Detailed Island Risk Assessment in Maldives

(Draft 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.

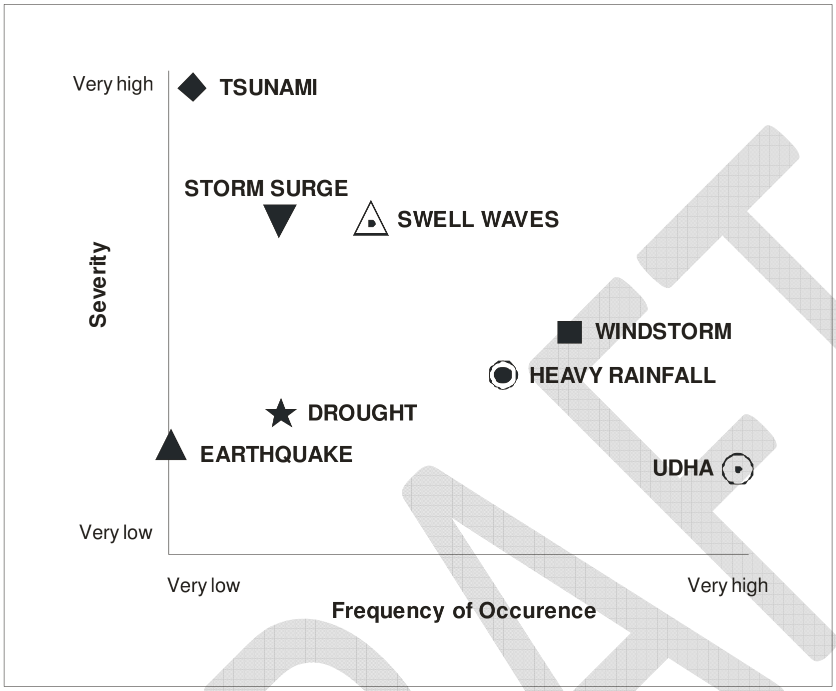

Figure 1.1 Relationship between hazard severity and frequency for major hazards

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.

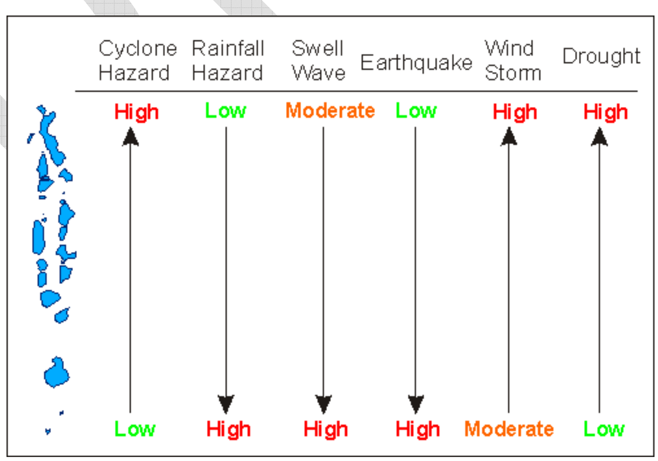

Figure 1.2 Latitudinal natural hazard variation across Maldives

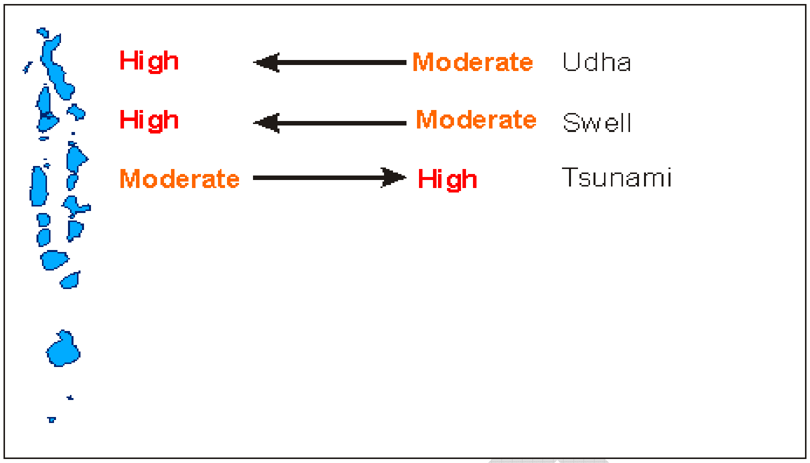

Figure 1.3 Longitudinal natural hazard variation across Maldives.

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	3.9	> 2.7	v. Low	Na	> 5.0	v.Low	0	> 5.0	Unlikely	248	>175	Low	<96.8	>45	Mod
	Mod		> 2.0	Low		> 4.0	Low		> 4.0	v. Low		>75	Mod		>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	Risk reduction options: 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.

Detailed Island Risk Assessment Maldives

(Draft Final report)

Volume II: Methodologies

DIRAM team
Disaster Risk Management Programme
UNDP Maldives

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1.1 Background

In order to reduce the social, economic and environmental vulnerability of the widely dispersed population of the country, the Government of Maldives initiated a programme for providing incentives for voluntary migration to larger islands in 2002 with the long term objectives of ultimately reducing the number of inhabited islands and consolidating the population in smaller groups of settlements across an identified number of islands. The Tsunami disaster in 2004 has yet again underlined the critical importance of providing environmentally safe zones for isolated communities living in distant islands. Most of the islands that were destroyed had little or no coastal protection. Some of them had also been reclaimed to the full extent of the lagoon. These conditions fully exposed them to the danger of hazards such as tsunami and storm surges. This has brought about a change in the approach to settlement planning and socio-economic development of the Atolls, in a way that is financially sustainable and ecologically safe. It is also crucial that the safety considerations are integrated into the planning and development. In this context the idea of Safe Island was developed as part of the overall Atoll development strategy.

The idea of Safe Islands extends the population consolidation approach to incorporate the aspect of extreme vulnerability and develop measures to mitigate ecological disasters. Such measures may include providing ecologically safe zones principally to mitigate tsunami hazards and other disasters, establishing building and construction codes that would enable vertical evacuation if and when necessary, etc. By developing such measures, communities are enabled to sustain social and economic development in times of emergencies and disasters. Moreover, the objectives of the safe island programme is also to provide all basic services in an emergency, particularly health, communication, transport infrastructure and have a buffer stock of basic food and safe drinking water. The features of the safe island would be appropriate coastal protection, improvement of communication and transportation facilities, improved standard of housing and infrastructure and social services, and adequate capacity/preparedness to manage emergencies and disasters. The bases for selection of the “safe Islands” were: size; availability of existing government offices; availability of free space, etc.

UNDP commissioned a study on Disaster Risk Profile of the Maldives in the year following the tsunami with the objective of developing a comprehensive national level assessment of the location and potential impact of multiple hazards facing Maldives and assess the full range of vulnerabilities. The study also presented an opportunity to closely examine the dynamics of such vulnerabilities so that they may be effectively dealt with, to reduce future disaster risks. The study has as its major output given a physical risk index, social risk index and a multi –hazard risk index to each island in the country.

The study was done on a national level and therefore has several limitations. It does not take into consideration intra-island variations and worked with limited information on all disaster events across regions and on buildings and other infrastructure. The social and economic vulnerability lack a deep sectoral approach, particularly to determine the risks faced by the tourism and fishery industries. The study was also limited in community interaction that reflects on the social vulnerability and existing or socially acceptable coping mechanisms in the islands. It also did not reflect the environmental dimensions of disaster risk with specific reference to the impacts of coastal erosion to disaster risk and vulnerability or the effects of disasters on environment. As the Government of Maldives works to develop safer islands with better natural protection and enhanced coastal defences, the locations where environmental changes are expected to increase vulnerability need to be identified and communicated to decision makers to support planning and long term development and risk reduction.

Thus a detailed risk analysis of the 13 selected safe islands that are currently the targeted growth nodes in their respective atolls in terms of development plans and population movements is designed. This study is proposed in order to understand the extent of vulnerability of these islands and to design elaborate mitigation measures. It also seeks to determine how safe these islands are from a disaster risk perspective and identify additional safety requirements needed in those islands to make them safer.

1.2 Objectives of the Study

The general objective of the study is to generate an elaborate disaster risk analysis of 13 islands designated as “Safe Islands” and capture the inter-intra island heterogeneity and issues therein. Specifically, the study intends to make develop a detailed hazard risks analysis and vulnerability assessment of the selected safe islands, present a list of disaster risks, identify changing patterns of risk and vulnerability associated with coastal erosion trends and recommend specific mitigation measures to make the islands safer including limits/regulations to expansion in the islands taking into account vulnerabilities of the natural and built environment.

1.3 Scope of the Assessment

A three-phase exercise will be conducted as part of the study: (1) Hazard Assessment of the 13 islands identified, (2) Vulnerability Assessment (i.e. socio-economic, environmental, infrastructural and other vulnerabilities), and (3) Composite Risk Assessment and Action Planning for prevention, mitigation, preparedness, response and recovery measures. The assessment will give detailed information on both hazards, vulnerabilities and risk of each of the studied islands. The previously released “Risk Profile of the Maldives” will be used as baseline study. The action planning will be done with each of the sectors, vulnerable groups and government officials. Within this framework, a pool of experts from a wide-range of relevant disciplines to include a Disaster Management Specialist (as the team leader), an Economist, a Social Scientist, an Environmentalist with Climate Change Specialization, a Meteorological Hazard Specialist, and a Structural Engineer will take overall responsibility of the study and management of the Disaster Risk Analysis of Safe Islands in Maldives.

1.3.1 Hazard Assessment

The hazard assessment would catalogue disaster events dated as far back as possible. This exercise will be enhanced and supported using the Disaster Information and Inventory Management System (DesInventar) database that is currently being established in by the Ministry of Planning and National Development. In addition to formal sources of information on location, time magnitude and impact, consultations with local people for type, frequency and damages and losses in a disaster event would be held. Information on topography, contour of the island would be used with information on damage losses, exposure factors to do a probabilistic modeling of hazard risks.

1.3.2 Vulnerability assessment

The Vulnerability assessment would be done at four five levels

- Vulnerability to various natural hazards
- Economic vulnerability
- Social Vulnerability
- Infrastructure and building vulnerability
- Coastal risk assessment

The economic sectors that would be studied in detail are Fishing, Tourism, Agriculture and Small business and home based industries. The economic vulnerability would also include a comparative analysis of the livelihood opportunities and costs for people of the islands from where they are being evacuated to where they are being relocated. A feasibility of the costs for upgrading services and infrastructure in the new islands vis-à-vis maintenance of services and infrastructure in the evacuated islands may also be included.

For social vulnerability, factors that will be studied is gender disaggregated population (defined by socio economic class), availability and access to basic services and emergency food stocks, community groups and their interactions, government policies that safeguard vulnerable families and how these groups are impacted in a disaster event. The social vulnerability assessment will also include the population profile of the islands and identify vulnerable groups within that population (including socio-economical groups and individuals groups) & and perception of the community members about integrating outsiders in their community/islands (since development of safe island requires relocating people from other islands in a designated island). It would also include an examination of any informal institutional mechanisms existing and how these can be enhanced and strengthened.

The infrastructure and building vulnerability assessment would take into account the exposure to different hazards, age, roof and wall materials of a building and its risk taking capacity at a particular hazard intensity. The infrastructure and building vulnerability will also among other things, identify "safe" buildings in the island and their capacity to shelter people in disaster events and an assessment of all public infrastructure and plans for retrofitting it.

The coastal risk assessment would look into the effects of coastal erosion on disaster risks and vulnerability of these islands. It would entail compilation of available data on coastal erosion, coastal hazards and related parameters. The coastal risk assessment would also include mapping of the coastal vegetation of the 13 islands. It would also include identification of sites that are especially susceptible to coastal erosion and to determine how the integration of environmental change parameters affects risk and vulnerability profile of these islands.

1.3.3 Composite Risk Assessment

This will be an in-depth analysis based on the interplay between island eco systems, infrastructure, economic activities and community social processes. Inputs from each of the above stated vulnerability assessments (prepared by individual experts in the field) will be consolidated and develop into a composite risk assessment of the islands. The action plans develop to recommend necessary measures for prevention, mitigation, preparedness, response and recovery in the safe islands will take cue from the composite risk assessment output.

1.4 Key Activities of the Team

- Develop and design the methodological framework of the study considering the inputs from the different areas/scope of the hazard and vulnerability assessment.

- In the 10-15 islands selected, conduct comprehensive risk assessment, including hazard risk mapping, socio-economic risk assessment including risk assessment of the most important economic sectors (mainly tourism and fisheries), risk assessment of infrastructures and building stocks, coastal risk assessment and participatory risk analysis involving the communities and the most vulnerable populations (both because of exposure and lack of coping capacities)

- To determine the probability of hazard events in the islands based on geological evidence, historical data, and projections derived from theoretical analysis. This analysis will help map out the overall hazard context of the island (including probable scenarios of occurrence) and its corresponding vulnerability variables such as physical, environmental and socio-economic factors.
- To assess the full range of vulnerabilities (hazard, economic, and social and environmental) experienced in the specific islands with reference to multiple hazard events and relocation. This analysis will assess the range of vulnerabilities experienced in post tsunami and extrapolate how these experiences, have informed lessons learned in coping and developing adaptive strategies for the future.

