Detailed Island Risk Assessment in Maldives

(Final report)

Volume I: Executive Summary

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1. Characterization of natural hazards

1.1 Major Hazards in the Maldives

The natural hazards prevailing in the Maldives can be categorized as follows:

- *Geological hazards:* Earthquakes and coastal erosion.
- *Meteorological hazards:* Tropical cyclones, tropical storms (strong wind), thunder storms and waterspouts.
- *Hydrological hazards:* Storm surges, swell waves, *udha*, tsunamis, heavy rainfall and drought.
- *Climate change related hazards:* Sea level rise, changes in precipitation, sea surface temperature rise, storm activity and swell waves.

Amongst these, the major hazards are tsunamis, swell waves, wind storms, heavy rainfall, storm surges, *udha*, droughts and earthquakes.

Tsunamis are the most destructive natural hazard observed for Maldives with predicted maximum wave heights between 3.2 to 4.5 m (MSL) in parts of the country. The event of December 2004 led to the only known significant fatalities in Maldives from a natural event and perhaps to the only event at a disaster scale. The waves are predicted to approach from the east as the most likely source for a significant tsunami is the Sumatran ridge located off the west coast of Indonesia. Swell waves and storm surges are the second most destructive with potential wave heights over 3.0 m (MSL). A difference is made between *Udha*, swell and storm surge events. Udha events occur annually during SW monsoon and cause low levels of flooding in most islands, almost always below 0.6 m (MSL). It is not known to be associated with single atmospheric or hydrologic events and is most likely the result of a combination of southern swell waves and onset of monsoon winds. Swell waves and surges are linked to specific atmospheric events which are more severe in intensity. Windstorms also have the potential to cause severe destruction across the islands especially during localised storm activity. Heavy rainfall and droughts can often cause disruptions within the islands but rarely cause significant damage. Rainfall hazards are almost always associated with improper human activities. Significant earthquake hazards are only present for the southern atolls.

Hazards can be expressed both by their severity and probability or frequency of occurrence. Often frequent hazards are less severe while infrequent rapid onset events could be catastrophic. The general patterns of hazard severity and frequency of occurrence in Maldives could be summarised in Figure 1.1.

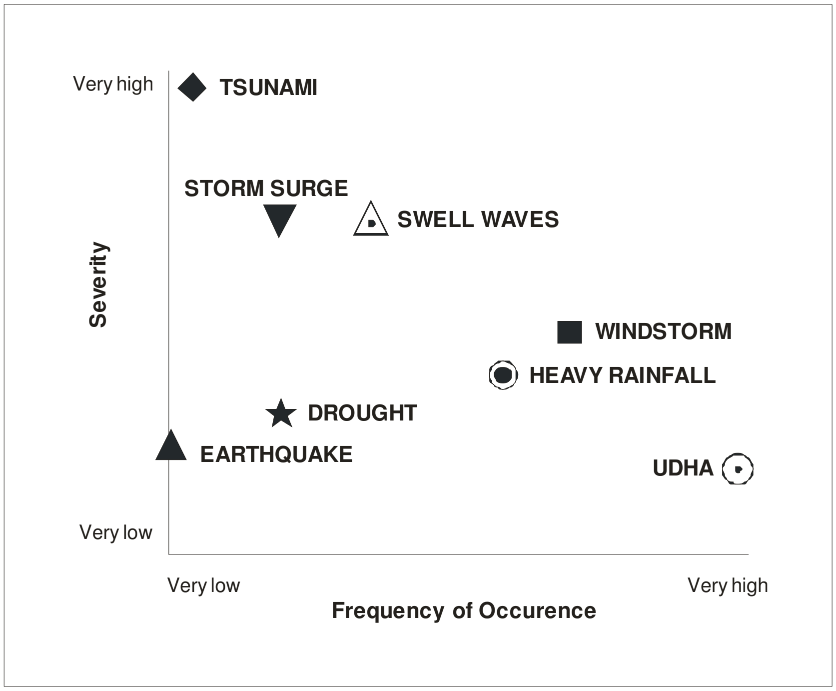

Figure 1.1 Relationship between hazard severity and frequency for major hazards

Tsunamis can be considered the most destructive hazard for Maldives but its frequency or probability of occurrence is very low. The event of December 2004 is often described as a once in a 219 year event (UNDP, 2006). Perhaps the most constant serious hazard to Maldives is the swell waves which have the potential to cause economic losses and socio-economic disruptions. Abnormal swell wave events have also been observed as more frequent since 1987. Heavy rainfall and windstorm are also significant hazards for majority of the islands due to their high frequency and potential to cause significant impacts. It should be noted that these findings are generalisations and the actual hazard patterns may vary between islands based on their geophysical setup.

1.2 Regional and Country Level Variations

Hazard patterns also vary across the archipelago and are influenced by the geophysical settings and climatic controls. Figure 1.2 and 1.3 shows a summary of latitudinal and longitudinal variation of hazards across the country. Cyclone hazards are highest in the north and very low in the south due to the proximity of northern latitudes to the cyclone belt. Hence, the possibility of the storm surges associated with the cyclones is also highest in the north. Swell waves are more prominent in the southern and western islands of Maldives due to the proximity to the Southern Indian Ocean and due to the predominant south westerly approach of the swell waves. Rainfall hazards are comparatively low in the north and highest in the south due to variations in rainfall and topographic setup. Conversely, the risk of drought is highest in the north and lowest in the south due to the same reason. Probability of earthquakes is highest in the south due to the proximity of the region to Carlsberg Ridge.

There are also longitudinal variations in hazards. The most notable being the occurrence of tsunami waves and their impacts. The eastern rim islands are predicted to have a higher intensity due to the direct exposure to waves, whereas the western rim and atoll lagoon islands are offered protection by the atoll formations. Impact of swell waves and udha events are also expected to be highest on the western rim island due to the south westerly and westerly approach of these events. However, their impacts aren't totally reduced on the eastern rim islands due to the propagation of swell waves through reef passes and wind fetch allowed within atoll lagoon.

