Southwest Indian Ocean Risk Assessment Financing Initiative (SWIO-RAFI):

Component 4 – Risk Profiles

FINAL Report Submitted to the World Bank

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Executive Summary

The South West Indian Ocean Risk Assessment and Financing Initiative (SWIO RAFI) was established at the request of the Indian Ocean Commission (IOC) on behalf of Comoros, Madagascar, Mauritius, Seychelles, and Zanzibar. The goal of SWIO RAFI is to improve the resiliency and capacity of the island states through the creation of disaster risk financing strategies. A key component of this effort involves the quantification of site-specific risk from the perils of floods, earthquakes, and tropical cyclones as well as their secondary hazards of storm surge and tsunamis.

The present report details project Component 4, which comprises the development of the financial loss models and generation of risk-profiles for each island nation, including an overview of the financial loss modeling framework, loss validation exhibits, and risk profiles for each island nation. The financial loss model requires an engineering relationship between hazard intensities and damage estimates for the considered exposure. To this end, regional damage, or vulnerability, functions for the construction and occupancy types most commonly found in the SWIO region have been developed. These functions are then integrated with the hazard and exposure developed in Components 1 and 2, respectively, in order to calculate expected financial losses for each modeled peril.

AIR generates statistical distributions of ground-up losses using the modeled loss for each event in the stochastic hazard catalogs. These probabilistic results are then used to calculate meaningful loss metrics, such as Average Annual Loss (AAL), loss Exceedance Probabilities (EP), and losses at specific Mean Return Periods (MRP). Each island nation risk profile contains ground-up financial losses aggregated to three administrative levels: Admin Region 0 (i.e., national), Admin Region 1 (i.e., islands, regions), and Admin Region 2 (i.e., provinces, districts). The risk profiles include AAL distributions by sector, peril, and Admin Region 2 and national total and emergency loss exceedance probabilities. The risk profile data-files are the primary outputs of Component 4 and are provided as a digital addendum to this report. A summary of the vulnerability function development is also provided in Appendix A.

1 Introduction

The financial loss module is the final integral component of all AIR models. The loss estimates from the AIR natural catastrophe models for the SWIO region are used to create the risk profiles, which are the final outputs of Component 4. As per the ToR provided by the World Bank, Component 4 comprises the following primary objectives for each considered SWIO island nation:

- Hazard catalogs consisting of synthetic events representing 10,000 years of peril activity. The perils should be for floods, tropical cyclone and earthquakes and include secondary perils of storm surge and tsunamis[1].
- A set of event-loss tables based on the 10,000-year stochastic catalog giving total ground-up loss and government emergency loss for the island nation, individual islands within a nation, and first level administrative regions. The event loss tables should include a chronology so that the losses can be aggregated into yearly loss tables.
- A risk profile for each island nation as a whole and for first level administrative regions. The profile should summarize exposure and risk of the perils individually and as a whole from both perspectives (total ground-up loss and government emergency loss). The profile should include:
    - Loss exceedance probability curves
    - A table with return period losses
    - A summary of exposure and assets[2]
    - A summary of construction costs[3]
    - A discussion of the drivers of risk in each country

This report serves as a summary of Component 4, which focuses on using state-of-the art catastrophe risk modeling methods to develop risk profiles for tropical cyclone (wind, precipitation flooding, and storm surge), non-tropical cyclone induced precipitation flooding, and earthquake ground shaking in the SWIO region. The impacts of historical events on the people and assets of the SWIO island nations have been investigated to understand the extent of adverse consequences that possible future events may bring. To estimate monetary losses in each island nation, simulations of 10,000 years of potential tropical cyclones and their associated coastal and precipitation induced flooding, non-tropical cyclone precipitation and earthquake activity have been carried out. While other hazards such as landslide and tsunami were considered qualitatively in the SWIO hazard assessment conducted in Components 1 and 3, these perils are not considered in the financial

[1] Hazard catalogs are provided within Component 1, refer to the Component 1 technical report for additional information
[2] Exposure and asset values are provided within Component 2; refer to the Component 2 technical report for additional information
[3] A construction cost summary is provided within Component 2; refer to the Component 2 technical report for additional information

risk profiles[4]. The risk profiles presented herein can be used to improve the resilience of the SWIO island nations to the modeled natural hazards. Additionally, various components of the study can be utilized to extend the evaluation to include the other hazards, as and when considered appropriate.

This report provides details on AIR's catastrophe risk methodology, which is overviewed in the following sections. While all modules are summarized in this report, the primary objective of is to present the loss module and risk profiles for each SWIO island nation. Although specific modules of existing AIR models have been modified or developed anew for the purposes of this study, for brevity and confidentiality reasons, discussion of AIR's existing loss models is not included in this report.

1.1 Limitations

The financial loss results and risk profiles summarized in this report are intended for use by the governments of the SWIO island nations and the World Bank to assist their understanding of the risk from natural catastrophes. Proper application of this information requires recognition and understanding of the limitations of both the scope and methodology of the entire study.

The scope of services performed during this assessment may not adequately address the needs of other users, and any re-use of (or failure to use) this report or the findings, conclusions, or recommendations presented herein are at the sole risk of the user. Our conclusions and recommendations are based on our professional opinion, engineering experience and judgment, analyses conducted during the course of the study, information and data available in the literature and those provided by the World Bank and various local agencies, and are derived in accordance with current standards of professional practice.

[4] The qualitative assessment of landslide susceptibility in Comoros and tsunami inundation in the SWIO region do not consider the frequency or intensity associated with individual events, which are both necessary conduct a probabilistic loss analysis. While Component 3 also includes pluvial flood modeling in Zanzibar, the flood model developed for all SWIO island nations considers pluvial flooding and Zanzibar is therefore not considered separately.

2 Probabilistic Risk Modeling

An overview of the methodology adopted by AIR for the development of the SWIO RAFI probabilistic catastrophe models and risk profiles is presented in this section. The general probabilistic risk modeling framework is illustrated in Figure 1 and consists of four primary components: Hazard, Exposure, Engineering, and Financial Loss.

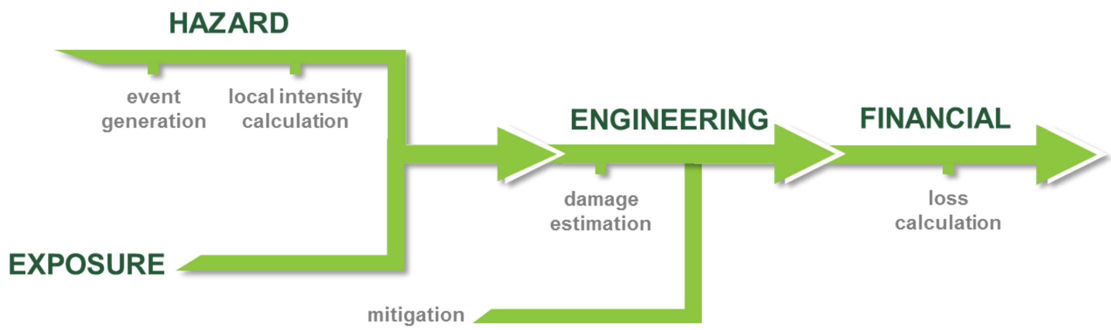


Figure 1: AIR's general catastrophe risk modeling framework

2.1 Hazard

The hazard module for the SWIO RAFI project includes a probabilistic assessment of the earthquake, tropical cyclone and associated precipitation induced and coastal flooding, and non-tropical cyclone flood hazard across the entire region. These models are based on regional information on historical events parameters, physical properties (e.g., land-use, land-cover, topography), and historical intensity recordings (e.g., wind speed, rainfall, flood depth). Using this historical information, AIR develops stochastic event catalogs, which comprise 10,000 simulated years of event activity and allow for the determination of the probability of exceedance of different levels of hazard intensity at any location within the modeled domain. The hazard module outputs underpin the subsequent risk calculations for each island nation. The hazard module additionally provides a deterministic assessment of tsunami risk zones in the region and the landslide risk in Comoros, which are not considered in the financial risk profiles. Hazard intensity calculations are provided on a 30 arc-second (approx. 1km) grid throughout the region. The hazard module was developed in SWIO RAFI Components 1 and 3. For additional information, please reference the documentation accompanying Component 1[5].

[5] Component 3, which considers landslide hazard in Comoros and pluvial flooding hazard in Zanzibar, is included in the Component 1 report and associated data files

2.2 Exposure

The exposure module consists of databases that characterize the physical attributes of the built environment in each island nation. Data regarding building counts, construction types, occupancy types, height classifications, and population distributions are included in the exposure module. The exposure databases provide a foundation for modeled loss estimates, whether for simulated events from a stochastic catalog, the reanalysis of historical events, and for actual events unfolding in real time. The SWIO RAFI exposure database considers 13 unique construction types, 18 unique occupancy types, 3 height classes, and is aggregated to a 30 arc-second (approx. 1km) grid. The exposure module was developed in SWIO RAFI Component 2. For additional information, please reference the documentation accompanying Component 2.

2.3 Engineering

The engineering module consists of vulnerability functions that relate hazard intensity to damage levels for each of the construction and occupancy pairs contained in the exposure database. These damage levels, or mean damage ratios (MDR), represent the percentage of the total replacement value of a structure that has been damaged in an event. For example, a MDR of 1 indicates that 100% of the value of a structure has been damaged and it will cost the entire original value of the structure to rebuild. Illustrative SWIO damage functions for tropical cyclone wind, precipitation flooding, storm surge flooding, and earthquake ground shaking intensity are presented in Figure 2. The damage module leverages vulnerability functions that have been developed specifically for the SWIO region based on research of local building practices, applicable building codes, engineering analysis, historical damage reports, and expert engineering judgement. Damage functions have been developed for the perils of tropical cyclone wind, flooding, and storm surge, non-tropical cyclone flooding, and earthquake ground shaking in terms of the intensity values reported in the Component 1 documentation. The engineering module is developed in SWIO RAFI Component 4. For additional information, please refer to Appendix A of this report.

The engineering module can also be used to assess the impact of damage mitigation measures, such as tropical cyclone storm shutters, flood protection systems, or seismic isolation systems. While mitigating measures are not included in the present investigation, future investigations may leverage this feature to, for example, quantify the monetary benefits of improving construction practices or implementing a national building code.

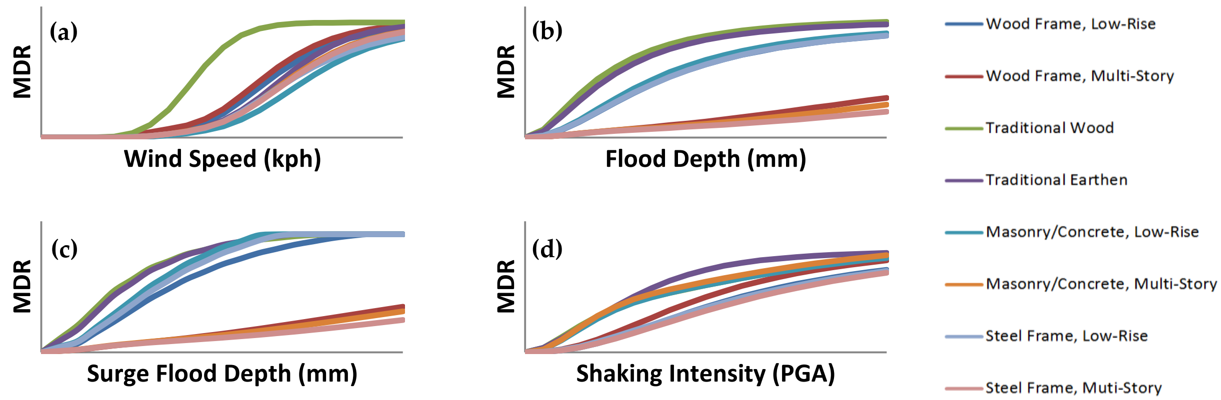


Figure 2: Illustrative SWIO vulnerability functions for (a) tropical cyclone wind, (b) tropical cyclone precipitation flooding, (c) tropical cyclone storm surge flooding, and (d) earthquake ground shaking[6]

2.4 Financial Loss

The financial loss module combines data from the hazard, exposure, and engineering modules to generate probabilistic estimates of financial loss. The financial module calculates the spatially distributed losses for each event in the stochastic catalog and subsequently aggregates all stochastically simulated losses to generate useful statistics. The resulting financial losses are associated with different probabilities of exceedance, which provide different views of the risk for individual exposure locations, administrative regions, or the island nation as a whole. For example, these results can be used to determine the loss that an administrative region (e.g., province) has a 10% probability of being exceeded in the next 10 years. These losses are also presented in terms of a Mean Return Period (MRP), which is the inverse of Exceedance Probability (EP), and represents the average recurrence interval for a modeled ground-up loss.

MRP and EP results are generated using the loss for each simulated event in each modeled year. As in the historical record, certain modeled years may have multiple events, while other may have a single event or no events. The modeled losses in each year are then ranked from highest to lowest and annual losses are calculated as either *occurrence loss* (i.e., based on the largest event loss within each modeled year) or *aggregate loss* (i.e., based on the sum of all event losses of each modeled year). Finally, EPs corresponding to each loss—occurrence or aggregate—are calculated by dividing the rank of the loss year by the number of years in the catalog. Thus for a 10,000-year catalog, the top-ranked (highest loss) event would have an EP of 0.0001 (1/10,000) or 0.01% annual EP, the 20th-ranked event an EP of 0.002 (20/10,000) or 0.40% annual EP, the 100th-ranked event an EP of 0.01 (100/10,000) or 1.00% annual EP. As noted previously, the mean return period for a loss level equals the inverse of the EP: For example, EPs of 0.01%, 0.20%, and 1.00% correspond to 10,000-, 500-, and 100-year mean return periods.

[6] Horizontal and vertical axes removed from damage functions to protect proprietary AIR data

Average Annual Loss (AAL) is the mean value of a loss EP distribution. AAL is a long term measure of loss that, on average, can be expected to be experienced annually. It is computed by summing all of the *aggregate loss* estimates for each year for all of the events in the stochastic catalog and dividing the total by the number of years the catalog considers. For example, if all losses generated using the 10,000 year catalog sum to $1,000 M the AAL for the catalog period would be $1,000 M/10,000 = $0.1 M.

The MRP defines the time period over which, on average, a particular event can be expected to occur or be exceeded. For example, assume in Nation X an event with a modeled loss of $10M USD is associated with a 100-year mean return period, which means that a loss of $10M USD can be expected to occur once every 100-years. This does not mean that a $10M USD loss or higher *will occur* in the next 100-years, rather, on average in a 100-year period a loss of $10M USD or higher occurs once. Table 1provides useful relationships for relating EP and MRP for various time intervals. In this report, MRP is used to convey the likelihood of an event in a given year, which refers to the first column to the right of MRP in Table 1.