- To identify the hazard safety measures the islands are lacking currently and where to direct the different nature of investment for infrastructure.

- To make specific programme and policy recommendations, on appropriate prevention, mitigation, preparedness, response and recovery measures taking into account vulnerabilities, and hazard risks and environmental change and in consonance with overall development strategy of the country. Such should also elaborate a general criteria and disaster mitigation issues for safe development of other islands.

1.5 Expected Outputs

Hazard assessment:

- Detailed hazard risk assessment with multiple return periods (25, 50 100 year period) for major hazards affecting each island.
- A typology and inventory of elements at risk would be defined to determine what will be the potential loss or vulnerability of that element in a particular hazard would be.

Economical vulnerability:

- Total risk in economic impact of termspotential losses of the building stocks and other critical infrastructure (monetary value would be assigned to assets –all buildings and public infrastructure) would be provided for probable losses in aeach hazard (economical impact).
- Livelihoods costs and opportunities /scope in sectors of Tourism, Fisheries, Agriculture and other sectors, a feasibility analysis of costs of improved basic services in designated islands. (socio-economical vulnerabilities).

Social Vulnerability:

- Typology and quantification of vulnerable population, including socio-economical groups (fishermen, unemployed, boat owners, etc…) and groups based on individuals characteristics (such as older inhabitants, children, widows, etc…).

- Report of vulnerable population by island that will be more adversely affected in a disaster event and by the process of relocation and recommendations for measures to harmonize relocated population with host communities.

Infrastructure vulnerability:

- A typology and inventory of physical elements at risk would be defined to determine what will be the potential loss or vulnerability of that element to a particular hazard.

Coastal risk assessment:

- Analysis and compilation of data on coastal erosion, coastal hazards and related parameters such as (a) sea level rise, (b) increased storm frequency and intensity associated with sea level rise, (c) degradation of coastal ecosystems, reefs and land cover for the islands.
- List of identified sites that are especially susceptible to coastal erosion based on an established key parameters and critical thresholds for identifying sensitive sites.
- Detailed analysis of how coastal erosion in these identified sites will affect disaster risk and vulnerability.
- A typology and inventory of physical elements at risk would be defined to determine what will be the potential loss or vulnerability of that element to a particular hazard.

Composite Risk Assessment:

- Elaborate a comprehensive report analyzing hazards, vulnerabilities and risk of the each selected island;
- Action Plan: Action plan for hazard mitigation and vulnerability reduction, including economical and financial cost of the measures and their budget implications.
- Livelihoods costs and opportunities /scope in sectors of Tourism, Fisheries, Agriculture and other sectors, a feasibility analysis of costs of improved basic services in designated islands.

- Elaborate report of vulnerable population by island that will be more adversely affected in a disaster event and by the process of relocation and recommendations for measures to harmonize relocated population with host communities.
- Action plan for hazard risk mitigation and vulnerability reduction.
- Written reports on the assessments that include data collated, process and methodology adopted, findings with measures suggested and recommendations.
- GIS data containing detailed maps and tables of each island studied, with physical elements at risk, different hazard potential impact, vulnerable groups typology and quantification, and core locations where coastal erosion is expected to significantly contribute to disaster risk and vulnerability.

Chapter 2 Conceptual Framework

By Dr. Jianping Yan

2.1 Concept review

There is still no fully acceptable discipline-free definition for risk available. Some researchers define “risk” as the chance of something happening that will have an impact upon objects. It is measured in terms of consequences and likelihood. The other means ‘risk’ the consequences of a hazard impact only. In the general literature of risk analysis, risk is often portrayed as a function of probability/frequency and consequences/impacts, and plotted on corresponding axes using a matrix.

Different definitions of risk lead to quite different risk models. Before commenting on the definitions of risk and corresponding risk models, let’s take a look at the risk of the tightrope walker on the highwire. In this example, the risk to the tightrope walker is falling and getting killed - a high-risk activity!? It totally depends. Let’s consider that the highwire is only one meter above the ground. The falling hazard still exists and the chance of falling remains constant, but the risk is considerably different than if the person were 100 meter above the ground. Thus risk does not mean chance, probability or likelihood only. Risk is a function of the likelihood of occurrence of a hazard and the severity of possible impacts. Perhaps there is a crowd below the tightrope walker vulnerable to injury. The severity of impacts to the tightrope walker and the crowd can be mitigated by a safety net, the chance of falling can be reduced by special training and the extent of injury to the tightrope walker and the crowd can be mitigated by emergency medical response capacity.

After examining the tightrope walker case, it is obvious that ***Risk can be defined as a measure of the probability (likelihood) and severity of an adverse effect to health, property, the environment, or other things of value (UNDRO, 1979).***

The concept of risk combines our understanding of the likelihood of a hazardous event occurring with an assessment of its impact. Hazardous events can either be naturally occurring, such as earthquakes, tropical cyclones or coastal erosion; or they can be anthropogenic, such as water pollution, or terrorist attack. Moreover, events can be sudden, as in the case of an earthquake; or they can occur over a period of time, as in the case of most environmental hazards. The impact of a hazardous event depends on the elements at risk, such as population or buildings, and their associated vulnerability to damage or change as a result of the event. Estimating risk is an ***uncertain science*** because it involves forecasting future events whose time and location of occurrence may be largely unknown. We capture this uncertainty mathematically in terms of probability.

2.2 Risk modeling

Risk models that have a physical basis enable us to better predict future events and their impacts, particularly those whose chance of occurrence might be affected by ***a change in natural environment (e.g. climate change, sea level rise, and environmental degradation), built environment (e.g. new building codes), or social environment (e.g. increased public awareness)***. Most present-day models capture the risk in a rather limited context, commonly in terms of the direct damage or cost of a future disaster. Research is needed to extend these estimates to include indirect effects (e.g. loss of income, quality of life) as well as other social, political, and economic factors that invariably play a role in decisions about risk treatment. Advances in risk modeling can also be used to develop disaster scenarios for disaster response and urban planning, to educate the community, and to evaluate risk acceptance levels for a wide range of stakeholders.

Skeptics often say that because the uncertainty of risk is large and the perception and acceptance of risk is variable, no standard model can be developed or used reliably. It is quite true that no models will ever capture all the variables needed to make informed decisions about risk, and they will never eliminate human intervention and judgment in the face of a variety of economic, social and political factors. With sufficient support and cooperation among researchers, stakeholders, and users, however, risk models can be developed to provide technical information for a wide range of decision making applications.

Risk models can be used to perform cost-benefit / -effectiveness analyses of various types of risk reduction measures. Risk reduction strategies include short-term solutions such as monitoring, early warning and response, as well as long-term ones such as land-use planning, building codes, and 'hardening' or of critical facilities and infrastructure. Ultimately, some residual risk is inevitable, which can be moderated through insurance or other forms of risk transfer, such as catastrophe risk bonds. Risk models can also be used to develop ***disaster scenarios*** for emergency response and recovery, to improve ***community risk awareness*** and to evaluate ***risk acceptance thresholds*** for a wide range of stakeholders. Risk modeling has been supposed to be one of the essential decision-support tools for assessing and reducing risk to community.

The prospect of a national programme for natural disaster risk assessment provides the impetus for a discussion of the importance of risk models to the process. Natural hazard risk models provide the essential building blocks or tools for conducting risk assessments as part of an overall risk management framework. ***Composite risk models use information about past events together with physical models of earth processes, and economic and social models of communities, to forecast the probabilities and impacts of future events.***

2.2.1 Conceptual risk model

In terms of the above definition, risk can be expressed in the following pseudo-mathematical form:

$$Risk = f(S, P(t)) \qquad (2.1)$$

Where

S is the impact severity of an extreme event or process. It can be determined by the event intensity, the degree of exposure of elements at risk, and the vulnerability of a specified element at risk to a specific event of a given intensity (Fig. 2.1).

P(t) is the probability of that event occurring within a given time frame.

t stands for a given time frame.

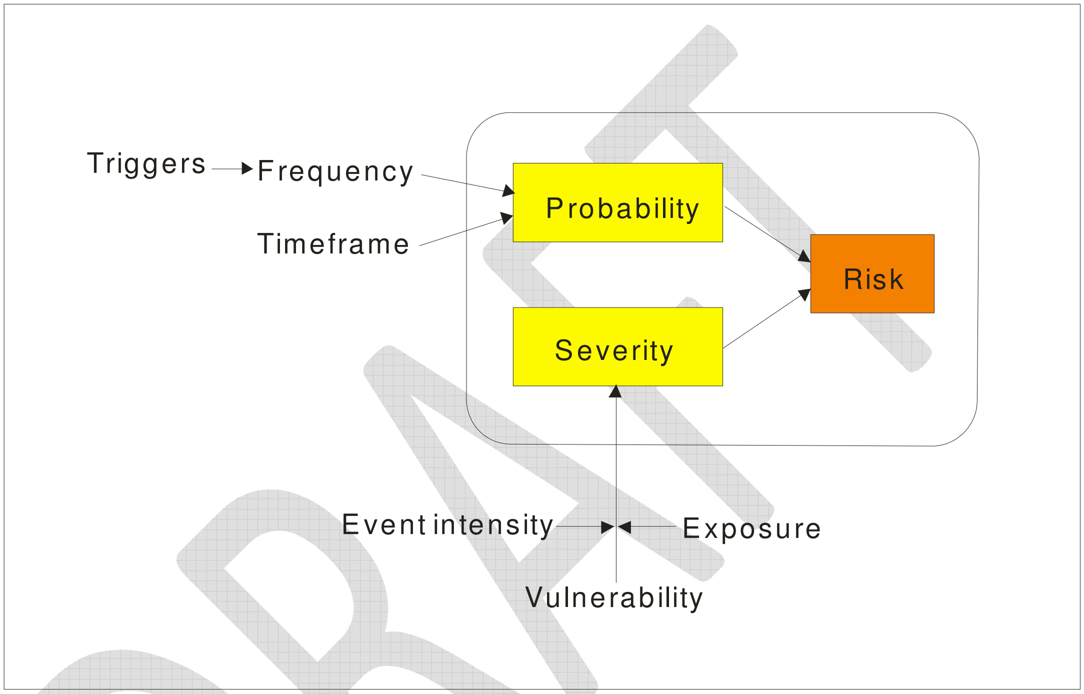

Fig. 2.1 A conceptual model for natural hazard risk.

2.2.2 Severity Model

Severity usually refers to the extent of a loss/impact. It is used to indicate the seriousness of a given problem or hazard. In the case of natural disasters, The severity of impact is dependent upon the intensity of hazard, the exposure and vulnerabilities of elements at risk. For example, the vulnerability to a tsunami may depend on (a) the flow depth and velocity of the landfalling tsunami wave; (b) the conditions of the elements at risk (building and other structure); and (c) the proximity to the shoreline.

The combination of these elements can be expressed diagrammatically as the '***Severity Triangle***' in Fig. 2.2. Hazardous events can either be naturally occurring, such as earthquakes, tropical cyclones or coastal erosion; or they can be anthropogenic, such as dry-land salinity, water pollution, or terrorist attack. Moreover, events can be sudden, as in the case of an earthquake; or they can be inherently uncertain because it involves forecasting future events whose times and places of occurrence may be largely unknown. As shown in Fig. 2.2, the severity can be zero if no exposure occurs. On the other hand, the severity of an event may be not that high as imagined because the vulnerability of elements at risk is very low, even if these elements at risk are located within the impact of an intense natural event. For example, a house or a public facility can be built on the top of a landslide body or located within the impact zone of an intense earthquake, however, they can resist to an earthquake of a high intensity due to their well-designed building code.

The severity may be decreased by reducing the size of any one or more of the three contributing variables - the hazard intensity, the elements exposed and/or their vulnerability. This can be illustrated by assuming the 'dimension' of each of the three variables represents the side of a triangle, with severity represented by the area of the triangle. In the image above the larger (red) triangle portrays each of the variables as being equal, whilst in the smaller (red) triangle the severity has been mitigated by halving both exposure and vulnerability. The reduction of any one of the three factors to zero would consequently eliminate the severity.

