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Supplement of

Construction of regional multi-hazard interaction frameworks, with an application to Guatemala

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-- Supplementary Material --

This supplementary material contains the following material which supports relevant sections in the associated paper published in NHESS (Gill *et al.*, 2019):

[Associated NHESS Paper] Section 2.3 Publications and Reports (Locally Accessible)

Table S1. Summary of the CONRED (*Coordinadora Nacional para la Reducción de Desastres*) information bulletins. Given is a description of the civil protection information bulletins issued by CONRED between 11 June 2010 and 15 October 2010 (127 days).

Source	CONRED *(Coordinadora Nacional para la Reducción de Desastres)*
Title	Boletines Informativos (Information Bulletin)
File Format	PDF
File Language	Spanish
Date Range	11 June 2010 to 15 October 2010 (127 days)
Number of Published Bulletins in Given Date Range	413
Number of Bulletins Received	291 (70%) of 413
• Number of Bulletins Received and Usable	267 (92%) of 291
• Number of Corrupted Files	24 (8%) of 291
Number of Bulletins Received and Usable from Total Possible	267 (65%) of 413

[Associated NHESS Paper] Section 2.3 Publications and Reports (Locally Accessible)

Table S2. Keyword search results (after contextual processing) from CONRED (*Coordinadora Nacional para la Reducción de Desastres*) civil protection information bulletins, 11 June to 15 October 2010. See text in main paper (Sect. 2.3) for description of procedure whereby interactions are identified from a keyword search on civil protection bulletins, after removal of irrelevant results. Shown are 39 event descriptions (from 36 different bulletins, 28 unique days) translated from original Spanish to English, along with type of interaction and the hazard group described.

Bulletin Details		Event Details		Type		Hazard Group			
#	Date	Event location	Event description (translated from the original Spanish to English)	Triggered	Increased Probability	Geophysical	Hydrological	Shallow Earth	Atmospheric
858	17-Jun-10	Lake Amatitlán	A rise in the lake level increased the likelihood of rains **causing** flooding. Rains can **cause** flooding due to increased level of lake waters, soil saturation means increased likelihood of landslides/mudslides.						
902	29-Jun-10	South West Guatemala	Storm Alex **causes** floods, landslides/mudslides.						
915	02-Jul-10	Atlantic Coast	Rain associated with hurricane **causes** flooding.						
916			Storm Alex **causes** soils to be saturated and increases likelihood of flooding.						
931	06-Jul-10	Agua Volcano, Escuintla	Rains **cause** overflowing of the Michatoya river [flooding], and strong slides [mudslides] down Agua volcano.						
931		Pacaya, Escuintla	Heavy rains over 2010 rainy season, helped **produce** floods.						
933	07-Jul-10	Zone 2, Guatemala City	Continued risk from sinkhole/collapse feature. Blockage of water may **cause** ponding and further erosion at the bottom of a sinkhole/collapse feature. Water can increase erosion and risk of future landslides.						
950	13-Jul-10	El Cambray II, Santa Catarina Pinula	Heavy rains **cause** landslides.						
993	28-Jul-10	--	Heavy rain **caused** saturation of soils and has increased risk of landslides and floods.						
1003	03-Aug-10	--	Weather system **causes** clouds, showers and lightning.						
1006	04-Aug-10	Santiaguito Volcano	Degassing in volcanic crater with explosions and ash columns around Santiaguito, **caused** lahars and erosion, affecting rivers.						
1006		Fuego Volcano	Fuego volcano had weak explosions ejecting ash 200-300 m above crater, and noises 5 km from volcano. **Generated** a lahar.						
1013	06-Aug-10	West Guatemala	Rains **caused** landslides and mass movements, undercutting of slopes.						
1022	10-Aug-10	Huehuetenango, Solola, Suchitepequez, Sacatepequez	Saturated soils **caused** landslides.						
1023		Zone 2, Guatemala City	Water runoff from drains and river erosion caused leaks and cracking, long process of landslides and finally producing collapse. Leakage from drainage, **caused** erosion and cracking.						
1043	17-Aug-10	Fuego, Santiaguito, Pacaya Volcanoes	**Generating** of lahars in rivers that descend active volcanoes. Take precautions for possibility of scattered ash around volcanoes						
1062	23-Aug-10	Mixco, Guatemala City	The collapse of a hillside into a river **caused** damage, with dredging of the river required.						
1069	24-Aug-10	Santiaguito Volcano	Volcanic eruption **generated** rock avalanches. [Explosions and concentration of material in crater, generating constant [rock] avalanches and pyroclastic flows].						

Bulletin Details		Event Details		Type		Hazard Group			
#	Date	Event location	Event description (translated from the original Spanish to English)	Triggered	Increased Probability	Geophysical	Hydrological	Shallow Earth	Atmospheric
1072	25-Aug-10	Baja Verapaz, Guatemala City, San Marcos, Zacapa	Heavy rains **generate** landslides.						
1076	26-Aug-10	--	Low-pressure system present unstable conditions and **generate** cloud with drizzle or moderate rains, with some lightning.						
1078	27-Aug-10	Meseta Central Pacific Regions	Weather system **generates** showers and lightning.						
1078			Rain **causes** soil saturation, which results in landslides, some damaging roads.						
1079			Weather system **generates** showers and lightning.						
1086	30-Aug-10	--	Strong winds **cause** rough seas and possible storm surges.						
1095	02-Sep-10	--	Increased rainfall has saturated soil and **produced** 709 landslides, mudslides and floods since late May after Tropical Storm Agatha.						
1126	09-Sep-10	Quetzaltenango, Chimaltenango, Alta Verapaz	Rains **produced** floods, landslides/mudslides.						
1129		San Sebastian, Retalhuleu, Santiaguito	Santiaguito volcano lahars **caused** flooding of the Samalá river, causing damage to bridges.						
1134	11-Sep-10	--	Intense rains **cause** overflowing rivers, saturated soils, which **cause** floods and mudslides.						
1137	12-Sep-10	Santiaguito Volcano	Eruption at Santiaguito, **generated** two pyroclastic flows that transported material 3 km away						
1165	21-Sep-10	North Guatemala and Caribbean.	Humid and warm environment **generates** electrical activity and rain showers.						
1174	23-Sep-10	--	Monitoring of rivers during Storm Matthew as it could **provoke** damage						
1175	24-Sep-10	Nicaragua, Honduras	Storm winds and rainfall, **cause** flash floods, landslides and mudslides						
1183	25-Sep-10	--	Tropical Storm Matthew **produces** heavy rains, which **causes** rivers to rise. Rains **cause** soil saturation, expected that rivers will exceed water levels and flooding occur.						
1184		Motagua River, Morales, Izabal	Tropical Storm Matthew **causes** heavy rains and Motagua river to increase in volume. Overflow **caused** a flood.						
1185		--	Saturated soils could **cause** landslides or mudslides.						
1186		--	Tropical Storm Matthew **causes** heavy rains, rising tides and floods.						
1199		Centre/South Guatemala	Low-pressure system **generates** clouds, showers and lightning.						
1222	05-Oct-10	Ixcán, Quiché, Chixoy River	Heavy rains **cause** river overflow.						
1227	06-Oct-10	Fuego, Pacaya Santiaguito/	Monitoring the **generation** of lahars on slopes of active volcanoes.						

[Associated NHESS Paper] Sections 2.5 and 2.6 Stakeholder Engagement: Interviews and Workshop

Table S3. Description of individual stakeholders in Guatemala. A summary of 33 participants who took part in interviews and/or a workshop. Descriptions include their sector/organisation, an identifying code, the process by which they were selected, interview translation styles (**1**. Translator from KCL. **2**. Third-party translator. **3**. Translator from same organisation as participant. **4**. Interview in Spanish. **5**. Interview in English), and the key themes discussed in interviews.