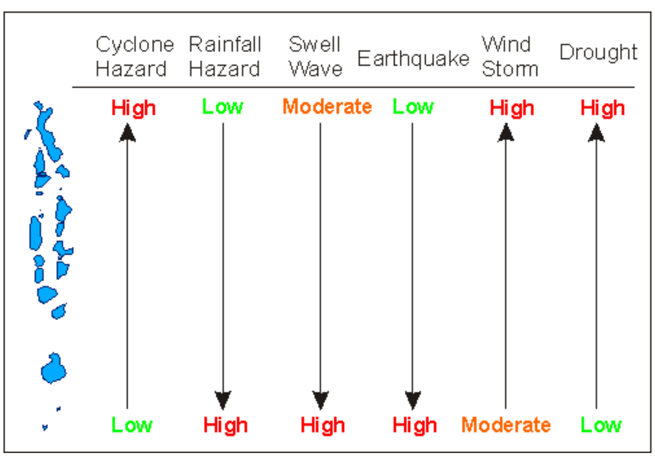

Figure 1.2 Latitudinal natural hazard variation across Maldives

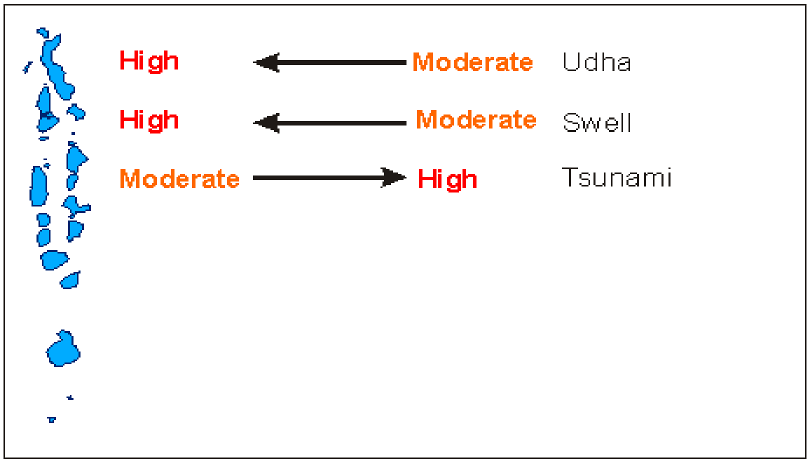

Figure 1.3 Longitudinal natural hazard variation across Maldives.

1.3 Island specific hazard patterns

Almost all islands are exposed to the major hazards explored in this assessment. However, their predicted intensities and probability of occurrence varies significantly. Table below summarises the island specific hazard scenarios including threshold level for intensity and probability levels for analysed hazards.

In general, the threshold level for wind damage is constant throughout the country as intensity is the same for an entire island or region in a given event. Flood related impacts vary over individual islands as other factors such as geophysical setup plays a crucial role in determining exposure. Topography and location within archipelago was found to be the most dominant geophysical factor for flood related hazards. These characteristics are explored in more detail in the physical environment vulnerability section.

The findings from island level hazard assessment confirm the variations in natural hazard intensity across different islands even within events of the same intensity. There appear certain thresholds for intensity which are controlled by geophysical factors. In events below this threshold, intensity could be substantially controlled. Occasionally this threshold is lower than the predicted highest intensity.

1.4 Implications for safe island development

Safe Island Development Programme dwells on the assumption that any island could be made safer using appropriate technology. The findings from this report both supports the claim but challenges some of the assumptions put in the current design of safe islands. It is recommended that the Safe Island Development Programme be reviewed in light of the findings of this report. Particular attention should be given to the following findings:

- There are no safe islands in Maldives. Each island has a maximum threshold level, especially for flood events, above which an event could flood the entire island regardless of its existing geophysical characteristics.
- All islands are generally exposed to natural hazards, but some islands are comparatively less exposed due geophysical setup of the island.
- It may be possible to control the impact of hazards for existing events using engineering solutions. However, suitability of adopted solutions to slow onset hazards such as climate change is questionable especially in the coral island environment.
- Safe Islands cannot be developed based on a standard set of designs such as a constant ridge height and artificial topography. If engineering options are to be adapted, it should be designed to withstand a predicted severe intensity event, if not a maximum predicted event specific to the island under consideration.

The main limitation for any hazard assessment is the level of uncertainty in them. Predictions are made from assessing historic event records and patterns within them. These predictions do not give exact values but probabilities of occurrence. They could often turn-out inaccurate when the worst disaster strikes. Moreover, events beyond that of historic records are treated as non-existent. In reality, there is a chance that an event of a specific high magnitude has not occurred in the life time of recorded history.

A second major limitation is that of data. Any information or prediction derived from natural hazard assessment is as good as the data used. Unfortunately, Maldives lacks critical data such as long term- climatologic data and severe event data. Moreover, the project had difficulty acquiring available meteorological data from the Department of Meteorology due to the newly introduced user-pays policy and the lack of resources to pay the high costs. Data had to be interpolated using the given sparse information available or restricted to the short term observations acquired freely from third-parties, in the case of climatologic data.

In conclusion this study has identified a practical methodology to understand and quantify the natural hazards faced by the proposed safe islands or any inhabited island of Maldives. The findings could be used in enhancing the Safe Island Development Programme and to better understand the hazard exposure in other islands of Maldives.

Table 1.1 Summary of hazard scenarios for the studied islands.