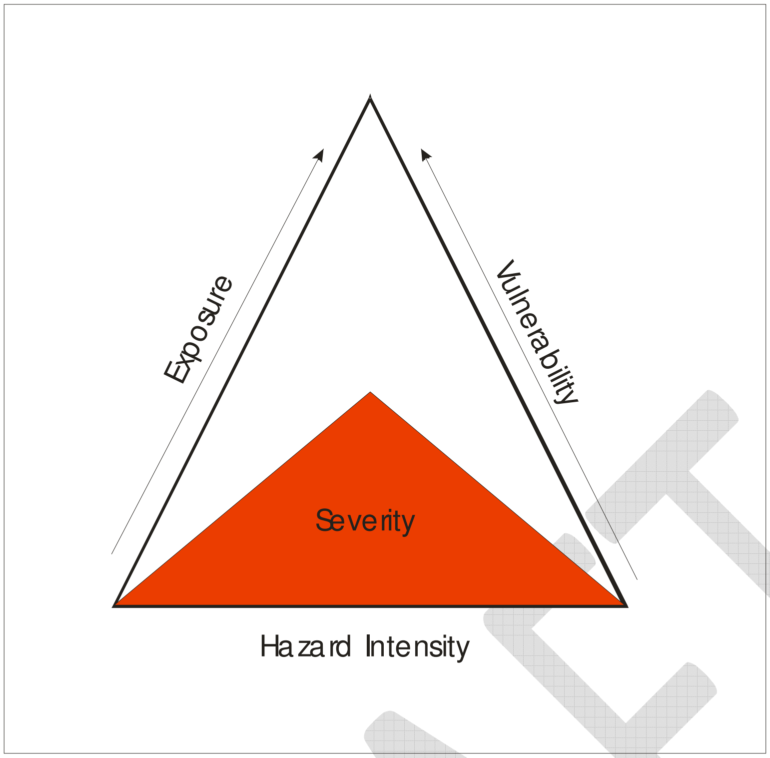

***Fig. 2.2 Hazard severity triangle*.**

Based on the above discussion, the conceptual model shown in Fig.2.2 can be mathematically expresses as follows:

$$S_i = f(E_i, V_i(I)) = PL_i \cdot V_i(I) \qquad (2.2)$$

$$S_{total} = \sum_{i=1}^{n} S_i = \sum_{i=1}^{n} (PL_i \cdot V_i(I)) \qquad (2.3)$$

Where

E_i represents the degree of exposure of the i^{th} element at risk, it can be measured by the potential loss of the affected element at risk;

$V_i(I)$ is the vulnerability of the i^{th} element at risk to an event of a given intensity;

S_i is the aspect severity;

S_{total} is total severity of a given impact area.

2.2.3 Probability Model

The allocation of event probabilities is an area of particular uncertainty. For example, a common description of event probabilities is the so-called "return period" of a particular phenomenon, typically given in a form such as "a one-in-one hundred year flood". Not only are such figures typically based on less than 100 years of record, but also it has been widely reported that such an expression of probability is prone to be misinterpreted and misused. Description of an event as a "1:100 year event" is frequently taken (wrongly) to indicate that there will not be another such event for another 100 years.

Therefore, it would be better to adopt the terms "average recurrence interval (ARI)" and "annual exceedence probability (AEP)" which are considered less ambiguous. A typical ARI statement would be:

On the basis of the existing record, a flood measuring 11 m or more on the reference gauge occurs, on average, once every 25 years.

A comparable AEP statement (for the same event) would be:

There is a 4% probability of a flood of 11 m or more occurring in any given year.

To put the issue of probability in a more familiar context we have produced to illustrate probabilities related to the chance of one or more events of a given magnitude occurring in a given time frame. Mathematically, Samuels (2001) put forward a model for the probability of occurrence of an event that can be expressed as follows:

$$P = 1 - (1 - AEP)^{t} \qquad (2.4)$$

where

P is the probability of occurrence of an event of a given intensity occurring within a given time frame;

AEP stands for annual exceedence probability;

t is a given time frame.

2.2.4 Data support for risk modelling

The development of essential databases and models on a national scale requires the commitment of all three levels of government to a systematic data collection and management process. As discussed above, data needs to span the model requirements posed by all three elements of risk: hazard, exposure and vulnerability. Model development of economic losses needs to be done by a range of experts spanning a wide range of physical sciences (e.g., earth science, meteorology, hydrology), engineering (e.g., structural, environmental, software, computational methods), and social sciences (sociology, economics, emergency management). Models will require input from a wide range of stakeholders and end users, such as local governments, emergency managers, planners, insurance companies, and utilities. Models and databases will also need to be tested and validated using a variety of means, including data collected from past disasters. Tools will also need to be developed to translate the results of complex analysis into user-friendly decision-support tools for use in making decisions about risk treatment options. The development of rigorous and robust natural hazard risk models and attendant decision support tools should be viewed as important complements to information gained from other sources of analysis. Sceptics often say that because risk uncertainty is large and perception and acceptance of risk is variable, no standard model can be developed or used reliably. We agree that no models will ever capture all of the variables needed to make informed decisions about risk, and they will never eliminate human intervention and judgment in the face of a variety of social and political factors. However, with sufficient support and cooperation among researchers, stakeholders, and users, risk models can be developed to provide technical information for a wide range of decision making applications.

2.3 Risk Assessment Process

Risk assessment is a process for estimating risk associated with a specific hazard, defined in terms of probability and frequency of occurrence, magnitude and severity, exposure and consequences. It can be divided into two phases: risk analysis and risk evaluation (Fig. 2.3).

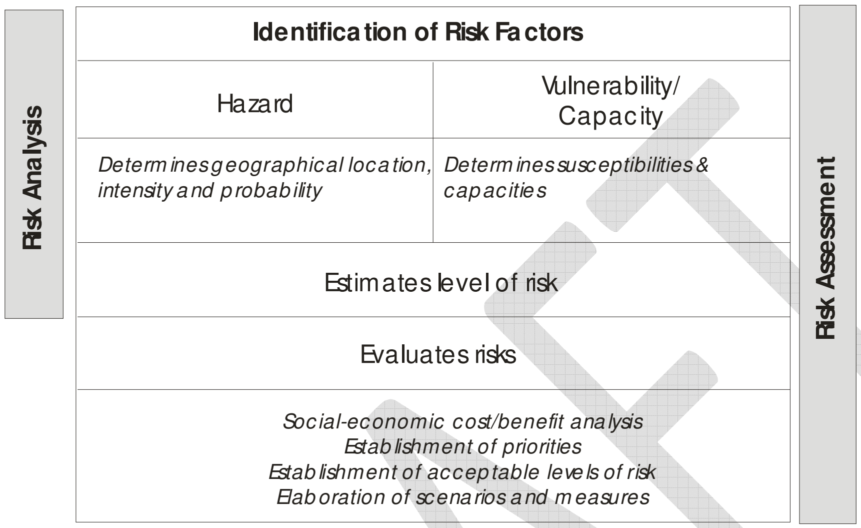

Fig. 2.3 Stages of risk assessment (from UN/ISDR, 2004)

2.3.1 Risk analysis

Risk analysis is a process to determine the natural and extent of risk by analyzing potential hazards that could pose a potential threat or harm to people, property, livelihoods and the environment on which they depend and evaluating existing conditions of vulnerability (ISDR, 2004). Risk analysis includes detailed quantitative and qualitative information and understanding of risk. It is a necessary first step for any other risk reduction measures. Risk analysis can provide a sound basis for risk reduction planning and for allocation of funds and other resources. As a process, it is generally agreed upon that it includes the following activities:

- Identifying the nature, location, intensity and probability of an extreme event;

- Determining the existence and degree of exposure and vulnerabilities to the event;
- Estimating potential loss/impacts caused by the event;
- Identifying the capacities and resources available; and
- Determining acceptable levels of risk.

2.3.2 Risk evaluation

It is difficult, if not impossible, to be categorical about levels of acceptable or tolerable risk. Such risk criteria vary wildly over time, from circumstance to circumstance, and from the different perspectives of each individual member of the community. For example, many people will tolerate the minor levels of flooding that might occur every five or so years, especially if it affects few properties. The community generally will be less tolerant of moderate to major flooding that causes widespread dislocation and does damage. Major levels of inundation or wind damage that kill people and produce massive economic loss are typically 'unacceptable'. Whilst this seems to be an eminently reasonable approach, it can also be viewed as being unrealistic, especially where the event that creates tragic losses is very rare.

It is relatively easy and inexpensive to control, or even eliminate the nuisance levels of flooding that most people tend to tolerate. It is, however, economically impractical, if not physically impossible, to eliminate the risk of rare but catastrophic levels of tsunami inundation. Similarly, it would be prohibitively expensive to build structures to withstand the impact of the largest likely earthquake or the strongest likely cyclone. There is clearly an inverse relationship between ***risk acceptability and risk controllability***. The widely adopted response to this paradox is to establish ***thresholds of risk*** that are economically viable to implement and socially acceptable. Events that exceed those thresholds are coped with when they occur.

2.4 Risk modeling framework

The methodological framework this study follows belongs to a scenario-based approach. Composite risk model involves the development of a series of scenarios that can be grouped into 4 modules: hazard, exposure, composite consequences/impacts, and risk (Fig. 2.4). Specifically, the scenarios to be developed with this methodological framework include hazard zone, probability of occurrence, exposure, physical damage, functional impact, economic impact, social impact, and a composite risk profile of a targeted system (Fig. 2.5).

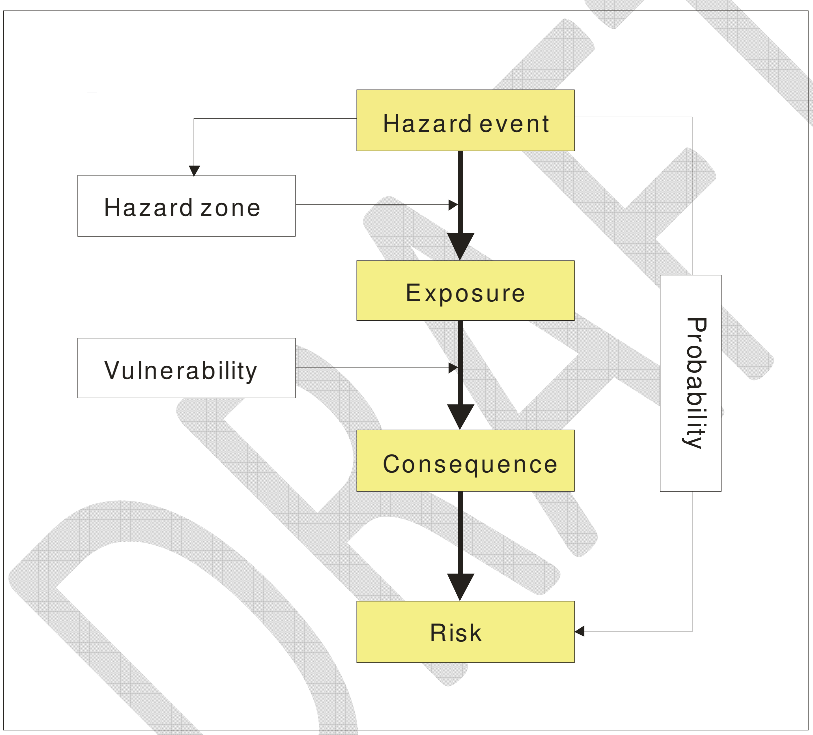

Fig. 2.4 A generic framework for risk modeling.

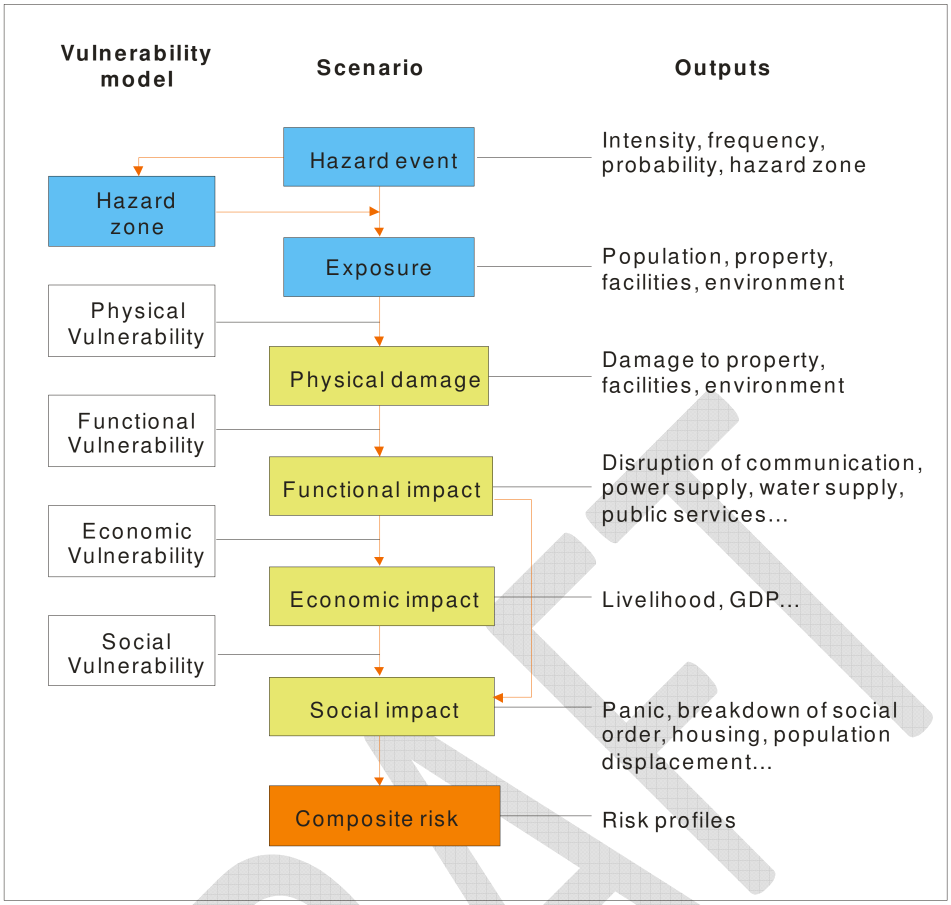

Fig. 2.5 An extended framework for composite risk assessment.