Table 1: Relationship between mean return period and exceedance probability

Mean Return Period (years)	Exceedance Probability for a specified Time Period (years)							
	1	10	15	20	25	30	50	100
10	0.1	0.65	0.79	0.88	0.93	0.96	0.99	0.999
25	0.04	0.34	0.46	0.56	0.64	0.71	0.87	0.98
50	0.02	0.18	0.26	0.33	0.4	0.45	0.64	0.87
100	0.01	0.1	0.14	0.18	0.22	0.26	0.39	0.63
250	0.004	0.04	0.06	0.08	0.1	0.11	0.18	0.33
500	0.002	0.02	0.03	0.04	0.05	0.06	0.1	0.18
1,000	0.001	0.01	0.01	0.02	0.02	0.03	0.05	0.1
2,500	0.0004	0.004	0.006	0.008	0.01	0.01	0.02	0.04
5,000	0.0002	0.0002	0.0003	0.0004	0.0005	0.0006	0.001	0.002
10,000	0.00001	0.0001	0.0001	0.0002	0.0002	0.0003	0.0005	0.001

Risk-profiles for each island nation are presented using the aforementioned financial loss measures and provide common exceedance probabilities for different levels of loss resulting from each modeled peril. Risk profiles for each island nation are presented in Section 3 of this report.

2.4.1 Historical Financial Losses

While the hazard, exposure, and engineering functions are extensively validated independently, it is equally important to ensure that the final modeled losses are consistent with historical expectations and are suitable for estimating potential future losses. All AIR financial loss modules are compared with any losses reported following major historical catastrophic events. Losses are typically reported by the national government, local agencies, insurers, NGOs, or foreign aid groups. Reported losses for the SWIO region are collected and collated into a Consequence Database, which comprises all publically reported historical natural catastrophe losses from sources such as DesInventar, ReliefWeb, EM-DAT, GFDRR PDNAs, among others. The Consequence Database and a comprehensive list of data sources are summarized in Appendix B of the Component 1 report. Reported loss summaries for different timespans are excerpted from the SWIO Consequence Database and presented in Table 2 for tropical cyclones and non-tropical cyclone flooding events and in Table 3 for earthquakes.

Table 2: Reported tropical cyclone and flood related losses for the considered SWIO island nations

Timespan	*Economic Loss ($M USD)*	*Casualties*	*Events*
1950-1959	-	524	1
1960-1969	64	284	8
1970-1979	795	281	11
1980-1989	1,024	475	25
1990-1999	265	783	22
2000-2009	4,518	1,308	74
2010-2015	437	476	29

Table 3: Reported earthquake related losses for the considered SWIO island nations

Timespan	*Economic Loss ($M USD)*	*Casualties*	*Total Events*
Pre-1900	-	-	2
1900-1949	-	17	3
1950-1999	-	1	7
2000-2009	30	12	7
2010-2015	-	-	3

Overall, the reported loss history for the SWIO region is considered incomplete, as reliable loss estimates have not been captured for all events in the historical record. Furthermore, reported losses for multi-hazard events, such as tropical cyclone wind, precipitation, and storm surge, are not reported disaggregated by sub-peril, which complicates the calibration and validation of individual model components. Nonetheless, the historical reported losses suggest that tropical cyclones and flooding are the dominant perils in the SWIO region and demonstrate that these perils are responsible for the majority of natural catastrophe induced loss of life and economic damage. Appendix B of the Component 1 documentation contains additional information about reported economic losses and major historical events in the SWIO region.

2.4.2 Financial Loss Validation

For major historical events, which are also referred to as marquee events, losses are generated using the hazard and financial loss modules with historical event parameters. The resulting modeled losses are compared to available reported historical losses in order to assess the accuracy of the loss model for each considered peril. The modeled losses for these events are used as the primary metric for assessing the accuracy of the loss model and, if necessary, for preforming model calibration. As noted previously, the historical economic loss record in the SWIO region is limited and the most represented peril is tropical cyclone. Thus, the majority of loss calibration and comparison is performed using reports for tropical cyclones. A comparison between the tropical cyclone wind and earthquake modeled losses and an available third-party investigation is also presented herein.

Reported Loss Validation

The loss comparison for the key historical tropical cyclone events are shown in Figure 3 for Comoros, Madagascar, and Mauritius[7]. The SWIO financial loss model outputs correlate well with historical reports of tropical cyclone losses in Comoros, Madagascar, and Mauritius and do not indicate an appreciable high- or low-bias in the model. Both reported historical and modeled losses are considerably uncertain, which is not illustrated in the mean loss values displayed in Figure 3. Reported loss variability typically results from inconsistencies associated with quantification and accounting of damage following an event and the vintage of the loss reports, which both tend to be less reliable with age and may lose accuracy when trended to present day monetary values. Modeled loss variability results from uncertainty in the exposure data, event parameters, physical model properties, hazard intensity calculation, and vulnerability functions. Thus, although individual event mean model losses may not precisely match reported losses, good correlation between mean modeled and reported losses is indicative of a well-conditioned model. Additionally, the absence of any high or low bias in the calculated mean historical losses suggests that the country-level losses for stochastic events are representative of potential future losses for each island nation.

[7] No reliable historical tropical cyclone loss reports are publically available for Seychelles or Zanzibar

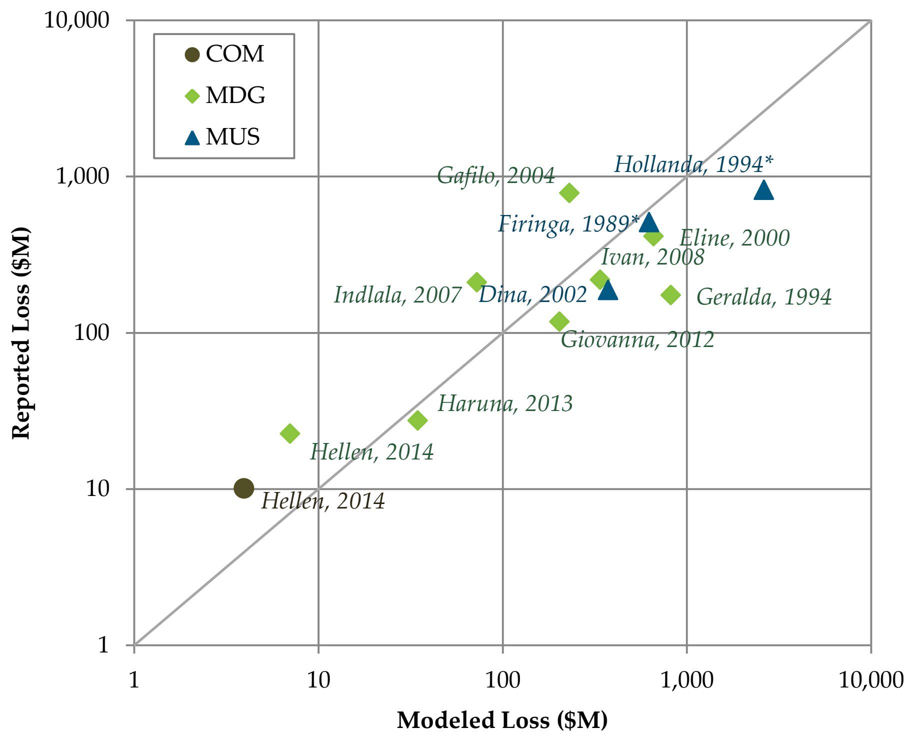


Figure 3: Tropical cyclone modeled vs. reported losses[8]

Comparison to Third-Party Investigations

Due to the limited availability of loss data and, particularly in the case of earthquakes, loss-causing events, a loss validation exercise was also performed using data from the recent UNISDR study in the SWIO region (UNISDR, 2015). This study investigated the perils of tropical cyclone wind and earthquake ground shaking in each of the investigated SWIO island nations. While the UNISDR analysis employs generic damage functions and a simplified historical hazard catalog[9], the study represents the most comprehensive historical loss

[8] Reported losses demarcated with a * include agriculture and infrastructure only. Sources for reported losses are provided in Appendix B of the Component 1 report

[9] UNISDR losses are derived from the Global Assessment Report (GAR) on Disaster Risk Reduction and utilize the generalized global framework developed by CIMNE/INGENIAR. Several limitations of this framework are provided in the CIMNE/INGENIAR documentation, but of primary importance for this investigation are the limitations associated with the application of (1) generic vulnerability functions and (2) historical-only hazard catalogs. (1) The vulnerability functions applied in the UNISDR study are unmodified functions derived from HAZUS-MH, which do not include regional modifications designed to capture the unique construction characteristics of the SWIO region. (2) The hazard analysis conducted in the UNISDR study exclusively uses historical global event catalogs (162,516 events for EQ, 2,594 events for TC), which is a significant limitation for assessing the risk from potential future events that are statistically plausible but have not been observed in the historical record. These important limitations of the UNISDR/GAR study are explicitly addressed in the present investigation.

assessment to-date in the SWIO region. The exposure-normalized results of the UNISDR investigation are compared to the results from this study on the basis of AAL, 100, 250, and 500 year losses for tropical cyclone wind in Table 4 and earthquake shaking in Table 5. Exposure-normalized losses, which represent the percentage of the modeled exposure value that is damaged in an event, are useful for comparing loss estimates calculated using different exposures. In general, the results of the AIR investigation compare favorably with the UNISDR study, particularly on the basis of AAL, which represents the broadest measure of risk in each country. Both studies identify TC wind as the most impactful hazard in the region, particularly for Comoros, Madagascar, and Zanzibar, while EQ shaking is determined to have less loss-causing potential for all countries. While it is challenging to identify precise differences between the two results, it is important to consider the potentially significant simplifications applied in the UNISDR study, namely the usage of generic vulnerability functions, lower resolution global physical property data, and a historical event hazard catalog.

The stochastic results produced as a result of the present investigation suggest a heightened TC risk in Comoros when compared to the UNISDR results, which may result from the use of the limited historical tropical cyclone event catalog in Comoros. Conversely, the stochastic losses in Mauritius are lower than those calculated by UNISDR, which, in addition to the historical-only event catalog, may result from the temporally incomplete disaster loss database used to construct the loss exceedance probabilities in the UNISDR study. Earthquake shaking is not historically a dominant hazard in any of the SWIO island nations, which is substantiated by the low loss results calculated in both the present AIR and previous UNISDR studies.

Table 4: Comparison of AIR and UNISDR/GAR AAL and selected return period loss results for TC wind

Exceedance Probability:	AAL		0.01		0.004		0.002	
Mean Return Period (years):			100		250		500	
Study:	AIR	UNISDR	AIR	UNISDR	AIR	UNISDR	AIR	UNISDR
COM	0.08%	0.02%	1.36%	0.39%	5.09%	0.48%	9.32%	0.56%
MDG	0.16%	0.29%	2.03%	1.73%	3.07%	2.15%	4.31%	2.30%
MUS	0.22%	0.83%	5.34%	16.41%	10.71%	21.76%	16.69%	26.37%
SYC	<0.01%	N/A	<0.01%	N/A	<0.01%	N/A	<0.01%	N/A
ZAN	<0.01%	N/A	<0.01%	N/A	<0.01%	N/A	0.01%	N/A

Table 5: Comparison of AIR and UNISDR/GAR AAL and selected return period loss results for EQ shake

Exceedance Probability:	AAL		0.01		0.004		0.002	
Mean Return Period (years):			100		250		500	
Study:	AIR	UNISDR	AIR	UNISDR	AIR	UNISDR	AIR	UNISDR
COM	0.004%	0.003%	0.069%	0.150%	0.272%	0.710%	0.435%	2.120%
MDG	0.004%	0.002%	0.041%	0.010%	0.100%	0.060%	0.385%	0.150%
MUS	<0.001%	N/A	<0.001%	N/A	<0.001%	N/A	<0.001%	N/A
SYC	<0.001%	N/A	<0.001%	N/A	<0.001%	N/A	<0.001%	N/A
ZAN	0.003%	0.015%	<0.001%	0.080%	0.092%	0.300%	0.440%	0.950%

3 Risk Profiles

The risk profiles presented herein are derived from calculated ground-up losses resulting from direct damage to buildings and infrastructure assets caused by stochastically generated events. The ground-up losses comprise the cost of repairing or replacing the damaged assets, but do not include other losses, such as building contents, agriculture, and business interruption, or policy terms, such as limits and deductibles. The modeled losses for tropical cyclones include losses caused by wind, flooding due to excess precipitation, and storm surge. The modeled losses for non-tropical cyclone precipitation are caused by flooding due to excess precipitation. The modeled losses for earthquakes are caused by ground shaking. As discussed further in the Component 1 report, the regional tsunami model and the landslide model for Comoros are deterministic, which are unsuitable for use in the financial loss module and are not included in the risk-profiles.

After modeling the cost of repairing or rebuilding the damaged assets due to the impact of all stochastic events, it is then possible to estimate the likelihood, or exceedance probability (EP), and severity of losses for potential future catastrophes. As discussed further in Section 2, the total losses for any potential future event are equal to the sum of the losses at all locations affected by each event. Annual average losses (AAL) are calculated by averaging all losses incurred in the 10,000 year stochastic catalog, which represents 10,000 independent realizations of the loss potential in a given year.

Emergency losses are provided in addition to ground-up losses and represent losses associated with immediate relief activities, such as emergency food, medical care, transportation, temporary shelter, debris removal, etc., that the government can expect to incur following a catastrophic event. These emergency losses are in addition to the direct losses generated by the event. Based on historical data, emergency losses are considered to be lognormally distributed with a mean of 16% of the total ground-up losses for earthquakes and 23% of the total ground-up losses for other perils, as suggested by Bitrán (2004). These mean values are employed to estimate emergency losses from total ground-up losses in the risk-profiles presented below.

3.1 Comoros

The combined tropical cyclone, non-tropical cyclone flood, and earthquake ground-up average annual loss (AAL) profiles for Comoros are presented in Figure 4 by exposure sector and by peril.

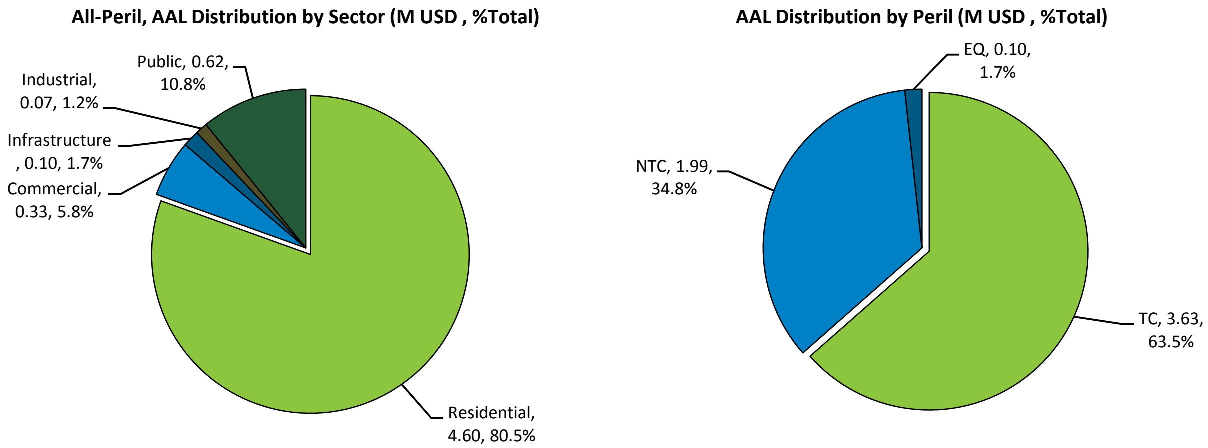


Figure 4: Average annual loss distribution in Comoros by sector (left) and by peril (right)

The country-level loss results for Comoros can also be disaggregated to various Administrative Regions by peril or exposure sector. For example, the AAL distributions for each Administrative Region 2 (i.e., prefectures) and primary peril are presented in Figure 5. Full risk-profiles, including exposure sector disaggregation, for the island nation and each Administrative Region 1 and 2 and are provided in the digital addendum to this report.