Island		Tsunami			Swell Waves			Storm Surge/Tide			Heavy Rainfall			Strong Wind		
	Intensity	Max (m)	Threshold (m)	Prob	Max (m)	Threshold (m)	Prob.	Max (m)	Threshold (m)	Prob.	Max (mm)/ 24hr	Threshold (m)	Prob.	Max (knts)	Threshold (m)	Prob.
H.Dh Kulhudhuffushi	High		> 3.2	v. Low		> 3.0	Low		> 3.0	v. Low		>160	Low		>45	Mod
	Mod	5.2	> 2.5	Low	Na	> 2.5	Mod	2.9	> 2.5	Low	176	>60	Mod	96.8	>30	High
	Low		< 2.5	Mod		< 2.3	High		< 2.3	Mod		<60	High		<30	v.High
Sh. Funadhoo	High		> 3.0	v. Low		> 3.0	Low		> 3.0	v. Low		>150	Low		>45	Mod
	Mod	5.2	> 2.3	Low	Na	> 2.3	Mod	2.9	> 2.3	Low	176	>70	Mod	96.8	>30	High
	Low		< 2.3	Mod		< 2.3	High		< 2.3	Mod		<70	High		<30	v.High
K. Thulusdhoo	High		> 3.0	v. Low		> 3.0	Low		> 3.0	v. Low		>175	Low		>45	Mod
	Mod	5.2	> 2.3	Low	Na	> 2.3	Mod	2.23	> 2.3	Low	176	>60	Mod	84.2	>30	High
	Low		< 2.3	Mod		< 2.3	High		< 2.3	Mod		<60	High		<30	v.High
Dh. Kudahuvadhoo	High		> 3.0	v. Low		> 3.0	Low		> 3.0	v. Low		>160	Low		>45	Mod
	Mod	3.9	> 2.3	Low	Na	> 2.3	Mod	2.23	> 2.3	Low	241	>60	Mod	69.6	>30	High
	Low		< 2.3	Mod		< 2.3	High		< 2.3	Mod		<60	High		<30	v.High
Th. Vilufushi	High		> 4.1	v. Low		> 4.1	Unlikely		> 4.1	Unlikely		>175	Low		>45	Mod
	Mod	5.2	> 3.4	Low	Na	> 3.4	v.Low	2.23	> 3.4	Unlikely	241	>75	Mod	69.6	>30	High
	Low		< 3.4	Mod		< 3.4	Mod		< 3.4	Low		<75	High		<30	v.High
L. Gan	High		> 2.7	v. Low		> 2.7	v.Low		> 2.7	Unlikely		>175	Low		>45	Mod
	Mod	5.2	> 2.0	Low	Na	> 2.0	Low	2.23	> 2.0	v. Low	241	>60	Mod	55.9	>30	High
	Low		< 2.0	Mod		< 2.0	Mod		< 2.0	Low		<60	High		<30	v.High
GA. Viligilli	High		> 2.7	v. Low		> 2.7	v.Low		> 2.7	Unlikely		>175	Low		>45	Mod
	Mod	5.2	> 2.0	Low	Na	> 2.0	Low	0	> 2.0	v. Low	248	>60	Mod	<55.9	>30	High
	Low		< 2.0	Mod		< 2.0	Mod		< 2.0	Low		<60	High		<30	v.High
G.dh Thinadhoo	High		> 2.7	v. Low		> 2.7	Low		> 2.7	Unlikely		>175	Low		>45	Mod
	Mod	3.2	> 2.0	Low	Na	> 2.0	Mod	0	> 2.0	v. Low	248	>60	Mod	<96.8	>30	High
	Low		< 2.0	Mod		< 2.0	High		< 2.0	Low		<60	High		<30	v.High
S. Feydhoo	High	3.9	> 2.7	v. Low	Na	> 2.7	Low	0	> 2.7	Unlikely	248	>175	Low	<96.8	>45	Mod

	Mod		> 2.0	Low		> 2.0	Mod		> 2.0	v. Low		>60	Mod		>30	High
	Low		< 2.0	Mod		< 2.0	High		< 2.0	Low		<60	High		<30	v.High
S. Hithadhoo	High		> 2.7	v. Low		> 5.0	v.Low		> 5.0	Unlikely		>175	Low		>45	Mod
	Mod	3.9	> 2.0	Low	Na	> 4.0	Low	0	> 4.0	v. Low	248	>75	Mod	<96.8	>30	High
	Low		< 2.0	Mod		< 4.0	High		< 4.0	Low		<75	High		<30	v.High

2. Environmental vulnerability

The physical environment aspect of this study has evaluated the hazard exposure of the natural environmental features, their resilience and vulnerabilities, and the implications for safe island development. Detailed attention was paid to existing ocean induced hazards as they pose the biggest threat to the natural environment. Elements of climate change and sea level rise are broadly assessed. This section provides a summary of individual island assessments.

Generally, the natural environment of Maldives is known to be highly resilient. The very fact that islands have survived over 3000 years amidst fluctuating sea level, varying climatic conditions and numerous natural hazard events is evidence of their natural resilience. Hazard events such as sea induced flooding may have been regular events across the archipelago over hundreds of years. Such events rarely destroy an islands vegetation system, modify its geomorphology or even damage healthy coral reefs. If damages or changes do occur, the natural recovery and adaptation is known to be rapid in terms of the geological timescale. In order for the islands to remain resilient, the formula is simple: maintain its natural environment. In the face of human habitation and the desire for continued development in the islands, the hazard events while tolerated by the natural environment have become life threatening and unacceptable to human beings. Human alteration of natural environment has further led to implications for their natural resilience against hazards. This study therefore is more aligned towards a human perspective of hazard exposure.

