellite derived for 345 'stations' globally	Experimental but useful for ungauged locations
FL15	Real-time NASA Rainfall Data	M	EO	Rainfall rate (mm / time period) at 0.1 to 0.25 degree (~11-24km) resolution	This needs to be paired with other sources to derive index / footprint
FL16	NOAA STAR Satellite Rainfall Estimates - Hydro-Estimator (Experimental)	H	EO	Rainfall rate (mm / hour) at 0.057 x 0.045 degree (~5km) resolution	This needs to be paired with other sources to derive index / footprint
FL17	NOAA Operational Hydro-Estimator Satellite Rainfall Estimates	H	EO	Rainfall rate (mm within different time periods) at 0.057 x 0.045 degree (~5km) resolution	This needs to be paired with other sources to derive index / footprint

Table 2-6: Flood global / regional live data sources rated high (H) and medium (M) for potential parametric contract utility. 'EO' denotes earth observation data sources.

All of the medium- and high-rated live data sources are satellite based. However, the spatial resolutions and hazard parameters derived from each source vary. Four different hazard intensity parameters are available from the different data sources: river flow, rainfall rate, flood extent and flood depth. These are discussed below:

2.3.1.1 River flow

This input parameter that can be used in conjunction with a catastrophe model to define an event footprint. River flow data provides a direct measurement of the event severity. However, river flow datasets from river gauges are managed, collected and distributed by local entities (e.g. Met-Hydro offices) (see section 3) and are not typically available as consistent, regional wide datasets. Typically, river flow stations in this region lack complete spatial coverage leading to events being missed or under represented. Short-temporal coverage can also make statistical analysis of historical records difficult. Furthermore, reporting delays and errors can be caused where retrieval and publishing of data is not automated, and where gauges are overwhelmed during a flood event. There is no substitute for direct measurement, however, investment in increasing the spatial coverage of river flow stations would be significant. The one region-wide dataset of river flow (FL13) listed in Table 2-6 is an interesting but experimental approach derived from satellite passive microwave sensors. It is currently only available for 345 virtual 'stations' globally, although with potential to enlarge its coverage.

2.3.1.2 Rainfall rate

This is a useful parameter and can be input directly for surface water (pluvial) models at compatible gauging stations. Rainfall can also be passed through a rainfall-runoff model to derive river flow. Most catastrophe model providers will have developed the necessary algorithms during the model development process and will be able to perform this action. Once rainfall / river flows have been derived the catastrophe model providers will be able to input this data to the catastrophe model in order to obtain a flood event footprint and an associated modelled loss. Some considerations for using rainfall rate are as follows:

- Frequent rainfall rates allow information to be obtained during the onset, peak, and recession of the flood, which are useful to provide a full temporal evolution of the heavy rainfall event.
- Intense rainfall is not always correlated with flooding, because of its dependency on other factors such as orography and antecedent conditions (e.g. soil moisture). Therefore, this data would be best used as an input to a catastrophe model (which is used to define the flood footprint) or as a composite index in combinations with other live data sources.

The high rated rainfall datasets included in Table 2-6 are as follows:

- The JAXA Global Rainfall Watch - Global Rainfall Map in Near-Real-Time (GSMaP_NRT; FL14) offers hourly global rainfall maps at 0.1 degree spatial resolution in near real time (about four hours after observation) using combined rainfall satellite products.
- The NOAA STAR Satellite Rainfall Estimates and NOAA Operational Hydro-Estimator Satellite Rainfall Estimates (FL16, FL17) offers rainfall rate within different time periods at 0.057 x 0.045 degree resolution in near real time (about two hours after observation) using combined rainfall satellite products.

2.3.1.3 Flood extent

This parameter must be combined with a digital elevation model (DEM) in order to derive flood depth. Once flood depth has been derived, it could be run through a catastrophe model in order to establish modelled loss. An issue with the data sources that provide this information at high resolution (FL2, FL3, FL4, FL5) is that it is possible for the satellites to potentially miss the peak of the flood extent due to the satellite revisit time. This can be mitigated by using multiple satellites and flood forecasting products to trigger or prioritise the retrieval of satellite images in order to capture the best proxy for the maximum flood extent. Satellites that provide a more frequent monitoring (FL9) and have wider spatial coverage have courser geographical resolution and so are less suitable and accurate. Therefore, a composite satellite flood extent may be required to obtain the best available spatial and temporal flood extent coverage. Another issue is that accuracy may be lower in urban, forested, and mountainous areas and higher in agricultural fields due to inherent limitations of the satellite sensors techniques. Ultimately, the output resolution of the processed flood extent/depth dataset will be that of the DEM. Various DEM and Digital Terrain Models (DTM) exist in the region with national or subnational coverage at 15-100m resolution. Consistent regional DTMs are available at 30m resolution. Some further considerations for satellite derived flood extent live data are as follows:

- The activations from FL2, FL3, FL4 and FL5 have global coverage, but EMS (FL3) and Sentinel Asia (FL2) do not make activations for all flood disasters as this is based on the authorised users request for activations they receive. Activations for the EarthLab Luxembourg FloodWatch® (FL4) and MDA FloodWatch (FL5) can be requested by commercial users.
- A free and open licence exists for the EMS (FL3) and Sentinel Asia (FL2), but activation requests can only be made by authorised users. Authorised Users are public entities active in the field of disaster management in the EU Member States, the Union Civil Protection Mechanism, the Commission's Directorates General (DGs) and the participating European Agencies. Authorised Users are the only entities authorised to trigger the service, i.e. by sending a service request directly to the ERCC.
- There is a cost for EarthLab Luxembourg FloodWatch® (FL4) and MDA FloodWatch (FL5) but commercial users can request activations for specific events.
- High resolution flood extents (up to 3 m) can be produced in all weather conditions and through cloud cover, smoke and haze by using SAR satellite sensors. However, the satellite revisit time may mean that the flood peak and maximum flood extent is missed. Satellite acquisition will therefore be more successful for flood events lasting several days on large rivers with extensive floodplains.
- Depending on the satellite operator full geographic coverage of the event may not be available at high resolution; it may be limited to the satellite overpass areas, or commercial constraints.

Even though multiple Earth Observation missions have global coverage and are currently targeted to capture flood extents (among other uses) the challenge of obtaining the maximum flood extent for each flood event remains. Higher-resolution sensors usually have a longer revisit times than coarse resolution sensors. Images from each available sensor typically have a different coverage, revisit frequency, resolution, and processing algorithm. Nevertheless, a merged product from available images for different sensors at each flood event might provide the best estimate of a maximum flood extent, with the added cost of acquiring commercial images and post-processing of all raw satellite products. A complementary approach might be to pre-define areas of interest (e.g. high exposure) in order to target the retrieval of higher-resolution images (in most occasions associated with high cost) when a flood event strikes, and use coarser and/or open source free satellite products for other areas of lower exposure and for monitoring purposes.

2.3.1.4 Flood depth

This is the hazard intensity parameter that probabilistic flood models use. However, the spatial resolution of the only live dataset to report this (FL7) is at 0.125 degree resolution which is too coarse a resolution to be useful for defining a footprint for disaster risk financing purposes.

Of all the perils considered in this study, flood is perhaps the most difficult to define a high quality event footprint suitable for running through a catastrophe model shortly after an event has taken place, because of the weaknesses of each live data source described above. A combined approach using rainfall rate propagated through a model to describe the overall flood extent, river flow data to establish the return period of the event, and flood depth and flood extent to validate the final footprint is likely the best approach. Further information on this can be found in the prototypes described in Appendix C.

2.3.2 Tropical cyclone

Table 2-7 shows the tropical cyclone global / regional live data sources identified by the consortium and rated either medium or high.