						Discussion Themes (Interviews Only)						
Sector/ Organisation	**Code**	**Interview**	**Workshop**	**Selection Process**	**Translation Style** *(codes in key)*	**Interactions - Knowledge Sources**	**Interactions – Community Knowledge**	**Visualisation Improvements**	**Anthropogenic Processes**	**Spatial Extent**	**Users of Visualisations**	**Completed Network Diagram**
Academia	A1	X		Introductions in Guatemala.	4/5	X	X	X	X		X	X
	A2	X			1	X	X	X	X		X	X
Private Sector	B1	X		Online profiles, existing networks and introductions in Guatemala.	5	X	X		X			
	B2	X			2	X			X			
	B3	X			5	X	X	X	X	X	X	X
CONRED	C1	X		Identified using guidance from a CONRED host. Our primary selection criteria was diversity of departments and professions (mitigation, monitoring, early-warning, recovery, reconstruction).	5		X	X	X			
	C2	X			5				X		X	
	C3	X	X		1/5	X	X					X
	C4	X			3		X	X	X	X	X	
	C5	X			1	X	X	X	X		X	X
	C6	X	X		1							X
	C7	X	X		4/5	X	X	X	X		X	X
	C8a	X			5							
	C8b	X			3		X					
	C9		X		1							
	C10	X	X		3	X	X	X	X	X	X	X
	C11		X		1							
	C12		X		1							
	C13		X		1							
	C14		X		1							
	C15		X		1							
	C16		X		1							
	C17		X		1							
	C18		X		1							
	C19		X		1							
	C20		X		1							
	C21		X		1							
INSIVUMEH	D1	X		Identified using guidance from an INSIVUMEH host, prioritising diverse views (geophysical, meteorology and hydrology).	4/5	X	X	X	X	X	X	X
	D2	X			5		X					
	D3	X			1	X	X	X	X	X	X	X
	D4	X			4/5	X	X		X			X
	D5	X			4/5	X	X	X	X		X	X
	D6	X			4	X	X	X	X		X	X

[1] C2/C4 interviewed together, with C2 helping as a translator. C2 also gave an opinion on some questions.
[2] C6 was interviewed during a field-trip, with questions mostly directed at observations made in the field.
[3] C8a acted as a translator during an interview with C8b, giving some personal opinions on some questions.

[Associated NHESS Paper] Section 2.5 Stakeholder Engagement: Interviews

Table S4. Interviewee comments on natural hazards, hazard interactions, and anthropogenic processes in Guatemala. A summary of comments made in 19 semi-structured interviews (21 people) that related to natural hazards, hazard interactions and anthropogenic processes in Guatemala. We use participant codes as introduced in **Table S3**.

Code	Interview Discussion: Natural Hazards and Hazard Interactions	Interview Discussion: Anthropogenic Processes
A1	• Most common hazards are hydro-meteorological. • Distinct topography of Guatemala Pacific coastline means that it may not be possible for submarine landslides to occur. • Tsunamis on Pacific coast occur but are small. Highest risk is in the Gulf of Honduras where the Motagua fault goes into the Caribbean. • 2012 earthquake caused liquefaction on the Pacific coast. • Floods are a function of storms/rain. • Storms trigger landslides and lahars. • Earthquakes trigger landslides. • 1976 M_w = 7.5 earthquake was associated with both vertical and horizontal displacement. • Earthquakes can trigger aftershocks and transfer stress on to other faults. • Landslides blocked rivers during the 1976 M_w = 7.5 earthquake and Hurricane Mitch (1997–98). • Information to relate earthquakes to volcanic eruptions, through the process of transferring stress.	• Urbanisation
A2	• Earthquakes trigger volcanic eruptions and volcanic eruptions trigger earthquakes. • Earthquakes can transfer stress on to other faults. • Main earthquake zones relate to volcanic activity, subduction zones and transform faults. • Hurricanes and rain trigger lahars. • Natural examples of sinkholes in karst region of Coban/Petén. • Heatwaves mainly occur in the lowlands. • Wind and lightning occur. • Liquefaction occurred in 1976 and in 2012 associated with earthquakes.	• Artificial fills; hillslope development. • Possible subsidence (20 cm) due to groundwater abstraction. • Forest fires commonly have human origin.
B1	• One example of a landslide triggering a small (2 m) tsunami in Lake Atitlán, resulting in flooding. • Sedimentation in rivers can result in flooding. • Flooding in one basin can trigger flooding in another basin. • Lots of hazards related to weather patterns. • The source of flooding can be 13 km away from where the flooding occurs. Landslides in the highlands carry sediment to lowlands and have an impact.	• Industry impacts flood patterns through river straightening programmes. • Sinkholes are a function of drainage systems. • Landslides a function of slope modifications, poor building practices (in the highlands) and modification of river beds in the lowlands. • Many landslides are human triggered around Lake Atitlán.
B2	• Hazards include rain, landslides, earthquakes, flooding. • Both 1976 earthquake and Hurricane Mitch (1997–98) triggered approximately 10,000 landslides. • Erosion and sedimentation problems are dynamic, including both anthropogenic processes and natural sediment from volcanoes.	• Landslides problems include human activity, corruption, poor road cuttings and bridges not being built according to regulations. • Deforestation around Panabaj (Solola) resulted in erosion and sedimentation in rivers.

Code	Interview Discussion: Natural Hazards and Hazard Interactions	Interview Discussion: Anthropogenic Processes
B3	• Landslides occur on steep slopes of Guatemala City. • Main groups of hazards are 'wet', including floods, landslides, and subsidence. Rainfall is the start of these chains. • Normal rain can trigger localised flooding, landslides and other small events. The sum of these may be the same as larger, extreme weather events in the Caribbean and Pacific. • Landslides can occur in clusters of 2–3 catastrophic landslides or thousands of smaller landslides. • Few examples of landslide dams • Flooding can trigger health hazards. • Lahars have a serious impact on the Samalá river. • When river deltas are full of sediment they are blocked and therefore the deltas grow backwards, resulting in flooding. • Guatemala is not affected by tsunamis. • Earthquakes trigger landslides. • No clear relationship between forest fires and debris flows in Guatemala. Biggest areas affected by forest fires are in Petén (low-relief). Grass grows quickly between fires and rainy season, preventing mud flows.	• Poorly cut slopes • No drainage (water and sewage entering the system). • No technical training for slope treatment. • High density of housing.
C1	• Hazards include flooding, landslides and volcanic eruptions. • Eruptive phases of Santiaguito can result in problems in the Samalá watershed, with sedimentation. • Rain triggered landslides is most recurrent interactions. Landslides can also be triggered by earthquakes if they are large. • In volcanic areas there are interactions such as mudslides and lahars. At Fuego, sediment enters the watershed close by, and then has an impact further from the volcano. • Mixco (Guatemala City) had a slow onset landslide, which then had displacement of over 2 m at once	• Informal settlements. • Industry modification of watershed. • Building licenses for flood plains.
C3	• Relevant interactions include pyroclastic flows, and El Niño and La Niña. • The relationship between flooding and geotechnical hazards is important. • Drought and extreme high temperatures (with lightning) can trigger wildfires. These are common in the country. • The border with Honduras acts as a natural barrier to hurricanes, only one hurricane (Hattie) has impacted Guatemala, in 1961. This caused flooding.	
C4 & (*C2*)	• *In some regions, floods occur about every two years.* • Key events generally occur if there is heavy rain at Fuego. This triggers lahars, with sediment coming down and impacting infrastructure. Lahars trigger floods, on the plains away from Fuego. Floods can occur 120 to 140 km away from Fuego. • At Santiaguito, lahars also occur, but their impact is closer to the volcano. Generally, there is one lahar a day at Santiaguito, depending on the rain. • Landslides occur, not always triggered by rain/earthquakes. • Droughts can result in forest fires. It is not that common to have forest fires increase the likelihood of landslides.	• *Sugar-cane industry is changing the dynamics of the watershed.* • Landslides are triggered by deforestation, poor road cuttings and people working.
C5	• Hazards include floods, droughts, forest fires, cold seasons, earthquakes and landslides. • Landslides are rain triggered, but also by conditions such as soil and dryness. • Cold weather can lead to droughts, resulting in vegetation loss.	• Poor road construction. • Forestation adds fuel for forest fires.
C6	• Strong impact of ash at Fuego.	
C7	• Hazards include earthquakes and hydro-meteorological events. • Four active volcanoes, also affected by rain, floods and landslides.	• Conflict. • Poor mine management.