2.4.1 Hazard module

Hazard assessments are studies that provide information on the probable location and intensity of dangerous natural phenomena and the likelihood of their occurrence within a specific time period in a given area. These studies rely heavily on available scientific information, including geologic, geomorphic, and soil maps; climate and hydrological data; and topographic maps, aerial photographs, and satellite imagery. Historical information, both written reports and oral accounts from long-term residents, also helps characterize potential hazardous events. Ideally, a natural hazard assessment promotes an awareness of the issue among all stakeholders in an affected area, evaluates the threat of natural hazards, and describes the distribution of historical or potential hazard effects across the study area.

In a physically based model, we are interested in the underlying causes of the hazard events as well as the manner in which they affect the landscape. Although each hazard is manifested differently and requires different model parameters, the basic framework is the same. Thus, we can break the problem into two parts: 1) the probability of occurrence of an event scenario; and 2) the propagation of the 'event' through the atmosphere (e.g. windstorm), the earth's sub-surface (e.g. earthquake), or on the earth's surface (e.g. flood).

In the case of an earthquake, the rate at which earthquakes of various magnitudes happen at any location defines the probability of occurrence; while a specific event is expressed via the pattern of ground shaking resulting from seismic waves traveling through the earth. For floods, event occurrence is governed largely by rainfall, while the geological and hydrological characteristics of the water catchment govern the flow of water and the extent of the flood. Techniques for modeling various hazards are generally well developed. Hazard models are, however, only as good as the data used to define them. Historical event catalogues for earthquakes, floods, fires, landslides, severe storms and tropical cyclones are critically important. Because our historical record is very short, we are often forced to extrapolate the effects of historical events to potentially catastrophic or 'probable maximum' events. If we understand the underlying hazard process, then this knowledge can be used to define the model parameters that allow us to extrapolate in a realistic and scientifically credible manner. We can also use information from hazards that have occurred in one location, and apply appropriate modifications to estimate the effects if applied to another.

Our ability to adapt models to local characteristics is highly dependent on the availability of detailed map data such as geology, elevation and slope, and vegetation, as well as basic meteorological data such as rainfall and temperature. Models also need to incorporate potential effects of climate change and urbanisation to determine future trends in hazardous events, which may differ substantially from those of the historical past. To incorporate the changing needs of risk model development, we need to ensure on-going capture of comprehensive hazard data and access to integrated databases.

Hazard identification means the process of defining and describing a hazard, including its physical characteristics, magnitude and severity, probability and frequency, causative factors, and locations/areas affected. For our mitigation planning purposes, we have not examined physical characteristics and causative factors in detail, but have generally characterized:

- Description
- Severity (intensity)
- Magnitude (potential size of impact area)
- Probability/frequency
- Hazard Zone (location/extent of impact area)

2.4.2 Exposure module

Exposure means the number, types, qualities, and monetary values of various types of property or infrastructure and life that may be subject to an undesirable or injurious hazard event. Exposure is merely a quantification of what is at risk in the identified hazard zone. In exposure analysis, the following should be quantified:

- Number of critical facilities (e.g. emergency communications, fire, law enforcement facilities, emergency operation centers, etc.);
- Number of special facilities (e.g. government, health, major industry, incarceration, military, nursing, potential shelters, cultural facilities);
- Number of infrastructure facilities (e.g. electrical, sewer, transportation, water - major facilities);
- Number of hazardous materials facilities;
- Number of residential buildings;
- Value of residential buildings;
- Number of non-residential buildings;
- Value of non-residential buildings;
- Population; and
- Economic activities (e.g. livelihood, production)

In this study, two GIS exposure datasets, i.e. houses and critical facilities, will be compiled from various data sources.

2.4.3 Vulnerability module

Vulnerability assessments are systematic examinations of building elements, facilities, population groups or components of the economy to identify features that are susceptible to damage from the effects of natural hazards. Vulnerability is a function of the prevalent hazards and the characteristics and quantity of resources or population exposed (or "at risk") to their effects. Vulnerability can be estimated for individual structures, for specific sectors or for selected geographic areas, e.g., areas with the greatest development potential or already developed areas in hazardous zones.

Vulnerability to natural hazards is an integral factor in understanding the true extent of risk. While there is no one definition of vulnerability, it generally refers to how people, infrastructure and the economy are affected by a hazard event. The concept of vulnerability is complex and cannot be comprehensively answered by one research method alone. However, aspects of vulnerability to natural hazards can be measured which value-add to hazard models and provide a greater picture of total risk. Exploring quantitative methods of assessing vulnerability is essential to ongoing risk research, in particular, risk decision-making, which is a fundamental part of natural hazard risk management. Vulnerability can be viewed from structural and non-structural perspectives.

Each day, risk managers and risk researchers make decisions about the well being of communities based on available data, anecdotal evidence, training and personal experience. Individuals within communities also make decisions about their own risk to natural hazards, including mitigation and recovery.

Approaches to determining non-structural vulnerability rely upon the complementary integration of quantitative and qualitative methodologies. Qualitative approaches have explored the capacity of communities to manage risk information in order to cope with natural hazard events. Quantitative methods to assess non-structural vulnerability explore the integration of subjective information and analytical processes to develop measures of vulnerability. Such quantitative methods may also be useful in exploring decision-making processes concerning social-economic and community factors. In any case, as with all vulnerability models, data from past disasters should be used where available to calibrate and validate the results.

Vulnerability assessment results in an understanding of the level of exposure of people and property to the various natural hazards identified, including physical assets, the loss potential of crops, trees, livestock and fisheries. This is the process used to identify vulnerable elements which are exposed to natural hazards. In general, vulnerability assessment provides information on:

- Physical (buildings, infrastructure, lifelines, ecosystem, etc.). Environmental vulnerability refers to the protection of natural resources, deforestation, degradation, desertification;
- Functioning (disruption of the operations of public infrastructure and facilities, housing, etc.);
- Economic (livelihoods, means of production, stocks, incomes, business interruptions);
- Social (vulnerable groups, perception of risk, local institutions, and poverty).

Physical vulnerability refers to the potential for physical impact on the built environment or infrastructure and population. This type of vulnerability is perhaps the easiest to quantify because it depends directly on the physical impact of a hazard event. The best-developed vulnerability models have focussed on the behaviour of building stock as the most significant component of the built environment. In general, such models are in need of development and validation using both empirical data from post-disaster reconnaissance, laboratory testing such as from shake tables and wind tunnels, as well as computer simulation techniques. Much information can be taken from other areas (e.g., US, Europe), but due to differences in building techniques, standards and materials, significant model calibration and testing under local conditions is still required. Casualty models have been developed based primarily on assumptions tied to the likelihood of occupants being injured or killed in the event of building damage or failure. These models draw on the well developed HAZUS risk assessment model used throughout the USA to determine risk from earthquake. The vulnerability of lifelines and other critical infrastructure has been studied internationally using past disasters as case studies. However, there are limitations to the value of this knowledge applied to any specific infrastructure system because it is often the complex network or systems interactions that dictate the extent of impact and duration of recovery.

A physical vulnerability assessment focuses on the vulnerability of the built environment, including buildings, homes, infrastructure and roads. Such an assessment includes reviews of the standards used in design and construction, location vulnerability factors, current status and maintenance practices. Physical vulnerability assessments are useful tools for identifying deficiencies in current building and maintenance practices, for determining appropriate locations and uses for buildings and facilities and for prioritizing the use of resources for retrofit and upgrading of structures.

Environmental vulnerability: Many environmental systems stabilize potential hazards or buffer their effects. Intact forests stands can support unstable steep slopes and reduce soil runoff and sedimentation. Coral reefs and mangroves can help anchor coastlines and reduce the impact of storm surges and waves. Degraded systems are less able to perform these functions, more vulnerable to damage and are less resilient in recovery from hazard effects. Improper development, management or repeated hazard damage contribute to this degradation.

Economic vulnerability: Economic losses tend to be broadly classified as tangible and intangible and sub-categorised into direct and indirect losses. In terms of estimating losses due to natural hazards, tangible direct losses are defined as losses resulting from the impact of the event such as physical damage to buildings, infrastructure, contents, and vehicles. Tangible indirect losses measure disruption to businesses, transport and utility networks, clean up costs, emergency response and relief incurred as a consequence of the event. The extent of the indirect costs is dependent on the availability of alternative sources of supply, markets for the products and the length of the production disturbance. Intangible indirect losses from natural disasters include death and injury, and loss of memorabilia. Intangible direct losses incorporate household disruption (schooling, social life), and health effects. There are no market values for intangible losses but non-market valuation techniques can be implemented to provide proxy values. Ideally, an economic assessment of potential or actual losses from a disaster will incorporate all the above loss categories. However, in the first instance, tangible losses are likely to be sufficient in providing conservative estimates of economic losses. Intangible losses are more complex to estimate, given the need for proxy values. In any case, as direct tangible losses follow most directly from the physical impact, and are the simplest to obtain, they are also the most readily developed and applied on a regional or national scale.

Social Vulnerability: Each day, risk managers and risk researchers make decisions about the well being of communities based on available data, anecdotal evidence, training and personal experience. Individuals within communities also make decisions about their own risk to natural hazards, including mitigation and recovery. Approaches to determining social vulnerability rely upon the complementary integration of quantitative and qualitative methodologies. Qualitative approaches have explored the capacity of communities to manage risk information in order to cope with natural hazard events. Quantitative methods to assess social vulnerability explore the integration of subjective information and analytical processes to develop measures of vulnerability. Such quantitative methods may also be useful in exploring decision-making processes concerning socio-economic and community factors. In any case, as with all vulnerability models, data from past disasters should be used where available to calibrate and validate the results.

2.4.4 Consequence module

Consequences mean the damages (full or partial), injuries, and losses of life, property, environment, and business that can be quantified by some unit of measure, often in economic or financial terms. A loss estimation attempts to quantify the consequences of hazard events.

In this study, the consequences of a hazard event will be examined from 5 perspectives, as shown in Fig. 2.6.

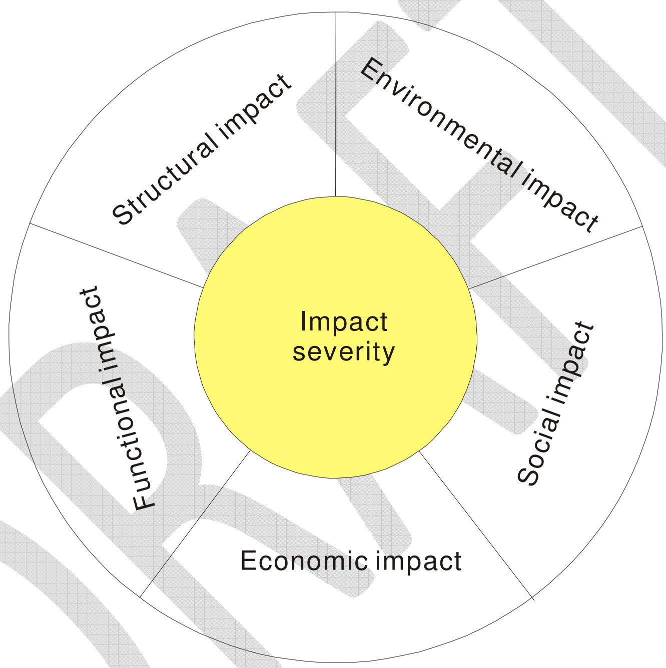

Fig. 2.6 Dimensions of composite impacts.

2.4.5 Risk module

There are many techniques for estimating or 'profiling' risk. The simplest of these are based on the statistics of past events and their impacts. For example, risk from flooding is normally determined based on an assumption that future floods will follow a pattern similar to the past. Thus, given enough data from past events, the risk can easily be determined. However, many natural hazards have no or limited historical-event precedents upon which we can properly assess the risk, particularly for rare or extreme events that can have the largest impact on society.