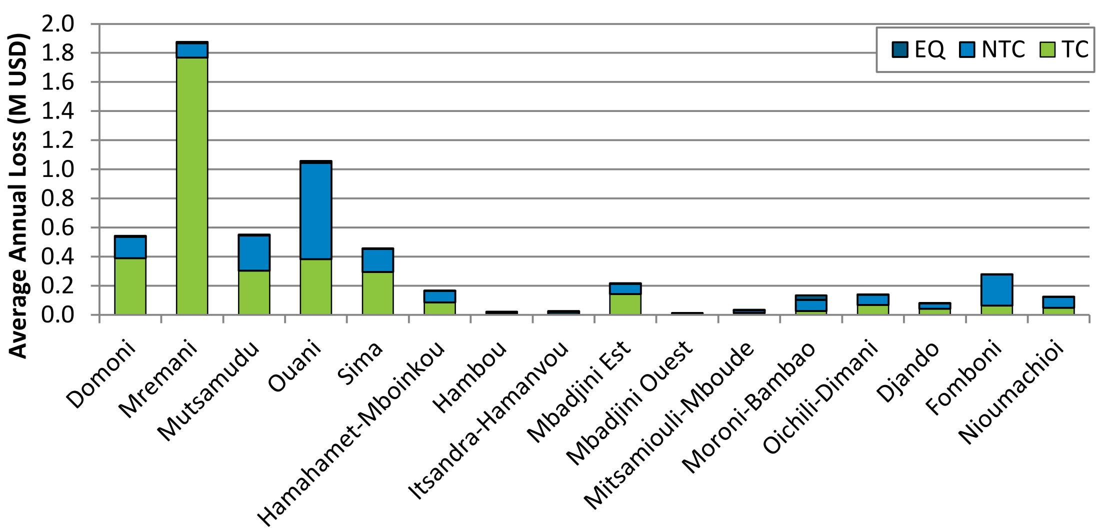


Figure 5: Spatial distribution of AAL for Comoros by Administrative 2 Region (i.e., Prefecture)

The distribution of the loss within Comoros can also be visualized spatially across the island nation. For example, the distribution of Administrative Region 2 AAL, normalized by total AAL for each peril, is presented in Figure 6 for all perils combined, tropical cyclone, non-tropical cyclone flood, and earthquake.

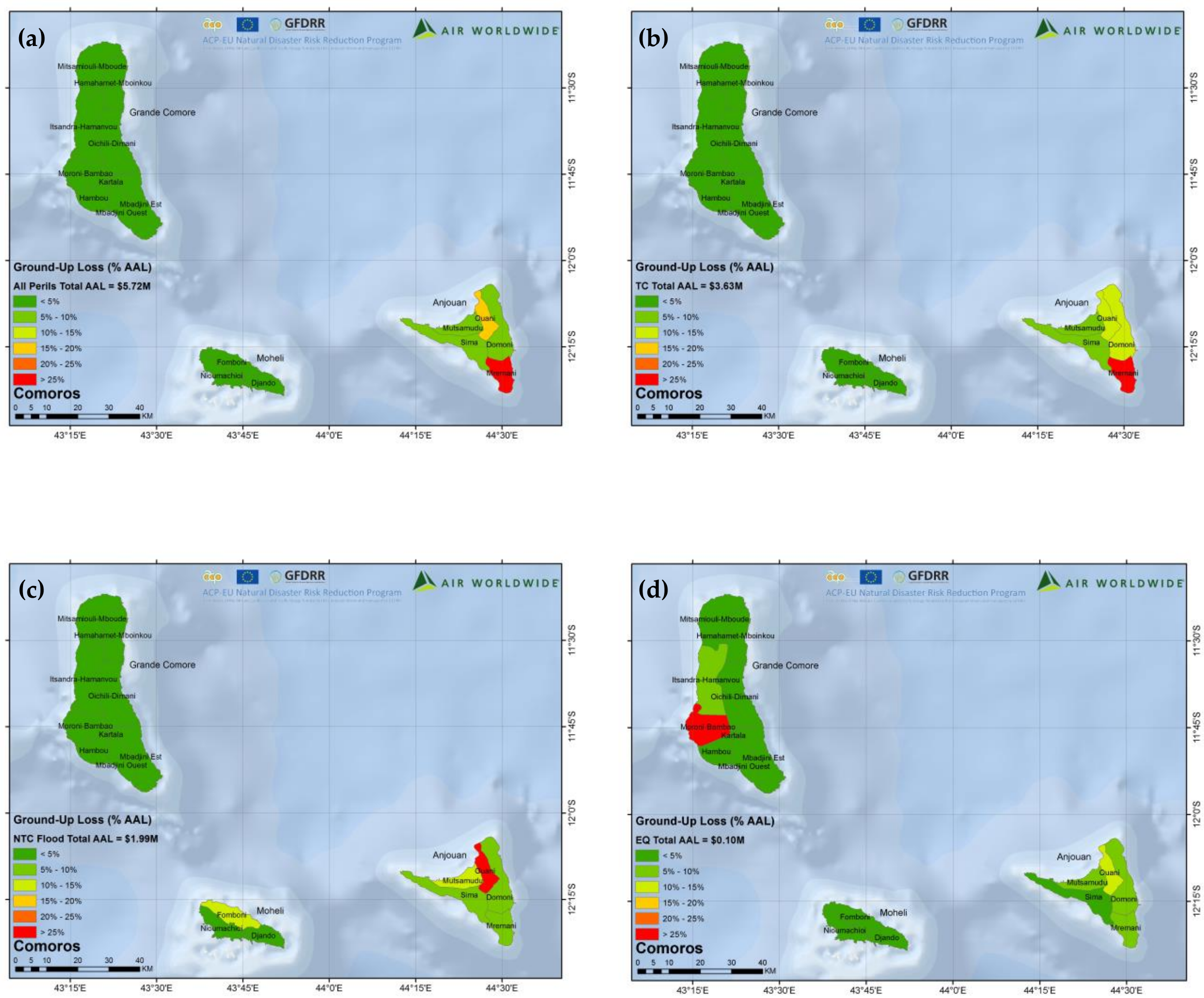


Figure 6: Distribution of normalized average annual loss for Comoros from (a) All Perils Combined, (b) Tropical Cyclones, (c) Non-Tropical Cyclone Floods, and (d) Earthquakes

Table 6 summarizes the risk profile of Comoros in terms of ground-up loss, exposure-normalized ground-up loss, and emergency loss. Ground-up losses are the expenditures needed to repair or replace the damaged assets while emergency losses are the expenditures incurred in the aftermath of a natural catastrophe, which include relief and post-disaster activities. The emergency losses are estimated as a percentage of the total (government and private) direct losses, as described in the front-matter of Section 3.

Table 6 outlines the annual probability of exceeding various levels of direct and emergency losses caused by tropical cyclones, earthquakes and for all perils combined in Comoros. For example, a tropical cyclone loss exceeding 43 M USD, which is equivalent to about 1.7% of the nation's total asset replacement value, and an estimated earthquake loss exceeding about 1.8 M USD, which is equivalent to <0.1% of the nation's total asset replacement value, have a 1.0% probability of occurring or being exceeded in a year (or, alternatively, a MRP of 100 years). In Comoros, the risk analysis indicates that, on average, TC and NTC flooding contribute similarly to the financial risk of Comoros. However, infrequent (i.e., higher return period) TC events are expected to generate significantly higher losses than similarly infrequent non-tropical cyclone floods. Both TC and NTC have larger impacts than EQ, which is consistent with historical observations in Comoros and the SWIO region in general. Note that exceedance probability metrics are not additive across individual risk profiles for different perils. As a result, the risk profiles for tropical cyclone, non-tropical cyclone flooding, and earthquake shown below will not add to the losses shown for all perils at the same return period.

Table 6: Natural Catastrophe Risk Profile for Comoros

Exceedance Probability:	AAL	0.1	0.04	0.02	0.01	0.004	0.002
Mean Return Period (years):		10	25	50	100	250	500
Risk Profile: All Modeled Perils (AP)							
Ground-up Loss (M USD)	5.7	8.4	12.5	18.1	48.4	148.0	258.7
(% Total Exposure Value)	0.2%	0.3%	0.5%	0.7%	1.9%	5.7%	10.0%
Emergency Loss (M USD)	1.3	1.9	2.8	4.0	11.1	34.0	59.5
Risk Profile: Tropical Cyclone (TC)							
Ground-up Loss (M USD)	3.6	4.8	8.6	13.7	43.0	147.6	258.2
(% Total Exposure Value)	0.1%	0.2%	0.3%	0.5%	1.7%	5.7%	10.0%
Emergency Loss (M USD)	30,640.7	0.0	2.0	3.1	9.9	33.9	59.4
Risk Profile: Non-Tropical Cyclone Flood (NTC)							
Ground-up Loss (M USD)	2.0	4.8	6.8	8.4	10.0	11.5	12.4
(% Total Exposure Value)	0.1%	0.2%	0.3%	0.3%	0.4%	0.4%	0.5%
Emergency Loss (M USD)	0.5	1.1	1.6	1.9	2.3	2.7	2.9
Risk Profile: Earthquake (EQ)							
Ground-up Loss (M USD)	0.1	0.0	0.0	0.1	1.8	7.0	11.2
(% Total Exposure Value)	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0.3%	0.4%
Emergency Loss (M USD)	0.0	0.0	0.0	0.0	0.3	1.1	1.8

Table 6 can be visualized using Figure 7, which shows the annual probability of exceeding the ground-up losses generated by each modeled peril and for all modeled perils combined. The exceedance probabilities in Table 6 can also be read off the plot in these figures. Figure 7 clearly illustrates the contribution of TC to the total losses in Comoros at higher return period (i.e., MRP≥ 100 years), whereas NTC dominates more frequent losses (i.e., MRP≤50 years).

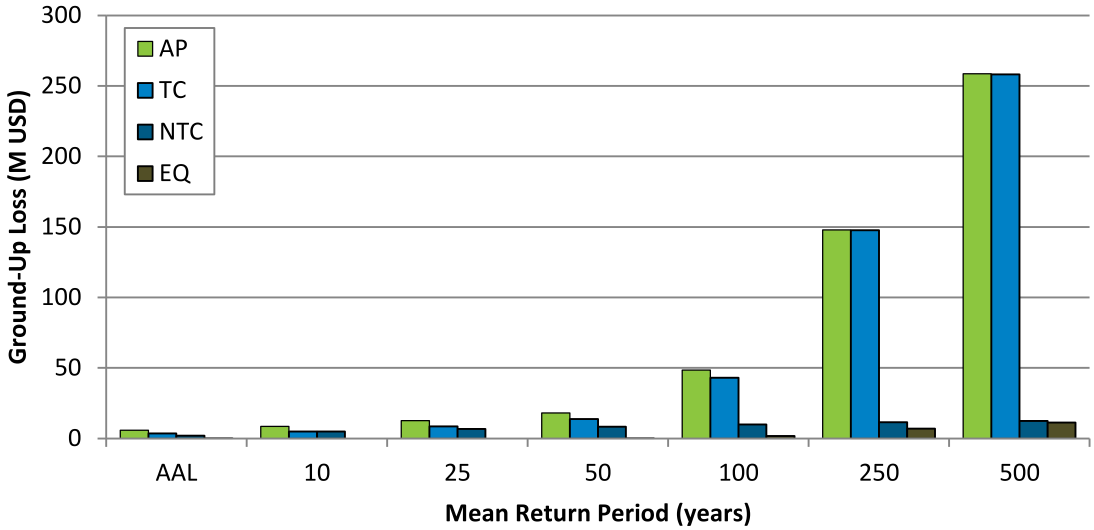
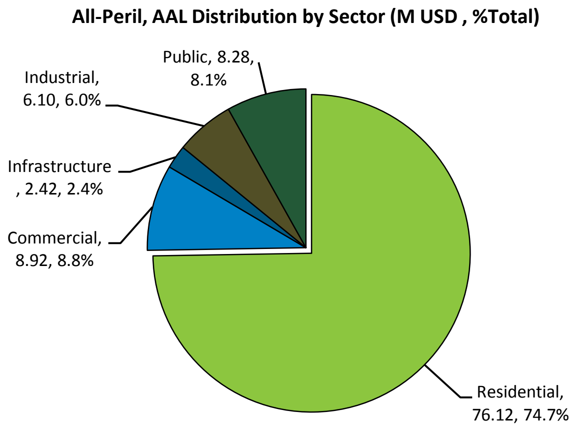


Figure 7: Mean return periods associated of exceeding various levels of ground-up losses caused by tropical cyclones, non-tropical cyclone floods, and earthquakes in Comoros.

3.2 Madagascar

The combined tropical cyclone, non-tropical cyclone flood, and earthquake ground-up average annual loss (AAL) profiles for Madagascar are presented in Figure 8 by exposure sector and by peril.



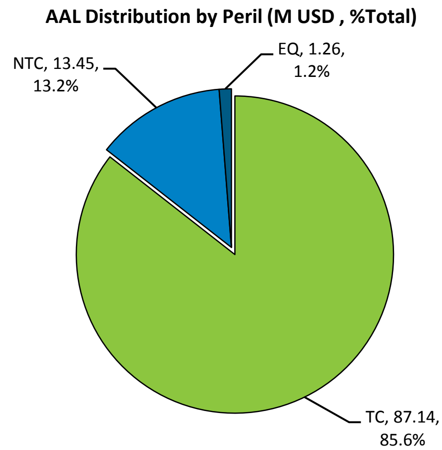


Figure 8: Average annual loss distribution in Madagascar by sector (left) and by peril (right)

The country-level loss results for Madagascar can also be disaggregated to various Administrative Regions by peril or exposure sector. For example, the AAL distributions for each Administrative Region 2 (i.e., regions) and primary peril are presented in Figure 9. Full risk-profiles, including exposure sector disaggregation, for the island nation and each Administrative Region 1 and 2 and are provided in the digital addendum to this report.

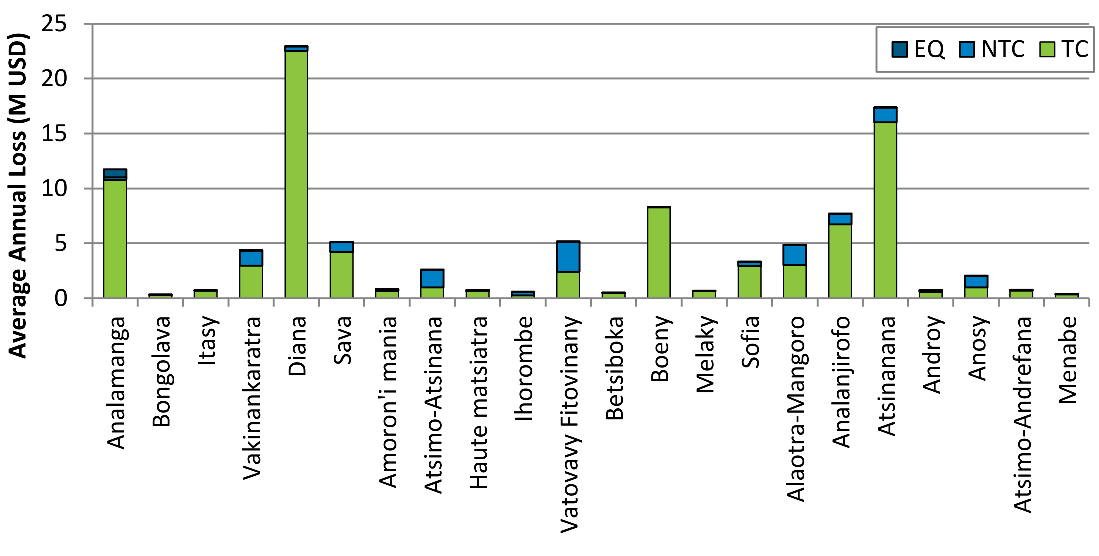


Figure 9: Spatial distribution of AAL for Madagascar by Administrative 2 Region (i.e., Region)

The distribution of the loss within Madagascar can also be visualized spatially across the island nation. For example, the distribution of Administrative Region 2 AAL, normalized by total AAL for each peril, is presented in Figure 10 for all perils combined, tropical cyclone, non-tropical cyclone flood, and earthquake.