2.1 Natural vulnerabilities and assets to hazards

This study has confirmed the presence of certain natural vulnerabilities and assets against major natural hazards, especially sea induced flooding hazards. The key geophysical features include, island size, width, topography, coastal vegetation, inland vegetation, geographic location within reef, atoll and archipelago, size of water lens and the health of marine environment. On one end of the spectrum, these feature become assets to natural hazard mitigation while on the other end it become vulnerabilities. Table 2.1 shows a summary of the key features in the 10 islands studied.

Table 2.1 Summary of key geophysical characteristics of surveyed islands

Island	Land Area (ha)	Average Elevation	Width of Coastal vegetation Belt (narrowest; oceanward side)	Coastal Ridge Height (ocean ward)	Coastal Ridge Height (lagoon ward)	% of Vegetation Cover	Island Width
H.Dh Kulhudhuffushi	195.5	1.4m	70m	2.4m	1.1m	48%	700-900m
Sh. Funadhoo	84.5	1.1m	40m	1.8m	1.4m	57%	150-500m
K. Thulusdhoo	38	1.4m	10m	1.7m	0.8m	35%	550 – 800m
Dh. Kudahuvadhoo	69.7	0.88m	300m	1.5m	1.0m	55%	880
Th. Vilufushi	61	1.1m * (1.4m)+	0 m (20m)	1.5m (2.4m)	0.8m (1.4m)	15%	550
L. Gan	582	0.9m	15m	1.5m	0.8m	75%	400-1500m
GA. Viligilli	54.8	0.7m	10m	1.3m	1.1m	45%	180-600m
G.dh Thinadhoo	115.5	1.1m	0 m	1.6m (1.9m)	1.0m	27%	745 – 900m
S. Feydhoo	62.5	1.0m	10m	1.5m (2.0m)	0.9m (1.2m)	37%	550m
S. Hithadhoo	523.9	1.0	5m	3.6m	0.7m	48%	600-1800m

* *Original island data* + *Reclaimed island data*

The most dominant of these features against sea induced hazards are the island size, width and topography. In general terms, larger islands are more geologically stable, and resilient to hazards such as coastal erosion and inundation. Smaller islands tend to dramatically shift its position in the reef system over time and are more likely to be completely inundated during flooding events. Size itself may be misleading as width of the island is as crucial against flood events. Certain gravity waves such as tsunami's and long distance storm waves have specific wave lengths which could run-up over land regardless of the island size. If the island is narrow and oriented parallel to the waves, a larger wavelength could completely inundate an island while wider islands would restrict the extent of inundation from a similar wave. This pattern is partly evident in the difference in flooding between narrower islands such as L.Fonadhoo, Th. Vilufushi, GA. Viligilli and the larger islands such L.Gan and Dh. Kudahuvadhoo.

Island topography is on one of the main natural vulnerabilities as well as the most efficient natural mitigation measures against flooding. Maldivian islands are generally low lying with all the island studied having average elevations below 1.5m. The difference in resilience to flooding lies in the oceanward ridge height. The higher the ridge system the more resilient the island is to flooding events. Ridges are generally a response to high wave energy and storm activity, and vary geographically across the archipelago. The northern and southern atolls which are more exposed to storm events and monsoonal winds generally have higher ridges, while islands in the mid atolls which are less exposed do not have substantial ridges. The island size and width may be of little help during flooding events if the oceanward ridges are substantially low. For example, flood waters during the tsunami of 2004 reached 1000m inland in L.Gan where the ridge height is just 1.5m while it failed to overtop the 2.4m high ridge in H.Dh Kulhudhuffushi. While high ridges protect the oceanward side of the island, the lagoonward side, which are generally low lying (see table 1), remain highly exposed. Island with high oceanward ridges are likely to be resilient to gravity waves and surges from the ocean ward side but remain exposed to storm surges, seasonal surges (Udha) and long distance storm waves approaching from the lagoonward side. Unfortunately most settlements are located on the lagoon ward coastline, exposing them to such flooding events.

The topographic profile within the island was also found to facilitate or prevent flood run-up. Usually, circular islands or large islands tend to form depressions in the middle as island evolves over time (eg. Dh. Kudahuvadhoo, K. Thuludhoo, L.Gan and S.Hithadhoo). Some islands, especially narrow and elongated islands tend to have relic ridge systems within the island. Island with low depressions without high ridge systems are more exposed to flood run-up due to the inward sloping gradient. Extensive flooding in L.Gan and GA. Viligilli was believed to be caused by such depressions and low ridges. Islands with inland relic ridge systems have a distinct advantage in controlling flood run-up as they form a barrier against further run-up. Examples of such systems were found in Dh.Kudahuvadhoo, K.Thuludhoo and G.Dh. Thinadhoo. In almost all islands studied, the extent of 2004 tsunami flood run-up is marked by a distinct change in topography. Unfortunately, the depressed areas make good agricultural land due their proximity to watertable and are often characterised by less salt tolerant vegetation species. At times of flooding widespread mortality is eminent especially amongst introduced species. The island of GA. Viligilli lost 90% of its Mango and Bread fruit trees during the tsunami of 2004, which were incidentally located within former wetland areas. Settlements located within the depressed zones are also more likely to experience regular flooding during high rainfall. Islands in the south are particularly exposed to such flooding due to high rainfall and due to the presence of wetlands.

Coastal vegetation was also found to play an important role in reducing wave energy propagation on land. However, vegetation does not appear to restrict the extent of run-up, especially during the 2004 tsunami, since the entire wavelength was disposed regardless of the obstructions. The effects during storm surges are expected to be similar. A strong coastal vegetation belt is found to be ideal as natural mitigation measure when formed in high ridge system and with certain vegetation composition and density. Usually in inhabited islands, the undergrowth in coastal vegetation is cleared for aesthetic reasons. However it was found that undergrowth is a key element of a coastal vegetation belt in terms of reducing wave and wind energy.