Code	Interview Discussion: Natural Hazards and Hazard Interactions	Interview Discussion: Anthropogenic Processes
C8b & (*C8a*)	• Rainfall close to Santiaguito can result in lahars and flooding. The same event also occurs close to Fuego. • If there is a high tide and a rainy season, rivers do not go out to sea and there is coastal flooding. It floods 'backwards'. • Earthquakes can trigger landslides. • Tsunamis are not very big. • Ash alters meteorological atmosphere, changing the intensity of rain. • At Fuego, hazards include ash. • At Pacaya, there is seismicity associated with eruptions. • Forest fires occur after eruptions as do lahars/pyroclastic flows.	
C10	• Assessments for sinkholes, landslides, floods, volcanic eruptions and earthquakes as these are the main types of risk. • *North of Guatemala:* There is a karst area with sinkholes, floods and liquefaction. • *Middle Metamorphosed Zone:* Landslides • *Volcanics Zone:* landslides, lahars and eruptions. This is the biggest landslide risk, and closest to the faults. • *Coast:* Floods occur. • Most important interactions are those between storms and landslides/flooding. • During Tropical Storm Agatha, at Pacaya, there were mudflows, landslides, sinkholes and floods. • The Rio Chixoy and Los Chorros landslide blocked rivers and caused a dam. This resulted in a water rise of 14.8 m. This is the largest example of dam. Rivers are fast and dynamic and it only takes a few days for the material to erode and the dam removed.	• Hydroelectric dams result in flooding. • Floods relate to food production. • In some areas flooding results in snake bites. • Sanitation and pesticides result in contamination of rivers.
D1	• Earthquakes are relevant hazard. • No historical records of tsunamis in Guatemala. The water between the coast and trench is too shallow to trigger tsunamis. Most earthquakes occur between the coast and the trench. • Liquefaction can occur, and photographs were seen of liquefaction on the Pacific coast. Liquefaction also occurred close to Lake Amatitlán during the 1976 earthquake. • Unsure whether earthquakes have triggered subsidence. • Earthquakes trigger landslides. • Not enough events to confirm if there is a correlation between volcanic eruptions and earthquakes. More evidence of large earthquakes causing volcanic eruptions than volcanic eruptions causing large earthquakes. • Landslides can block rivers but they are cleared quickly by the flow of water. Landslide dams are therefore rare.	• Industrial changes to watersheds. • Deforestation. • Fires (agriculture/fields).
D2	• Annually there are hydro-meteorological phenomena. • New phenomena also occur, including droughts, El Niño and La Niña events, and famine. • Volcanic eruptions occur every 10 years, big earthquakes occur every 30 years, big flooding and landslides approximately every 5 years.	

Code	Interview Discussion: Natural Hazards and Hazard Interactions	Interview Discussion: Anthropogenic Processes
D3	• Typical secondary hazards around volcanoes include lahars at Santiaguito and Fuego. At Santiaguito rainfall of 50–60 mm/hour can trigger a lahar. At Fuego rainfall of 60 mm/hour can trigger a lahar. • *Pacaya:* It is not normal to have lahars at Pacaya, although one did occur prior to 2000. There is a growing problem with erosion at Pacaya, so this may change. Associated with ash deposits. • *Fuego*: Erupts with explosions, and with 'boiling over' where lava flows and pyroclastic flows. Pyroclastic flows can run 6 to 8 km. Material moves into barrancas [valleys]. Acid rain may also occur. Lahars generate from these flows, which cause floods near to Fuego and 20–25 km away from the site. Little evidence of these lahars blocking rivers as they have too much force. • *Santiaguito*: Ashfall occurs on a daily basis. There is also a problem with lahars, which travel as far as 60 km to the sea and have the same effect on flooding as those near Fuego. There are some phreatic eruptions, with interactions between water and magma (in relation to deep groundwater, not rainfall). • All three areas have issues of wildfires. There is also lightning at Fuego and Pacaya. • Triggers of eruptions may include earthquakes, this is uncertain and currently being investigated.	• Deforestation
D4	• Main frost events take place in November to February, affecting 20% of the country. In the Highlands, temperatures vary from 0–13 °C meaning there are higher levels of frost above 1800 m altitude. Frosts normally last 1 to 2 hours, but it can be up to 10 hours. • Along the Pacific coast there is an artificial channel, which many rivers run into. Sediment from the volcanic belt enters this and floods occur at the end of the rivers near the Pacific Ocean. • Flooding in the Pacific is short duration, high energy and induced by volcanic sediments. • Gulf of Mexico is very flat, and flooding can have a long duration (3 months). Rocks are impermeable limestone with caverns and karstic soils. The water table is close to the surface. • Polochic Basin, near Lake Izabal is associated with liquefaction and soil saturation. There are also landslides and rockfalls. • There are few examples of landslide dams in Guatemala, perhaps 2–3 cases after an earthquake occurs. The Rio Chixoy was blocked by a large landslide in 2002. • Around the Polochic Basin there are expansive soils/clays, at the end of the basin. In volcanic soils there are some valleys with expansive soils also. Near the Chixoy and La Pasion Rivers there are some montmorillonite soils. • It is possible that earthquakes may intersect rivers, but no examples were known.	• Heavy soil use. • Mining contamination. • Sewage contamination.
D5	• Most important area for storms is the Atlantic, but they also come in across the Pacific. • Many landslides occur close to Atitlán and Amatitlán. • The principal cause of landslides is rain. They are worse in the rainfall is after dry weather. Hurricane Mitch came after a dry year. As the cover soil was dry this resulted in lots of problems. • Tornadoes are not common, there was possibly one in Guatemala City in 2012 but it did not cause too much damage. • Hailstorms normally occur in May to October (rainy season). Snowstorms are rare, but have occurred. • Lightning is very problematic in Guatemala. • Wind extends forest fires, as does the lack of rain. • It is possible that volcanic eruptions trigger storms, that particles in the atmosphere resulted in rain.	• Drainage maintenance impacts sinkholes. • Fires are often triggered by humans.

Code	Interview Discussion: Natural Hazards and Hazard Interactions	Interview Discussion: Anthropogenic Processes
D6	• Every year there are landslides and floods, normally occurring in the same places. • Floods occur in volcanic areas close to the Pacific coast and close to the Caribbean coast near to Lake Izabal. Precipitation is very strong in July to October. Floods are generated by fast movement down volcanic chains and in rivers. There are lahars on volcanoes and lots of sediment in the basin. • Other key hazards are landslides, sinkholes, seismic hazards, mudflows and volcanic hazards. • Tsunamis are possible but rare. There has been one in the past 100 years in the Pacific. In the Atlantic they have had two in the past 100 years. They generally have little impact. • During the 1976 and 2009 earthquakes, there was liquefaction and flooding. • Lahars result in erosion and flooding, with Santiaguito cited as an example. • There are also clay palaeosols which shrink and swell when there are droughts and no droughts. These can result in small landslides. • Hail can result in landslides.	• Large (sugar and coffee) farms build levees and divert rivers.