Ref	Name	Rating	Type	Hazard Parameter(s)	Notes
TC1	JTWC TC Warning Text	H	EO	Wind speed Radii to 34, 50, 64kn winds	TC1 & TC2 provide the same data via different access portals. Suitable source for defining 6-hourly wind hazard footprint.
TC2	US NRL Tropical cyclone warning	H	EO	Wind speed Radii to 34, 50, 64kn winds	TC1 & TC2 provide the same data via different access portals. Suitable source for defining 6-hourly wind hazard footprint.
TC4	NOAA Dvorak Fix-Based Wind Radii	H	EO	Radius of specific wind speeds	
TC5	NCEP Global Data Assimilation System (GDAS)	H	Ass	10m wind speed and surface pressure, rainfall rate at 0.25 degree resolution	Suitable as supplementary index parameter only. Not ideal resolution to resolve TCs. Model run 4 times daily.
TC6	ECMWF Single level analysis	H	Ass	10m wind speed and surface pressure, rainfall rate at 0.1 degree resolution	Suitable as supplementary index parameter only. Model run 4 times daily.
TC8	JAXA Global Rainfall Watch	H	EO	Rainfall rate (mm / hour) at 0.1 degree (~11km) resolution	This needs to be paired with wind sources to derive index / footprint. Same source as FL14.
TC9	NASA Real-time Rainfall Data	H	EO	Rainfall rate (mm / time period) at 0.1 to 0.25 degree (~11-24km) resolution	This needs to be paired with wind sources to derive index / footprint. Same source as FL15.
TC10	NOAA STAR Satellite Rainfall Estimates - Hydro-Estimator (Experimental)	H	EO	Rainfall rate (mm / hour) at 0.057 x 0.045 degree resolution	This needs to be paired with wind sources to derive index / footprint.
TC11	NOAA Operational Hydro-Estimator Satellite Rainfall Estimates	H	EO	Rainfall rate (mm within different time periods) at 0.057 x 0.045 degree resolution	This needs to be paired with wind sources to derive index / footprint.
TC3	Unisys Hurricane/Tropical Data	M	EO	Max sustained winds (1min or 10min)	Suitable source for defining 6-hourly wind hazard footprint.
TC7	UKMO Global Atmospheric Hi-Res Model	M	Ass	10m wind speed and surface pressure, rainfall rate at 0.15 degree resolution	Suitable as supplementary index parameter only. Model run twice daily.
TC12	UKMO MetDB dataset	M	Sta	Surface wind speed, wind direction, max gust, pressure, rainfall Number of stations per country varies – see detailed spreadsheet	Suitable as supplementary index parameter only.
TC13	UKMO MIDAS: Global Weather Observation Data	M	Sta	Surface wind speed, wind direction, max gust, pressure, rainfall. Number of stations per country varies – see detailed spreadsheet	Suitable as supplementary index parameter only.
TC14	Regional Specialised Monitoring Centre, Japan Meteorological Agency	H	EO	Six-hourly position, intensity (min central pressure, max sustained winds, gusts), movement, radius of >30kn and >50kn winds	Suitable as event identifier and primary index parameter.

Table 2-7: Tropical cyclone global / regional live data sources rated high (H) and medium (M) in terms of potential usage for parametric contract. 'EO' denotes an earth observation data source, 'Ass' denotes an assimilation / numerical model based data source, 'Sta' denotes data from observational stations.

Tropical cyclone risk is not only related to wind damage, but also the damage from rainfall-induced flooding and storm-surge. No single source above captures all of the information necessary to define a detailed tropical cyclone footprint, which is why a combination of data products have been identified as the best candidates. In general, the EO products providing storm location, wind speed, radius and rainfall information provide a good basis for a hazard footprint. Station-based observations provide the ability to 'ground-truth' or calibrate the EO products for the specific locations. However, the extreme wind speeds of tropical cyclones can cause damage to weather stations and lead to loss of data. This, coupled with the heterogeneous and often sparse distribution of stations, means that station data should not be used as a primary source for parametric contract settlement. Assimilation products essentially use numerical weather prediction models to interpolate station data in a physically consistent way, and so the sparseness and randomness of station data is mitigated. However, the resolution of assimilation-based products is often not quite sufficient to fully resolve tropical cyclones, and there is a danger of smoothing real extremes in hazard intensity through the interpolation process, implying that these products should also be used as supplementary sources of live data.

The different hazard intensity parameters and live data sources for tropical cyclone risk are discussed below.

2.3.2.1 TC maximum sustained wind speed

This is a simple hazard intensity parameter, and can be used in isolation for a crude estimate of hazard wind field footprint by assuming an applicable cyclone size. This parameter is most frequently estimated based on satellite data. However, when "in-situ" data (station, ship, buoy or aircraft) are available, these will be used to correct the satellite estimate.

This parameter is reported as either 1- or 10-minute averages, dependent on the data source; it may also be reported in kn, kph, mph or m/s, dependent on source. Considerations in using this parameter are as follows:

- This parameter is always included along with TC location updates; long historical records of TC tracks usually include this parameter.
- Reliable six-hourly updates of this parameter are provided with very short latency (of order a few hours) from sources TC1, TC2 and TC3.
- This is usually determined based on satellite imagery using a standard methodology (the Dvorak (1982) technique) aiming to minimise subjectivity, although this is usually a manual process by forecasters who will take account available in situ observations when TCs are close to land.
- The availability of this parameter from the global sources TC1 and TC2 and the internal consistency between these two sources imply there will be few regional inconsistencies in this parameter from these sources.
- This parameter can be determined using polar-orbiting or geostationary satellite data; there is no reliance on a single source of imagery.
- This parameter can be used in isolation to define a crude wind field footprint by assuming TC size appropriate to the location.
- This parameter is included in data products which are freely available for commercial use from all relevant sources.

2.3.2.2 Specific wind radii

Combining this parameter with TC maximum wind speed can provide a more accurate description of the TC size and the distribution of wind speed across the TC. This will allow for an improved hazard wind field footprint. This parameter is most frequently estimated based on satellite data. However, when "in-situ" data (station, ship, buoy or aircraft) are available, these will be used to correct the satellite estimate.

The specific wind speeds for which radii are provided are typically in kn and may reference the wind speed thresholds of the Saffir-Simpson Scale categories (i.e. 34kn for Tropical Depression, 50kn for Tropical storm, 64kn for Category 1 Hurricane, etc.) or categories of other TC intensity scales. Considerations in using this parameter are as follows:

- This parameter is defined based on satellite imagery and can be determined using polar-orbiting or geostationary satellite data; there is no reliance on a single source of imagery.
- This is included on reliable six-hourly updates of TC location and maximum sustained wind speed, usually provided with very short latency (on the order of a few hours) from sources TC1 and TC2, and routinely updated at 6-hourly intervals for source TC3.
- The availability of this parameter from the global sources TC1, TC2 and TC3, implies there will be few regional inconsistencies in this parameter from these sources.
- This parameter is freely available for commercial use from all relevant sources.

2.3.2.3 Satellite rainfall rate

This is a necessary parameter for defining the rainfall footprint for a tropical cyclone. Converting rainfall rate to a depth and accumulating rainfall within a certain distance from the TC centre, over all appropriate time periods, yields a TC rainfall footprint. Considerations in using this parameter are as follows:

- Sources TC10 and TC11 provide rainfall rates at close to 500m resolution; hourly rainfall rate is available from source TC10 in digital format with a latency of a few hours; sub-hourly is available in image (and possibly digital) format from source TC11 with zero latency.
- Sources TC8 and TC9 provide rainfall rates at approximately 1km resolution at hourly and at least three-hourly intervals, respectively.
- This parameter has global coverage from all sources which ensures there will be no regional inconsistencies.
- This parameter is satellite-derived and therefore may be vulnerable if dependent satellite data are unavailable for any reason.
- The update frequency of this parameter from all sources ensures the majority of short-duration heavy rainfall periods within the entire hazard duration should be included in the final hazard rainfall footprint.
- This parameter is freely available for commercial use from all relevant sources.

2.3.2.4 Surface wind speed and pressure (model)

Surface wind speed can provide a direct input to a catastrophe model when the instantaneous wind speed is converted to a 1- (or 10-) minute average wind speed or 3-second gust.

Surface pressure can provide a direct input to a catastrophe model where the wind field can be deduced based on the surface pressure field.

Considerations when using these parameters are as follows:

- These parameters are produced by global atmospheric models, which have assimilated global atmospheric observations to produce a suitably accurate representation of the atmospheric state at the time of the model analysis.
- All sources are reliable global centres for atmospheric modelling; the availability of their products is excellent. Where products have costs associated with them, the modelling centre has an obligation to its client to ensure delivery in a timely manner.
- The global coverage of these parameters from all sources ensures there will be no regional inconsistencies.
- These parameters are available at six-hour intervals from sources TC5 and TC6, and at 12-hourly intervals from source TC7; all sources have a latency of about six hours.
- The horizontal resolution of sources TC5 and TC7 are 10 and 15km respectively. The resolution of source TC 6, 25km. A downscaling process may be required in order to be compatible with the catastrophe models which, for this region, typically run at 1km resolution.
- This parameter is freely available for commercial use from source TC5; sources TC6 and TC7 have costs associated with them.

2.3.2.5 Surface wind speed, pressure, and rainfall accumulation (station)

Surface wind speed from stations can be combined with other wind field footprint parameters (model or satellite-derived) to yield an enhanced wind field footprint.

Surface pressure from stations can be combined with model surface pressure to allow the generation of an enhanced wind field footprint.

Rainfall accumulation from stations can be combined with the satellite rainfall accumulations to allow the generation of an enhanced rainfall footprint.

Considerations when using these parameters are as follows:

- Sources TC12 and TC13 provide station observations with global coverage. In-country coverage by stations varies by country. The frequency of reporting and the latency of observations varies by station.
- The minimum latency of reporting for source TC12 is one day, with data undergoing only very basic quality control; for source TC13, the latency is one month but the data undergo more involved quality control.
- The inclusion of in-country station observations in sources TC12 and TC13 is reliant on the country's transmitting the data. Consequently, these data are potentially vulnerable to in-country observation network outages associated with the hazard in question.
- Commercial use of any station data within sources TC12 and TC13 requires the permission of the respective in-country organisation responsible for that station; there may be costs associated with commercial use of these data, determined by the respective country.

2.3.3 Earthquake

Table 2-8 shows the earthquake global / regional live data sources identified by the consortium and rated either medium or high.