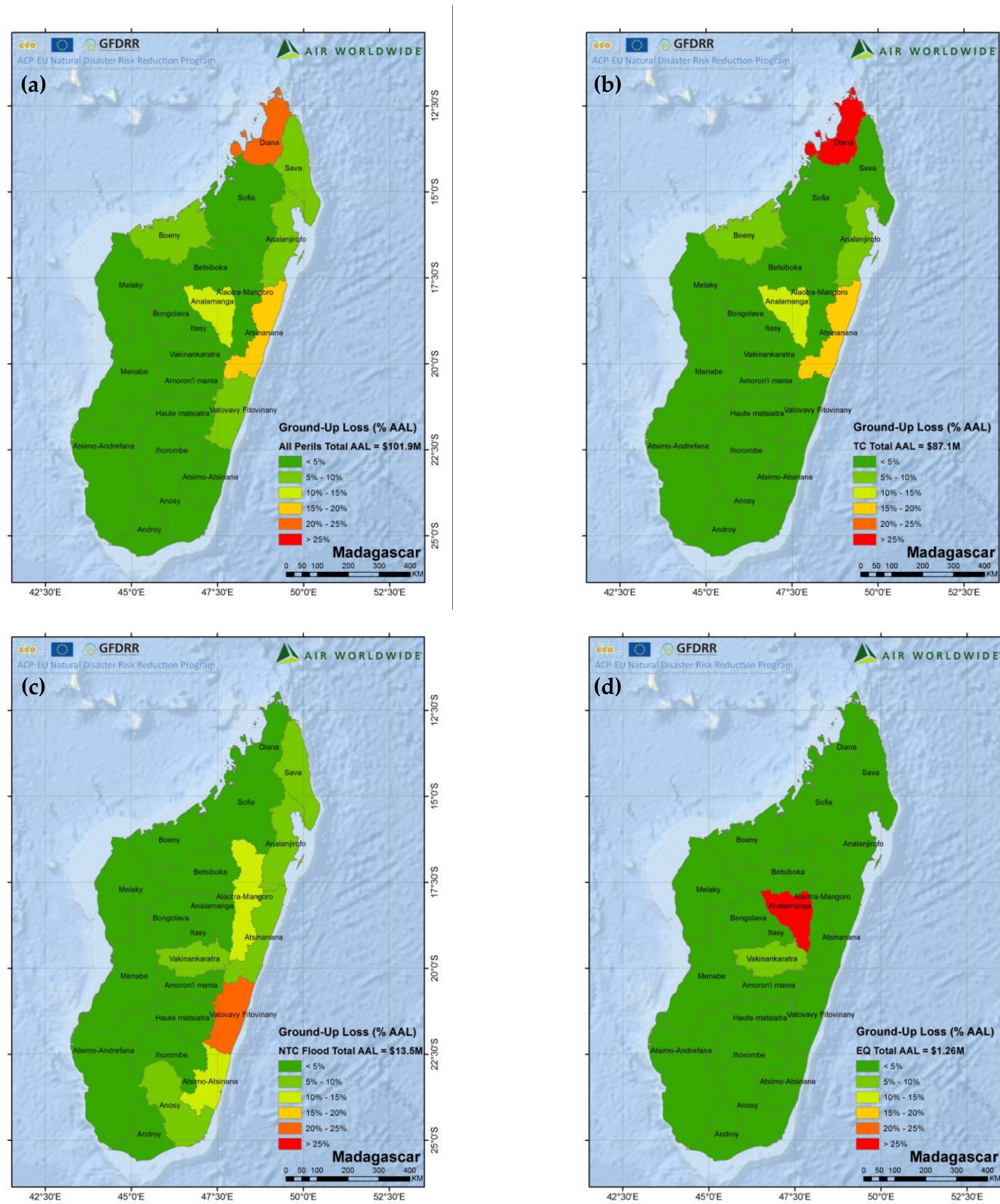


Figure 10: Distribution of normalized average annual loss for Madagascar from (a) All Perils Combined, (b) Tropical Cyclones, (c) Non-Tropical Cyclone Floods, and (d) Earthquakes

Table 7 summarizes the risk profile of Madagascar in terms of ground-up loss, exposure-normalized ground-up loss, and emergency loss. Ground-up losses are the expenditures needed to repair or replace the damaged assets while emergency losses are the expenditures incurred in the aftermath of a natural catastrophe, which include relief and post-disaster activities. The emergency losses are estimated as a percentage of the total ground-up direct losses, as described in the front-matter of Section 3.

Table 7 outlines the annual probability of exceeding various levels of direct and emergency losses caused by tropical cyclones, earthquakes and for all perils combined in Madagascar. For example, a tropical cyclone loss exceeding 813 M USD, which is equivalent to about 2.3% of the nation's total asset replacement value, and an estimated earthquake loss exceeding about 14.6 M USD, which is equivalent to <0.1% of the nation's total asset replacement value, have a 1.0% probability of occurring or being exceeded in a year (or, alternatively, a MRP of 100 years). In Madagascar, the risk analysis indicates that TC losses are both more frequent and more severe than losses due to NTC flooding or EQ. Both TC and NTC have larger impacts than EQ, which is consistent with historical observations in Madagascar and the SWIO region in general. Exposure normalized losses in Madagascar are lower than many of the other SWIO island nations due to large size of the island and geographically diverse exposure, which, unlike smaller islands, is unlikely to be impacted in its entirety by a single event. Note that exceedance probability metrics are not additive across individual risk profiles for different perils. As a result, the risk profiles for tropical cyclone, non-tropical cyclone flooding, and earthquake shown below will not add to the losses shown for all perils at the same return period.

Table 7: Natural Catastrophe Risk Profile for Madagascar

Exceedance Probability:	AAL	0.1	0.04	0.02	0.01	0.004	0.002
Mean Return Period (years):		10	25	50	100	250	500
Risk Profile: All Modeled Perils (AP)							
Ground-up Loss (M USD)	101.9	244.4	446.8	600.9	826.7	1,176.2	1,745.0
(% Total Exposure Value)	0.3%	0.7%	1.3%	1.7%	2.4%	3.4%	5.0%
Emergency Loss (M USD)	23.3	56.0	102.6	138.2	189.0	270.5	401.4
Risk Profile: Tropical Cyclone (TC)							
Ground-up Loss (M USD)	87.1	224.0	433.0	585.0	813.0	1,150.0	1,740.0
(% Total Exposure Value)	0.3%	0.6%	1.2%	1.7%	2.3%	3.3%	5.0%
Emergency Loss (M USD)	20.0	51.5	99.6	135.0	187.0	265.0	401.0
Risk Profile: NTC Flood (NTC)							
Ground-up Loss (M USD)	13.4	31.4	58.7	83.0	115.8	146.3	170.2
(% Total Exposure Value)	<0.1%	<0.1%	0.2%	0.2%	0.3%	0.4%	0.5%
Emergency Loss (M USD)	3.1	7.2	13.5	19.1	26.6	33.6	39.1
Risk Profile: Earthquake (EQ)							
Ground-up Loss (M USD)	1.3	1.0	3.5	7.4	14.6	35.2	134.0
(% Total Exposure Value)	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0.1%	0.4%
Emergency Loss (M USD)	0.2	0.2	0.6	1.2	2.3	5.6	21.5

Table 7 can be visualized using Figure 11, which shows the annual probability of exceeding the ground-up losses generated by each modeled peril and for all modeled perils combined. The exceedance probabilities in Table 7 can also be read off the plot in these figures. Figure 11 clearly illustrates the contribution of TC to the total losses in Madagascar at both high (i.e., MRP≥ 100 years) and low (i.e., MRP≤10 years) return periods, whereas NTC and EQ contribute most meaningfully to more frequent or less severe events and the AAL.

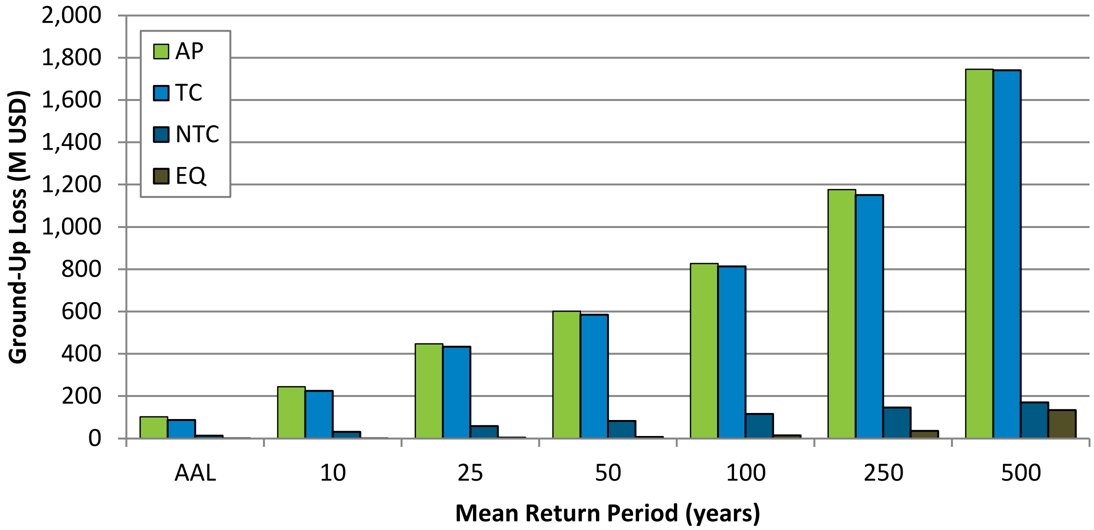
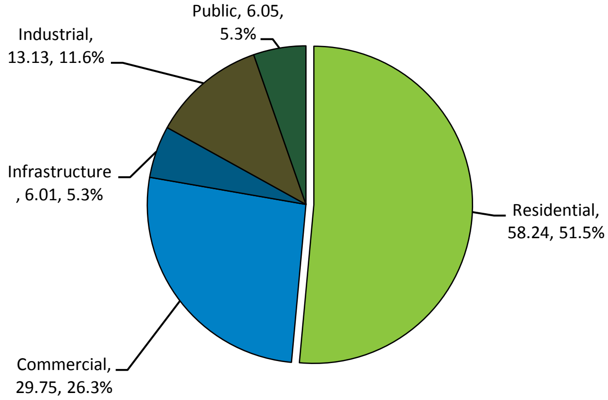


Figure 11: Mean return periods associated of exceeding various levels of ground-up losses caused by tropical cyclones, non-tropical cyclone floods, and earthquakes in Madagascar.

3.3 Mauritius

The combined tropical cyclone, non-tropical cyclone flood, and earthquake ground-up average annual loss (AAL) profiles for Mauritius are presented in Figure 12 by exposure sector and by peril.



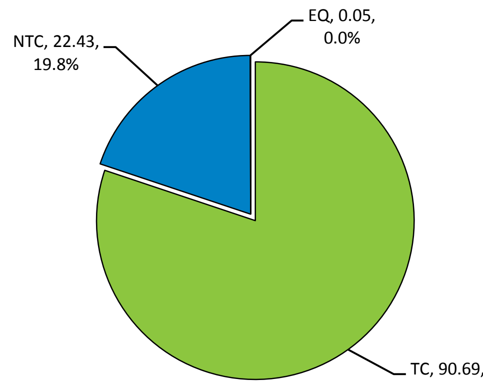


Figure 12: Average annual loss distribution in Mauritius by sector (left) and by peril (right)

The country-level loss results for Mauritius can also be disaggregated to various Administrative Regions by peril or exposure sector. For example, the AAL distributions for each Administrative Region 2 (i.e., regions) and primary peril are presented in Figure 13. Full risk-profiles, including exposure sector disaggregation, for the island nation and each Administrative Region 1 and 2 and are provided in the digital addendum to this report.

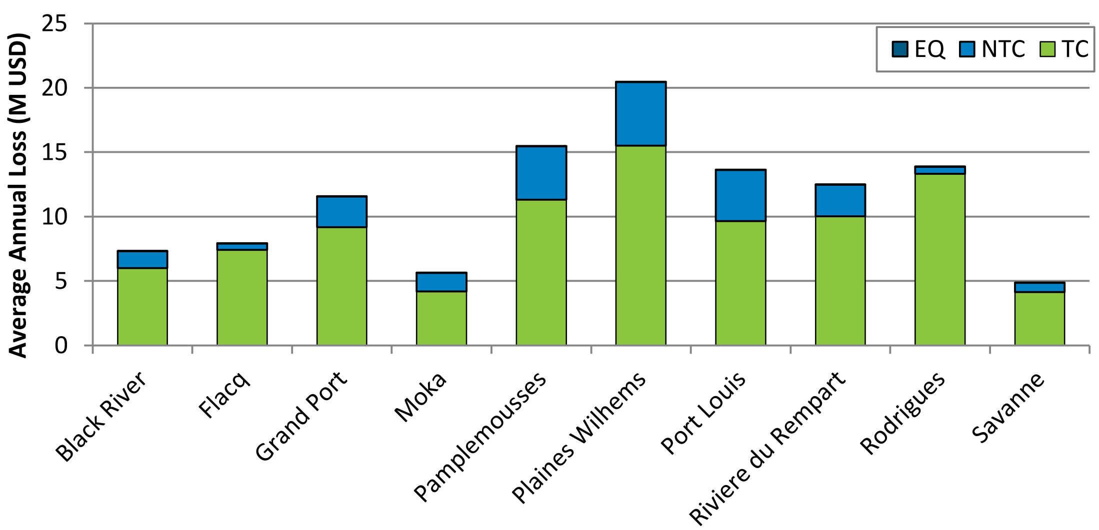


Figure 13: Spatial distribution of AAL for Mauritius by Administrative 2 Region (i.e., Region)

The distribution of the loss within Mauritius can also be visualized spatially across the island nation. For example, the distribution of Administrative Region 2 AAL, normalized by total AAL for each peril, is presented in Figure 14 for all perils combined, tropical cyclone, non-tropical cyclone flood, and earthquake.