Island location within the archipelago or within the atoll exposes them to different natural hazards. Islands on the eastern rim of atolls are more exposed to tsunami’s while islands within the atoll and on the western side are comparatively less exposed. Islands in the south are more exposed to southwest monsoon related surges and long distance swells originating from the southern Indian Ocean. Islands in the north are more exposed to storm events and their impacts including storm surges and strong wind. Islands in the south are more exposed to rainfall related flooding due to high rainfall. Island on the eastern rim of open atolls[1] such as the northern atolls are exposed to south west monsoon related flooding due to wave activity and low elevation of lagoon ward side.

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[1] Defined as atolls with larger reef passes or *Kanduolhi,* allowing propagation of waves through the atoll

Other geographic features which increase the resilience of islands include a large water lens and healthy marine environment.

2.2 Human-induced vulnerabilities

In addition to the natural environment vulnerabilities identified above, a number of human activities have led to further deterioration of the natural vulnerabilities and introduction of new vulnerabilities. The most serious impacts appear to result from the alteration of topography and coastal environment, and from improper land use patterns. Alteration of topography involves land reclamation and road maintenance activities. As noted above, islands have natural variations in topography which facilitates drainage. Similarly the oceanward coastline retains natural defences against prevailing sea induced hazards. Land reclamation on the reef flat, especially on the oceanward size alters the natural defensive mechanisms of the islands and the drainage systems. This is usually the result poor land reclamation practices which at present do not take impacts on natural features of an island into consideration. In the island of Thinadhoo, land was reclaimed close to the wave breaker zone without considering the natural elevation of ridges or the existing topography of the island. As a result the reclaimed area is frequently flooded during South West monsoon high tides (Udha) and during heavy rainfall. Land reclamation in wetland areas often does not consider the implications on island topography and drainage systems. As a result subsequent developments in the region are subject to frequent rainfall related flooding as found in GA. Viligilli, G.Dh Thinadhoo, Hdh. Kulhudhuffushi and S. Hithadhoo.

Alteration of coastal environment through development activities such as harbour construction, beach erosion mitigation and land reclamation often alter the coastal processes operating around the island. As a consequence most islands undergo rapid transformation in coastal processes, in some cases leading to coastal erosion and decrease in natural adaptive capacity against hazards. Similarly land use patterns in the islands have major impacts on the natural defensive systems of an island. Land uses with negative impacts include encroachment of settlement into coastal vegetation belt and subsequent removal of vegetation protection, and alteration of the protective oceanward ridges. These areas should be considered buffer zones against natural hazards which are bound to be affected during hazard events. Development in the zone usually guarantees exposure of such structures to hazards.

Removal of vegetation for settlement purposes is another factor which further exposes islands to natural hazards. Strong vegetation cover minimises the impact of strong winds. However, demand for housing land is leading to gradual decline in vegetation cover across highly populated islands. Similarly, gradual deterioration of the natural environment due human habitation is slowly decreasing the natural resilience of the islands and its surroundings. The most critical of these are the deterioration of coral reefs around inhabited islands and salinisation of ground water due to over extraction.

2.3 Environmental impacts

As noted earlier, the natural environment of Maldives in very resilient to periodic natural hazards. Significant impacts from hazard events are usually limited to vegetation and geomorphology. Vegetation is hardest hit for introduced species such as crops and large fruit trees (eg. mango and breadfruit). Natural processes tend to adapt these changes and recover rapidly, although vegetation regrowth of larger trees may be slow. Often natural events have positive impacts on the environment with stronger defensive systems established due alteration of coastal geomorphology (eg. creation of coral ramparts in Sh.Funadhoo) and with re-distribution of vegetation species and nutrients across the island. Such positive impacts, although small, provide long term benefits for the environment.

The environmental impacts from sea level rise are much more complicated to predict at this stage. There are two scenarios. First, if the sea level continues to rise as projected and the coral reef system keep up with the rising sea level and survive the rise in Sea Surface Temperatures then, the negative geological impacts are expected to be negligible. Second, if the sea level continues to rise as projected and the coral reefs fail to keep-up, then their could be substantial changes to the land. The question whether the coral islands could adjust to the latter scenario may not be answered convincingly based on current research. However, it is clear that the highly, modified environments of islands studied here, stands to undergo substantial change or damage (even during the potential long term geological adjustments), due to potential loss of land through erosion, increased inundations, and salt water intrusion into water lens.

2.4 Recommendations for safe island development

Recommendations for Safe Island development have been made for each island based on the physical environment risk assessment and are provided for individual island in the following chapters. The generalised summary of key recommendations is as follows:

- Alterations to physical environment will have consequences for hazard exposure in any island. Current high impact development activities need to be re-evaluated and streamlined to minimise impacts on hazard exposure. Land reclamation activities require urgent attention in this regard. The regulations and best practices guide for reclamation needs to be established based on informed studies. Potential steps that can be considered include replicating defensive features of natural environment such as proper topographic profiling, soil profiling, revegetation, drainage establishment and minimise construction phase negative impacts on the environment.

- A number of vulnerabilities already exist on the surveyed islands. It is important that the most critical environmental vulnerabilities be addressed within any safe island development programme. These include restoring terrestrial and marine environment, addressing negative affects of past improper reclamation activities and protecting exposed zones in the islands.

- Elements proposed in the present safe island development concept needs to be reviewed based on the findings from this study. Some elements require further studies to determine the appropriateness but others should be reviewed immediately. These include the drainage zones, vegetation belt and their proposed functions within the EPZ zone, and the concept of topographically raised evacuation zones. The vegetation zone needs to reconsider their width, composition and timely introduction within the broad development programme. Constant height of ridges needs to be reviewed as there are different wave regimes across different zones and location in Maldives.