Ref	Name	Rating	Type	Hazard Parameter(s)	Notes
EQ1	USGS ShakeMap	H	Sta	Location, Depth, Intensity, PGV, PGA, MMI, SA at 0.3, 1.0 and 3.0 seconds	ShakeMap is a map of shaking intensity footprint that consists of the listed hazard parameters produced and distributed by USGS in near real time. Catastrophe models typically can use one of more of these intensity parameters as input to generate modelled loss
EQ2	USGS PAGER	M	Sta	Fatalities and economic loss estimates	Same approach for ground motion footprint as for ShakeMap. Uses ShakeMap with exposure and population data to rapidly estimate economic loss and casualties
EQ3	IRIS Time Series Data	M	Sta	Raw waveform data, capturing ground motions over the duration of an earthquake	Waveform (time series) data can be used to measure peak ground motions, such as peak ground acceleration (PGA) and peak ground velocity (PGV)
EQ6	LDEO Centroid Moment Tensor (CMT)	H	Sta	Centroid Moment Tensor Solution for M>5.5, estimating orientation of slip distribution of fault	Moment Tensor provides rapid information about focal mechanism of an event, which is one of the common source parameters used by catastrophe models to construct intensity footprints. It also provides information about two nodal rupture planes, but cannot uniquely determine the one that represents actual rupture. Other supplemental techniques, such as waveform inversion, faulting information and aftershock patterns, are used to determine a more accurate fault rupture plane solution, often with a three- to four-month delay
EQ7	ICES QLARM	M	Sta	Location, Depth, Intensity, human deaths, injuries and building damage	Includes worldwide information on building stock and population, based on a collection of input seismic sources including GFZ, USGS, EMSC, TWC.

EQ8	EMSC Earthquake Notification	M	Sta	Location, depth, moment magnitude	EMSC collects real-time parametric data (source parameters and phase pickings) provided by 70 seismological networks of the Euro-Mediterranean region.
EQ11	GEOFON Recent Earthquakes	M	Sta	Location, magnitude, depth, waveform	Monitors earthquake data from 22 seismic stations located within Indonesia, 1 seismic station located near Pakistan/Afghanistan border. The global network includes 78 permanent stations.
EQ12	NEIC Fast Finite Faults	H	Sta	One definition of nodal plane (min), seismic moment, moment magnitude	Fast Finite Faults are rapid (few hours) slip models for major earthquakes – used to constrain ground shaking, determine tsunami generation and/or stress change.
EQ13	USGS W-phase Moment Tensor Solution (Mww)	H	Sta	Strike, dip, rake of nodal planes as well as principal axes	Used to determine orientation of the fault plane that slipped and the slip vector
EQ14	USGS Body-wave Moment Tensor Solution (Mwb)	H	Sta	Strike, dip, rake of nodal planes as well as principal axes	Used to determine orientation of the fault plane that slipped and the slip vector
EQ16	EC Copernicus Emergency Management Service (EMS)	M	EO	Number of destroyed / damaged buildings in each grid cell.	Same source as FL3. Compares post disaster maps to pre-disaster maps to estimate.
EQ20	APRSAF Sentinel Asia	M	EO	Aggregator database for post event satellite imagery	Satellite imagery (and data permitted by data provider) and value-added images with extraction of stricken area
EQ 21	The International Charter Space and Major Disasters (Multiple Charter members)	M	EO	Provides access to high and moderate resolution imagery for interpretation of damage	Upon activation, the Charter provides high and moderate resolution imagery for interpretation of damage.

Table 2 -8: Earthquake global / regional live data sources rated high (H) and medium (M) in terms of potential usage for parametric contract. 'EO' denotes an earth observation data source, 'Sta' denotes data from observational stations.

The earthquake sources identified are predominately derived from seismographs; with the exception of three EO sources (rated as medium). There are five different types of live data. The strengths and weaknesses of each are discussed below:

2.3.3.1 Raw waveform (EQ3, EQ6, EQ11, EQ12, EQ13, and EQ14)

Raw waveform (i.e. ground-motion time history) can be used to derive shaking intensity parameters, such as MMI, PGA, PGV or Spectral Acceleration (SA), at or near places of recordings. For example, USGS ShakeMap uses shaking intensity parameters, derived from the recorded time history from local seismic networks, to define the shaking intensity footprint at or near the places of recordings post event when they are accessible to USGS. (However, in general, the amount of local seismometer information included in global products such as the USGS ShakeMap product is limited for this region – see Appendix C).

For places where no seismometers are available, ShakeMap uses GMPEs to generate shaking intensity. For countries with poorer global network coverage (most of this region), using the ShakeMap product will lead to higher basis risk due to the higher uncertainty in predicted intensity footprint (see Section 2.3.3.3).

These data need pre-processing before they can be used for improving the accuracy of assessed ground motion footprints, which catastrophe models use in order to generate modelled loss.

- **Strengths**
  - Near real-time acquisition of data.
  - Near real-time information regarding solutions to faulting mechanisms following significant earthquakes.
  - One aspect of earthquake information used in the development of ground motion footprints.
- **Weaknesses**
  - Pre-processing may be required.
  - EQ6: Although a real-time estimate of a fault mechanism is produced, there is typically a three to four-month delay of the final moment tensor solution for earthquakes of M>5.5.
  - Coverage (with the exception of Indonesia due to data source EQ11) may be sparse in the countries of interest; see Appendix C.
  - IRIS (EQ3) only captures time series information. This information would need to be combined with other datasets and tools to create a ground motion footprint across the impacted region.
  - To estimate earthquake impacts, supplemental information will be required for exposure mapping, local geologic mapping and regional empirical ground motion prediction equations (GMPEs) derived from local historical events or similar tectonic settings (if catastrophe models are unavailable).

2.3.3.2 Event source parameters (EQ9, EQ10, and EQ11)

These data typically provide event source information, such as event occurrence time, magnitude, epicentre, hypocentre depth and focal mechanism. (This describes the source rupture mechanism, such as "strike-slip", "reverse" and "normal", which is an important part of the inputs used to estimate a ground-motion footprint from the GMPEs, post-event). These parameters consist partially of the inputs that catastrophe models use to generate ground motion maps.

- **Strengths**
    - Near real-time acquisition of important earthquake rupture source information.
- **Weaknesses**
    - Current seismic networks for the countries of interest may be lacking; see Appendix C.
    - Additional information such as local geologic mapping and regional empirical ground motion prediction equations are required to generate an accurate ground motion footprint.

2.3.3.3 Ground motion maps (EQ1)

These data provide the parameters that catastrophe models use in order to generate modelled loss.

- **Strengths**
    - Typically, free and open-licence.
    - Near real-time acquisition of data.
    - USGS ShakeMaps provides post-event ground shaking footprints (MMI, PGA, PGV, SA) maps at 1-km gridded seismicity.
- **Weaknesses**
    - Current ground motion instrumentation for the countries of interest may be lacking or limited; ShakeMap has few live data from local seismometer networks included besides its own broadband global seismic network; see Appendix C.
    - Lack of high-resolution local geological maps for site classification.
    - Inconsistency of predicted ground motion footprint with the GMPEs and site classification maps used within the catastrophe models leading to a mismatch between the live data modelled loss estimate and the losses from stochastic events used to structure and price the contract

2.3.3.4 Estimated economic damage and fatalities derived from estimates of ground shaking (EQ2, EQ7)

These sources estimate economic losses and fatalities directly, however consistency with catastrophe model estimations may cause issues.

- **Strengths**
    - Loss estimates typically produced in less than one hour after the earthquake.
    - PAGER (EQ2) provides earthquake impact scales showing distribution of human and economic losses.
    - QLARM (EQ7) provides estimates of human fatalities and injuries and mean damage information by location.
    - Provides basic earthquake source parameters.
    - Provides list of major cities impacted and the intensity felt at those locations.
- **Weaknesses**
    - Full geographic coverage of the event may not be available.
    - Methodology and datasets used to transform ground shaking estimates into impacts give a rapid, rough approximation, but it may be possible to reduce basis risk further by using other methodologies and sources to derive impacts from hazard.
    - Inconsistency with the catastrophe model estimations used to structure and price the contracts.

2.3.3.5 Satellite imagery (EQ16)

These estimate damage based on ‘before’ and ‘after’ satellite images. However, consistency with catastrophe model estimates could cause issues.

- **Strengths**
    - Rapid visual assessment of heavily damaged and destroyed buildings.
- **Weaknesses**
    - Possible delays in acquisition of post-event satellite imagery.
    - Pre-event high-resolution satellite imagery for comparison may be limited.
    - Damage-grade assessments derived from post-event satellite imagery by means of visual interpretation are subjective.
    - Destroyed and heavily damaged buildings may be visible in high resolution satellite imagery, however lower damage states will be difficult to assess.
    - Additional "in-situ" data will be required to estimate the proportion of buildings unaffected, or with slight to moderate damage, and to validate levels of heavy damage and collapsed structures.

2.3.4 Drought

Table 2-5 shows the drought global / regional live data sourced identified by the consortium and rated either medium or high.