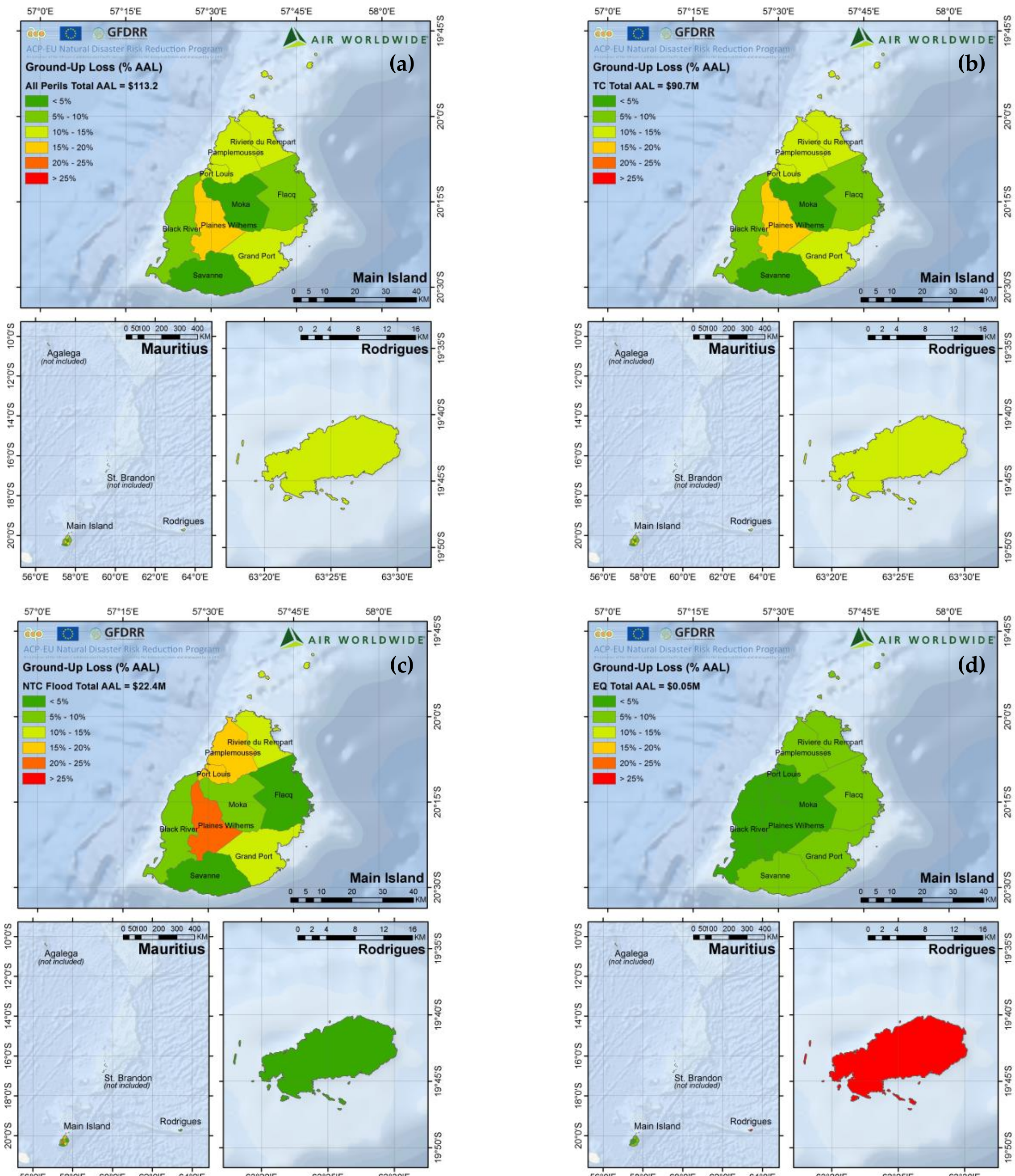


Figure 14: Distribution of normalized average annual loss for Mauritius from (a) All Perils Combined, (b) Tropical Cyclones, (c) Non-Tropical Cyclone Floods, and (d) Earthquakes

Table 8 summarizes the risk profile of Mauritius in terms of ground-up loss, exposure-normalized ground-up loss, and emergency loss. Ground-up losses are the expenditures needed to repair or replace the damaged assets while emergency losses are the expenditures incurred in the aftermath of a natural catastrophe, which include relief and post-disaster activities. The emergency losses are estimated as a percentage of the total ground-up direct losses, as described in the front-matter of Section 3.

Table 8 outlines the annual probability of exceeding various levels of direct and emergency losses caused by tropical cyclones, earthquakes and for all perils combined in Mauritius. For example, a tropical cyclone loss exceeding 1,881 M USD, which is equivalent to about 5.6% of the nation's total asset replacement value, and an estimated non-tropical cyclone flooding loss exceeding about 149.7 M USD, which is equivalent to about 0.4% of the nation's total asset replacement value, have a 1.0% probability of occurring or being exceeded in a year (or, alternatively, a MRP of 100 years). In Mauritius, the risk analysis indicates that TC losses are both more frequent and more severe than losses due to NTC flooding or EQ. Both TC and NTC have larger impacts than EQ, which is consistent with historical observations on the main island of Mauritius, Rodrigues, and the SWIO region in general. Particularly for TC, the exposure normalized losses in Mauritius tend to be higher than many of the other SWIO island nations due to relatively concentrated exposure, which can be impacted in its entirety by a single event. Note that exceedance probability metrics are not additive across individual risk profiles for different perils. As a result, the risk profiles for tropical cyclone, non-tropical cyclone flooding, and earthquake shown below will not add to the losses shown for all perils at the same return period.

Table 8: Natural Catastrophe Risk Profile for Mauritius

Exceedance Probability:	AAL	0.1	0.04	0.02	0.01	0.004	0.002
Mean Return Period (years):		10	25	50	100	250	500
Risk Profile: All Modeled Perils (AP)							
Ground-up Loss (M USD)	113.2	145.2	356.8	800.6	1,906.5	3,642.3	5,730.4
(% Total Exposure Value)	0.3%	0.4%	1.1%	2.4%	5.7%	10.9%	17.1%
Emergency Loss (M USD)	26.0	33.4	82.1	184.1	438.5	837.7	1,318.0
Risk Profile: Tropical Cyclone (TC)							
Ground-up Loss (M USD)	90.7	97.3	329.1	757.3	1,880.7	3,632.9	5,702.3
(% Total Exposure Value)	0.3%	0.3%	1.0%	2.3%	5.6%	10.9%	17.0%
Emergency Loss (M USD)	0.0	0.0	75.7	174.2	432.6	835.6	1,311.5
Risk Profile: Non-Tropical Cyclone Flood (NTC)							
Ground-up Loss (M USD)	22.4	63.0	100.5	126.1	149.7	179.5	203.5
(% Total Exposure Value)	<0.1%	0.2%	0.3%	0.4%	0.4%	0.5%	0.6%
Emergency Loss (M USD)	5.2	14.5	23.1	29.0	34.4	41.3	46.8
Risk Profile: Earthquake (EQ)							
Ground-up Loss (M USD)	0.1	0.0	0.0	0.0	0.0	0.0	0.0
(% Total Exposure Value)	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%
Emergency Loss (M USD)	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 8 can be visualized using Figure 15, which shows the annual probability of exceeding the ground-up losses generated by each modeled peril and for all modeled perils combined. The exceedance probabilities in Table 8 can also be read off the plot in these figures. Figure 15 clearly illustrates the contribution of TC to the total losses in Mauritius at both high (i.e., MRP≥≥ 100 years) and low (i.e., MRP≤≤10 years) return periods and suggests that TC is the primary catastrophic peril for the island nation. NTC flooding contributes most meaningfully to more frequent events and the AAL, which suggests that NTC events in Mauritius are generally more geographically isolated or less severe. While significant EQ events in Mauritius are possible, loss-causing EQ events are considered rare.

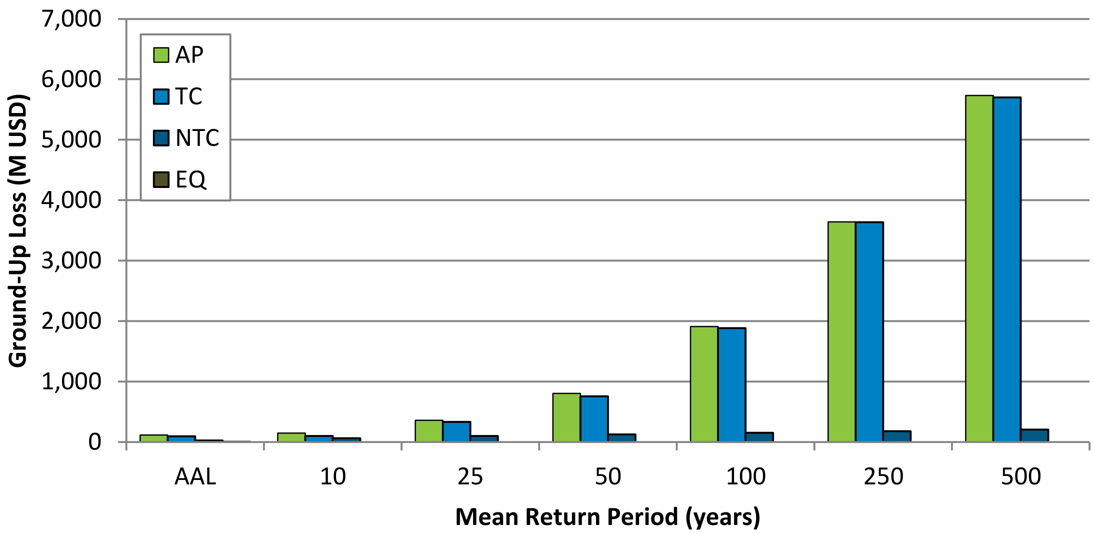


Figure 15: Mean return periods associated of exceeding various levels of ground-up losses caused by tropical cyclones, non-tropical cyclone floods, and earthquakes in Mauritius.

3.4 Seychelles

The combined tropical cyclone, non-tropical cyclone flood, and earthquake ground-up average annual loss (AAL) profiles for Seychelles are presented in Figure 16 by exposure sector and by peril.

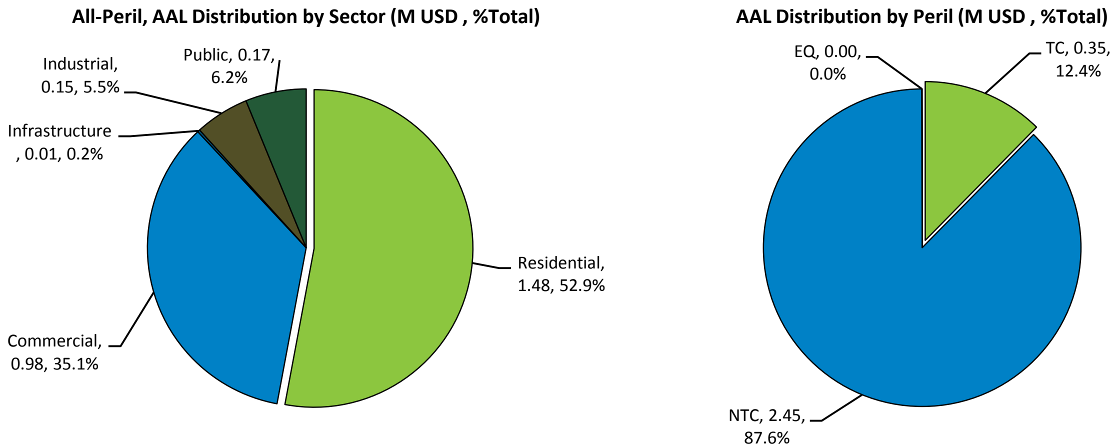


Figure 16: Average annual loss distribution in Seychelles by sector (left) and by peril (right)

The country-level loss results for Seychelles can also be disaggregated to various Administrative Regions by peril or exposure sector. For example, the AAL distributions for each Administrative Region 2 (i.e., regions) and primary peril are presented in Figure 17. Full risk-profiles, including exposure sector disaggregation, for the island nation and each Administrative Region 1 and 2 and are provided in the digital addendum to this report.

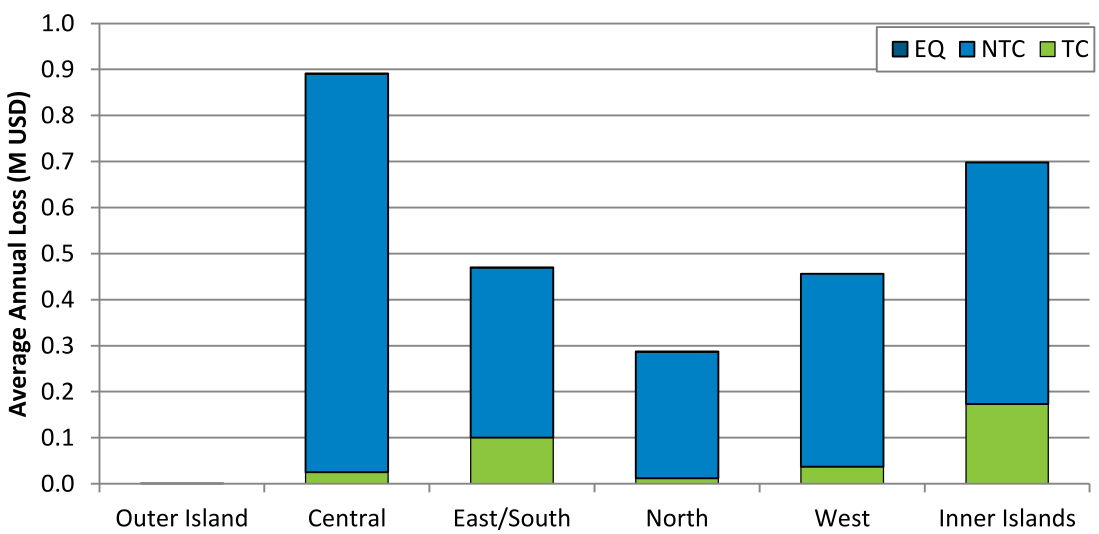


Figure 17: Spatial distribution of AAL for Seychelles by Administrative 2 Region (i.e., Region)

The distribution of the loss within Seychelles can also be visualized spatially across the island nation. For example, the distribution of Administrative Region 2 AAL, normalized by total AAL for each peril, is presented in Figure 18 for all perils combined, tropical cyclone, non-tropical cyclone flood, and earthquake.