- Population consolidation increases the risk of exposure to hazards, if consolidation is taking place in a known vulnerable location and if mitigation measures are non-existent. Consolidating population creates high density settlements which itself exposes more people in single location should the hazard strike in that location. Evidence from other high density settlements show that development takes priority in such islands and hazard risks are often ignored. It is therefore imperative that hazard mitigation is incorporated as an essential part of general land use planning within the Population Consolidation Programme and not just Safe Island development programme.

In conclusion, none of the islands in Maldives is safe from the high impact natural hazards facing them. The natural environment is highly resilient to impacts from hazard events, but may not prevent or protect the islands from major hazard events. However, the probabilities of such large scale hazards are low and perhaps unavoidable with any practical level of planning. The majority of present hazards facing Maldives, however, can be avoided through natural resilience, proper land use and artificial means. It is crucial that development activities in Maldives be aligned to consider precarious nature of islands and impacts from natural hazards. The natural environment has provided the best examples of mitigation measures through their defensive mechanisms. It's important that these mechanisms be maintained and facilitated where present. If artificial measures are required, replicating the natural systems perhaps may provide the most efficient defensive system for Maldives.

3. Structural vulnerability

3.1 House vulnerability

Most vulnerable houses are found on Hithadhoo and Feydhoo Islands, followed by Viligili, Thinadhoo, Kulhudhuffushi, and L. Gan. However, Feydhoo and Viligili Island have the highest percentage of vulnerable houses, more than 20%; L. Gan, Thinadhoo and Hithadhoo 10-20%; and Vulnerable houses on Kulhudhufushi and Funadhoo Island account for less than 10% only.

The regionality of the house vulnerability is prominent. In the north, structural factor dominates the house vulnerability. For example, the vulnerable houses identified on Kulhudhuffushi and Funadhoo are without exemption due to their weak structure. This implies that houses on these islands are well protected against ocean-originated flooding and not exposed to road flooding. However, from north to south, non-structural factors (i.e. protection and location) become dominant. For example, L. Gan and Ga. Viligili in the middle of the Maldives, are exposed to ocean-originating flooding either without proper protection or too close to shoreline in the ocean-originated flood-prone area. Weak structure plus poor protection makes the houses of these islands especially vulnerable to flooding events. In the south, islands such as Thinadhoo, Hithadhoo, and Feydhoo are less exposed to ocean-originated flooding, but houses on these islands are extensively subjected to household-wide flooding, a human-induced flood due to the improperly raising of the road surface.

Some characteristics of the house vulnerability are summarized in Table 3.1.

Table 3.1 Summary of house vulnerability.

Island	# of Vul. H.	% Vul.H. of total houses	Vul. Type	Vulnerable house groups						
				WB	WB PP	WB LE	WB PP LE	PP	LE	PP LE
H.dh.	62	6.2	WB-	62	0	0	0	0	0	0

Kulhudhuffushi			dominated							
Sh. Funadhoo	8	2.1	WB-dominated	8	0	0	0	0	0	0
K.Thulusdhoo	-	-	-	-	-	-	-	-	-	-
Dh. Kudahuvadhoo	-	-	-	-	-	-	-	-	-	-
Th. Villufushi	-	-	-	-	-	-	-	-	-	-
L.Gan	53	14.1	WB-PP-dominated	28	5	1	0	19	0	0
Ga. Viligilli	91	23.2	WB-PP-dominated	23	6	2	10	44	2	4
G.dh. hiThinadhoo	80	10.8	WB-LE-dominated	40	0	11	0	17	12	0
S. Hithadhoo	248	13.4	WB-LE-dominated	111	8	37	0	27	65	0
S. Feydhoo	195	34.9	LE-dominated	9	0	38	5	29	114	0

Note: WB-Weak building; PP-Poor protection with respect to ocean-originated flooding; LE-House plinth lower than its adjacent road surface.

3.2 Houses at risk

In terms of the exposure of houses, tsunami flooding should be the No. 1 flooding hazard in the Maldives. On Thulusdhoo, Vilufushi, Gan, and Viligili Islands, around 80% of the existing houses are exposed to tsunami flooding. Kulhudhuffushi and Funadhoo have 30-40% of the houses exposed and Kudavadhoo and Thinadhoo less than 20%. There is no house exposure to tsunami flooding on Hithadhoo and Feydhoo Islands. Tsunami flooding is the most destructive hazard as well. As shown in Table 5.2, most moderate to serious damage to houses is caused by tsunami flooding. However, population displacement due to house damage is not that high, around 2%. The highest population displacement may occur on Viligili Island, reach up to 3.2% of the total population; Vilufushi and Gan 2%; the rest of islands less than 1%.

The exposure of houses to rainfall flooding is high as well. On Hithadhoo and Feydhoo, around 60% of the existing houses are located in the rainfall flood-prone area, subjected to up to 0.5 m high flooding. Thulusdhoo and Kudavadhoo have the moderate exposure, with a rate of 20-40%. On Kulhudhuffushi and Funadhoo, a few houses are exposed to rainfall flooding. Most rainfall floods, with a maximum water depth of 0.5 m, don't result in physical damage to houses, but they do affect the contents within them.

The house exposure to swell wave/surge flooding is high on the islands in the middle and south of the Maldives. On Thulusdhoo and Gan, more than 50% of the existing houses are exposed and Feydhoo around 30%. The house exposure on Thinadhoo, Villigili and Hithadhoo is less than10% of the existing houses. Potential damage caused by swell wave/surge flooding is slight, given a water depth of 0.5-1.0 m.

More details on house exposure and corresponding potential damage are summarized in Table 3.2.

Table 3.2 Summary of houses at risk.