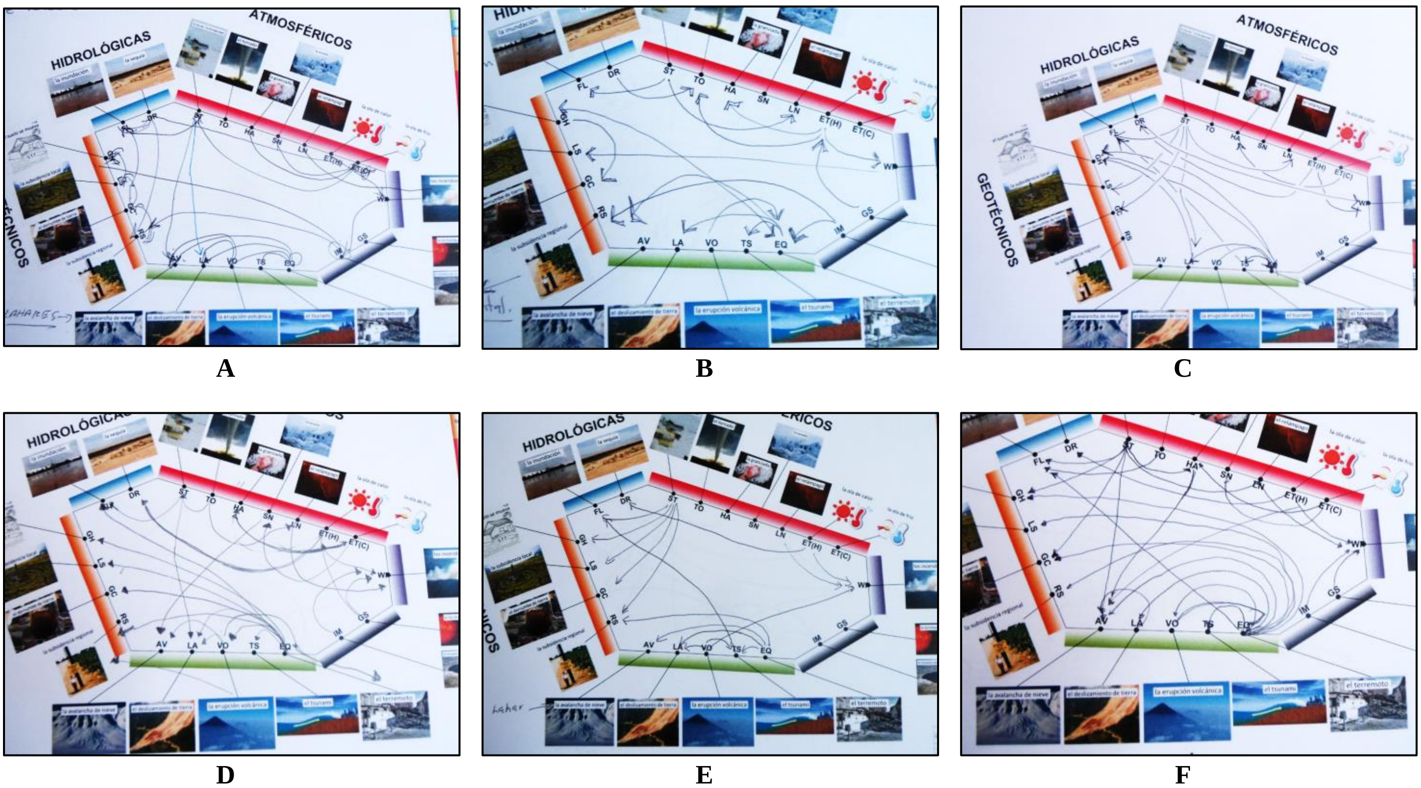
[Associated NHESS Paper] Section 2.6 Stakeholder Engagement: Workshop

Methodology and Analysis – Additional Information. During a 3-hour workshop on 6 March 2014, with 16 hazard and civil protection professionals in Guatemala, participants independently completed two tasks.

Task 1. *Network Linkage Diagram for 21 Natural Hazards (16 participants)*. Participants used this to record triggering relationships that they believed to be relevant to Guatemala. We did not expect any participant to map out all relevant interactions. In **Fig. S1**, we show 16 network linkage diagrams, each completed by a different workshop participant. Completed network linkage diagrams vary in the number and range of interactions proposed to be relevant in Guatemala. The number of interactions proposed by any one participant ranged from 8 to 35, with a mean of 18 and a median (50th percentile) of 15.

Task 2. *7 × 11 Natural Hazard Interaction Matrix (15 participants)*. Participants completed a blank hazard interaction matrix, with seven primary hazards on the vertical axis and eleven secondary hazards on the horizontal axis. In our second task, 15 participants completed a *7×11 Hazard Interaction Matrix*, with seven primary hazards on the vertical axis and eleven secondary hazards on the horizontal axis. Participants noted both relevant *triggering* and *increased probability* interactions in Guatemala. Completed matrices again show variation in the number and range of proposed interactions. In **Fig. S2**, we show 15 hazard matrices, each completed by a different participant. The number of *triggering* interactions proposed by any one participant ranged from 3 to 36, with a mean of 12 and median (50th percentile) of 7. The number of *increased probability* interactions proposed by any one participant ranged from 0 to 29, with a mean of 9 and median (50th percentile) of 6. Using all 15 matrices, we develop a representation of the combined knowledge of participants.

We therefore collected two sets of visual records that document participants' perceptions of relevant hazard interactions in Guatemala. These are presented in **Figs. S1** and **S2** of this supplementary material. Using the results of these tasks we can represent the combined knowledge of the workshop participants (**Figs. S3** and **S4**).



A B C

D E F

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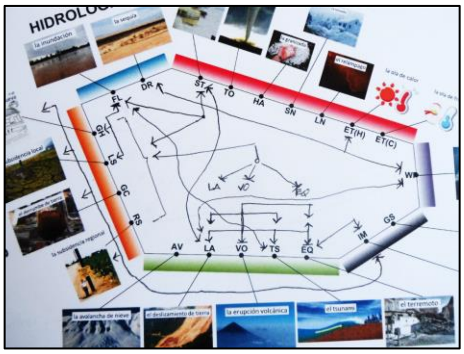

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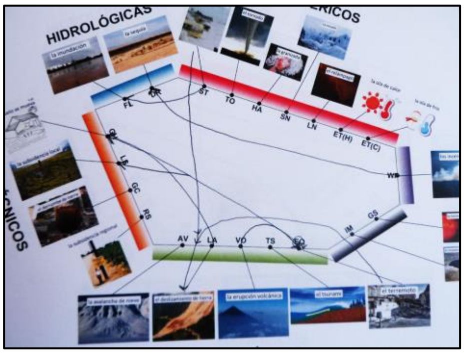

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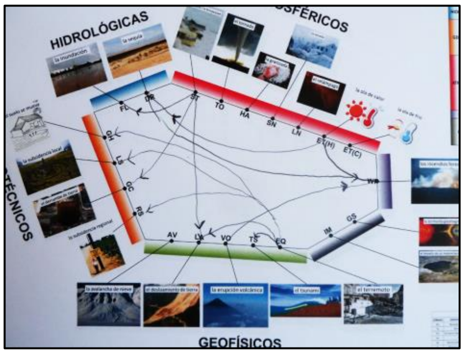

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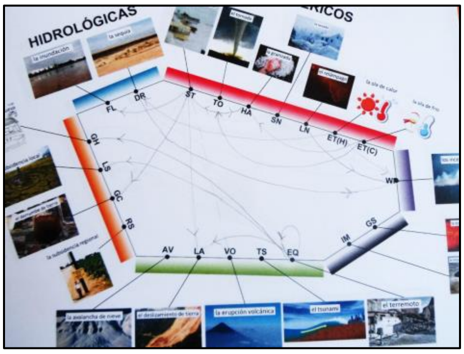