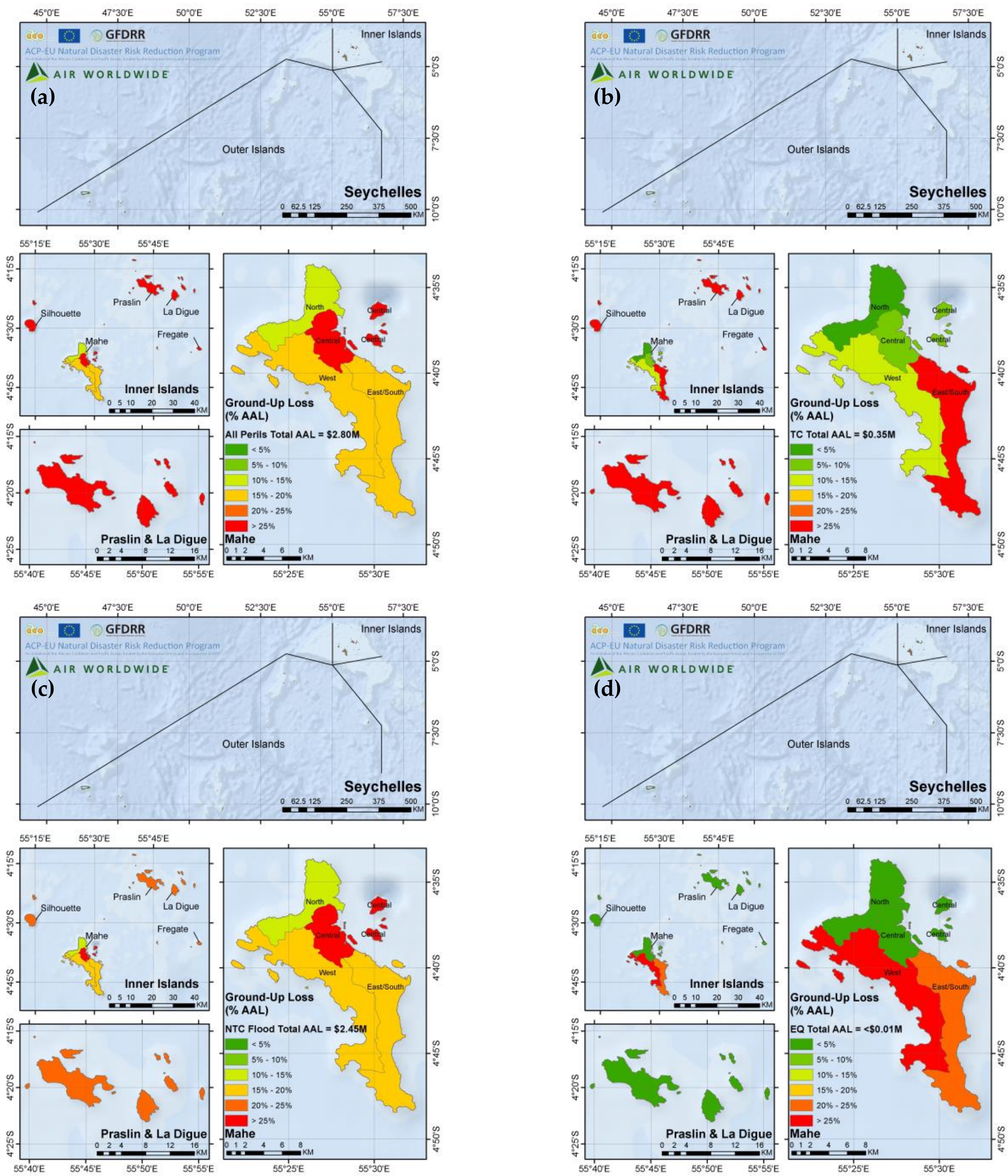


Figure 18: Distribution of normalized average annual loss for Seychelles from (a) All Perils Combined, (b) Tropical Cyclones, (c) Non-Tropical Cyclone Floods, and (d) Earthquakes

Table 9 summarizes the risk profile of Seychelles in terms of ground-up loss, exposure-normalized ground-up loss, and emergency loss. Ground-up losses are the expenditures needed to repair or replace the damaged assets while emergency losses are the expenditures incurred in the aftermath of a natural catastrophe, which include relief and post-disaster activities. The emergency losses are estimated as a percentage of the total ground-up direct losses, as described in the front-matter of Section 3.

Table 9 outlines the annual probability of exceeding various levels of direct and emergency losses caused by tropical cyclones, earthquakes and for all perils combined in Seychelles. For example, a tropical cyclone loss exceeding 10.2 M USD, which is equivalent to about 0.1% of the nation's total asset replacement value, and a non-tropical cyclone flooding loss exceeding about 15.9 M USD, which is equivalent to about 0.2% of the nation's total asset replacement value, have a 1.0% probability of occurring or being exceeded in a year (or, alternatively, a MRP of 100 years). In Seychelles, the risk analysis indicates that NTC flooding losses are both more frequent and more severe than losses due to TC or EQ, which is consistent with historical observations in Seychelles. Exposure normalized losses in Seychelles are lower than many of the other SWIO island nations due to low probability of significant loss from any peril and the geographically diverse exposure, which is unlikely to be impacted in its entirety by any single event. Note that exceedance probability metrics are not additive across individual risk profiles for different perils. As a result, the risk profiles for tropical cyclone, non-tropical cyclone flooding, and earthquake shown below will not add to the losses shown for all perils at the same return period.

Table 9: Natural Catastrophe Risk Profile for Seychelles

Exceedance Probability:	AAL	0.1	0.04	0.02	0.01	0.004	0.002
Mean Return Period (years):		10	25	50	100	250	500
Risk Profile: All Modeled Perils (AP)							
Ground-up Loss (M USD)	2.8	8.6	12.2	14.8	17.9	21.0	23.4
(% Total Exposure Value)	0.0%	0.1%	0.2%	0.2%	0.3%	0.3%	0.3%
Emergency Loss (M USD)	0.6	2.0	2.8	3.4	4.1	4.8	5.4
Risk Profile: Tropical Cyclone (TC)							
Ground-up Loss (M USD)	0.3	0.3	2.2	4.8	10.2	14.9	19.5
(% Total Exposure Value)	<0.1%	<0.1%	<0.1%	<0.1%	0.1%	0.2%	0.3%
Emergency Loss (M USD)	0.0	0.0	0.5	1.1	2.4	3.4	4.5
Risk Profile: Non-Tropical Cyclone Flood (NTC)							
Ground-up Loss (M USD)	2.5	7.9	11.1	13.4	15.9	18.6	20.4
(% Total Exposure Value)	<0.1%	0.1%	0.2%	0.2%	0.2%	0.3%	0.3%
Emergency Loss (M USD)	0.6	1.8	2.6	3.1	3.7	4.3	4.7
Risk Profile: Earthquake (EQ)							
Ground-up Loss (M USD)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(% Total Exposure Value)	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%
Emergency Loss (M USD)	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 9 can be visualized using Figure 19, which shows the annual probability of exceeding the ground-up losses generated by each modeled peril and for all modeled perils combined. The exceedance probabilities in Table 9 can also be read off the plot in these figures. Figure 19 clearly illustrates the contribution of NTC to the total losses in Seychelles at both high (i.e., MRP≥≥ 100 years) and low (i.e., MRP≤≤10 years) return periods, whereas TC contributes meaningfully to only infrequent severe events. While significant EQ events in Seychelles are possible, loss-causing EQ events are considered rare.

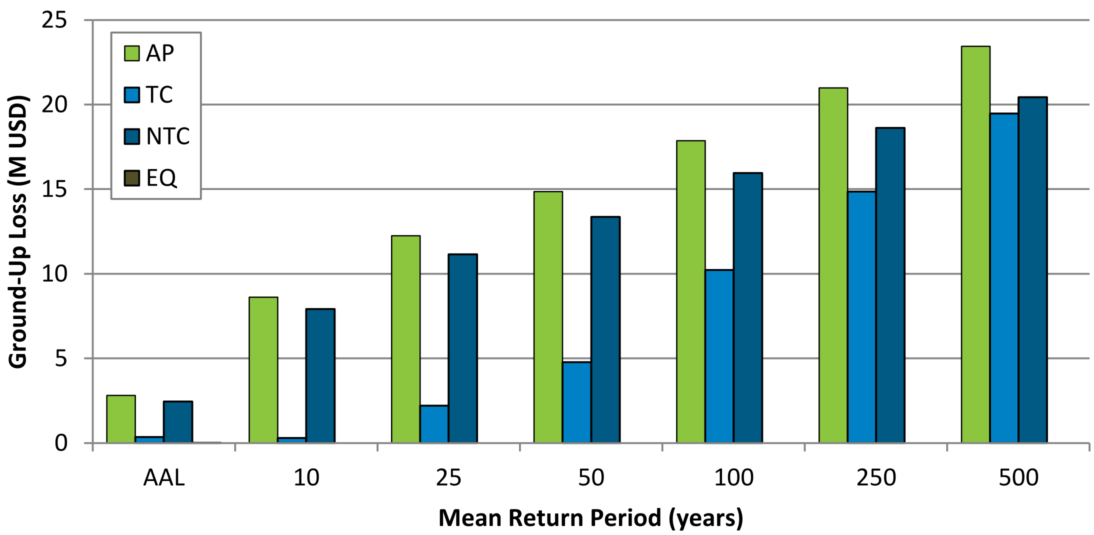
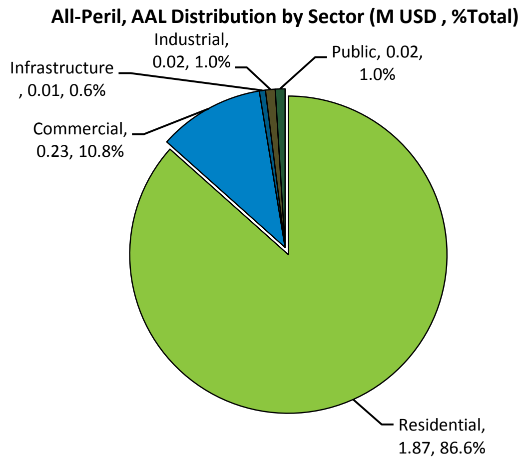


Figure 19: Mean return periods associated of exceeding various levels of ground-up losses caused by tropical cyclones, non-tropical cyclone floods, and earthquakes in Seychelles.

3.5 Zanzibar

The combined tropical cyclone, non-tropical cyclone flood, and earthquake ground-up average annual loss (AAL) profiles for Zanzibar are presented in Figure 20 by exposure sector and by peril.



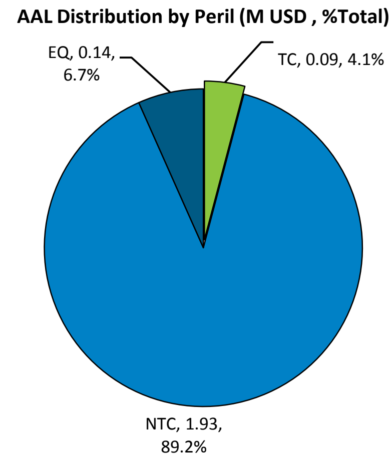


Figure 20: Average annual loss distribution in Zanzibar by sector (left) and by peril (right)

The country-level loss results for Zanzibar can also be disaggregated to various Administrative Regions by peril or exposure sector. For example, the AAL distributions for each Administrative Region 2 (i.e., districtsdistricts) and primary peril are presented in Figure 21. Full risk-profiles, including exposure sector disaggregation, for the island nation and each Administrative Region 1 and 2 and are provided in the digital addendum to this report.

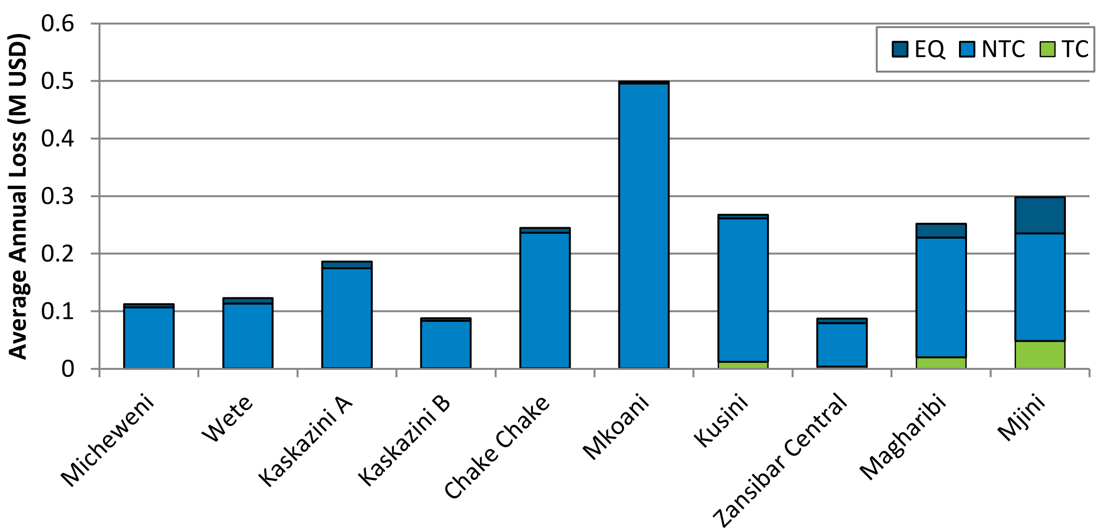


Figure 21: Spatial distribution of AAL for Zanzibar by Administrative 2 Region (i.e., District)

The distribution of the loss within Zanzibar can also be visualized spatially across the island nation. For example, the distribution of Administrative Region 2 AAL, normalized by total AAL for each peril, is presented in Figure 22 for all perils combined, tropical cyclone, non-tropical cyclone flood, and earthquake.

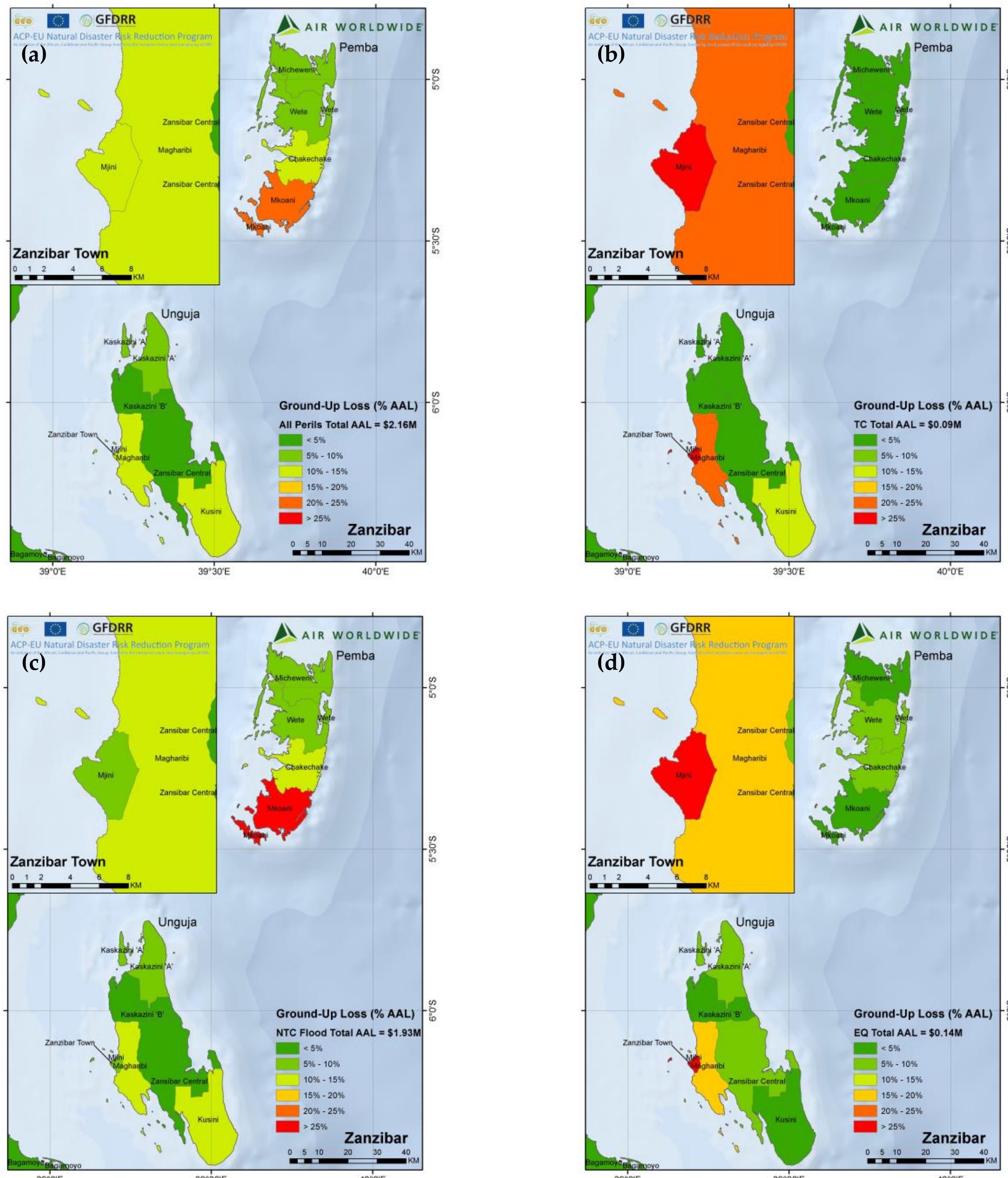


Figure 22: Distribution of normalized average annual loss for Zanzibar from (a) All-Perils Combined, (b) Tropical Cyclones, (c) Non-Tropical Cyclone Floods, and (d) Earthquakes

Table 10 summarizes the risk profile of Zanzibar in terms of ground-up loss, exposure-normalized ground-up loss, and emergency loss. Ground-up losses are the expenditures needed to repair or replace the damaged assets while emergency losses are the expenditures incurred in the aftermath of a natural catastrophe, which include relief and post-disaster activities. The emergency losses are estimated as a percentage of the total (government and private) direct losses, as described in the front-matter of Section 3.