Ref	Name	Rating	Type	Hazard Parameter(s)	Notes
DR1	NOAA GVH	H	EO	Seven-day composite index based on vegetation health, soil moisture deficit and temperature. 1km spatial resolution.	The index indirectly reflects a combination of chlorophyll and moisture content in the vegetation health and also changes in thermal conditions at the surface.
DR2	GIEWS ASI	H	EO	10-day index based on vegetation health. 1km spatial resolution.	Current format only provided as image
DR3	NOAA SPI	M	Sta & EO	Monthly meteorological drought index: based on precipitation only (SPI). Rain gauge based and remote sensing based at 1° spatial resolutions.	This needs to be paired with other global sources for an index due to basis risk issues in using a precipitation-only view of drought occurrence
DR4	CSIC SPEI	M	EO	Monthly index based on precipitation and temperature. 0.5° spatial resolution.	This needs to be paired with other global sources for an index due to basis risk issues
DR8	IWMI South Asia Drought Monitoring System	M	EO	Composite index based on vegetation, precipitation, temperature and soil condition indexes. Eight-day temporal resolution, unknown spatial resolution.	System under development – potential for future index. Only covers: Afghanistan, Bangladesh, Bhutan, India, Sri Lanka, Maldives, Nepal, Pakistan

Table 2-9: Drought global / regional live data sources rated high and medium in terms of potential usage for parametric contract.

The drought live data sources identified are all predominantly EO based sources. They vary according to the type of drought represented (defined by temperature, rainfall, soil condition or vegetation condition). There is no single index or indicator that can account for and be applied to all types of droughts, climate regimes and sectors affected by droughts. The preferred and recommended approach is for users to take a multiple or composite/hybrid indicator approach. Indices based on precipitation measurements only, do not provide information on key factors such as temperature, soil moisture and vegetation health, which are needed to understand the regional implications and drought effects on agriculture.

Features of the two high-rated drought indexes, NOAA GVH (DR1) and GIEWS ASI (DR2), are as follows:

- Global coverage
- Full coverage of the event, with composite values every 7 and 10 days, respectively.
- Free and open licence
- NOAA GVH (DR1): 1, 4, and 16 km resolution and 7-day composite global drought index based on several vegetation health indexes derived from remote sensing: Vegetation Health Index (VHI), Vegetation Condition Index (VCI, soil moisture), and the Temperature Condition Index (TCI, temperature)
- GIEWS ASI (DR2): 1km resolution and 10-day composite global drought index based on a spatio-temporal analysis of the Vegetation Health Index (VHI)
- They can be used as a "quick-look" indicator for early identification of agricultural areas that may be affected by dry spells, or drought in extreme cases
- Duration and severity could be derived and used to calculate the number of crops and the population size affected by drought, but detailed exposure information may be difficult to obtain in some regions

3 Local catastrophe models and live data

3.1 Overview

The methodology for local live data and catastrophe model cataloguing follows the same approach described for the regional cataloguing; a desktop / internet search combined with reaching out to contacts and catastrophe model providers known by the consortium. However, to ensure all of the local live data sources were captured, the country-specific meteorological / seismological institutes were also contacted. Appendix A and Appendix B detail the local live data and catastrophe models catalogued during this exercise. Five priority countries were selected for the exercise; Bangladesh, Indonesia, Pakistan, Sri Lanka, Viet Nam.

3.2 Bangladesh

The perils of focus within the scope of this report in Bangladesh are flood, tropical cyclone and earthquake.

3.2.1 Catastrophe models

No earthquake or flood catastrophe models were identified for Bangladesh. However, JBA has a flood hazard event set for both river and surface water for tropical cyclone (TC) and non-TC events.

There are no "off-the-shelf" catastrophe models available for Bangladesh tropical cyclone. However, AIR has a model that can be made available on a consultancy basis, which includes both wind and precipitation-induced flooding. In addition, ARA has a TC event set comprising wind hazard only. Neither model includes the storm surge peril.

3.2.2 Live data

Table 3-1 shows the local live data sources for flood, tropical cyclone and earthquake in Bangladesh.

Ref	Peril	Name	Rating	Hazard Parameter(s)	Notes
EQ26	Earthquake	Bangladesh strong motion network from Bangladesh University of Engineering & Technology	M	Location, magnitude, depth and PGA	60 potential accelerographs, 38 confirmed as currently active
EQ27	Earthquake	Digital Seismic Real Time Monitoring Network from the Bangladesh Meteorological Department	M	Location, distance to epicentre (from station), and magnitude	BMD's seismic monitoring system nation-wide consists of four digital broadband seismometers, two boreholes, two digital short-period seismometers and six accelerometers with GPS synchronization
EQ29	Earthquake	National seismic network of India from the India Meteorological Department	L	Location, magnitude, depth, intensity	55 seismological stations (30 digital, 25 analogue)
FL18	Flood	River levels from the Bangladesh Water Development Board	M	Water levels (m)	105 river gauges
FL19	Flood	Rainfall from the Bangladesh Water Development Board	L	Rainfall rate (mm/day and mm/month)	58 rain gauges
FL20	Flood	Ganges-Brahmaputra Flood Awareness and Prediction system	M	Satellite derived streamflow (m^3 / s)	Related to Dartmouth Flood Observatory River Watch dataset (FL13). 18 virtual gauges within the Ganges-Brahmaputra basin extent.
TC19	Tropical Cyclone	Observed Track from Bangladesh Meteorological Department	L	Graphic of TC track (location and intensity)	
TC20	Tropical Cyclone	Rainfall from the Bangladesh Water Development Board	M	Rainfall rate (mm/day and mm/month)	Same source as FL19. 58 rain gauges.
TC31 & TC 32	Tropical Cyclone	Automatic weather station data from Bangladesh Meteorological Department	M	Wind speed, direction, rainfall	74 stations. May be included in UK Met Office MetDB or MIDAS datasets but position is unclear.

Table 3-1: Local live data sources for earthquake, flood and tropical cyclone for Bangladesh

The earthquake data sources are all rated between low (EQ29) and medium (EQ26 and EQ27) in terms of their potential as live data sources for parametric contract settlement. These sources are rated low to medium because of the lack of processes to consistently create event footprints from the raw parameters and the potential for large uncertainties in such results.

All three data sources publish source data (location, depth and magnitude) and are expected to provide local information near real time. However, access to the data is uncertain. Coverage is provided for the region with 38 confirmed accelerograph installations, four digital broadband seismometers, two boreholes, two digital short-period seismometers and six accelerometers with GPS synchronization; see Appendix C for the seismic network map for EQ27.

Several challenges exist in the region that are applicable to Bangladesh and the other countries of interest under this project:

1. Seismometers of local networks are often sparse (with the exception of Indonesia) and usually not included in global products such as USGS ShakeMap. Our understanding is that the local sources for Bangladesh (EQ26, 27 and 29) are not routinely included in the USGS products. Near real-time processing of seismometer recordings, adaption to intensity map construction and product publication can be difficult without an automated process in place.
2. Detailed site classification maps are lacking. Local site conditions can significantly affect the ground shaking intensity. Detailed site classification maps can significantly improve the accuracy of the predicted shaking intensity in places where no seismometers are available. In some locations (e.g. Dhaka) good examples of site classification exist, however full coverage across the countries in this region is not readily available.
3. Near real-time finite fault models are not always available, particularly for mid-size events (magnitude < 7.0). The finite fault model is another important factor that significantly affects the accuracy of predicting ground motions post-event. In Asian developing countries, due to the dense population and generally vulnerable construction, events with magnitude between 6 and 7 could cause enormous damage and significant economic and societal disruption.

For the flood peril, water levels from the Bangladesh Water Development Board (FL18) and the satellite derived streamflow from the Ganges-Brahmaputra Flood Awareness and Prediction system (DFO; FL20) were rated medium due to their potential as live data sources for parametric contract settlement, but they will need to be paired with other data sources or models in order to generate a flood footprint. Reported event coverage will be limited to river (fluvial) flooding in gauged catchments. The current known location of gauges in Bangladesh is insufficient, but additional river gauges are maintained by the Bangladesh Water Development Board, and therefore it will be beneficial to obtain them to enhance the use of this data source. It is likely that a once a Bangladesh flood catastrophe model is built, the vendor company will have the capability to interpolate information to adjacent ungauged catchments. To increase event coverage, data could be combined with rainfall measurements such as those from the Bangladesh Water Development Board (rated low; FL19) where catastrophe models are built with rainfall inputs or include both river and surface water hazard.

Tropical cyclone live data is available for rainfall from the Bangladesh Water Development Board (TC20) and as wind speed from the Bangladesh Meteorological Department (TC31, TC32). Both were rated medium. The temporal resolution of wind observations is excellent, but the spatial coverage of weather stations is relatively poor, especially near the capital city and near the coastline. These are potentially useful sources to supplement information on cyclone location, intensity and cyclone size from the JTWC (TC1); model surface wind and pressure analyses, e.g. from NCEP GDAS (TC5); station observations of wind speed to complement rainfall observations, direction and max gust, e.g. from Met Office MetDB dataset (TC12) or in-country datasets such as Bangladesh AWS (TC31 and TC32); regional/country-wide rainfall from e.g. NASA GPM (TC9) or JAXA (TC8). Observed track data from the Bangladesh Meteorological department (TC19) is not ideal as it is only in graphical format; digital data is not readily available.