Ideally, risk profiling integrates information about past events with social models of our communities, economic models and the physics of earth processes to estimate the probabilities and impacts of future events. Capturing the risk requires modeling the probability of many events and their impacts. Thus, thousands of scenarios are developed through computational simulations in which sophisticated computing techniques are used to capture the interaction of hazard phenomena with the elements at risk and their associated vulnerabilities.

2.5 Uncertainty Analysis

The analysis of issues as complex as hazard risk is highly dependent on the accuracy, currency and appropriateness of the data that it employs. Every effort has been made to ensure that the best available data have been used in the various analyses included in this study.

2.5.1 Sources of Uncertainty

Uncertainty can create difficulties for public officials in their dealing with developers and others. In quantifying risk, hazard, exposure and vulnerability information are integrated to produce a risk estimate. Uncertainties in the hazard, exposure and vulnerability information may result in unrealistic risk estimates. Sources of uncertainty in a risk assessment area:

Hazard Identification: Knowledge of past site, historic records and analytical data are generally used to identify potential hazards. Incomplete knowledge, lack of records, sampling strategies that do not adequately address site conditions, use of inappropriate analytical methods, and inappropriate scenarios are common sources of uncertainty in hazard identification.

Exposure assessment: Uncertainties associated with assessing exposure can generally be categorized as: (1) lack of precise knowledge of the potential exposure scenarios (i.e. delineation of hazard impact zones and recurrence interval of a given hazard intensity), and (2) distributional uncertainty, which deals with the variation of exposure factor or parameter values for a defined exposure scenario or setting (i.e. for each parameter, there is a range of values that could be used to represent the parameter). For example, variations in social-economical factors and exposure frequency and duration illustrate this type of uncertainty. Professional judgment exercised by risk assessors may reduce uncertainty in the exposure assessment.

Vulnerability assessment: What kinds of vulnerability indicators are selected and how they are evaluated can affect the manner in which the risk is calculated and presented for a risk management decision. On the other hand, there are still no efficient ways to weight different indicators or indicator groups. This may lead to the exaggeration of one indicator over the other and thus distort the risk assessment results.

2.5.2 Analysis Approach

Uncertainty analysis provides a yardstick to measure how "conservative" the risk estimate is. In the uncertainty analysis, the potential sources of error (data gaps, assumptions and bases of judgment) are identified for each step in the risk assessment and their overall impact on the site risk estimate(s) is evaluated qualitatively and/or quantitatively. Understanding the uncertainty in a risk assessment will help risk managers to make more informed and reasoned risk-based decisions. Unrealistic or highly conservative risk assessment could lead to costly cleanup decision.

It has been suggested the use of multiple descriptors to characterize risk, in addition to qualitatively identifying the sources of uncertainty in the risk assessment. The objective is to provide a full range of risk estimates, not only the high-end risk estimate, to the risk managers, decision-makers and stakeholders so that they can make informed decisions based on the degree and probability of actual site risk.

Sensitivity analysis and probabilistic risk assessment are also acceptable ways to characterize uncertainty in exposure and risk. Either a deterministic or a probabilistic approach may be used to estimate individual hazard or risk. In general, presenting the high-end and central tendency point estimate of risk, or the entire risk distribution can be regarded as a way to characterize uncertainty in individual risk.

Probabilistic analyses represent one means of characterizing uncertainties in risk assessment. Monte Carlo Simulation (MCS) is one tool used to generate probabilistic risk estimates and is a computer-assisted propagation of risk based on various combinations of exposure parameters to simulate the entire spectrum or distribution of risk and hazard for a potentially exposed individual. Using MCS techniques, it is possible to represent the uncertainty in the risk characterization model by generating sample values (in the form of frequency distributions) for the model input and running the model repetitively. Instead of obtaining a single risk estimate to represent the model output as in a deterministic risk assessment, a set of sample results are obtained that can present the output as a frequency distribution or a cumulative density function.

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Chapter 3 Hazard Assessment Methodology
By Aslam Tey and Shaig Ahmed

3.1 Introduction

This section presents the methodology used in the identification and assessment of natural hazards. The objectives of this section is to provide the methodology used in the assessment and to provide a hands-on guide to future replication of this study into other islands of Maldives.

A natural hazard is defined as a potentially damaging natural extreme process or phenomenon within a specified period of time in a given area. Hazard Assessment consists of systematically identifying hazardous events, their potential causes, consequences and patterns – both in qualitative and quantitative terms. The major categories for natural hazards considered in this study are as follows:

- Geologic hazards: Earthquakes, landslides and coastal erosion.
- Meteorological hazards: Tropical cyclones, tropical storms (strong wind), thunder storms and waterspouts
- Hydrologic 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.

The lines between these hazards are rarely straight forward and categorization can often be contentious. Much of these hazards are interlinked. For example, tsunamis result from earthquakes and storm events are associated with strong winds, heavy rainfall and surges. Moreover, the climate change related hazards are manifestations of changes to atmospheric and hydrologic hazards. In addition, these hazards can be mitigated or exacerbated due to human activities.

The methodologies used in this study are mostly simple, straight forward and easily replicable. There are number of detailed models and techniques for assessing hazards. However, most of them require substantial technical knowledge and resources (especially high resolution data) to get the best out of them. One of the aims of this project is to establish methodologies which could be easily replicated by non-technical staff into other islands. The experience from this project showed that sufficient data is unavailable to utilize much of the existing models. In addition the technical knowledge to utilize those models could be limited among the non-technical staff. Hence care has been taken during the selection of methodology to maintain a balance between scientific quality and practicalities of its future usage, in the planned context.

A major starting point for hazard assessment is the Developing Disaster Risk Profile Report (UNDP 2006), where regional level assessments were made for the entire country. Hence, this study follows on from the existing report to expand at a localized level. Extensive references were made to the findings of the report where regional level assessments are required.

3.2 Major natural hazards in the Maldives

3.2.1 Swell Waves

Swells waves were not analyzed in the DDRR and had to be undertaken as a detailed assessment for this study. The Storm Track Data required for this assessment was obtained from Unisys and Joint Typhoon Warning Centre (Unisys and JTWC, 2004). Moreover, records of historical flood events across Maldives and neighboring countries were also collected.

The origins and propagation patterns were estimated based on exiting scientific literature and Storm Track Data between 1945 and 2007. Flood events of previously unknown origin on the islands studied were analyzed against known Storm Track Data to determine possible links. The dates of flooding events were matched to storm dates, distance to storm and possible propagation time. In addition, tide levels and timing during monsoon was also evaluated for any possible links. Tidal data was obtained as hourly data from the University of Hawaii Sea Level Centre (http://uhslc.soest.hawaii.edu/) for the three tidal stations: Hanimaadhoo, Male' and Gan.

Threshold level for flooding could not be determined for climatic parameters due to the unavailability of synoptic charts of storm events in South Indian Ocean and low resolution of tide data. Hence, known flood heights on islands were used as the pain parameter to determine threshold levels for flood intensity.

3.2.2 Storm Surges and Tsunamis

Regional level assessments carried out in detail in the DDRR were utilized to establish the origins, propagation patterns, magnitudes, probabilities, frequencies and potential hazard scenarios.

Threshold levels for severity are defined based on historic event data and geophysical data. The predicted water and wave height on reef flat is plotted against the island topographic profile to determine the threshold levels of flooding. In addition other geophysical data such as, width of island, location within atoll, location on reef, island orientation, reef flat width and location within archipelago were used to determine the severity of event.

Event probabilities are event are expressed in qualitative scales of occurrence: Low Impact, Moderate Impact and Severe Impact. Hazard events are expressed as high, moderate or low for ease of reference for non-technical reader (refer to Table 3.3).

3.2.3 Heavy Rainfall, windstorm and droughts

Findings from regional level assessments in DDRR were used to determine the origins, propagation patterns and future probabilities and magnitudes. Long term high resolution data from weather stations were unavailable for this study, but is recommended for any further risk assessment studies.

Rainfall records and wind records between 2001 and 2007 were obtained from the Annual and monthly weather reports on Department of Meteorology (DoM) website (http://www.meteorology.gov.mv/). However, these reports only contained the maximum rainfall in 24 hours and wind gusts for a given year (for annual reports between 2001 and 2003) or a month (for monthly records of 2003-2007). No records on drought were available.

Threshold levels and severity for rainfall related flooding and wind damage for the individual islands were measured by matching historic hazards and their impacts against extreme event records from DoM website. For example, a heavy rainfall event with 75mm for a 24 hour period causing closure of schools and businesses in a given island was considered the threshold level for socio-economic disruptions. Damage that could be caused by an event of such magnitude is established as its severity. Similarly damages caused by winds reaching specific speeds were established as threshold levels. The final threshold levels represent the result of all available records.

Event probabilities are event are expressed in qualitative scales of occurrence: Low Impact, Moderate Impact and Severe Impact. Hazard events are expressed as high, moderate or low for ease of reference for non-technical reader (refer to Table 3.3).

3.2.4 Earthquakes

Regional level assessments carried out in detail in the DDRR were utilized to establish the origins, propagation patterns, magnitudes, probabilities, frequencies and potential hazard scenarios. There were no historical events of significance and no further assessment was conducted on the island.

Potential impacts from earthquakes were expressed using the rate of decay of Peak Ground Acceleration (PGA) for specified return periods. These values were then translated to Modified Mercalli Intensity (MMI) for easier reference. The MMI is a measure of the local damage potential of the earthquake. No specific attempt was made to model the MMI based on local hosing structural data. Instead the following classical specification by Ritcher (1958) was utilized. The last 4 MMI values have been summarized as a single value as they are not applicable to Maldives based on the findings of DDRR.

Table 3.1 Modified Mercalli Intensity description (Richter, 1958).

MMI Value	Shaking Severity	Description of Damage
I	Low	Not felt. Marginal and long period effects of large earthquakes.
II	Low	Felt by persons at rest, on upper floors, or favourably placed.
III	Low	Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.
IV	Low	Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV, wooden walls and frame creak.
V	Low	Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.
VI-XII	Light - Catastrophe	Light to total destruction

Event probabilities are event are expressed in qualitative scales of occurrence: Low Impact, Moderate Impact and Severe Impact. Hazard events are expressed as high, moderate or low for ease of reference for non-technical reader (refer to Table 3.1).

3.2.5 Climate Change

Assessments primarily based on existing literature. No attempt was made to undertake site specific assessments as time and resources were limited. The main literature referred is as follows:

Threshold levels for climate change related changes remain the same as it was assumed that no significant changes will be made to existing geophysical setup. However, the probability of event occurrence will increase within all threshold levels.

Event probabilities are event are expressed in qualitative scales of occurrence: Low Impact, Moderate Impact and Severe Impact. Hazard events are expressed as high, moderate or low for ease of reference for non-technical reader (refer to Table 3.3). Probabilities have been adjusted based on a 100 year prediction.

Table 3.2 References used in assessing impacts of climate change.

Hazard	**Source**
Sea Level Rise	IPCC (2001, , 2007), Singh et. al, (2001), Khan et. al. (2002), Sheppard (2002), Kench et. al (2005), Woodroffe (1993) and Hay (2006)
Air Temp	IPCC (2001, , 2007), Singh et. al, (2001), Hay (2006) and Khan et al. (2002)
SST	IPCC (2001, , 2007), Singh et. al, (2001), Hay (2006) and Khan et al. (2002)
Rainfall	Giorgi and Francisco (2000), Adger et. al. (2004), Hay (2006) and IPCC (2001, , 2007)
Wind gusts	IPCC (2001, , 2007) and Hay (2006).
Swell Waves	IPCC (2001, , 2007) and Kitoh et al.(1997)

3.3 Assessment Methodology

3.3.1 Outline of process

As noted above, hazard assessment consists of systematically identifying hazardous events, their potential causes, consequences and patterns. We are interested in the underlying causes of the hazard events and the potential impacts on inhabited islands. In general hazard assessment requires different model parameters for varying hazard types. However, the usually accepted basic framework is simple and based into two parts: 1) the probability of occurrence of the event or hazard scenario; and 2) the propagation of the 'event' through the atmosphere (e.g., windstorm), the earth's sub-surface (e.g., earthquake), or on the earth's surface (e.g., flood).The proposed methodology follows a three stage process to cover both these elements and modeling requirements for individual hazards. They are:

- Hazard Identification
- Hazard Analysis
- Hazard Evaluation

Figure 3.1 summarizes the stages, their inputs and outputs. The overall process is designed to deliver the following outputs.