Island	Major Haz.	# of H. Exp.	% Exp. of total	# of Vul. H.	Potential damage				Displ. POP (% of total)
					Serious	Moderate	Slight	Content-affected	
H.dh. Kulhudhuffushi	TS	279	28%	21	0	4	17	258	0.2%
	RF	85	8.5%	0	0	0	0	0	0%
Sh. Funadhoo	TS	135	36%	0	0	0	0	0	0%
K. Thulusdhoo	TS	111	79%	n.a.	0	17	63	31	4.4%
	WS	71	51%	n.a.	0	0	0	71	0%
	RF	27	19%	n.a.	0	0	0	27	0
Dh. Kudavadhoo	TS	19	8%	n.a.	0	0	0	19	0%
	RF	53	23%	n.a.	0	0	0	53	0%
Th. Villufushi	TS	678	89%	n.a.	0	66	362	250	2%
L.Gan	TS	336	89%	44	5	29	10	292	2%

	WS	206	55%	32	0	0	13	174	0%
Ga. Viligilli	TS	317	80%	85	4	55	25	233	3.2%
	WS	54	14%	23	0	0	5	49	0.1%
	RF	141	36%	32	0	0	5	136	0.1%
G.dh. Thinadhoo	TS	116	16%	19	0	16	3	97	0.4%
	WS	60	8%	2	0	0	1	59	0%
	RF	213	29%	11	0	0	2	211	0%
S. Hithadhoo	WS	134	7%	6	0	0	6	128	0%
	RF	1045	57%	123	0	0	97	948	0.3%
S. Feydhoo	WS	192	34%	70	0	0	19	173	0.2%
	RF	341	61%	117	0	0	31	310	0.3%

Note: The numbers marked in red are not calculated based on the vulnerability assessment, rather in terms of their exposure to hazard intensity. TS-Tsunami; WS-Wave/surge; RF-Rainfall.

3.3 Critical facilities at risk

All facility buildings of the targeted islands have strong foundations and are well structured. They are well protected with strong, well-structured boundary wall, as well. Most buildings of critical facilities are physically resistant to any floods of 0.5-1.5 m water depth. However, for those that are located in the destructive tsunami flooding zone, moderate damage can be expected. All facility buildings are resistant to earthquake according to their building codes and the maximum PGA prevailing in the Maldives. Table 3.3 summarizes critical facilities at risk associated with major hazards of each targeted island.

3.4 Functioning impacts

The functioning impacts of physical damage were not investigated during this survey. The data given in Table 3.4 are just based on a few occasional interviews with islanders. So, Table 3.4 should be used with caution and for reference only.

Table 3.3 Critical facilities at risk

Island	Major Haz.	Exposed	Vulnerable	Potential Max. Damage
H.dh. Kulhudhuffushi	TS/WS	1 power house, 1 waste site	power house, waste site	slight
	RF	2 schools, 1 mosque	none	no
Sh. Funadhoo	TS/WS	Proposed waste site & power house	?	?
K. Thulusdhoo	TS	2 communication sites, 1 mosque, 1 office, 1 waste site, transformers	Wataniya site	serious
	WS	2 communication sites, 1 mosque, 1 office	none	content-affected
	RF	1 schools, 1 office	none	no
Dh. Kudavadhoo	TS/WS	Power house, waste site	none	no
Th. Villufushi	TS	1 power house, 5 transformers or pump stations, part of a waste site and 1 school	?	?
L.Gan	TS	3 power houses, 1 hospital, 3 island office, 4 schools, 3 mosques, 3 communication sites, 2 proposed waste water plans, 2 proposed waste sites	1 school, 1 proposed waste water plant	moderate-serious
	WS	1 power houses, 2 island office, 3 schools, 2 mosques, 2 communication sites, 2 proposed waste water plans, 2 proposed waste sites	none	no
Ga. Viligilli	TS	1 hospital, 1 power house, 2 communication sites, 1 waste site	Hospital, power house, waste site	content-affected
	WS	Oil storage, hospital	none	content-affected
	RF	1 mosque, 1 hospital, 1 wataniya site	none	no
G.dh. Thinadhoo	TS	1 island court, 1 hospital, 1 mosque, 1 warehouse	none	content-affected
	WS	2 proposed mosques, 2 proposed nursery schools	none	?
	RF	2 schools, 4 mosques, 1 power house	none	content-affected
S. Hithadhoo	WS	4 mosques, 3 schools, 4 admin offices, 1 communication site, 1 TV cable	none	content-affected
	RF	12 mosques, 7 schools, 5 admin offices, 2 communication sites	none	content-affected
S. Feydhoo	WS	2 mosques, 1 Wataniya site	none	no

	RF	1 hospital, 3 mosques, 2 schools, 1 island office, and 1 media center	none	no

3.5 Recommendations for risk reduction

Some options for risk reduction from physical perspectives are summarized in Table 5.5 and briefly explained as follows:

- **Location of key critical facilities (Land use planning):** Avoid locating key critical facilities, such as hospital, power house, waste site, storage, in the destructive hazard zone, because the failure of these key critical facilities has community-wide adverse impacts and especially important to emergency response and disaster relief.
- **Enhancement of building codes:** The enhancement of building codes may differ from hazard zone to hazard zone. Options for ocean-originated floods, i.e. tsunami and swell wave/surge inundation, should focus on strong building in the destructive hazard zone, supplemented by strong boundary walls with appropriate height and proper orientation of the buildings with respect to wave propagation direction. In contrast, options for rainfall floods are strong foundation with proper height. In terms of the potential sea level rise of 30-50 cm, a height of 0.5 for house plinth level should be reasonable, in particular, in the rainfall flood-prone areas that were originally reclaimed from wet lands.
- **Protection and improvement of natural drainage systems:** Avoid the degradation of natural drainage systems while constructing critical infrastructure, such as road, harbour, etc. or reclaiming land from wetlands. Improper leveling of the ground may cause unexpected flooding to other areas that are not affected before. Two of the typical examples are the road maintenance applied on the south islands of the Maldives and the harbour construction. The former has resulted in household-wide flooding in its adjacent households and the latter has made the loading and unloading area subjected to flooding frequently due to the blockage of natural groundwater flow systems.