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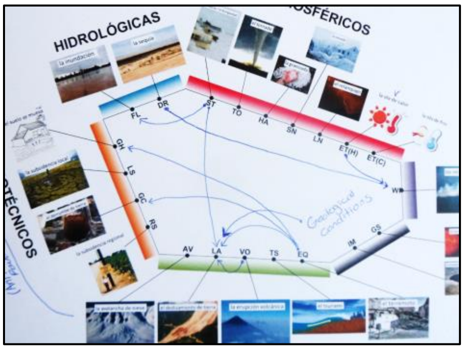
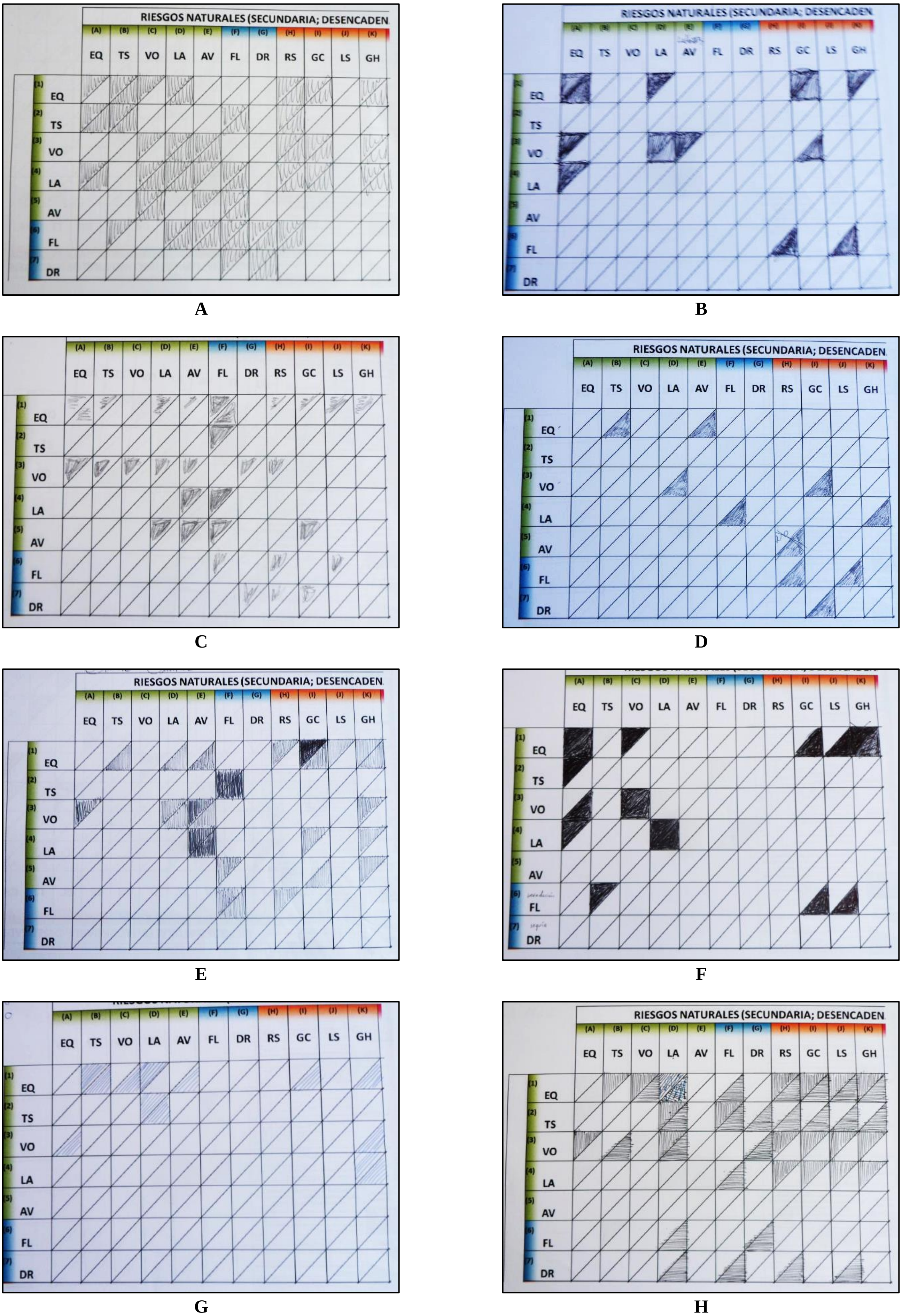


P

Figure S1. Stakeholder identification (using network linkage diagram for 21 natural hazards) of possible hazard interactions in Guatemala. A total of 16 network linkage diagrams (**A** to **P**) were completed during a 3-hour workshop on 6 March 2014 by hazard and civil protection professionals at CONRED.



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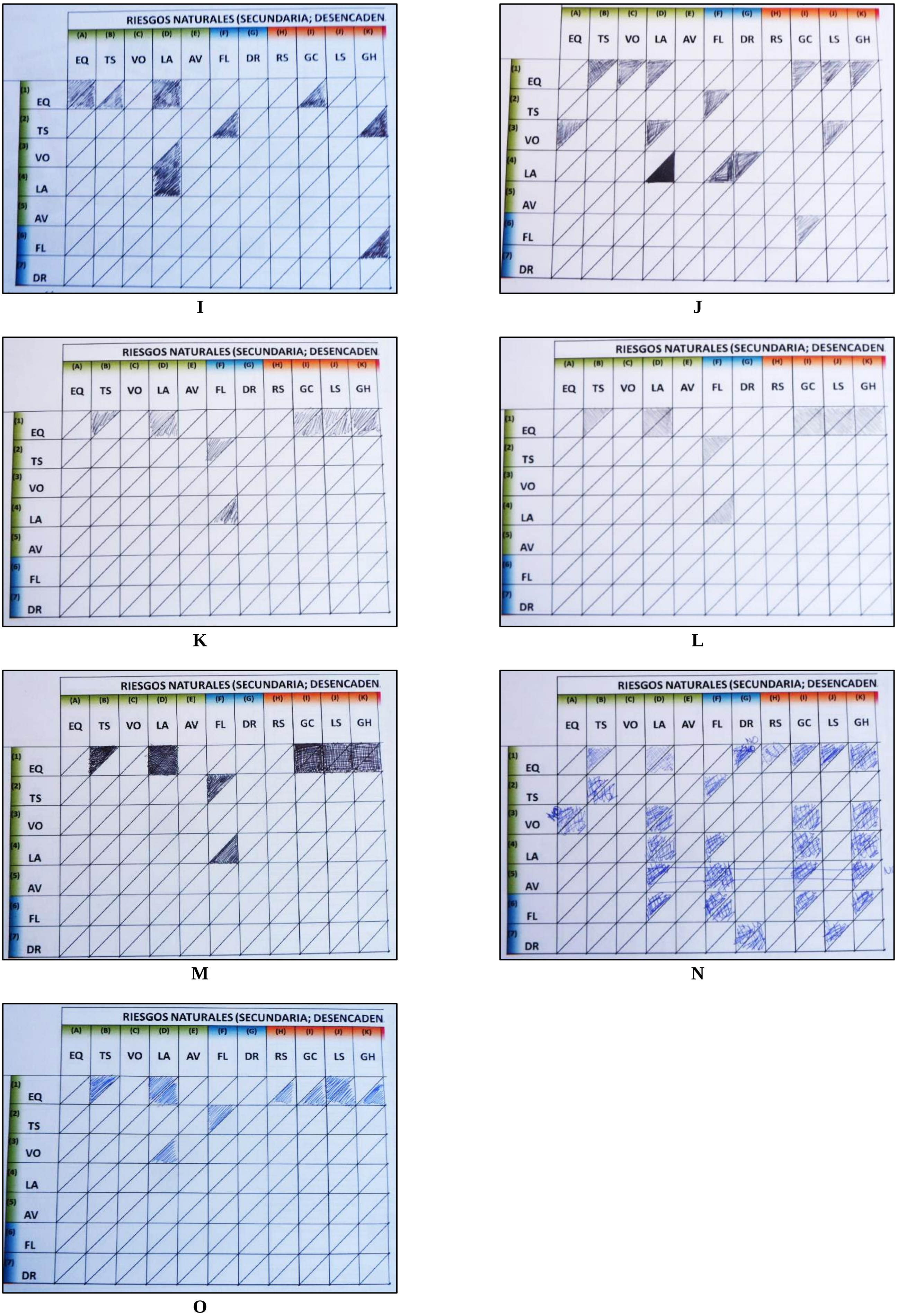


Figure S2. Stakeholder identification (using 7×11 natural hazard interaction matrix) of possible hazard interactions in Guatemala. A total of 15 network linkage diagrams (**A** to **O**) were completed on 6 March 2014 during a 3-hour workshop by hazard and civil protection professionals at CONRED.

Task 1: Network Linkage Diagram for 21 Hazards

In **Fig. S3**, we overlay evidence from 16 completed network linkage diagrams on a *global* interaction framework. Grey shading indicates those interactions included in the *global* interaction framework, not all of which are relevant in Guatemala. **Fig. S3**, shows the number of participants (out of 16) proposing each triggering relationship.