- Description
- Severity (intensity)
- Magnitude (potential size of impact area)
- Probability/frequency
- Hazard Zone (location/extent of impact area)

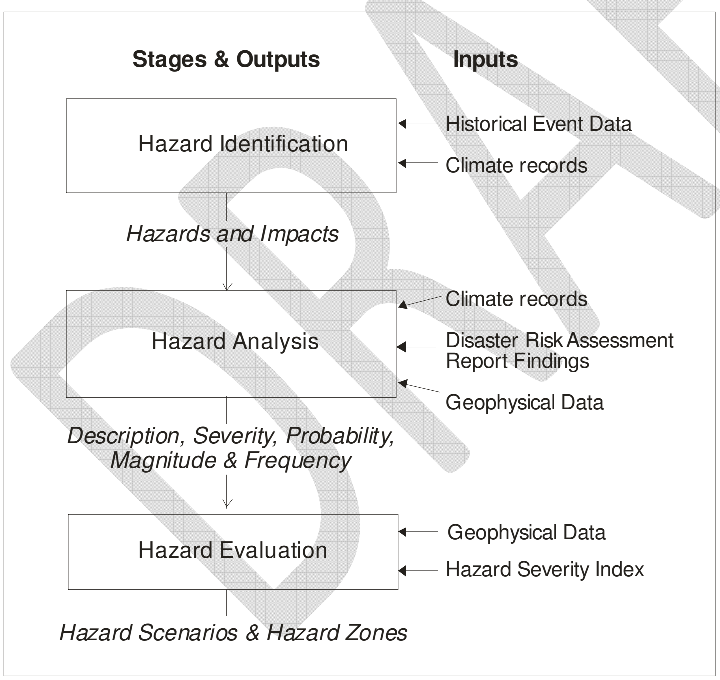

Figure 3.1 Hazard assessment process.

3.3.1.1 Hazard Identification

The first stage of hazard assessment is to identify the hazards facing the study location. The most commonly accepted method for hazard identification is to catalogue the historical natural hazard events and their impacts. Unfortunately there is no centralized catalogue or a database of historical natural hazards in Maldives. Much of the information are contained in geographical and historical publications, archived newspapers dating back to 1970's and the island gazette maintained by the Island Offices. However, these publications except the newspapers only provided the major events and often contained conflicting reports especially on dates and extent of impacts. It was found that the best source of localized information were the elderly residing on the islands. Hence, the following methods of combining literature review and field interviews were adopted for the purposes of this study.

- Undertake literature review of regional and local level natural hazard events. The main sources of information are provided in Table 3.1.
- Compile natural hazards events list from the Island Office gazette. Data kept in this manner is dependent on the island administration and would vary from island in terms of quality and regularity of recording.
- Conduct interviews with elders on the island (usually a minimum of 3) to document historic events and their impacts. Interview forms are provided in appendix 1 Form A.
- Compile available climate data for the known dates of the events.
- Compile the findings from first three sources and reconstruct a natural event history for the island including event impact maps.

3.2.1.2 Hazard Analysis

The overall process followed in hazard analysis is as follows.

- Analyze the Developing Disaster Risk Profile Report (DDRR) for regional hazard patterns and predictions.
- Analyze climatic data and literature to determine regional hazard patterns for hazards not studied under the DDRR.
- Undertake island level hazard assessment based on regional level findings, climatic data and local geophysical data. The assessments undertaken are as follows:
    - Establish the origins and propagation patterns for each hazard.

- Analyze historical hazard records of specific islands against existing climate records to determine threshold levels for severity.
- Determine the magnitude and probable hazard scenarios.
- Establish the probability and frequency of occurrence for various hazard scenarios.

3.2.1.3 Hazard Evaluation

Based on the outputs of hazard analysis, namely hazard description, severity (intensity), magnitude, probability and frequency, further evaluation is conducted to determine island specific hazard scenarios and hazard zones.

Probabilities for the event are expressed in qualitative scales of occurrence: Low Impact, Moderate Impact and Severe Impact. Hazard events are expressed as high, moderate or low for ease of reference for non-technical reader. The approximate quantitative values were measured based on Average Recurrence Interval (ARI) and Annual Exceedence Probability (AEP). ARI is the average interval amongst all available records. AEP is mathematically expressed as follows:

$$AEP = 1/ARI$$

Where,

AEP is annual exceedence probability;

ARI is Average Recurrence Interval;

Then probability of occurrence of an event can be expressed as follows:

The quantitative thresholds used for expressing quantitative values are as follows:

Table 3.3 Qualitative equivalents of event probability thresholds

ARI	AEP	Qualitative classification
1	1	Very High
2	0.5	High
3	0.3	
4	0.25	
5	0.2	

10	0.1	
25	0.04	Moderate
50	0.02	
100	0.011	Low
250	0.004	
500	0.002	Very Low
1000	0.001	Unlikely

The index is severity rating for a given area on the island between 0 and 5. The Index values are summarized below:

Table3.4 Hazard Severity Index and its description.

Hazard Severity Index	**Description**
0	No Impact
1	Very low intensity
2	Low intensity
3	Moderate intensity
4	High intensity
5	Very high intensity

The index is assigned based on the following principles.

- Areas known to experience high severity and impacts during past events are likely to show similar exposure unless substantial geophysical changes have been made, such as land reclamation. Hence, past hazard zones are the primary source of information for hazard zoning.
- Existing geophysical characteristics that may lead to high severity for predicted events are likely to demonstrate predicted patterns. Hence, features such as topography, coastal ridge height, island size, island width and vegetation cover should be used predict severity levels within islands.
- The threshold levels for the severity index should be determined by the predicted extent of impact based on given hazard event parameters. Parameters for swell waves, udha, storm surge and tsunamis are flood water height on land, direction of wave approach and relative speed of

flood water. Parameters for heavy rainfall include estimated flood height in any given area and parameters for wind storms are wind speeds in knots. A general pattern of threshold levels are presented in Table 5 below. The figures may vary between island especially for heavy rainfall and wind speed based on other parameters.

- To maintain consistency in the assessment, only severe scale events provided in the hazard scenario will be used for hazard zoning.

Table 3.5 General trends in threshold levels for Hazard Severity Index.

HSI	**Description**	**Swell waves, Udha, tsunamis & storm surges (flood height)**	**Heavy Rainfall (Flood height)**	**Strong Wind (wind Speed in knots)**
0	No Impact	< 0.1m	< 0.1m	< 10 knts
1	Very low intensity	> 0.1m	> 0.1m	> 10 knts
2	Low intensity	> 0.25m	> 0.2m	> 20 knts
3	Moderate intensity	> 0.5m	> 0.3m	> 30 knts
4	High intensity	> 1.0m	> 0.4m	> 40 knts
5	Very high intensity	> 1.5m	> 0.6m	> 45 knts

3.2.2 Event scenario building

Hazard scenarios were generally developed using a combination of above mentioned outputs and geophysical data. Scenarios are developed into three qualitative scales of impact thresholds: Low, moderate and severe. Hazards events are expressed in standard units as summarized in the table below. The sea induced hydrological hazard events are measured as wave height on reef flat rather than the Mean Sea Level. This change has been considered due to the ease of measurement.

The geophysical data parameters considered are also summarized in the table below. Not all these parameters are readily applicable for scenario development. Most of these parameters provide a qualitative guide to the predicted severity of the events especially at a comparative scale. However certain parameters are crucial for scenario development. They are island ridge height (tsunami, swell waves, storm surge and udha), topography (rainfall) and vegetation cover (wind storms). The island ridge height determines whether a wave of certain height could flood the island. For example a wave of 2.5 m height on oceanward reef flat may not flood Kulhudhuffushi Island due to a 2.6 m high ridge but would easily flood L.Gan Island with an average ridge height of 1.6m. Similarly islands with saucer shaped topography (eg. Thulusdhoo) will be easily flooded during heavy rainfall compared to mound shaped topography (eg. Sh. Funadhoo). Similarly islands with stronger vegetation cover would have less damage to housing structures compared to an island with less vegetation cover, for any given intensity.

Hence, based on these parameters, hazard scenarios are presented as threshold levels for low, moderate and severe impacts.

Table 3.6 Geophyscial parameters used for hazard scenario and zone construction.

Hazard	**Hazard events expressed as**	**Geophysical parameters used in hazard scenario and zone construction**
Swell waves, Storm surge and *Udha*	Wave height on reef flat	Island coastal ridge height, topography, width of island, location within atoll, location on reef, island orientation, reef flat width and location within archipelago.
Tsunamis	Wave height on reef flat	Island coastal ridge height, topography, width of island, location within atoll, location on reef, shape of island, island orientation, reef flat width and location within archipelago.
Heavy Rainfall	Rainfall in millimetres for a 24 hour period	Topography, size of island and location within archipelago.
Wind storms	Wind speed in knots for single event or day	Size of island, vegetation cover and location within archipelago.
Earthquakes	Modified Mercalli Intensity (MMI) value	Location within archipelago

3.2.3 Hazard Zoning

Similar to hazard scenarios, hazard zones were generally developed using a combination of outputs from hazard anlaysis and geophysical data. More specifically hazard severity (intensity), magnitude and geophysical parameters listed in table 4 were used.

Hazard zoning is a two-step process. First, a Hazard Severity Index (HSI) is developed based on the above mentioned parameters. The second step of hazard zoning includes composition of hazard zones in a Geographic Information System (GIS). Basemap layers for the GIS are compiled from existing sources such as Ministry of Planning and National Development and field surveys. The base layers include the following:

- Coral reef outline (including deep lagoon areas)
- Island shoreline
- Island vegetation line
- Wetlands
- Roads
- Housing blocks
- Access infrastructure (eg. Harbor)
- Coastal protection

In addition the following layers are compiled based on field surveys. Most of these data are compiled under the physical environment component of this study.

- Topography
- Vegetation Cover
- Measured ridge heights and widths
- Reclaimed areas
- Past event extents and impact zones

In an ideal situation the study should have access to high resolution topographic and bathymetric data and detailed automated modeling of flood characteristics in various hazard scenarios should be undertaken. However, as mentioned earlier, we do not have access to such detailed data and hence a high level of manual modeling needs to be done. This includes the delineation of hazard zones based on principles outlines under stage 1 and data available in base layers. In particular the delineation of low and high areas is based on approximation using surveyed topographic profile data. Similarly, estimation of flood distance based on flood decay curves and tide levels require high level of manual estimation based on historic events, topography, structural obstruction, vegetation cover, wetland areas and ridge heights.

The compiled hazard for any given hazard will have hazard zones assigned based on threshold levels for Hazard Severity Index. Due to the high level of manual modeling involved the areas depicted are best estimates rather than absolute zones. The maps are presented based on the Hazard Intensity Zones for individual hazards.

As a final step, a composite hazard map is compiled using GIS software. The exiting hazard zones which have been assigned a Hazard Severity Index is overlaid each other and added using Raster GIS functions. The resulting map simply represents a summation of Hazard Severity Index and would present an overall pattern of hazards distribution on the island. For consistency in indexing the values in the composite hazard maps are reduced to the same scale as individual hazard maps. It should be noted that the composite hazard map is simply a representation of hazard intensity and does not provide any information on probability of occurrence. Moreover, the scales of intensity for individual hazards are different. For example the impact in a high intensity rainfall zone due to rainfall related flooding is cannot the same as the impact from a high intensity tsunami in tsunami prone zone. Hence the composite hazard map should only be used as a general planning guide for hazard prone zones and the individual hazard zones should be the basis for detailed plans.

3.3 Working Procedures

3.3.1 In-house Data Collection & literature review

In-house data collection and literature review primarily involves compilation of data about historical records and their impacts. In addition scientific literature on the natural hazards occurring in Maldives is evaluated to determine the origins, patterns, future estimations and propagation patterns of hazards. Literature used for historical event data collection is provided in Table 6.

Geophysical data not collected under the physical environment component of the project is also acquired under hazard assessment component.

In addition to the sources identified in table 6 other island specific documents such Environmental Impact Assessments, Land use plans, and general planning documents were referred.

Table 3.7 Historical event references

Item	Description
1	Geography of Maldives *(Dhivehirajjeyge Geographyge Vanavaru)* by Mohamed Ibrahim Luthfy (Luthfy, 1994) – Local language
2	Topography of Maldives by Hassan Ahmed Maniku (Maniku, 1990)
3	Island of Maldives by Hassan Ahmed Maniku (Maniku, 1983)
4	The Maldive Islands: Monograph on the History, Archaeology, and Epigraphy by H.C.P. Bell (Bell, 1940)
5	Haveeru Newspaper – Local language
6	*Viyafaari Miadhu;* Old newspaper dating back to 1960's

3.3.2 Field Surveys

Field surveys were carried out in the nine islands between 5 and 29 January 2007. These surveys concentrated on collecting the information outlined in Table 3.3. The table below highlights the main surveys, data collection procedures, the parameters assessed and resources required.