3.3 Indonesia

The perils of focus within the scope of this report for Indonesia are flood and earthquake.

3.3.1 Catastrophe models

ICRM and IF have flood models available for Jakarta DKI. However, the remainder of Indonesia (circa 70% by population) is not covered by probabilistic flood models. Catalytics is developing a model for Indonesia flood due for release in 2017. JBA has a flood hazard event set for both river and surface water for TC and non-TC events.

There is a good selection of models available for Indonesia earthquake from AIR, Catalytics, CoreLogic and RMS, some of which are recently-developed and sophisticated models which include the impact of secondary perils such as landslide, liquefaction and tsunami.

3.3.2 Live data

Table 3-2 shows the local live data for earthquake and flood for Indonesia.

Ref	Peril	Name	Rating	Hazard Parameter(s)	Notes
EQ23	Earthquake	Earthquake parameters and Tsunami simulation results from International Seismic Network of NIED	H	Location, Magnitude, Depth, Dip, Strike, Rake, estimates of Tsunami heights	184 broadband stations in Indonesia and surrounding region
EQ24	Earthquake	Indonesian Tsunami Early Warning System from BKMG	M	Location, depth, magnitude, areas at risk of tsunami inundation and time of arrival	257 stations across Indonesia and the surrounding region
FL26	Flood	Hydro-meteorological observation network from Tech4water group	H	Water levels in rivers	50 stations
FL27	Flood	Hydro-meteorological observation network from Balai Hidrologi dan Air	H	Water levels in rivers	240 stations

Table 3-2: Local live data sources for earthquake and flood for Indonesia

The earthquake live data sources are rated medium and high in terms of their potential as live data sources for parametric contract settlement. The coverage is relatively good for the region, with approximately 400 stations in and around the country; see Appendix C. Data are provided near real time and updated as needed (NIED; EQ23) or processed and analysed by on-duty seismologists (BMKG; EQ24). The source mechanism and waveform fits are provided by NIED. BMKG also produce their own version of the USGS ShakeMaps utilising their own, more detailed, seismic network. Our understanding is that the local seismic stations will not be routinely included in global products such as USGS ShakeMap.

For flood, water levels from the Tech4water group (FL26) and Balai Hidrologi dan Air (FL27) were rated high due to their potential as live data sources for parametric contract settlement for their spatial-temporal availability, but they will need to be paired with other data sources or models in order to generate a flood footprint. Reported event coverage will be limited to river (fluvial) flooding in gauged catchments. It is likely that a once an Indonesia flood catastrophe model is built, the vendor company will have the capability to interpolate information to adjacent ungauged catchments. To increase event coverage, data could be combined with rainfall measurements where catastrophe models are built with rainfall inputs or include both river and surface water hazard.

3.4 Pakistan

The perils of focus within the scope of this report for Pakistan are flood and earthquake.

3.4.1 Catastrophe Models

No catastrophe models were identified for Pakistan flood. However, JBA has a flood hazard event set for both river and surface water for TC and non-TC events.

CoreLogic has the only model available for Pakistan earthquake.

3.4.2 Live data

Table 3-3 shows the local live data for flood and earthquake for Pakistan.

Ref	Peril	Name	Rating	Hazard Parameter(s)	Notes
EQ25	Earthquake	National Seismic Monitoring Centre from Pakistan Meteorological Department	L	Location, magnitude, depth	Circa 30 stations
EQ30	Earthquake	SUPARCO Rapid Damage Assessment Maps	L	Earthquake Impact Area Maps	Pre and post-event satellite imagery rapid damage assessment
FL28	Flood	Flood observations and forecasts – Pakistan flood forecasting division	H	Inflow and outflow of dams and river level	22 inflow and outflow gauges on dams
FL29	Flood	Flood automatic weather stations – Pakistan flood forecasting division	L	Rainfall	7 stations
FL33	Flood	Real Time Regional Flood Information System, International Centre for Integrated Mountain Development	L	Water levels and rainfall	3 rain gauges, 3 water level stations, 1 weather station

Table 3-3: Local live data sources for earthquake and flood for Pakistan

The two earthquake live data sources are both rated as having low potential as a live data source for parametric contract settlement. Limited source information (depth, magnitude, location) is provided from the 30 station networks from PMD (EQ25); see Appendix C. The current ground-motion instrumentation network is limited and is not linked to the USGS ShakeMap. SUPARCO (EQ30) relies on EO pre- and post-event imagery data and may not be reliable for low levels of damage. Therefore, the extent of the affected region may not be fully established after an event rapidly.

Water levels from the Pakistan flood forecasting division and International Centre for Integrated Mountain Development were rated high due to their potential as live data sources for parametric contract settlement for their spatial-temporal availability for the most populated areas (North), but they will need to be paired with other data sources or models in order to generate a flood footprint. Reported event coverage will be limited to river (fluvial) flooding in gauged catchments. It is likely that a once a Pakistan flood catastrophe model is built, the vendor company will have the capability to interpolate information to adjacent ungauged catchments. To increase event coverage, gauges could be combined with rainfall measurements such as those from the Pakistan flood forecasting division (although with limited spatial coverage, rated as low) where catastrophe models are built with rainfall inputs or include both river and surface water hazard.

3.5 Sri Lanka

The perils of focus within the scope of this report for Sri Lanka are flood and tropical cyclone.

3.5.1 Catastrophe models

A Sri Lanka flood probabilistic model is available from JBA covering river and surface water hazard for TC and non-TC events.

ARA has a tropical cyclone wind hazard event set which includes Sri Lanka.

3.5.2 Live data

Table 3-4 shows the local live data for flood and tropical cyclone for Sri Lanka.

Ref	Peril	Name	Rating	Hazard Parameter(s)	Notes
FL24	Flood	Water levels from Hydro-meteorological observation network, Irrigation department	H	River water level	33 principal stations, 33 peripheral stations
FL25	Flood	Rainfall from Hydro-meteorological observation network, Irrigation dept.	L	Rainfall rate	55 stations
TC19	Tropical Cyclone	Observed Track from Bangladesh Meteorological Department	L	Graphic of TC track (location and intensity)	
TC21	Tropical Cyclone	Hydro-meteorological observation network, Irrigation department	M	Rainfall rate, river level	

Table 3-4: Local live data sources for flood and tropical cyclone for Sri Lanka

Water levels from the Sri Lanka Irrigation department (FL24) were rated high due to their potential as live data sources for parametric contract settlement given their spatial-temporal availability. Gauges report on an hourly basis for the principal stations and are available for the Kelani river, which flows through the capital city Colombo. As this represents the majority of exposure this is deemed sufficient coverage. Gauges will need to be paired with other data sources or models in order to generate a flood footprint. Reported event coverage will be limited to river (fluvial) flooding in gauged catchments. The existing Sri Lanka catastrophe model has the capability to interpolate information to adjacent ungauged catchments. To increase event coverage, gauges could be combined with rainfall measurements such as those from the Sri Lanka Irrigation department (FL25; rated as low) as the catastrophe model includes both river and surface water hazard.

Tropical cyclone live data is available for rainfall from the Sri Lanka Irrigation department (TC21) and was rated as medium. It has an excellent temporal coverage and the spatial coverage is good in the southern half, but poor in the northern half of the island. To give a fully rounded hazard intensity footprint, there is a need to consider the temporal evolution and supplement the rainfall data with: cyclone location, intensity and cyclone size information, e.g., from JTWC (TC1); model surface wind and pressure analyses, e.g. from NCEP GDAS (TC5); station observations of wind speed, direction and max gust, e.g. from Met Office MetDB dataset (TC12); regional/country-wide rainfall from e.g. NASA GPM (TC9) or JAXA (TC8). Observed track data from the Bangladesh Meteorological department (TC19) is not ideal as it is only in graphical format; digital data is not readily available.

3.6 Viet Nam

The perils of focus within the scope of this report for Viet Nam are flood, tropical cyclone and drought. For drought we considered a limited subset of available data, such that work was not carried out to examine direct in-country sources such as crop yield statistics; instead the focus was on satellite and other international/cross-border sources. However, we are aware that these other drought sources exist.

3.6.1 Catastrophe models

Catalytics, IF and JBA flood models are expected to be released towards the end of 2016.

For tropical cyclone, AIR, Impact Forecasting and KatRisk have models currently available and Catalytics is developing a model.

In addition, ARA and Imperial College London have a TC wind hazard event set available that covers Viet Nam.

No full catastrophe models were identified for drought. However a hindcast ensemble dataset produced by UKMO contains a stochastic history equivalent to circa 2000 years including parameters that could be used to derive a drought index.

3.6.2 Live data

Table 3-5 shows the local live data for flood, tropical cyclone and drought for Viet Nam.