PRIMARY HAZARD	SECONDARY HAZARD (TRIGGERED) (A) EQ	(B) TS	(C) VO	(D) LA	(E) AV	(F) FL	(G) DR	(H) RS	(I) GC	(J) SS	(K) GH	(L) ST	(M) TO	(N) HA	(O) SN	(P) LN	(Q) ET (H)	(R) ET (C)	(S) WF	(T) GS	(U) IM
(1) EQ	5	11	4	16	2	2		7	8	8	13	1							1		
(2) TS						4															
(3) VO	8	2		7	1			2	1	1	1								4		
(4) LA					1			1	1	1	3										
(5) AV																					
(6) FL							1			1	1										
(7) DR						1		1					1						5		
(8) RS									1	1	1										
(9) GC						1		1		1	2										
(10) SS								2	1		1								1		
(11) GH	2							1	2	2											
(12) ST				12	1	16		3	9	5	5			3		4					
(13) TO						1						1				1					
(14) HA					1							1									
(15) SN					1							1									
(16) LN																			8		
(17) ET (H)							12						1	1					11		
(18) ET (C)					1							1	1	6	4						
(19) WF				1			3														
(20) GS																	3		2		
(21) IM	3			1				3	1	1	2								3		

KEY

HAZARD GROUP	HAZARD	CODE
GEOPHYSICAL	Earthquake	EQ
	Tsunami	TS
	Volcanic Eruption	VO
	Landslide	LA
	Snow Avalanche	AV
HYDROLOGICAL	Flood	FL
	Drought	DR
SHALLOW EARTH PROCESSES	Regional Subsidence	RS
	Ground Collapse	GC
	Soil (Local) Subsidence	SS
	Ground Heave	GH
ATMOSPHERIC	Storm	ST
	Tornado	TO
	Hailstorm	HA
	Snowstorm	SN
	Lightning	LN
	Extreme Temperature (Hot)	ET (H)
	Extreme Temperature (Cold)	ET (C)
BIOPHYSICAL	Wildfire	WF
SPACE	Geomagnetic Storm	GS
	Impact Event	IM

SYMBOL	EXPLANATION
(grey cell)	Global Interaction Framework Indicates Hazard Triggers Secondary Hazard *(not all relevant in Guatemala)*
12 / 12	Number of Workshop Participants (*n* = 16) Identifying Interactions as Relevant in Guatemala

Figure S3. Stakeholder identification (using the network linkage diagrams presented in Fig. S1 and transferred to the above matrix) of possible natural hazard interactions in Guatemala. Given is a 21 × 21 matrix with primary natural hazards on the vertical axis and secondary hazards on the horizontal axis. These hazards are coded, as explained in the key. These matrices show cases where a primary hazard could trigger a secondary hazard. Grey cell shading indicates the triggering interactions in the global hazard interaction matrix of Gill and Malamud (2014). Numbers indicate the total number (from a maximum of 16) of stakeholders proposing each hazard interaction as being possible in Guatemala.

Of a total possible 441 (21×21) interactions, there are 86 different interactions proposed in **Fig. S3** as being relevant in Guatemala (by 1–16 participants), equivalent to 20% of the 441 possible interactions. Consequently, 355 interactions (80% of the 441 possible interactions) were determined by all 16 participants as not relevant in Guatemala.

Using **Fig. S3** we note that for the 86 hazard interactions proposed by ≥1 participant:

- 2 (2%) were proposed by all 16 participants (100% of the group). These were [*earthquake → landslide*] [*storm → flood*].
- 3 (3%) were proposed by ≥13 participants (≥ 75% of the group). These were [*earthquake → landslide*] [*earthquake → ground heave*] [*storm → flood*].
- 8 (9%) were proposed by ≥ 9 participants (≥ 50% of the group). These were [*earthquake → landslide*] [*earthquake → ground heave*] [*storm → flood*] [*earthquake → tsunami*] [*storm → landslide*] [*storm → ground collapse*] [*extreme temperatures → drought*] [*extreme temperatures → wildfire*].
- 19 (22%) were proposed by ≥ 5 participants (≥ 25% of the group). Additional examples to those noted above include [*drought → wildfire*] [*earthquake → regional subsidence*] [*lightning → wildfire*].
- The remaining 67 (78%) were proposed by 1–4 participants. Examples include [*volcanic eruption → tsunami*] [*snowstorm → avalanche*] [*impact event → landslide*].

There is strong agreement between participants on '*no interaction occurs*' (355 of 441 possible interactions), but much greater variation in agreement on '*interaction occurs*' (86 of 441 possible interactions). Some of the proposed interactions may not be relevant (false positives), and others not proposed by participants may be relevant (false negatives) in Guatemala.

Task 2: 7 × 11 Hazard Interaction Matrix

In **Fig. S4**, we overlay the 15 completed matrices in **Fig. S2** on a 7×11 section of a *global* interaction framework. Grey shading indicates interactions (triggering or increased probability) included in the *global* interaction framework, not all of which are relevant in Guatemala.

A — SECONDARY HAZARD (TRIGGERED)

PRIMARY HAZARD	(A) EQ	(B) TS	(C) VO	(D) LA	(E) AV	(F) FL	(G) DR	(H) RS	(I) GC	(J) SS	(K) GH
(1) EQ	5	12	3	13	1	1		5	10	9	10
(2) TS	1	2		2		11		1			
(3) VO	6	1	3	8	2		1	3	4	2	4
(4) LA	2		1	5	2	4	1	2	5	1	6
(5) AV			1		1	2					1
(6) FL		1		2	1	4	1	4	2	2	1
(7) DR						1	3	1	2	1	

B — SECONDARY HAZARD (INCREASED PROBABILITY)

PRIMARY HAZARD	(A) EQ	(B) TS	(C) VO	(D) LA	(E) AV	(F) FL	(G) DR	(H) RS	(I) GC	(J) SS	(K) GH
(1) EQ	4	4	3	9	2	2		3	10	5	9
(2) TS	1	2		2		4	1	2	1	1	2
(3) VO	2	1	1	7	2		1	1	3		3
(4) LA	1		1	5	1	6		1	2		3
(5) AV			1			1			1		
(6) FL				2	1	3	2	2		1	1
(7) DR				1		1	2	1		1	

Figure S4. Stakeholder identification (using interaction matrix) of possible natural hazard triggering and increased probability interactions in Guatemala. Two 7 × 11 matrices with primary natural hazards on the vertical axis and secondary hazards on the horizontal axis. Codes are used for each hazard type as outlined in **Fig. S2**, with colour coding for different hazard groups also outlined in **Fig. S3**. Grey cell shading indicates a triggering interaction (**A**) or increased probability interaction (**B**) existed in the global hazard interaction matrix presented in Gill and Malamud (2014). Each matrix is then used to represent the total number of stakeholders proposing each hazard interaction as being possible in Guatemala (from **Fig. S2**).

Here we show the number of participants (from 15) proposing each *triggering* relationship (**Fig. S4A**) and each *increased probability* relationship (**Fig. S4B**). Of a total possible 77 (7×11) *triggering* relationships, 53 different *triggering* relationships (69% of the 77 possible interactions) were proposed to be relevant in Guatemala by ≥1 participant. Consequently, all participants determined that 24 *triggering* relationships (32% of the 77 possible interactions) are not relevant in Guatemala.

Using **Fig. S4A** we note that of the 53 triggering interactions proposed by ≥1 participant:

- None were proposed as being relevant by all 15 participants.
- 1 (2%) interaction was proposed by ≥13 participants (≥ 87% of the group). This was [*earthquake → landslide*]
- 6 (11%) were proposed by ≥9 participants (≥ 60% of the group). Examples include [*earthquake → tsunami*] [*tsunami → flood*] [*earthquake → ground heave*].
- 13 (25%) were proposed by ≥5 participants (≥ 33% of the group). Additional examples to those noted above include [*earthquake → regional subsidence*] [*volcanic eruption → landslide*] [*landslide → ground heave*].
- The remaining 40 (75%) were proposed by 1–4 participants. Examples include [*earthquake → volcanic eruption*] [*landslide → flood*] [*drought → ground collapse*].

Of a possible 77 (7×11) *increased probability* relationships there were 51 different *increased probability* relationships (66% of the 77 possible interactions) proposed as being relevant in Guatemala by ≥1 participant. Consequently, all participants determined that 26 *increased probability* relationships (34% of the 77 possible interactions) are not relevant in Guatemala.

Using **Fig. S4B** we note that of the 51 increased probability interactions proposed by ≥1 participant:

- None were proposed by ≥13 participants (≥87% of the group).
- 3 (6%) were proposed by ≥9 participants (≥60% of the group). These were [*earthquake → landslide*] [*earthquake → ground collapse*] [*earthquake → ground heave*].
- 7 (14%) were proposed by ≥5 participants (≥ 33% of the group). Additional examples to those noted above include [*earthquake → soil (local) subsidence*] [*volcanic eruption → landslide*] [*landslide → landslide*] [*landslide → flood*].
- 44 (86%) were proposed by 1–4 participants. Examples include [*earthquake → volcanic eruption*] [*flood → landslide*] [*drought → soil (local) subsidence*].

Some of the proposed natural hazard interactions may not be relevant (false positives), and others not proposed by participants may be relevant (false negatives) in Guatemala.