Table 10 outlines the annual probability of exceeding various levels of direct and emergency losses caused by tropical cyclones, earthquakes and for all perils combined in Zanzibar. For example, a tropical cyclone loss exceeding 0.1 M USD, which is equivalent to <0.1% of the nation's total asset replacement value, and an estimated non-tropical cyclone flooding loss exceeding about 12.8 M USD, which is equivalent to about 0.5% of the nation's total asset replacement value, have a 1.0% probability of occurring or being exceeded in a year (or, alternatively, a MRP of 100 years). In Zanzibar, the risk analysis indicates that NTC flooding losses are both more frequent and more severe than losses due to TC and EQ, which is consistent with historical observations in Zanzibar. Infrequent (ii.e., higher return period) TC and EQ events have the potential to generate significant losses in Zanzibar, but these events are considered rare. Note that exceedance probability metrics are not additive across individual risk profiles for different perils. As a result, the risk profiles for tropical cyclone, non-tropical cyclone flooding, and earthquake shown below will not add to the losses shown for all perils at the same return period.

Table 10: Natural Catastrophe Risk Profile for Zanzibar

Exceedance Probability:	AAL	0.1	0.04	0.02	0.01	0.004	0.002
Mean Return Period (years):		10	25	50	100	250	500
Risk Profile: All Modeled Perils (AP)							
Ground-up Loss (M USD)	2.2	5.7	8.8	11.1	13.8	17.8	26.6
(% Total Exposure Value)	<0.1%	0.1%	0.2%	0.3%	0.3%	0.4%	0.6%
Emergency Loss (M USD)	0.5	1.3	2.0	2.5	3.2	4.0	4.8
Risk Profile: Tropical Cyclone (TC)							
Ground-up Loss (M USD)	0.1	0.0	0.0	0.0	0.1	0.3	0.7
(% Total Exposure Value)	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%
Emergency Loss (M USD)	0.0	0.0	0.0	0.0	0.0	0.1	0.2
Risk Profile: Non-Tropical Cyclone Flood (NTC)							
Ground-up Loss (M USD)	1.9	5.6	8.5	10.6	12.8	15.6	17.1
(% Total Exposure Value)	0.1%	0.2%	0.3%	0.4%	0.5%	0.6%	0.7%
Emergency Loss (M USD)	0.4	1.3	1.9	2.4	2.9	3.6	3.9
Risk Profile: Earthquake (EQ)							
Ground-up Loss (M USD)	0.1	0.0	0.0	0.0	0.0	3.9	18.9
(% Total Exposure Value)	<0.1%	<0.1%	<0.1%	<0.1%	<0.1%	0.2%	0.7%
Emergency Loss (M USD)	0.0	0.0	0.0	0.0	0.0	0.6	3.0

Table 10 can be visualized using Figure 23, which shows the annual probability of exceeding the ground-up losses generated by each modeled peril and for all modeled perils combined. The exceedance probabilities in Table 10 can also be read off the plot in these figures. Figure 23 clearly illustrates the contribution of NTC to the total losses in Zanzibar at both high (i.e., MRP≥≥ 100 years) and low (i.e., MRP≤≤10 years) return periods, whereas EQ contributes meaningfully to only infrequent and, severe events. While significant TC events in Zanzibar are possible, loss-causing TC events are considered rare.

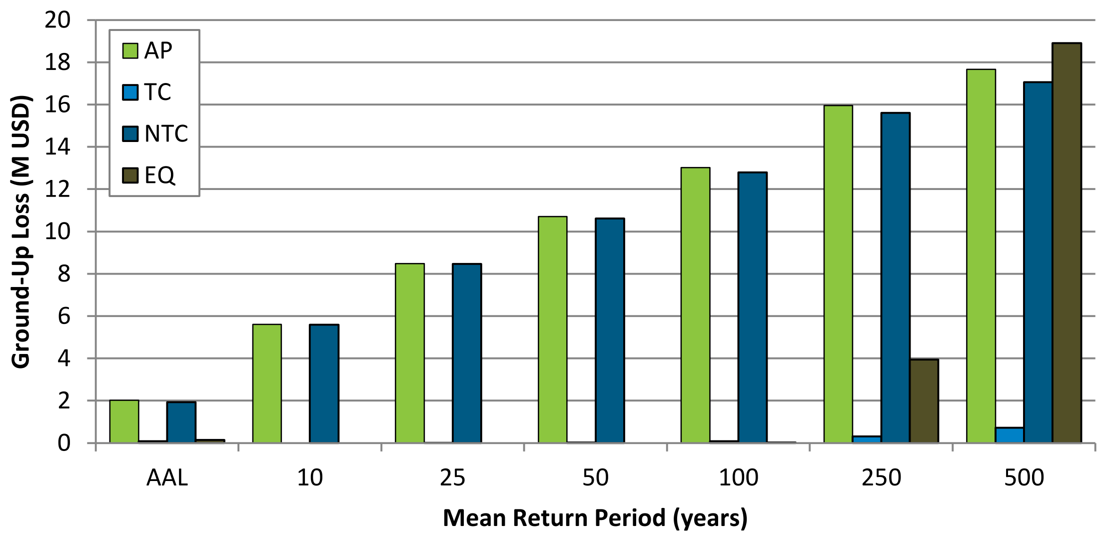


Figure 23: Mean return periods associated of exceeding various levels of ground-up losses caused by tropical cyclones, non-tropical cyclone floods, and earthquakes in Zanzibar.

4 Risk Uncertainty and Potential for Change in the Future

As outlined in Section 2, natural catastrophe risk is calculated as the combination of hazard, exposure, and vulnerability, all of which have uncertainty in their estimation and the potential to change in the future. In order to quantify that uncertainty, AIR employs probabilistic tools to estimate the impacts of both common and extremely rare events; however, no risk model is capable of predicting all potential outcomes from all future events.

The hazard in the SWIO region is calculated using the historical record for each peril. As described further in the Component 1 report, careful attention is given to selecting from the most reliable parts of the historical record in order to generate scientifically plausible and defensible probabilities of event occurrences and associated intensities. This strategy is inherently limited by the length of the available historical record. Rare or infrequent events may have occurred outside of the historical record and are therefore not reflected in AIR's stochastic catalogs of potential events. Additionally, for atmospheric perils, the historical record and stochastic catalog do not explicitly consider future changes to climate due to global warming, sea level rise, and other natural and anthropenic changes. Climate changes that are already reflected in the historical record, for example tropical cyclone or extreme rainfall frequency in recent years, are however implicitly considered in the modeled hazard. For all perils, the combined effect of the limited historical record and climate change have the potential to manifest in the occurrence of future events that are not considered in the stochastic catalogs. However, while the frequency and impact of the investigated hazards in the SWIO region may vary in the future, the stochastic catalogs for each peril consider thousands of rare and severe events that have yet to be realized in the historical record and are expected to reflect a wide range of future events, including those that may be driven by changes to the climate. Thus, until a clear change in the stochastic model input parameters can be reliably discerned from observed data, the stochastic catalogs and associated risk estimates are expected to remain valid and representative of future catastrophic events in the SWIO region.

Perhaps more impactful for risk, are changes to the exposed assets in each SWIO island nation. These may include changes to the spatial distribution of buildings, economic changes that affect the valuation of assets, or changes to the structural characteristics of buildings that either reduce or improve their resistance to natural catastrophes. For example, the development of buildings in flood-plains or in coastal regions susceptible to tropical cyclone storm surge, has the potential to significantly increase the risk to the SWIO island nations, perhaps moreso than the effects of climate change. Conversely, the adoption of stringent building codes, natural catastrophe informed zoning regulations, and improved building practices may significantly reduce the potential for economic and human loss. The SWIO region has widely varying levels of economic development, which is reflected in the construction practices, infrasture, and resilience of each island nation, all of which influence the level of risk. While future changes to the hazard are uncertain and challenging to predict, investment in risk-informed development strategies has the greatest potential to reduce the expected losses presented in this investigation.

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Appendix A: Damage Function Development

The SWIO vulnerability module estimates losses caused by ground shaking from earthquake events, , wind from tropical cyclone events, and flood from tropical cyclone-induced precipitation and storm surge, and flood from non-tropical cyclone-induced precipitation, in the five island-nations of Comoros, Mauritius, Madagascar, Seychelles and Zanzibar. The severity of the physical damage experienced by buildings, and infrastructure assets from perils is represented by damage functions (DFs). These functions are statistical relationships that estimate the loss an asset is expected to suffer when subjected to different hazard intensities induced by a catastrophic event. Figure A.1 shows examples of damage functions for wind and ground motion shaking. The degree of loss is customarily represented by the so-called mean damage ratio (MDR), which is defined as the ratio of the cost to repair the asset over the total replacement value of the asset. Losses are evaluated using the mean damage ratio only and inherent uncertainties in the intensity and damage ratio are not considered explicitly. Therefore, the losses calculated for this investigation represent an average value and may be higher or lower than the actual losses experienced during an event. Mean losses for infrequent, or high return period, events typically underestimate total losses that explicitly consider uncertainty.

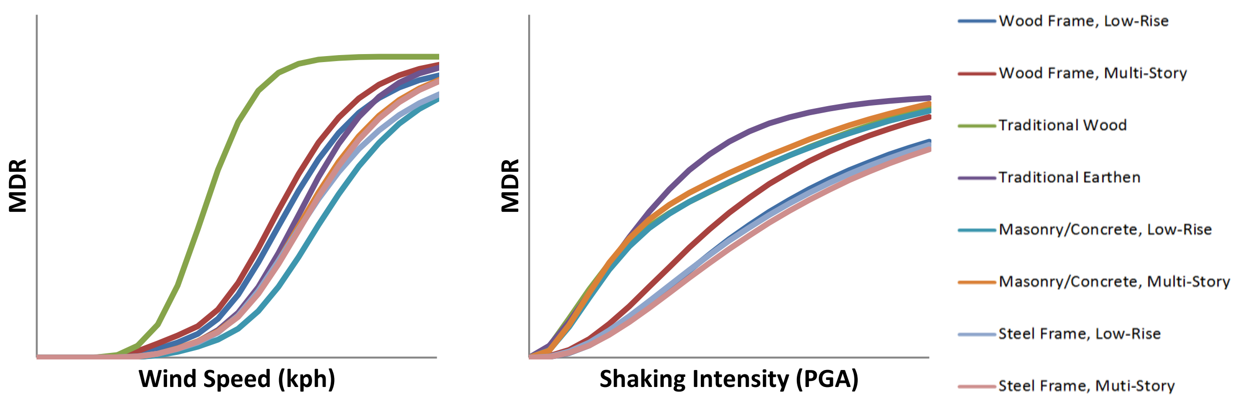


Figure A.1. Examples of Building Damage Functions for Wind (left) and Earthquake Shaking (right)

Earthquake, Tropical Cyclone, and Non-Tropical Cyclone Intensity Measures

The objective of the vulnerability model is to develop damage functions that facilitate the estimation of mean damage ratios for applicable construction and occupancy states as functions of increasing values of intensities for various perils.

Three types of primary perils were explicitly considered in this risk analysis: earthquakes (not including tsunami), tropical cyclones (wind, precipitation, and storm surge), and non-tropical cyclone precipitation. Refer to the Component 1 report for more information regarding historical events in this region and their characteristics. The effects of these events are measured by the intensity measures (IMs) described below. These IMs are used as input to the damage functions discussed herein.

- Wind speed (for tropical cyclones)
    - Wind speeds are defined as the maximum one-minute sustained wind speed at 10 meters above the ground surface at the exposure location, measured in mph
- Flood height (for tropical cyclones and non-tropical cyclone precipitation)
    - The height of the standing water measured from the first-floor elevation at the exposure location caused by either tropical cyclone induced precipitation (fresh water), non-tropical cyclone induced precipitation (fresh water), or by storm surge (salt water), measured in meters
- Ground motion intensity (for earthquakes)
    - The intensity of the ground motion is gauged by the horizontal peak ground acceleration (PGA) at the exposure location, measured in units of gravity acceleration, g.

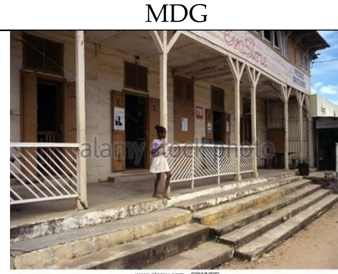
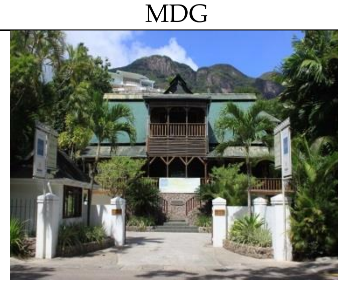
Note that other effects of these events, such as landslides, liquefaction, and fire-following earthquake were not explicitly considered. Their effects, however, are to some extent implicitly included in these analyses to the extent that the losses induced by such phenomena were included in the empirical data from historical events used to calibrate the damage functions adopted herein.

Based on the exposure in the five island-nations in the SWIO region, five major construction types are considered when building the damage functions:

- Single- and Multi-story Wood,
- Single- and multi-story Masonry/Concrete,
- Single- and multi-story Steel,
- Single- and multi-story, other materials, and
- Single-story Traditional Bamboo and Earthen.

Examples of representative building types for the investigated SWIO island nations are provided in the photography gallery shown in Table A.1. Pictures are grouped by construction type and each picture's caption indicates the country's identification code. Cross-comparison of SWIO construction types with those in other countries is used to develop an understanding of regions with similar construction practices.