Ref	Peril	Name	Rating	Hazard Parameter(s)	Notes
FL21	Flood	Water levels dataset, National Centre for Hydro-Meteorological Forecasting	H	Water level, flow	Twice daily, 248 river gauges (150 have water level and flow; 95 only have water level)
FL22	Flood	Rainfall dataset, National Centre for Hydro-Meteorological Forecasting	M	Rainfall	Sub daily (4 or 8 observations per day), 756 rain gauges
FL23	Flood	Rainfall radar, National Centre for Hydro-Meteorological Forecasting	M	Rainfall	Data retrieved every 5 min
FL30	Flood	Mekong river monitoring system forecast, Mekong River Commission	M	Water level, flow, rainfall	Daily (wet), weekly (dry season) updates, 23 stations along the Mekong river
FL31	Flood	Mekong river real time water level monitoring water level, Mekong River Commission	H	Water level	Every 2-hours measurements, 49 river gauges.
FL32	Flood	Mekong river real time water level monitoring rainfall, Mekong River Commission	M	Rainfall	12 stations
TC17	Tropical Cyclone	Track and Position of Tropical Cyclones, Hong Kong Observatory	L	3- to 12 hourly position, intensity (max sustained winds),	-
TC18	Tropical Cyclone	Tropical Cyclone Warning, Viet Nam National Hydro-Meteorological Service	M	12 hourly position, intensity	-
TC23	Tropical Cyclone	Mekong river monitoring system forecast, Mekong River Commission	M	Rainfall	Two stations
TC24	Tropical Cyclone	Mekong river real time water level monitoring water level, Mekong River Commission	M	Rainfall	12 stations
TC30	Tropical Cyclone	Weather station data, Viet Nam National Centre for Hydro Meteorological Forecasting	H	Weather station: Win (velocity, Direction); Precipitation.	220 to 234 stations
DR10	Drought	Water levels dataset, National Centre for Hydro Meteorological Forecasting	M	Water levels	Twice daily, 248 river gauges (150 have water level and flow; 95 only have water level)
DR11	Drought	Rainfall dataset, National Centre for Hydro Meteorological Forecasting	L	Rainfall	Sub daily (4 or 8 observations per day), 756 rain gauges
DR12	Drought	Mekong river real time water level monitoring water level, Mekong River Commission	M	Rainfall	Every 2-hours measurements, 49 river gauges.

Table 3-5: Local live data sources for flood, tropical cyclone and drought for Viet Nam for data sources rated low (L), medium (M) and high (H).

Water levels from the National Center for Hydro-Meteorological Forecasting (FL21) and Mekong River Real Time Water Level Monitoring (HYCOS; FL31) were rated high due to their potential as live data sources for parametric contract settlement given their spatial-temporal availability, whereas water levels from the Mekong river monitoring system forecast (FL30) were rated as medium due to the poor coverage of this system within Viet Nam (two gauges with daily updates during flood season and weekly updates during dry season). These water levels will need to be paired with other data sources or models in order to generate a flood footprint. Reported event coverage will be limited to river (fluvial) flooding in gauged catchments. The soon to be available catastrophe models are expected to have the capability to interpolate information to adjacent ungauged catchments. They could be combined with rainfall measurements such as those from the Viet Nam National Centre for Hydro-Meteorological Forecasting (rated as Medium; FL22, FL23) where catastrophe models are built with rainfall inputs or include both river and surface water hazard.

Tropical cyclone live data is available for cyclone parameters (six-hourly position, intensity, movement, radius of >30kn and >50kn winds) from the North West Pacific World Meteorological Organization (WMO) Regional Specialized Monitoring Centre (RSMC) Tokyo Tropical Cyclone Information (TC14; rated high). The spatial coverage is limited to WMO reporting area (0-60N, 100-180E), but if a cyclone occurs in that region it will be reported here, per WMO regulations. Furthermore, the Viet Nam National Hydro-Meteorological Service provides weather station wind speed and rainfall (TC30; rated high), and tropical cyclone position and intensity (TC18; rated medium). Rainfall is also provided by the Mekong River Commission (TC24; rated as medium). To give a fully-rounded hazard intensity footprint, there is a need to consider temporal evolution and to supplement local data sources with that from global sources, e.g.

- model surface wind and pressure analyses, e.g. from NCEP GDAS (TC5); and
- rainfall rate / accumulation, e.g. NASA GPM (TC9) or JAXA (TC8).

The track and position of tropical cyclones from the Hong Kong Observatory (TC17) also provide location and intensity information, although this data is not readily downloadable.

A specific country-scale drought index or monitoring system is not currently available for Viet Nam. However, rainfall deficit and low water levels can be useful indicators of drought at those gauged locations and near surroundings (few km). At specific rain and river gauges, the Viet Nam National Hydro-Meteorological Service and the Mekong River Commission provides rainfall and water levels/river flow, respectively. The network in Viet Nam has better spatial coverage than in many countries in the region. However, Viet Nam still has a restricted spatial cover, and it will be challenging to extrapolate rain gauge values in areas of poor coverage, especially in mountainous areas.

Viet Nam suffered in the first half of 2016 (to date) severe drought saltwater intrusion affecting 18 provinces in Viet Nam, generating critical water, sanitation, health and food emergency. The Mekong Delta district was largely affected causing severe damages on paddy rice and fruit production, as is by far Vietnam's most productive region in agriculture and aquaculture. It is home to 20 million people and accounts for more than half of Vietnam’s rice and fruit production, 90% of its rice exports and 60% of fishery exports. Measurements from river gauges can inform the development and recovery of the drought situation as they capture river flow deficit (and surplus). Long time series records can also be used to assess the severity of the hydrological drought.

4 Priorities for further work

4.1 Overview

This section considers the potential priorities for further work, focusing on improving the ability to facilitate disaster risk financing for the countries within the project scope. These potential areas for investment are outlined in the subsequent sections. A key decision is whether to invest in country-specific improvements or whether to try and achieve some level of region (or sub-region)-wide consistency. This will depend on the feasibility and demand for a regional, or multi-country, approach to disaster risk financing and is beyond the scope of this exercise, although the topic is discussed in Sections 4.3 and 4.4.

Other initiatives are also considering investment in this region. In particular, the Insurance Development Forum (IDF) is considering cataloguing hazard and vulnerability data for the V20 countries as well as building regional models. It would make sense to consider partnering with this or other initiatives for some of the longer term and costly options discussed.

4.2 Filling catastrophe model gaps

Catastrophe models are normally developed by vendors in response to market demand and thus potential revenue from the sale of such models. Given that a major use of catastrophe models is within the insurance sector, this has resulted in models being first developed for regions where there is both risk and a developed insurance market. While many (re)insurers understand the growth potential (both in terms of GDP and insurance market penetration) for many of the countries in the region that this report focuses on, it can still be difficult to develop a strong business case for catastrophe model development given the market size in this area at present and the low level of current insurance rates. With this in mind, it is unsurprising to discover that there are significant gaps in catastrophe model coverage in the region. Table 4-1 summarises these gaps; showing countries with some risk to a peril but where no fully developed catastrophe model has been discovered (or is imminent). Countries highlighted in bold do not have hazard components, or fully developed models available (or imminently available). The tropical cyclone risk for Indonesia, Malaysia, Nepal and Afghanistan is lower than for other countries in this region and so these countries are not included under the tropical cyclone section. The earthquake risk for Malaysia, Viet Nam, Sri Lanka and Cambodia is lower than for other countries in this region and so these countries are not included under the earthquake section.

Country	Peril Rank	Population (m)	Capital stock (USD bn)
Flood			
Cambodia	1	15	27
Bangladesh	2	157	381
Lao PDR	3	7	22
Pakistan	4	182	502
Myanmar	7	53	196
Philippines	8	98	567
Nepal	9	28	54
Afghanistan	11	28	54
Indonesia	12	250	2828
Tropical Cyclone			
Myanmar	2	53	196
Lao PDR	**6**	**7**	**22**
Sri Lanka	8	20	208
Cambodia	9	15	27
Earthquake			
Nepal	**1**	**28**	**54**
Afghanistan	**2**	**31**	**60**
Myanmar	**7**	**53**	**196**
Bangladesh	**9**	**157**	**381**
Lao PDR	**10**	**7**	**22**

Table 4-1: Gaps in catastrophe model coverage. All countries are considered to have flood risk; only the top 10 ranked countries are considered to have material risk for tropical cyclone and earthquake. Where neither fully developed models nor hazard components have been discovered, countries are highlighted in bold. Where fully developed models have not been discovered, but hazard components do exist, countries are not highlighted.

Given that catastrophe models are an extremely valuable tool for developing and placing disaster risk financing instruments, these countries and perils can be considered a priority for investment.

4.2.1 Drought

Although drought is not shown in this table, no event-based catastrophe models were discovered for this peril; in this sense, this is a gap for every country in the region. However, drought is not a commonly-modelled peril elsewhere either. Several indices with fairly long time series (circa 30 years) are available for drought; the suggested way forward for this peril is therefore to investigate methods of extrapolating existing indices rather than build a traditional component-based catastrophe model. This is discussed further in Section 4.6.1.

4.2.2 Flood

Flood is the peril with the most gaps from a catastrophe modelling perspective. This is not surprising as flood hazard is prevalent for every country in this region and flood models are challenging to build (extremely high resolution data are required) and costly to develop.

Viet Nam (rank 5) would also be on this list as a gap, were it not for three flood models under development (not released at the time of this report but due in 2016). Indonesia is shown on this list, despite there being two probabilistic catastrophe models available. However, both models only cover Jakarta DKI, and although this is a significant area of population and urban density there is still a substantial proportion of the population (>70%) not covered by a probabilistic flood model, and so this can be considered a gap from the point of view of national-scale probabilistic flood modelling.