Table 3.8 Field surveys conducted and their details

Survey	Survey Process	Resources Required	Parameters observed
Reconstruct natural disaster and severe weather event history of island and past impacts on natural & human environment	- Identify events from historical records - Conduct interviews with locals (erosion, flooding and wind related damages) - Get recent event information from island office - Explore field evidence, where available. (shoreline change, vegetation change, storm rubble on reef)	Historical event records, interview questionnaires, GPS, basemap and landuse maps.	- List of historical hazard events - List high impact events - Damages from historic events - Extent of past event impacts (eg flood extents) - Field evidence of historical impacts

Survey	Survey Process	Resources Required	Parameters observed
	- Identify impact extents and frequently impacted locations, especially floods, using GPS - Cross check event information form publications and interviews with one another.		

Field interviews are also conducted in conjunction with the physical environment component as data collected for that component is crucial for hazard assessment. Hence, for methodologies relating to geospatial data collection, refer to physical environment section.

Experience from this project shows that the following points should be considered when conducting field interviews related to natural hazards.

- The most knowledgeable persons in any island are the elders. However, it will require careful leading to get the best information out of them as their memories are often weak and only tend to concentrate or events with significant impacts. Prior knowledge of some historical events through literature review often yields best results as it is easier for them to recall. Moreover, care should be taken in recording dates as they cannot recall them properly. The best method is to relate natural events to other events of significance such as political or social.
- Interviewing in groups has its benefits and drawbacks. Group interviews can provide more accurate information due to discussion. However, if one member of the group is more dominant or is much respected, then the others fail to contribute and could yield inaccurate information.
- It is better to visit the elders at their home or at the beach rather than invite them to island office.
- Their sense of island geography is usually distorted and hence care should be taken when plotting information on map. Best results are

obtained by visiting the impact sites with them, while the exact locations can be plotted on to a GPS.

- Fishermen usually lack the information about hazard events as most of them are out at sea during day time.
- Women tend not to participate in such interviews but their views (and dates) are often more accurate if the event took place within the settlement.
- Interviews with visitors from neighboring islands or if possible visits and interviews in neighboring island will provide crucial information that could be cross-check with those gathered in main survey island. Usually events will occur in a regional or at least an atoll setting with nearby islands getting affected as well.

3.4 Result interpretation and presentation

The procedures used in results interpretation are described in detail in the Assessment Methodology section above. It is important to note that a good understanding of natural hazards experienced by Maldives is essential to undertake this assessment. The limitations caused by lack of data makes such knowledge invaluable as a large degree of professional judgment is required. Moreover, it would also be an advantage to have knowledge on the physical environment of Maldives or work in tandem with a physical environment specialist as these two components are highly interrelated in the Maldivian context.

The presentation of results takes into account the target end-users of this document: policy makers and planners. The presentation style follows a simple descriptive format rather than a scientific document format. Outputs such as hazard scenarios and hazard zones are expressed in descriptive form rather than quantitative values. Much of the scientific workings have been left out while the results are described in details. However, for the benefit other potential users such as researchers in the field of hazard science and future partitioners of this methodology, a more detailed assessment methodology is presented here. In any case, the methodology used in this assessment is not complex when compared to the risk assessment field and has been geared for rapid assessment of islands.

3.5 Limitations

The main limitation for this study is the inaccessibility to long-term meteorological data. Historical meteorological datasets are crucial in any hazard assessment activity as it forms the basis for assessing hazard patterns, thresholds, probabilities, frequencies and return periods. For much of the hazard assessment methods, the end results are as good as the source data used. The lack of data was a result of limitation in resources to acquire the data following the Department of Meteorology's recent decision to introduce a user-pays policy. The amount of data required for the project meant that a substantial charge is levied for acquiring them. In addition, the existing meteorological data has a very short timeframe due to the recentness of the meteorological stations. The data is also regional in nature due to the sparse distribution of meteorological centres. Hence site specific hazard extremes in events such as heavy rainfall and high wind speed may not be measures accurately. The lack of data has been partially compensated by borrowing data from alternate sources such as University of Hawaii (tidal data) and referencing limited records available as Monthly and Yearly climate records on Department of Meteorology's website. Moreover, available records from the Developing Disaster Risk Profile Report (UNDP, 2006) were also utilized. Extrapolation of data was necessary to cover for the minimal coverage of available data. However, extrapolation beyond the period of data availability introduces uncertainty. A more comprehensive assessment is thus recommended especially for wind storms, heavy rainfall and swell waves once and if high resolution meteorological data is available.

The second major limitation was the incompleteness of the historic data in some islands. A detailed understanding of what events have occurred in the past (including prehistoric events) and their effects provides the basis for understanding what could or will happen in the future. It is a key step in the risk identification process. The island authorities generally do not collect or record the impacts and their dates in a systematic manner. Where records are kept there is no consistent format for keeping records. In addition there is no centralized database of historical events. Data collected from field surveys and literature review often have inconsistencies in their dates especially for those events beyond the 1980's. The dates compiled from historical records are used to determine the probability of occurrence but their inaccuracies limit these assessments. However, event impact descriptions are often consistent and very useful.

Thirdly, when historical events are used predict future events, it is commonly assumed that there will be no change in the geophysical setup of the island and factors causing hazards. This assumption known as *stationarity,* ignores the possibility of environmental change. This assumption has major drawbacks in assessing hazards in the coral islands of Maldives where natural adaptation occurs against frequent hazards and human alteration of environment is common practice. Human geophysical alterations such as land reclamation and coastal process alteration is substantial enough to cause variations in any predicted hazard patterns. The probability of climate change further increases these variations slowly but dramatically over time. Hence, the assessment should be considered valid only for a shorter timeframe of between 30-50 years and less than for highly altered environments.

Fourthly, hazard assessment in general is a highly uncertain science, especially if the source data is limited or of average quality. Uncertainties in the data available for this study meant that detailed assessments using more accurate models were not possible. Fortunately this study follows on from the Developing Disaster Risk Profile study which was conducted using more detailed resources for hazard identification. Hence, regional projection and estimates derived from the DDRP study is sufficient in most cases to conduct a detailed assessment on individual islands. The level of confidence in the hazard scenarios is high but that of hazard zones are low due to limitations in data.

Finally limitations in acquiring high resolution geophysical data such as topography and bathymetry limit the accuracy of some assessments such as hazard zoning. For limitations in geophysical data refer to the limitation sections of Physical Environment Assessment.

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APPENDIX

A. Historical event interview worksheet

Name of Person:
Oragnization/Address:
Age:
Experience in island historical events:

Date of Event (s):______________________
Event Name (s) :____

Type of Event: *Udha ; Tidal Wave ; heavy rainfall ; earthquake ; tsunami ; Storm ; erosion ; temperature rise*

Description of Event (How it unfolded, direction of approach, flood height):

Damage caused by the event:

Extent of impact: *Note: Mark on Map as well*

Other Notes:

Chapter 4 Environmental Vulnerability Assessment
By Shaig Ahmed

4.1 Introduction

4.2 Assessment Methodology

4.3 Working Procedures

4.3.1 In-house Data Collection & literature review

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4.1 Introduction

This section explains the methodology used to evaluate physical environment vulnerability in the selected islands. In its truest sense physical environment vulnerability covers the exposure of the entire physical environment system to a specified hazard or range of hazards. The terminology used in risk assessment literature is usually confusing for the average reader, mainly due to their overlapping usage in varying circumstances. Much of risk assessment literature, usually with social perspectives, generalises both the *hazards* and *physical environment* as environmental risks (see for example Smith (2004) and Whyte and Burton (1980)). The term *hazard* is usually used to refer specifically to physical manifestations of episodic geologic or climate events (adopted from Brooks, 2003). A distinction has been made in this study between the hazards and the physical environment, whereby the physical environment (similar to the human environment) is exposed to risks from hazards. Hence, this study defines the concept of physical environment vulnerability as the vulnerability of the coral island environmental system and their surrounding reef systems to a specified hazard or range of hazards. These hazards have been explained in detail in the previous chapter.

This component of the assessment is being undertaken to assess the importance or the vulnerability of the physical environment against natural hazards. The coral islands of Maldives are geologically unique from much of the rest of the world due to their small size, elevation, unconsolidated nature (of land) and reliance on natural environment features for its defence against natural hazards. The entire archipelago is dependent on the natural coral reef environment for its existence, especially in the geological timeframe, where sea levels fluctuate and island existence is dependent on the ability of coral reefs to keep up with any rise in sea level (Kench et al., 2005, Woodroffe, 1993). The islands themselves are formed and maintained through a combination of climatic, hydrologic and geomorphologic forces which over time could be subject to variation. Hence it is quite common for islands to undergo readjustment to prevailing conditions. The generally volatile nature of the coral islands exposes the physical environment to a number of hazards. The islands themselves develop resilient features overtime to mitigate hazards which perhaps have led to the survival of the archipelago over the 3000 years of its existence. Hence, the specific geophysical features of an island may partially dictate the exposure of the human environment to hazards. It is imperative that any assessment of safe islands in Maldives must therefore consider the physical environment features and how they may act to reduce or increase the vulnerability of any given island.

While the concept of physical environment vulnerability is defined separately for assessment purposes, the assessment methodology and results presentation are aligned to function as inputs to other sectors of this study. Hence, the approach of this study is broadly geared towards the human environment and as such should not be considered just a physical environment assessment. As noted in previous chapters, this study covers physical, structural, economic and social environment vulnerability against natural hazards and hence has a dominant human environment perspective to vulnerability. In fact the entire study could be characterized as a strategic risk assessment which is geared towards providing inputs to informed decision making relating to establishment of safe islands. In order to facilitate the broad theme and due to time restrictions, certain detailed assessments which may be usually considered in physical environment studies, but were found to be less important to this study, were sacrificed. This includes detailed ecological impact assessments from hazards, especially on the fauna. However, the ecological assessments for vegetation and wetland areas were undertaken due to their prominence in the terrestrial environment of a coral island. The exclusion of ecologic assessments is partially justified by the lack of significant faunal environments in coral islands.

Due to the human environment orientation of the broad study and the resilience of natural environment, much of the physical environment assessment has been devoted to assess the impact on human environment due to characteristics of the natural environment, rather than direct impact on natural environment. This decision was taken based on preliminary assessments which showed that the physical environment of the coral islands, while exposed to hazards, is highly resilient in their natural state. The major impacts on natural environment are usually restricted to the terrestrial environment where vegetation loss and water lens salinisation. Impact on the coastal and marine environment was found to be minimal even during the worst hazard events such as the tsunami. Furthermore, the recovery of the natural environment was very rapid in terms of the geological timeframe. Hence, it was more important to assess the implications of the existing natural environment and environmental change on the human environment exposure.

This section of the report is intended as methodological guide to this study but also as a methodological framework for future similar assessments in other safe islands. Hence, this section has been compiled in a manner which it forms part of the document as well as a standalone methodological document for safe island assessment. The following subsections will describe the methodological framework, data sources required, specific field procedures and methods used in data interpretation.

4.2 Assessment Methodology

The prediction of environmental impacts in coral islands based on probability assessments of episodic geologic or climate events and climate change is not straightforward. There is no standard methodology for coral island hazard assessment (Mossler, 1996) and much of the methodology is in the development stage and yet to become robust.

Whyte and Burton (1980) specified a list of question which need to be asked before any specific environmental assessment method is chosen. They are:

- Is the problem an analysis starting from a suspected or known hazard?
- How is the problem distributed geographically? *(hazard patterns across archipelago)*[1]
- How much time is available to asses the risks? *(long-term problems and episodic problems)*
- Where do the effects lie? *(Which part of the island environment?)*
- Is the target normal or particularly susceptible? (unstressed ecosystems or altered systems).
- *What data is available and what data needs to be collected?*

By specifying the problem in terms of these questions, it is possible to understand the magnitude of the tasks, where to start and what can be achieved within the given timeframe. The answers to these questions in the context of this study are as follows:

- The hazards and their geographic distribution has already been identified in the Disaster Risk Profile of Maldives (UNDP, , 2005)

[1] italics show elaboration and edition to Whyte and Burton's proposed questions.

- The time available for assessment, especially field assessments are very limited and hence cannot consider detailed quantitative assessments

- Impacts are felt throughout an island depending on island size; primary impact zone is the coastal environment and low lying terrestrial environments.

- The ecosystems are highly altered due to human activity; risks may arise due to both *environmental processes* and *human behaviour.*

- There is very limited historical and long-term scientific data, and site specific data; will have limits on quantitative assessments.

A number of methods for environmental risk assessment are available. These methods are based on large scale assessments in continental settings and are often too complex to be considered for small coral island environments. The preferred quantitative methods within the scientific community are impact modelling and testing. Impact modelling methods include ecosystem models, phsycial transport models, hydrologic and atmospheric models (US EPA, 1992). Other technical models include probabilistic tree modelling and monte-carlo modelling. Specific quantitative models for small islands have been developed in relation to climate change impact assessment. These include coastal erosion modelling (Kench and Cowell, 2001, Kench and Cowell, 2002) and reef impact modelling (Yamano, 2000). These methods, while highly efficient, rely on considerable amount of site specific data, preferably with a spatial and a temporal dimension. Unfortunately, the timeframe available for this study and the lack of historical and long-term scientific data makes undertaking such empirical modelling an impossible task.