Table A.1. Gallery of photographs of the building stock in SWIO

Building Type	Photograph with Country ID		
Single-story/ Multi-story Masonry/ Concrete	 COM	 MDG	 MDG
	 MUS	 SYC	 ZAN
Single-Story/ Multi-Story Steel Frame	 MUS	 MDG	 SYC
Single-Story/ Multi-Story Wood Frame	 COM	 MDG	 MUS
	 SYC	 SYC	 ZAN

Single-Story/ Multi-Story Traditional	 COM	 MDG	 MDG
	 SYC	 ZAN	 ZAN
Other Single-Story/ Multi-Story	 MDG	 MUS	 SYC

Methodology for Damage Functions Development

The availability of post-event loss data, property damage reports, and national building codes are limited or non-existent in the SWIO region, which makes the development of damage functions that reflect the unique characteristics of each island nation challenging. As discussed further in this section, AIR leveraged data and experience from similar regions elsewhere in the world to create a generalized component-based methodology for estimating the multi-peril intensity-damage relationships in the SWIO region. This methodology incorporates numerous approaches and data sources, including proprietary AIR datasets, consultation with a vulnerability and loss modeling expert, a framework proposed for developing vulnerability functions in island countries (Stubbs, 1999), and an adaptation of the framework proposed by the FEMA HAZUS-MH.

The component-based approach for developing damage functions in small-island countries proposed by Stubbs considers the relative isolation of island countries and assumes that differences in construction practices and performances across buildings in island countries is minimal. This approach employs simplified linear vulnerability functions for components and uses best estimates of the starting and ending component damage states. This approach is adapted to SWIO by enhancing the linear component damage functions proposed in the original study using cumulative lognormal cumulative distribution functions, and by considering the uncertainty around the median values of each damage state.

In addition to the small-island methodology, the FEMA HAZUS-MH building vulnerability framework is used to calculate weighted average of building vulnerability functions from component functions at specific damage states. While HAZAUS employs four damage states (e.g., Slight, Moderate, Extensive, and Complete), the SWIO functions use only two (e.g., Slight, Extensive). This simplification is due to the limited available regional damage data from which to develop additional damage states and to reduce the impact of the subjectivity associated with selecting mean damage ratios associated with each damage state, which requires detailed local engineering judgment and is highly uncertainty. The two damage states chosen are Slight, which assumes damage ratios in the range of 5-10%, and Extensive which assumes damage ratios of 80-85%. These damage states are more intuitive and easier to identify than intermediate damage states. The Slight damage state marks the state of a building with noticeable loss-causing damage, while Extensive defines a damage state in which the building approaches irreparable damage and becomes inoperable.

The combined approach for the development of the damage functions is also supported by the available regional technical literature, which primarily focuses on the frequency of tropical cyclones (Cyclone Resilient Landscape; Case for Madagascar; Esther Bergstra and Roxanne Hornman), historical flood events and their affected areas (Diagnosis of Flood and Plan of Actions in Seychelles; Government of Seychelles; 2015), historical disasters' parameters (Disaster Risk Profile of the Republic of Seychelles; Chang Seng, and Guillande; 2008), and an incomplete sample of Madagascar building types (Damage, Loss, and Needs Assessment for Disaster Recovery and Reconstruction after the 2008 Cyclone Season in Madagascar; 2008).

Due to absence of detailed pre- and post-disaster field surveys and limited literature and data detailing regional building construction practices and performance, the approach adopted herein is enhanced further by a building vulnerability and loss modeling consultant retained by AIR to conduct and manage the development of the SWIO vulnerability functions. The consultant's engineering judgement for parameters, exposure and importance weights, performance expectations of components and buildings, etc. is based on his experience on managing the development of vulnerability modules for major catastrophe modeling vendors (e.g., AIR, EQECAT, RMS, and Impact Forecasting), conducting post-event reconnaissance and damage survey after major catastrophes (e.g., Northridge, Chuetsu, Chichi, and Niigata earthquakes; Tropical Cyclones Pakka, Ivan, Isabelle, Bonnie), and managing the development of vulnerability modules for World Bank projects in Morocco, Belize and Vietnam.

Finally, vulnerability functions in other regions of the world are used as a benchmark in the development of component damage functions for the SWIO countries, by comparing them with regions with relatively similar construction practices. Countries identified by the vulnerability consultant for this purpose are Belize, Vietnam, Jamaica and Taiwan. The common characteristics used to select the countries with assumed similar construction practice with SWIO are the following:

- Small size:
    - Limited natural resources base, high competition over land-use, intensity of land-use, immediacy of interdependence in human-environment systems, spatial concentration of productive assets
- Insularity and remoteness:
    - High external transport costs, time-delays and high costs in assessing external goods, delays and reduced quality in information flows, geopolitically weakened
- Environmental factors:
    - Small exposed inland areas, large coastal zones
- Disaster mitigation capability:
    - Limited hazard forecasting ability, little insurance cover
- Demographic factors:
    - Limited human resources base, small population-size, rapid population-changes, single urban center, population concentrated on coastal zone, diseconomies of scale leading to higher capital costs for infrastructures and services
- Economic factors:
    - Small economies, dependence on external finance, small internal market, dependence on natural resources, highly specialization production

Additional information derived from field surveys of component performance after disaster events were also incorporated into the development of component damage states. Based on the methodology described above, the development of the building vulnerability functions in the SWIO region uses the following generalized steps and assumptions:

- Assume that buildings consist of four main components: Structure (C1), Envelope (C2), Non-Structural Elements (C3), and Foundation (C4).

- For each component, assume two damage modes: Slight (a), and Extensive (b)
- Assume that the damage of a component follows a lognormal distribution, according to standard practice (i.e., HAZUS-MH, ATC-58 recommendations).
- Assign parameters for the lognormal distributions based on technical literature, comparison with functions in similar regions, and engineering judgement to create damage functions for each component at each damage state (e.g. C1a, C1b).
- Calculate the component damage functions (e.g. C1) by weight-averaging the component damage function for the two damage states (e.g. C1a, C1b). The weights are established based on technical literature, comparison with functions in similar regions, and engineering judgement.
- Aggregate the component (i.e., foundation, structure, envelope and non-structural elements) damage functions using weights for each component to create damage functions for each construction type, for each peril. The weights are functions of the construction type and the peril and take into account the contribution of each component in the performance of each construction type and the importance of each component with respect to each peril. The choices for these weights are based on engineering judgment and regional construction practices.
- Generate Construction-Occupancy mapping matrix, which is a matrix of peril-dependent factors used to scale the damage functions for construction types to produce damage functions for corresponding combination of occupancies available in the exposure. The weights are suggested based on engineering judgment. An example of a construction-occupancy matrix is shown in Figure A.2.
- Generate vulnerability functions for all construction-occupancy combinations in the exposure and for each peril.

Construction-Occupancy Matrix		Single Story Frame, Timber/Wood Wall	Multi Story Frame, Timber/Wood Wall	Single Stor Masonry/Concrete,	Multi Story Masonry/Concrete	Traditiionbal Wood, Bamboo/Wood Wall	Traditiionbal Earthen, Stone	Other Single Story, Unknown Wall	Other Multi Story, Unknown Wall	Single Story Steel Frame	Multi Story Steel Frame
Height Band		1	2	1	2	1	1	1	2	1	2
RES	Single Family	105%		105%		105%	105%	105%		105%	
	Multi-Family		100%		100%				100%		100%
COM	Accomodation		95%		95%				95%		95%
	General	95%	95%	95%	95%			95%	95%	95%	95%
IND	General	110%		110%				110%		110%	
PUB	Education Primary	100%	100%	100%	100%			100%	100%	100%	100%
	Education University	90%		90%				90%		90%	
	Public Services	100%	100%	100%	100%			100%	100%	100%	100%
	Government		90%		90%				90%		90%
	Healthcare	110%		110%				110%		110%	
	Religion	110%		110%				110%		110%	

Figure A.2. Example of Construction-Occupancy Matrix

Validation of Vulnerability Functions

Due the unavailability of damage and claims data in the SWIO region, validation of the vulnerability functions is performed by comparing damage functions developed for the SWIO region with sets of damage functions developed by AIR in other regions with similar construction practices and similar hazard characteristics. The regions selected for validation are different than the ones used for the calibration process described previously, thus these comparisons represent independent evaluations of the SWIO functions. Validation is done against functions developed by AIR for the Philippines, South Pacific island-nations (SOPAC), Australia, and India. As noted previously, validation against recorded data was not performed as no detailed claims data split by construction type or occupancy class is publically available in the SWIO region for any historical catastrophic events. Examples of this validation are shown in the figures below for tropical cyclone wind (see Figure A.3) and earthquake shaking (see Figure A.4) for timber, traditional earthen, concrete/masonry and other construction types.

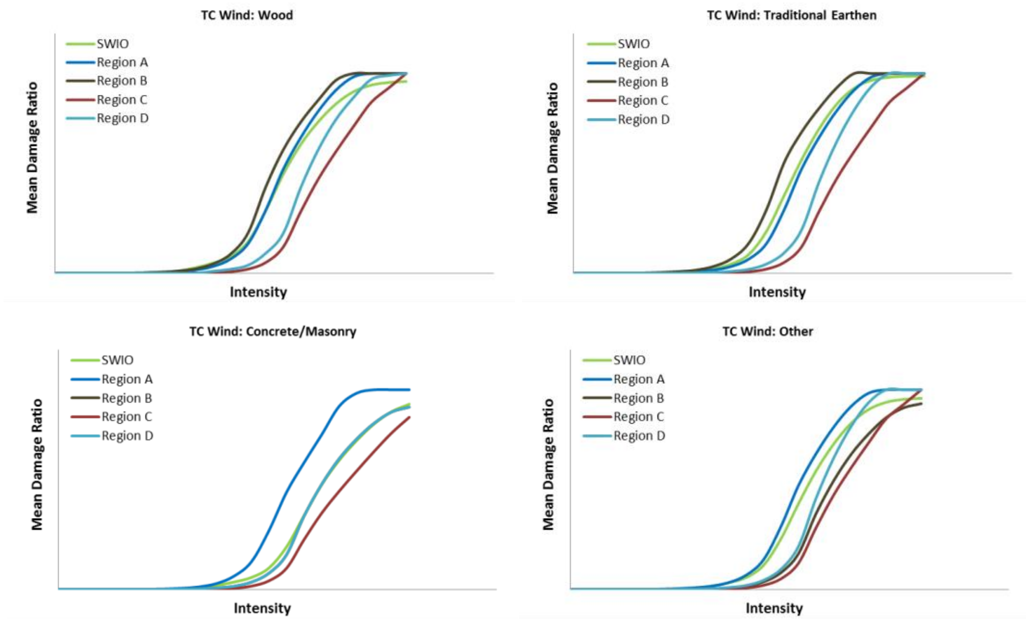


Figure A.3. Validation of the tropical-cyclone wind damage functions for SWIO with respect to other similar regions for timber, traditional, concrete/masonry and other construction types.

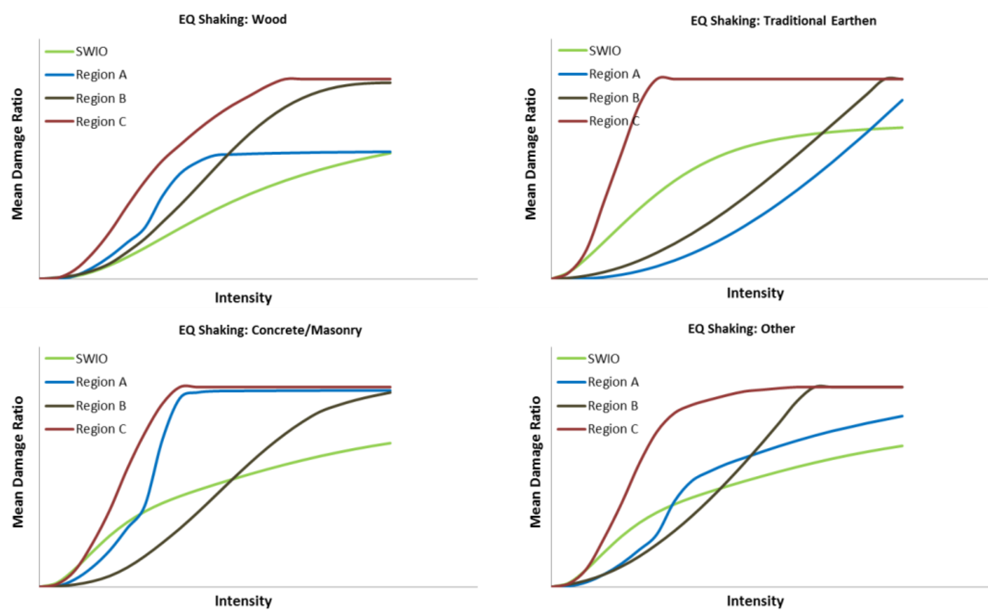


Figure A.4. Validation of the earthquake shaking damage functions for SWIO with respect to other similar regions for timber, traditional, concrete/masonry and other construction types.

Damage Functions for Infrastructure Assets

The development of the infrastructure damage function is based on AIR's proprietary vulnerability model and, therefore, a detailed description is omitted in this report. The damage functions for infrastructure assets are adapted from AIR's model in the South Pacific island-countries, which have similar construction practices as the island-nations in the SWIO region. The development of the damage functions for infrastructure assets follows a similar approach as that described for buildings, except that the damage functions are developed for typical assets in each vulnerability class and the validation and calibration is based on historical loss data in the South Pacific island-countries. Examples of infrastructure damage functions for earthquake shaking and tropical-cyclone wind are shown in Figure A.5.

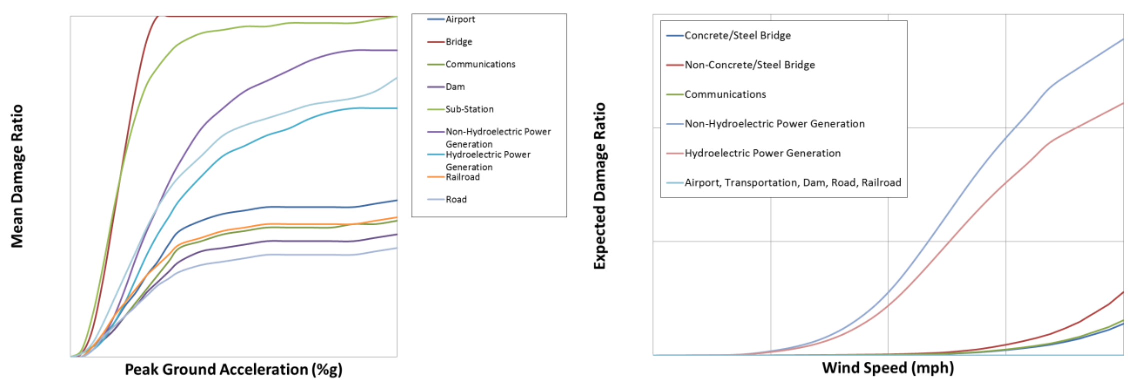


Figure A.5. Examples of Infrastructure Damage Functions for Ground Shaking (left) and Wind Speed (right)

Regional Modification

The SWIO damage functions for earthquake ground shaking, non-tropical cyclone flooding, tropical cyclone flooding, and tropical cyclone storm surge are assumed uniform throughout all the SWIO island nations. This assumption is a function of the scarcity of country-specific damage data and the generally good correlation between modeled and available reported losses. The tropical cyclone wind damage functions for Mauritius and Seychelles are modified to be less vulnerable than the SWIO base functions, which reflects the higher level of development and history of more stringent construction practices in Mauritius and Seychelles relative to the other investigated SWIO island nations. All damage functions for infrastructure assets are assumed uniform for all perils throughout the SWIO region.

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