It is interesting to note that no catastrophe models exist for the top four ranked countries from the perspective of the ratio of potential loss to economic stock (Cambodia, Lao PDR, Bangladesh and Pakistan). Bangladesh and Pakistan in particular have fairly large populations and capital stock together with a high ranking for flood risk.

4.2.3 Earthquake

In terms of earthquake there are catastrophe model gaps for five countries including Nepal and Afghanistan which rank 1 and 2 respectively for this peril, yet no model exists.

4.2.4 Tropical cyclone

In terms of tropical cyclone there are catastrophe model gaps for four countries. Although Bangladesh (rank 3 for TC) is not shown in this table, the one full probabilistic model for this country is only available on a consultancy basis and is not generally released.

4.2.5 Priority considerations

Filling the gaps in catastrophe model coverage can be considered a priority from the perspective of enabling parametric risk financing so that contracts can be structured and priced, and settled in the case of third generation triggers. This could be done on a country by country basis. However, for several reasons it makes sense to ensure that regionally consistent models exist for each peril and so this should be a consideration when thinking about investment priorities. This is the topic of the next section.

4.3 Developing regional models

The catastrophe modelling gaps are listed in Table 4-1. Although it would be possible to fill these gaps on an individual country basis, there are benefits in setting up parametric disaster risk financing on a regional or sub-regional basis. This is the approach taken by sovereign insurance schemes in the Caribbean (the Caribbean Catastrophe Risk Insurance Facility (CCRIF)), the Pacific (Pacific Catastrophe Risk Assessment and Financing Initiative) and Africa (Africa Risk Capacity), although there may be greater challenges implementing a regional scheme over the larger area and more diverse set of perils and countries considered in the scope of this report, including the ability to run a detailed model over such a large area, especially for a high-resolution peril like flood. These issues are outlined in the 2016 World Bank discussion paper 'TOWARD A REGIONAL APPROACH TO DISASTER RISK FINANCE IN ASIA'(1).

These benefits include the following:

- **Diversification benefit**: Most catastrophic events will not impact the whole region and so there is a diversification benefit from pooling risk within a region. This is a fundamental principle of any type of insurance and leads to a lower cost for individual countries.
- **Scale benefit for operational expenses**: There are always expenses involved in setting up a parametric transaction or facility. If these expenses are shared amongst a number of participating countries the expense per country is reduced.
- **Scale benefit for reinsurance purchases**: Depending on the nature of the contract or parametric transaction, protection may be required by the capital markets or traditional reinsurers. Packaging risk up at a regional level is more efficient than country by country (for the reasons already mentioned of diversification and expense benefit)
- **Other benefits**: The creation of a regional risk pool requires regionally consistent models and a supporting infrastructure. If performed in the appropriate manner this can facilitate and encourage local understanding of risk and can encourage and support local research and development efforts. This is discussed further in Section 4.4.

There is a difference between having region-wide coverage of models and region-wide consistency of models. Models developed by different companies, or developed by the same company at different times, can be very different in the way they are developed. This may be due to methodological improvements or simply due to inconsistent datasets being available between countries. Such an inconsistency between models within the same region would lead to issues if attempting to pool risk within the region, in particular

- difficulty in quantifying the diversification benefit with inconsistent models due to a lack of consistent events that span the region;
- differences in the way the risk is modelled between countries, resulting from inconsistency in the treatment of secondary perils, demand surge and other model aspects, and potentially leading to inequity in terms of contract pricing and settlement;
- different levels of transparency and documentation in respect of different models; and
- different levels of basis risk due to a different level of model effectiveness for each country.

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1 *http://pubdocs.worldbank.org/en/622001465500604140/DRF-Rockefeller-FINAL-002.pdf*

In terms of developing consistent models across a region, it is necessary to define a suitable region or sub-region. From the perspective of some level of hazard consistency, the following groups of countries could be considered as coherent groups for sub-region models.

- **Flood** (see Section 2.2.1)
    - A Mekong river-basin group would include Lao PDR, Cambodia, Viet Nam and Thailand. Myanmar could also be included in this sub-region given its proximity.
    - The Ganges and Brahmaputra rivers span India and Bangladesh, with some of the upper catchment tributaries in Nepal. Sri Lanka could also be grouped with these countries given its proximity.
    - Indonesia, Malaysia and the Philippines could also be considered together as could Afghanistan and Pakistan given their proximity
- **Tropical Cyclone** (see Section 2.2.2)
    - Lao PDR, Cambodia, Thailand and Viet Nam
    - Bangladesh and Myanmar
    - India and Sri Lanka (or these could be grouped with Bangladesh and Myanmar, comprising a sub-region of the four Bay of Bengal countries)
- **Earthquake** (see Section 2.2.3)
    - Afghanistan, Pakistan, India, Nepal and Bangladesh. Myanmar could also be added to this group, given its proximity and relatively high hazard.
    - Indonesia could be considered in isolation, given its high hazard and location. Alternatively, a sub-region could be formed by it grouping with the Philippines, which also have a high earthquake hazard and proximity to some areas of Indonesia.
    - Thailand, Lao PDR, Vietnam, Cambodia and Malaysia have a lower hazard and are in proximity so could be considered another sub-region

In terms of packaging up risk, another perspective to consider is the size of the potential exposure each country would offer to any regional pooling of risk. If one country dominates this could lead to an imbalance in the pool. Countries such as India and Indonesia are substantially larger than other countries in this region from the perspectives of population, capital stock and GDP (see Table 1-2). An analysis of the economic considerations when considering how to pool risk at a regional level is, however, outside the scope of this report.

Given the above, a sensible investment priority would be to establish regionally- or sub-regionally-consistent catastrophe models built by the same vendor (or consortium of vendors). In considering this, it makes sense to build on the models, or hazard components, already in place and described in Section 2.2.

If regionally-consistent models are to be built for the purposes of disaster risk financing, there is benefit in ensuring this is done in as open and transparent a way as possible. In particular, the platform on which the models are built should be open and transparent. This is the topic of Section 4.4.

4.4 A regional model framework

Almost every model vendor has its own proprietary software platform on which its models are constructed. A platform typically enables the different catastrophe model components (hazard, exposure, vulnerability) to interact correctly as well as enabling the user to input exposure data (and sometimes geocoding) and retrieve results at the desired granularity. The financial engine, which performs the statistical calculations, is also a key model component and is normally an embedded part of the software platform.

Several years ago, each vendor would purely develop models on their own platform and not on other platforms. This position is now slowly starting to change, especially for the medium- and smaller-sized vendors. There are now examples of companies developing probabilistic models on other companies' platforms, for example:

- The Ambiental Australia flood model developed on the IF Elements platform
- The JBA UK flood model developed on the IF Elements and Oasis platform (as well as its own JCalf platform)
- The ERN Mexico flood and earthquake models developed on the AIR Touchstone platform

This demonstrates the potential opportunity to put in place a regional platform on which multiple suppliers build models (consistent within each sub-region-peril).

The Oasis Loss Modelling Framework is an initiative to develop and encourage the transparency and consistency of model development, as well as to foster the ability for multiple vendors to develop on the same platform. It is a not-for-profit initiative to create a community for catastrophe loss modelling based around open architecture, standards and software. Oasis has developed a set of standards and a financial loss calculation kernel in order to encourage catastrophe models to be developed in a consistent manner. This framework and kernel can be turned into a platform, and indeed Oasis has recently done this through the development of their Flamingo platform in order to allow the ARA US TC model and the CATRisk Solutions Middle East EQ model to be implemented and opened up to the London Market. The aim is for the Oasis code to be open source later in 2016 (the formats and specifications are already open).

Several vendors have committed to develop models within the Oasis framework including ARA, Impact Forecasting, JBA, KatRisk, CATRisk Solutions and ERN. There is also wide re/insurance industry support for the Oasis initiative: more than 40 re/insurance companies are Oasis "members". The largest vendors (RMS, AIR and CoreLogic) have not committed to develop models on the Oasis platform as they have their own platforms.

If investment in a regional catastrophe model is considered, then an important consideration is the platform on which models are developed.

Some advantages and disadvantages of using the Oasis framework as the basis for a regional platform are explored below.

4.4.1 Advantages

- A transparent model framework designed from the outset to accommodate multiple model vendors
- An open-source approach creating sustainability, with the community being used to upgrade and improve the platform
- Ability for multiple vendors to develop models on the same platform
- Potential for local institutions to develop model components on the same platform. (This loss modelling community development forms part of the Oasis mission)
- Strong existing re/insurance industry commitment to Oasis
- The Insurance Development Forum (IDF) may pilot the development of models on the Oasis platform; there is potential benefit from partnering with this initiative
- A generic approach to development, meaning the Oasis framework can cater for a wide variety of model types and keep results consistent with the host platform
- The simulation / financial kernel and the user interface can be installed and deployed separately if required: a different front-end to the standard Flamingo front-end could be developed if needed.