[Associated NHESS Paper] Section 3.3.1 Guatemala National 21×21 Interaction Framework (Matrix Form)

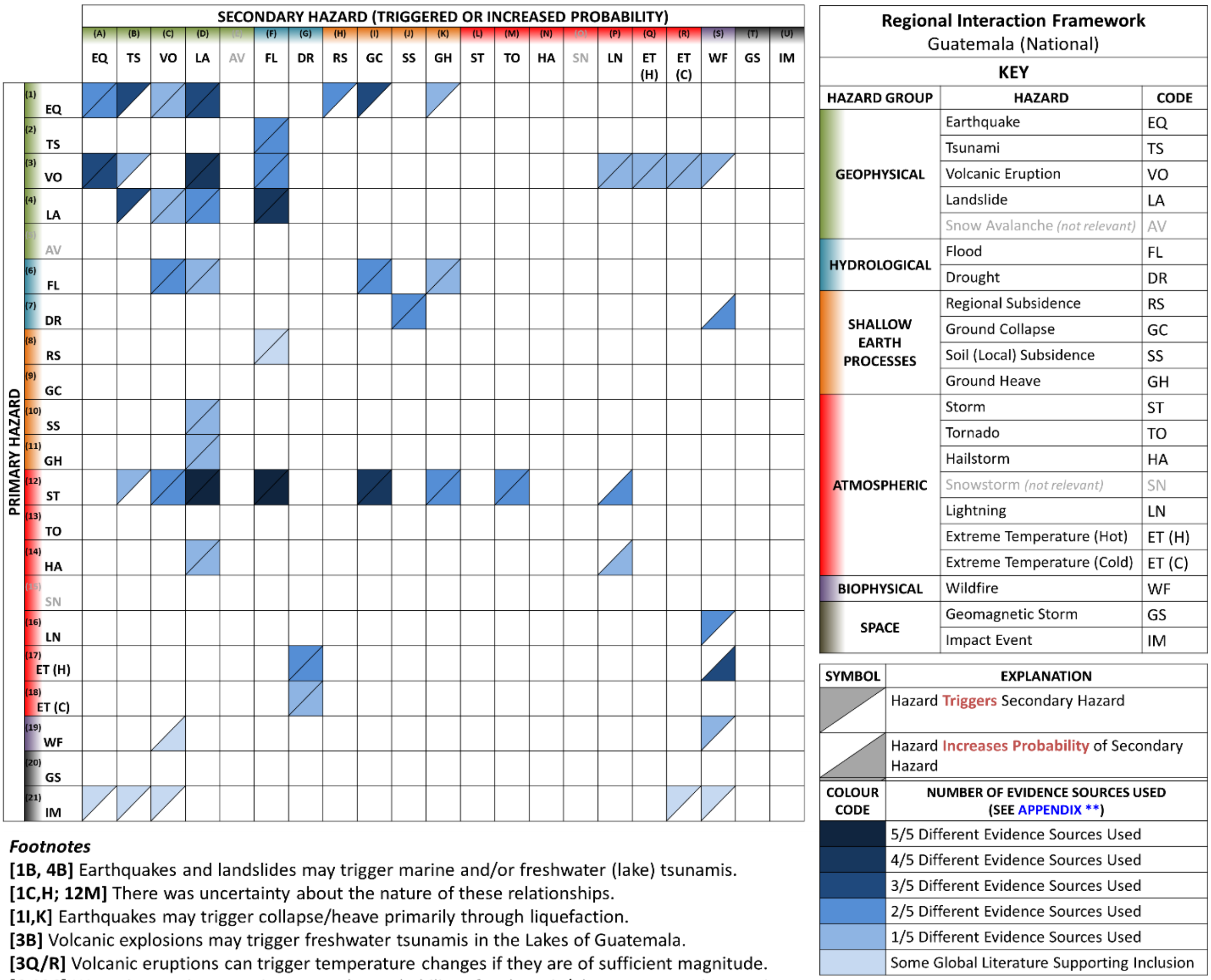
Table S5. Evidence used to populate each cell within the national interaction framework presented in Fig. 3 of the accompanying paper**.** Information is presented (mechanism) which describes the physical process by which primary natural hazards (relevant to Guatemala) trigger, or increases the probability, of secondary natural hazards (relevant to Guatemala). We note evidence sources used to evidence each interaction, described in detail in **Sect. 2** of the accompanying paper.

Primary Hazard	Secondary Hazard	Grid ID	Generic Mechanism Description	Evidence A = International Literature B = Civil Protection Bulletins C = Field Observations D = Stakeholder Interviews E = Workshop *(≥50% people)*
Earthquake	Earthquake	1A	A primary earthquake causes changes in lithospheric stresses, leading to aftershocks as the lithosphere responds to these changes.	A, D
	Tsunami	1B	A rupturing fault line causes the displacement of a large amount of water, triggering a tsunami.	A, D, E
	Volcanic Eruption	1C	Changes in lithospheric stress either (i) reduces confining pressure or (ii) increases pressure within the magma chamber.	D
	Landslide	1D	Seismic shaking results in changes in shear stresses and strength causing the movement of rock and soil material under gravitational forces.	A, D, E
	Regional Subsidence	1H	Vertical displacement caused by faulting results in subsidence on a regional scale.	A, D
	Ground Collapse	1I	Liquefaction can result in compression of soils and rapid downwards movement.	A, D, E
	Ground Heave	1K	Liquefaction can result in dilation of soils and upwards expansion.	E
Tsunami	Flood	2F	A tsunami will trigger coastal or lakeshore flooding and possible fluvial flooding through increased groundwater and surface run off.	A, E
Volcanic Eruption	Earthquake	3A	Injections of magma result in changes in lithospheric stresses, triggering volcano-tectonic earthquakes.	A, D, E
	Tsunami	3B	Tsunamis can be as a result of large volcanic explosions close to lakes.	A
	Landslide	3D	Volcanic activity can either (i) increase shear stress or (ii) decrease shear strength, resulting in landslides (flank instability).	A, B, C, E
	Flood	3F	Lava, ash and pyroclastic material can (i) dam waterways, (ii) block drainage, (iii) melt snow/ice, and thus result in flooding.	A, D
	Lightning	3P	The collision of ash particles can result in electric discharge in the form of lightning.	D
	Extreme Temperature (Heat/Cold)	3R/Q	The ejection of sulphur into the stratosphere can result in both net heating and net cooling.	A [if very large eruption]
	Wildfire	3S	High temperature lava, ash and pyroclastic material can directly trigger wildfires when it comes in contact with flammable material.	D
Landslide	Tsunami	4B	Landslides impacting upon or within water result in the displacement of water, thus triggering a tsunami. These landslides can be either subaerial or submarine.	A, C, D

Primary Hazard	**Secondary Hazard**	**Grid ID**	**Generic Mechanism Description**	**Evidence** A = International Literature B = Civil Protection Bulletins C = Field Observations D = Stakeholder Interviews E = Workshop *(≥50% people)*
	Volcanic Eruption	4C	Unloading of a volcano by landslides and flank collapse reduces confining pressures, changing lithospheric stress and strength conditions. Material input into lava may trigger the nucleation of bubbles, triggering an eruption.	A
	Landslide	4D	A landslide can result in the mobilisation and deposition of material in another location, increasing the weight on the head of a slope and promoting instability. The mobilisation of sediment by landslides can also increase the likelihood of debris flows in the event of a rainstorm.	A, B
	Flood	4F	Material from landslides can (i) dam waterways, and (ii) increase sedimentation in rivers, to promote flooding.	A, B, C, D
Flood	Volcanic Eruption	6C	Water can trigger or increase the probability of hydromagmatic or phreatomagmatic volcanism.	A, D [phreatic, groundwater interactions]
	Landslide	6D	Flood waters can (i) increase groundwater levels and therefore pore water pressures, decreasing effective stress, and (ii) increasing erosion of the slope toe.	B
	Ground Collapse	6I	Increased water can result in (i) dissolution of salt and carbonate deposits, (ii) hydrocompaction of metastable deposits.	B, D
	Ground Heave	6K	Increased water results in the swelling of clay minerals.	A
Drought	Soil (Local) Subsidence	7J	Reduced water results in the shrinking of clay minerals and thus local subsidence.	A, D
	Wildfire	7S	Drought results in dry and dead vegetation which increases the probability of wildfires.	A, D
Regional Subsidence	Flood	8F	Regional subsidence increases vulnerability to flooding.	Not noted in A–E, but if subsidence occurs then an increased susceptibility to flooding is inevitable.
Soil (Local) Subsidence	Landslide	10D	Local/soil subsidence changes the stress conditions within slopes.	D
Ground Heave	Landslide	11D	Ground heave changes the stress conditions within slopes.	D
Storm	Tsunami	12B	Perturbations in air pressure over the ocean can generate large amplitude standing waves.	A
	Volcanic Eruption	12C	Water can trigger or increase the probability of hydromagmatic or phreatomagmatic volcanism, forming small steam explosions or more intense activity.	A, D [phreatic, groundwater interactions]
	Landslide	12D	Rainwater increases groundwater levels and therefore pore water pressures, decreasing effective stress.	A, B, C, D, E
	Flood	12F	Heavy rainfall can increase groundwater and surface water levels - causing flash, fluvial and urban flooding.	A, B, C, D, E
	Ground Collapse	12I	Increased water can result in (i) dissolution of salt and carbonate deposits, (ii) hydrocompaction of metastable deposits.	A, B, D, E
	Ground Heave	12K	Increased water results in swelling of clay minerals.	A, D
	Tornado	12M	Tornadoes are produced in hurricanes or tropical storms due to vertical wind shear.	A, D
	Lightning	12P	The collision of particles can result in electric discharge in the form of lightning.	A, B