- **Hazard mitigation**: Under circumstances, hazard mitigation might be one of the cost/effective options for risk reduction, in comparison with the costly extensive retrofit of houses and critical facilities. For example, EPZ (Environmental Protection Zone) with a proper width and a ridge of proper height is a good option for mitigating flooding induced by ocean-originated hazards. Although EPZs may not significantly reduce the width of the destructive tsunami zones (an area with an inundation depth of more than 1.5 m), they can reduce the whole hazard extent dramatically. The width of an EPZ and the height of a ridge can be determined in terms of the hazard intensity, geomorphology of the hazard site, and the risk level of elements exposed. For rainfall flood-prone areas, natural drainage systems should be considered.
- **Retrofit of buildings:** If hazard can not be mitigated, retrofit of buildings is mandatory option. However, this approach might be uneconomic and irresolvable. For example, it has been recognized that many household-wide floods are found not due to the natural reasons, rather than because of improper human activities-preventing road flooding by raising the road surface. It has been a dilemma to mitigate such a flood type.
- **Maintenance of roads**: On the islands in the south Maldives, i.e. Thinadhoo, Viligili, Feydhoo, and Hithadhoo, raising the road surface to avoid road flooding has caused extensive household-wide flooding. A comprehensive solution has to be found to mitigate road and house flooding on these islands.

Table 3.4 Potential functioning impacts

Island	Major Haz.	Admin.	Health Care	Education	Religion	Power Supply	Water Supply	Transport	Communi -cation	Sanitation
H.dh. Kulhudhuffushi	TS					A day				A few days
	RF									A day
Sh. Funadhoo	TS					days - a week				localized secondary contamination
K. Thulusdhoo	TS				days				days	
	WS									
Dh. Kudavadhoo	TS/WS					A day				A few days
Th. Villufushi	TS									
L.Gan	TS	A few days	A day	A few weeks	days	a few weeks (PH12.4)				localized & months secondary contamination
	WS			A few weeks	A day					
Ga. Viligilli	TS		A few weeks			A week				
	WS		days							
	RF									A few days
G.dh. Thinadhoo	TS	A day	A day	A day	A day			days		
	WS			A day	A day					
	RF			A day	A day					A few days
S. Hithadhoo	WS									

	RF			1-2 days				A few days		A few days
S. Feydhoo	WS					days				A day
	RF			days						Island-wise, 3 -5 days

Table 3.5 Summary of recommended risk reduction options.

Islands	Risk reduction options	
	Prevention	**Mitigation**
H.dh. Kulhudhuffushi	• Enhance building codes in the rainfall flood-prone area in the north of the island, specifically, a plinth level of 0.5 m high above the ground is strongly recommended for new houses considering 30-50 cm sea-level rise.	• Mitigate ocean-originated flooding at the southern end of the island by setting up an EPZ with a proper high ridge (not definitely 2.4+); or • Retrofit power house, waste site and MCPW.
Sh. Funadhoo	• Avoid locating proposed power house and waste site in the ocean-originated flooding area.	
K.Thulusdhoo	• Avoid locating waste site in the flood-prone area to avoid secondary contamination. • Enhance building codes and protection in the ocean-originated flood-prone areas.	• Retrofit Wataniya site to be resistant against more than 1.5 m flooding.
Dh. Kudahuvadhoo	• Avoid locating proposed waste disposal site and waste water plant in the flood-prone area.	• Retrofit the power house on the northern coast of the island.
Th. Villufushi	• Avoid locating key critical facilities (i.e. waste water plants and disposal sites) in the intense hazard-prone area. • Enhance building codes in the hazard-prone area.	
L.Gan	• Avoid locating key critical facilities (i.e. waste water plants and disposal sites) in the intense hazard-prone area. • Enhance building codes in the ocean-originated flood-prone area on the eastern coast.	• Mitigate ocean-originated flooding by setting up a proper EPZ on the eastern coast. In particular, an EPZ with a buffer zone of proper width is required for the Mukurimagu coast; • Retrofit the power house and school in the Mukurimagu division, if no proper EPZ is available along the Mukurimagu coast.
Ga. Viligilli	• Enhance building codes in the hazard-prone areas.	• Mitigate ocean-originated flooding by setting up a proper EPZ on the eastern coast; • Mitigate household-wide flooding by introducing a proper way for road maintenance and drainage systems; • Retrofit hospital and communication sites to reduce the impacts of ocean-originated flooding.
G.dh. Thinadhoo	• Enhance building codes in the rainfall flood-prone area by raising the plinths of houses by at least 0.5 m, and in the ocean-originated flood-prone area by strong boundary wall, together with a buffer zone with reasonable width, say, 20 m. • Avoid protecting roads from flooding by raising the road surface.	• Mitigate rainfall floods prevailing in the south of the island by setting up effective drainage systems or proper leveling of the area. • Mitigate swell wave/surge floods on the western coast significantly by a ridge with 0.5 m high. • Mitigate tsunami floods at the southeastern corner of the island by a proper EPZ. In particular, a buffer zone with proper width is required.
S. Hithadhoo	• Enhance building codes in the rainfall flood-prone areas, in particular, in the southern part of the island. • Avoid maintaining the roads by raising the road surface.	• Mitigate wave/surge flooding on the western coast with an EPZ of proper width. • Retrofit vulnerable houses by raising their plinth level.
S. Feydhoo	• Retrofit of the vulnerable houses identified by raising their plinth to some level. • Avoid maintaining the roads of the island by raising their surface.	• Mitigate rainfall floods by improving the drainage systems of the island; • Mitigate swell wave/surge flooding by setting up an EPZ with a proper high ridge on the south coast.