4.4.2 Disadvantages

- May exclude the largest catastrophe model vendors who have existing models in the region and may not want to port models or develop models on the Oasis platform (although Oasis itself, as an open source platform, would enable use by all vendors)
- Currently a fairly immature platform; more IT development may still be needed compared to a more mature platform (although even mature platforms have technical issues)
- Although good documentation and training material are available (e.g. including videos), implementation of a model (e.g. from a local institution) will in practice need hands on assistance by expert consultants (e.g. Oasis PalmTree or other catastrophe modelling experts with experience of developing models within the Oasis framework) and there currently are limited resources available with this specific technical capability.
- A common framework does not necessarily mean a common cross-border approach to modelling hazard: this will depend on the cross-border model consistency which in practise is likely to mean utilising a single model provider for models in multiple countries.

Whether an Oasis approach is taken or a vendor proprietary platform used may well depend upon the overall goals for establishing a regional platform. If the intent is purely to establish a facility for enabling parametric contracts at regional level for a one-off transaction, then the quickest approach would most likely be to use an existing platform proprietary to one of the main vendors. These platforms are fairly mature and work could take advantage of the existing models that the large vendors have. If the intent is to not only establish a facility for parametric contracts, but also to stimulate local model development and a local risk modelling community, with the consequent longer term benefits, then the extra time taken to establish a more open model framework may well be judged worthwhile.

4.5 Country-specific model improvements

Country-specific catastrophe modelling development priorities are summarised in Table 4-2.

Country	Flood	Tropical Cyclone	Earthquake	Drought
Bangladesh	Develop new FL model or leverage existing JBA hazard components.	Develop new TC model or leverage existing AIR consultancy model or ARA hazard event set	No models available: Develop new EQ model	Out of Scope of exercise
Indonesia	Develop new Indonesia FL model with complete geographical coverage, perhaps leveraging CAT work in progress; or leverage JBA hazard components which have required coverage; or extend ICRM or IF Jakarta DKI FL models	Not a priority due to low risk	Good model coverage already: no need for new models	Out of Scope of exercise
Pakistan	No models available: Develop new FL model; consider leverage JBA hazard components.	Not a priority due to low risk	Only one model available, consider further development options for EQ	Out of Scope of exercise
Sri Lanka	One available model, consider further development options for flood.	Develop new TC model or leverage existing ARA hazard event set	Not a priority due to low risk	Out of Scope
Viet Nam	By end 2016 three models should be available: no immediate need for new models	Three models available and more in the pipeline: no immediate need for new models	Not a priority due to low risk	No models available: Apply statistical techniques to extrapolate existing time series of indexes

Table 4-2: Focus country-specific catastrophe modelling development priorities

Further details on the catastrophe models for each country can be found in Section 3 and Appendix B.

4.6 Live data improvements

Potential live data improvements at regional and local level are considered in the subsequent sections.

4.6.1 Regional live data improvements

4.6.1.1 Flood

Flood is the most difficult peril for which to define a post-event live footprint. There are issues in using any of the region-wide live data sources identified to form a post event maximum-inundation flood footprint with depth information. These issues are discussed in Sections 2.2.1 and 2.3.1. Research into the best method to derive and validate a post event flood footprint using the different live data sources for rainfall, river flow and inundation extent may well be considered a priority for action.

4.6.1.2 Tropical cyclone

At a regional level, prospects for tropical cyclone hazard footprint mapping from global sources are good. Global sources provide regionally uniform products with only small delays (at most 12 hours) from hazard occurrence. There are various high quality sources of information including track position and characteristics as well as wind and rain information. There seem no current priorities for investment for tropical cyclone live data at a regional level.

4.6.1.3 Earthquake

There is a significant amount of earthquake live data available globally. The main issue with this particular region of focus is that the global seismometer networks used are fairly sparse (see Appendix C), and so ground-motion footprints derived using the globally-available information may well not be a good representation of the actual ground shaking from an event in this region. An investment priority is therefore to ensure that local seismometer network information be incorporated to supplement the global networks when defining ground motion footprints for events in this region.

4.6.1.4 Drought

There are a number of regional live datasets for drought. Given the lack of catastrophe models for this peril, an investment priority for drought is to investigate methods for extrapolating these spatial time-series of drought indexes into stochastic events such that they can be used for parametric contract structuring and settlement. Techniques such as those developed by the University of Exeter and Imperial College London (Youngman and Stephenson, 2016) could be explored to investigate their effectiveness for extrapolating drought data. Another approach for drought that could be investigated is using the UKMO hindcast ensemble dataset (see Appendix B). This contains variables that could be used to develop a drought index (temperature, rainfall, soil moisture deficit) and represents roughly a 2000-year stochastic time period. A similar alternative is the global climatology dataset used by GlobalAgRisk- Global Parametrics.

4.6.2 Local live data improvements

Specific priorities for improvement for the focus countries and perils are shown in Table 4-3.

The main areas are as follows:

- **Increasing instrumentation in the long term:**
    - Improving the spatial coverage of the automatic river and rain gauges: local sources are very valuable sources of information, however these are not available for all areas next to major exposures (e.g. large areas of Pakistan, especially on the central-south regions are scarce on river gauges). Investment in the installation and maintenance of automatic river and rain gauges, at key locations, will enhance the coverage and potential of those measurements.
    - The availability of wind station data for Sri Lanka is poor. Given other meteorological variables are recorded and available, it is likely wind observations are being made, but the national coverage may be limited. Investment in wind instrumentation would enhance coverage.
    - It should be noted however that increasing instrumentation can be a costly and time intensive option.
- **Improving dissemination methods of meteorological station data** for most countries (with the exception of Viet Nam) and standardising the types of observations and formatting of the local datasets would improve the prospects of these datasets being included in parametric trigger analysis.
- **Promoting data sharing and standards protocols:** Improving the format and distribution of the some of the local datasets in order to ease parametric trigger analysis. Some datasets (e.g. FL19, FL21, and FL22) are available only as graphs or pdf reports from the national websites. In 2012, the World Meteorological Organisation and the Open Geospatial Consortium started to promote the WaterML 2.0, a standard information model for the representation of water observation data, developed to enable the exchange of hydrological data between information systems. This enables the linking of local, national, regional, and global water information sources. These include the exchange of data relating to
    - in-situ observations at hydrological (gauges, reservoirs) or climatological stations;
    - Forecast products (probabilistic or deterministic time series) at forecast locations
    - emergency or operator-oriented alerts (of threshold exceedance) and reports;
    - time-series of planned intake and release/discharge; and
    - groundwater observations of water level within wells.
- **Improving local digital elevation models:** Currently DEMs at 30m resolution exist at region- and country-level at 15-100m resolution. However, the vertical accuracy of those products will vary; it is also key for processing medium- and high-resolution flood extents into flood depths. It will be beneficial to produce higher resolution DTMs (e.g. LIDAR Composite DEM at 5m resolution) for the areas of high exposure in order to obtain more accurate derived flood depths measurements. A global DEM at 10m resolution is expected to be released in the coming months/years, and will improve the current 30m accuracy.
- **Facilitating the use of local seismometer networks** when developing ground shaking footprints as the global seismic networks are relatively sparsely instrumented in this region (see Appendix C)
- **Improving maps of local faulting and near-real-time data processing capability** of live data from local seismometer networks (for instance, collaboration between local network authority and USGS)
- **Improving maps of local site classification** (soil type, landslide and liquefaction potential) and local finite fault models

Country	Flood	Tropical Cyclone	Earthquake	Drought
Bangladesh	Will benefit from improved coverage of river gauges. The World Bank have a current project to improve coverage.	Will benefit from improved coverage of stations around the country, particularly near coastline.	Improve processes to consistently create event footprints from the raw parameters and improve access to data	Out of scope
Indonesia	Will benefit from improved coverage of river gauges. Need to verify with data provider how many are automatic and how many are manual.	Out of scope	Good coverage and dissemination.	Out of scope
Pakistan	Needs improved coverage of river gauges	Out of scope	Improve processes to consistently create event footprints from the raw parameters and improve access to data	Out of scope
Sri Lanka	Will benefit from improved coverage of river gauges	Local wind station data seems absent: clear priority for investment. Improvements in availability and dissemination of wind data would fill a data gap.	Out of scope	Out of scope
Viet Nam	Currently good coverage and additional gauges are to be installed by 2020.	Currently good coverage with additional stations being added by 2020.	Out of scope	A country-scale drought monitoring system based on ground and satellite observations will be beneficial

Table 4-3: Focus country live data improvement priorities

4.7 Other potential priorities for future action

The scope of this project was to focus mainly on live data and catastrophe models, concentrating on the hazard perspective. To put in place parametric disaster risk financing, some link between hazard and loss must be established.

From a catastrophe modelling perspective, this means establishing accurate sources of exposure and vulnerability data. Although these exist within catastrophe models, they will largely be geared towards re/insurance industry use. Consequently, a country's vulnerability to loss of life and to GDP impacts (for example) may not be well-modelled. Exposure databases or vulnerability curves for infrastructure are also less likely to be included in models than those for more traditional building stock. These areas, while not subjects of focus within this project, are also likely to be priorities for investment from the perspective of improving parametric disaster risk financing.

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