Primary Hazard	**Secondary Hazard**	**Grid ID**	**Generic Mechanism Description**	**Evidence** A = International Literature B = Civil Protection Bulletins C = Field Observations D = Stakeholder Interviews E = Workshop *(≥50% people)*
Hailstorm	Landslide	14D	Water from hailstorms can increase groundwater levels and therefore pore water pressures, decreasing effective stress.	D
	Lightning	14P	The collision of ash particles can result in electric discharge in the form of lightning.	A
Lightning	Wildfire	16S	Lightning discharge can spark fires.	D, E
Extreme Temperature (Hot)	Drought	17G	High temperatures result in an increase in evapotranspiration - thus promoting drought conditions.	A, E
	Wildfire	17S	The drying of vegetation by extreme temperatures can result in an increased probability of wildfires.	A, D, E
Extreme Temperature (Cold)	Drought	18G	Extreme cold conditions can lead to a winter drought when precipitation is in solid rather than liquid form.	D
Wildfire	Landslides	19D	Wildfires can remove vegetation, wakening slopes and increasing the likelihood of mass movements.	Supported by globally-relevant literature rather than location-specific evidence
	Wildfire	19S	Spotting from wildfires can trigger further wildfires.	A
Impact Event	Earthquake	21A	Impact events can cause major lithospheric disturbance, including the release of stress as earthquakes.	Identified as being generally possible, supported by globally-relevant literature rather than location-specific evidence.
	Tsunami	21B	Impact events in water can cause large scale displacement of water, thus triggering a tsunami.	
	Volcanic Eruption	21C	Impact events can cause major lithospheric disturbance, triggering volcanic eruptions.	
	Extreme Temperature (Cold)	21R	Impact events can cause large-scale injections of dust and other particles into the atmosphere - causing widespread cooling effects.	
	Wildfire	21S	Impact events can cause wildfires as super-heated material touches flammable materials.	

In **Fig. S5** we give the evidence types used in the construction of a National Interaction Framework for Guatemala. Blue shading indicates the number of evidence types (**A**–**E**) supporting the inclusion of each interaction. Darker shading indicates inclusion based on *more* evidence types and lighter shading indicates inclusion based on *fewer* evidence types. We group triggering and increased probability interaction types together and indicate the number of evidence types available per *primary hazard-secondary hazard* combination. This is due to the coarse resolution of the data used, and complexities of distinguishing in evidence types between triggered/increased probability interaction types.



Footnotes
[1B, 4B] Earthquakes and landslides may trigger marine and/or freshwater (lake) tsunamis.
[1C,H; 12M] There was uncertainty about the nature of these relationships.
[1I,K] Earthquakes may trigger collapse/heave primarily through liquefaction.
[3B] Volcanic explosions may trigger freshwater tsunamis in the Lakes of Guatemala.
[3Q/R] Volcanic eruptions can trigger temperature changes if they are of sufficient magnitude.
[6,12C] Water input triggers or increases the probability of a phreatic/phreatomagmatic eruption.
[8F] Although regional subsidence triggering flooding was not noted in any evidence sources consulted, this is an inevitable consequence of the lowering of the ground surface.
[12B] Pressure changes associated with storms may trigger meteotsunamis in marine environments.
[21A-C,R,S] Identified as being generally possible, supported by globally-relevant literature rather than location-specific evidence.

Figure S5. Evidence types used in the construction of a National Interaction Framework for Guatemala. A 21×21 matrix with 21 primary natural hazards on the vertical axis, and 21 secondary natural hazards on the horizontal axis. Interactions (shaded cells) include primary hazards triggering a secondary hazard, and primary hazards increasing the probability of a secondary hazard. This matrix is populated using different evidence types, as outlined in **Sect. 2** of the accompanying paper. Blue shading indicates the number of evidence types used to populate each matrix cell, as described in the key. The coarse resolution of the data used, and complexities of distinguishing between triggered/increased probability interaction types, means we group both interaction types together when indicating the number of evidence types. Visualisation structure based on Gill and Malamud (2014).

Using **Fig. S5** we note that of the 50 identified interactions:

- 2 (4%) have 5 evidence types to support their inclusion. Examples include [*storm → landslide*] [*storm → flood*].
- 3 (6%) have 4 evidence types to support their inclusion. Examples include [*landslide → flood*] [*storm → ground collapse*].
- 6 (12%) have 3 evidence types to support their inclusion. Examples include [*earthquake → tsunami*] [*landslide → tsunami*] [*extreme temperatures (heat) → wildfire*].
- 15 (30%) have 2 evidence types to support their inclusion. Examples include [*tsunami → flood*] [*drought → soil subsidence*] [*storm → ground heave*].
- 17 (34%) have 1 evidence types to support their inclusion. Examples include [*earthquake → volcanic eruption*] [*flood → landslide*] [*storm → tsunami*].
- 7 (14%) are included due to globally relevant literature, rather than Guatemala-specific literature. Examples include [*impact event → landslide*] [*regional subsidence → flood*].

[Associated NHESS Paper] Section 3.5 Anthropogenic Processes

Table S6. Relevant anthropogenic process types in Guatemala. A description of the four evidence types **A**–**E**, together with additional references, used to identify 17 anthropogenic process types as being spatially relevant in Guatemala.

Anthropogenic Process Type	**Evidence** A = International Literature B = Civil Protection Bulletins C = Field Observations D = Stakeholder Interviews E = Workshop (*anthropogenic processes not discussed)* * (Reference) = Additional citations, beyond A–E.				
Groundwater Abstraction				D	
Oil/Gas Extraction					* (OEC, 2016)
Subsurface Infrastructure Construction	A			D	
Subsurface Mining					* (OEC, 2016)
Material (Fluid) Injection					* (USGeothermal, 2016)
Vegetation Removal	A		C	D	
Agricultural Practice Change			C	D	
Urbanisation			C	D	
Infrastructure Construction (Unloading)				D	
Quarrying/Surface Mining (Unloading)					* (OEC, 2016)
Infrastructure (Loading)			C	D	
Infilled (Made) Ground	A				
Reservoir and Dam Construction	A			D	* (Salini Impregilo, 2014)
Drainage and Dewatering	A	B		D	
Water Addition	A	B		D	
Chemical Explosion					*Inferred relevant*
Fire				D	

OEC (Observatory of Economic Complexity): Economic Complexity of Guatemala [online] Available at: http://atlas.media.mit.edu/en/profile/country/gtm/ (accessed 29 November 2018), 2016.

Salini Impregilo: Pueblo Viejo Dam on the Chixoy river [online] Available at: http://www.salini-impregilo.com/en/projects/completed/dams-hydroelectric-plants/pueblo-viejo-dam-on-the-chixoy-river.html (accessed 29 November 2018), 2014.

USGeothermal: El Ceibillo Geothermal Project Overview [online] Available at: http://www.usgeothermal.com/projects/4/El%20Ceibillo%20-%20Guatemala (accessed 29 November 2018), 2016.