In the absence of quantitative data, there is also good reason to develop as a first step a quantitative model which maps out the all the possible interaction between hazards and natural environment, whether or not they can be quantified (Whyte and Burton, 1980). Numerical representation of critical parts of the system may be undertaken at a second stage and more complex assessment may be undertaken at a latter stage or during a more detailed assessment. Hence, this will be the methodological approach undertaken in this assessment. This approach is modelled as an assessment framework in Figure 4.1.

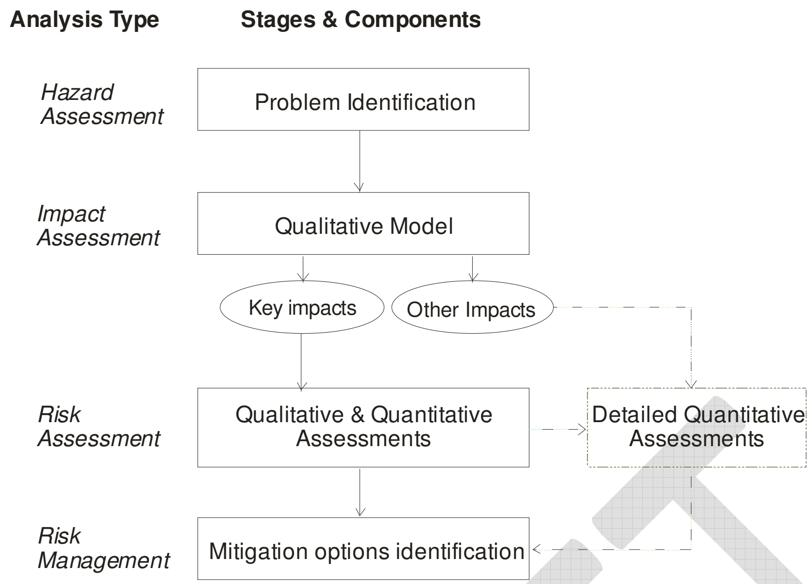

Figure 4.1 Physical environment assessment framework.

In defining the above framework, models proposed by Carter et al. (1994) and Beer and Ziolkowski (1995) were used as a starting point. Their proposals for analysis type have been mostly retained but the stages and components have been re-developed to suit the needs of this study. The problem identification stage assesses hazards and information using the questions identified earlier in the section. The qualitative model identifies the interactions between the environment and hazards, and eventually hazard exposure. The key impacts will be separated from the model and used for qualitative and quantitative assessment. Some of these assessments may not be undertaken due to time and data restriction, which will be proposed for future detailed quantitative assessment. The findings of the preliminary assessment will be used to propose mitigation options and recommendations.

The qualitative model of physical environment and hazard interaction is provided in Figure 4.2.

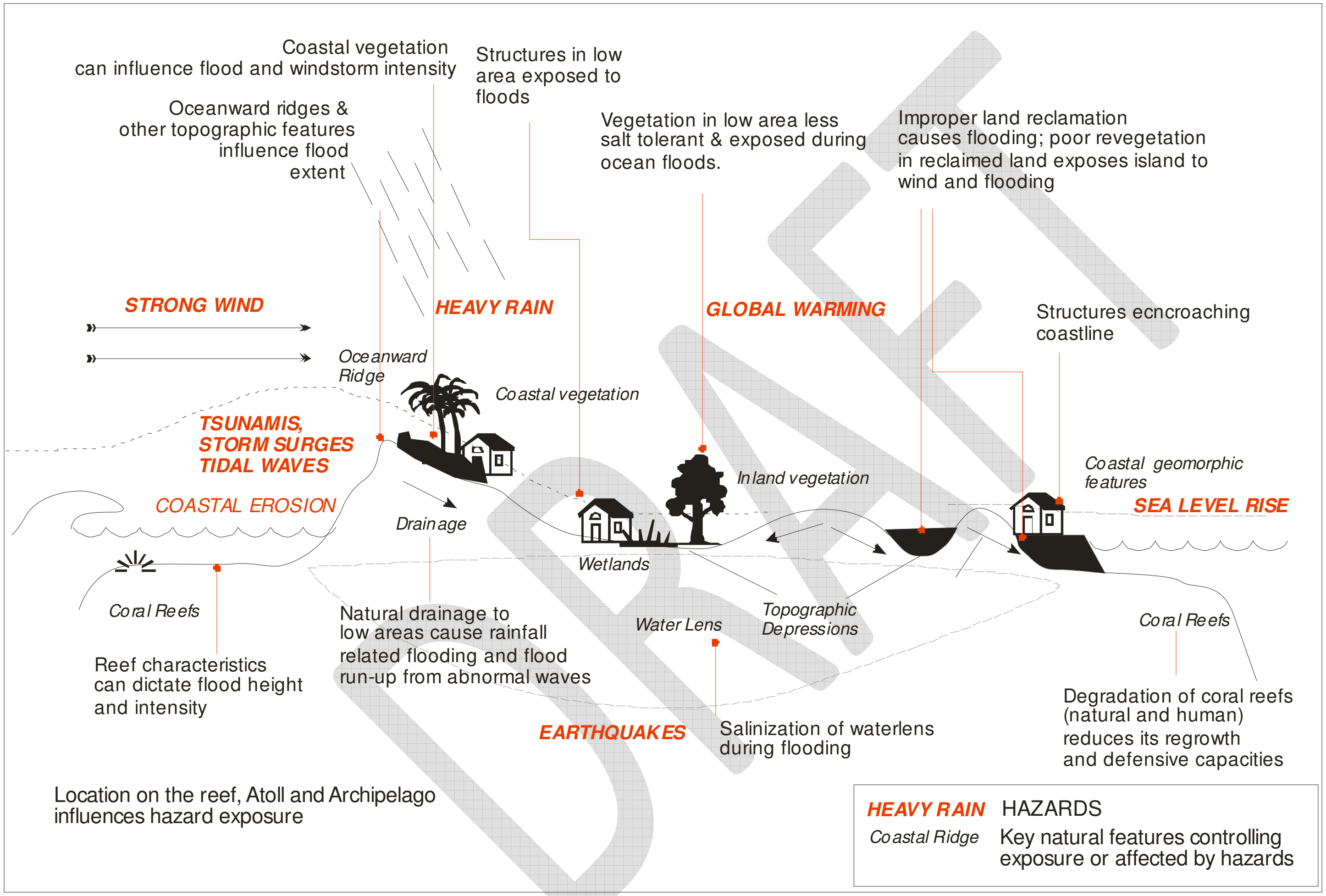

Figure 4.2 Qualitative model of hazard and key natural environment impacts in inhabited islands of Maldives.

This model was initially developed based on existing literature and professional experience in risk assessment. It has since been enhanced after the assessments in the 9 islands.

The hazards considered for assessment are ocean induced flooding from storm surges, tidal waves and tsunamis, heavy rainfall related flooding, climate change (specifically sea level rise and temperature increases), earthquakes, strong wind and coastal erosion. Amongst these the main risks to the environment are from sea induced flooding, global warming, sea level rise, strong winds and erosion. Coastal erosion is generally considered a consequence of sea level hazard exposure. However, erosion and accretion in the islands of Maldives is a natural function of island evolution and hence forms a hazard irrespective of climate change. It's impacts however are exacerbated due to changes in climate. Hence, in the context of Maldives it is more appropriate to consider erosion as a hazard.

The key aspects identified for risk assessment based on the model are:

- *Environmental impacts* on key *geophysical features*: vegetation, water lens, coastal geomorphology and coral reefs.
- Impact of key *geophysical features on hazard exposure*, namely; topography, vegetation characteristics, drainage system, geographic location, island geometric characteristics and reef characteristics.
- Impact of natural and human induced *environmental change* on hazard exposure.
- Role of past *natural and human adaptation* to hazards.

A number of qualitative and quantitative risk assessments procedures were followed to assess the above environmental aspects. They are summarised in Table 4.1.

Table 4.1 Major assessments and parameters used for assessment.

Assessment	Type	Parameters	Expected outcome
Environmental Impact prediction - Vegetation - Water Lens	Qualitative and	- Vegetation: Proportion and spatial distribution of salt-intolerant species,	Vulnerability of key geographic features to hazards in their

Assessment	Type	Parameters	Expected outcome
- Geomorphology - coral reefs	Quantitative	water table depth, proportion of non wind resistant species and cover within settlement, proportion of salt tolerant species in coastal vegetation. - Ground Water: quality (saltiness and contamination), size and width of island, topography (presence of depressions, wetlands) - Geomorphology: Historical beach stability, beach material composition on oceanward and lagoonward side, shape of island, beach width and length, beach ridge height, historical evidence of hazard exposure (beach rock, ridges) - Coral Reefs: Approximate live coral cover, general fish abundance, proximity to island beachline, reef width	natural state
Impact of Geophysical features on hazard exposure	Qualitative and Quantitative	- Topography: Topographic variations, coastal ridge(s) height, presence of depression and wetlands, average island elevation - Vegetation: coastal vegetation belt width,	Role of geophysical features in hazard exposure of islands

Assessment	Type	Parameters	Expected outcome
		density, composition, relative age, proportion of vegetation cover - Drainage: topography, drainage pattern - Geographic location: relative location within archipelago, atoll and reef system. - Geometric features: island shape, size, orientation, width - Reef: reef flat width, island distance to reef edge, bathymetry, quality of coral cover, oceanward reef length and reef size	
Impact of environmental change on hazard exposure	Qualitative	- Natural: historical erosion and accretion rate, relative changes to reef quality over the last 50 years - Human: Extent of coastal environment alteration (from harbour construction, dredging, land reclamation, erosion mitigation, waste disposal or sand mining), terrestrial environment alteration (wetland reclamation, drainage alteration, deforestation, ground water over-extraction, introduced species, effects of improper land use), and marine environment	Extent of impact on hazard exposure of islands due to environmental change.

Assessment	Type	Parameters	Expected outcome
		alteration (sand and coral mining, and over-sedimentation due to coastal development activities)	
Natural and human adaptation in hazard exposure	Qualitative	- Natural: remnant geomorphic features (presence of storm ridges, beach rock), biological features (micro atolls, mangroves, wetlands, young coastal vegetation) - Human: nearshore and foreshore coastal protection measures, and structural features of houses	Identify whether the settlement has historically been frequently exposed to hazards and identify the existing hazard mitigation measures.

The assessment procedures will follow a four stage process. The *first stage* will involve data collection and literature review of selected islands. This will primarily include data from published sources, unpublished data sources, unpublished historical data, geospatial data and historical records and accounts of hazard events.

The *second stage* also involves data collection in the field. Data will be collected covering all possible parameters identified in the table above. Surveys will include geophysical surveys, interviews with locals and collection of historical records. This stage will also involve verifying secondary data acquired during the first stage.

The *third stage* will involve in-house assessment using the methods highlighted in the table above. These methods will be further described in the 'result interpretation' section.

The *fourth stage* will involve identification of potential mitigation measures and recommendations for safe island development. This stage will cover report compilation and presentation of results to relevant authorities.

4.3 Working Procedures

4.3.1 In-house Data Collection & literature review

Three major groups of data will be collected: 1) geophysical data, 2) historical hazard records and 3) published records describing/assessing island environment and environmental change.

A complete list of data collected for the study is attached in table 2 below. Geospatial data collected includes historical and current aerial photographs/satellite images, GIS base maps, physical survey data from old surveys and a set of geophysical data collected by James Cook University of Australia.

Historical hazard records were identified using newspaper archives, geographic publications and information from government databases compiled at James Cook University.

Published records collected include Environmental Impact Assessments, Land use plans, and physical survey reports.

Table 4.2 Background data collected from different Government and Academic Sources.

Item	Description	Source	Note
1	Wave regime around Maldives	Naseer (2001)	-
2	Historical records/publications of severe weather events	- Geography of Maldives (Luthfy) - Topography of Maldives (Maniku 1990) - Islands of Maldives (Mankiu 1983)	Data compiled for selected 9 islands
3	Features which make an island comparatively vulnerable	James Cook University (unpublished PhD	Based on a nationwide assessment

		data)	
4	Aerial photographs (1969, 1998, 2004)	MPND	
5	Satellite images	James Cook University (unpublished PhD data), MPND, GoogleEarth	
6	Unpublished Maps	MPND	In paper & digital form
7	GIS Data	James Cook University (unpublished PhD data), MPND	Detailed data from MPND corrected for errors
8	Geographic characteristics data	James Cook University (unpublished PhD data)	Need to compile
9	Island environment profile	MEEW	Recieved in Paper form
10	Island reports (Poverty project)	MPND	Kudahuvadhoo only, Gan NA
11	Safe island EIA's (Viligilli, Vilufushi)	MPND	Received in Paper form
12	Island landuse plans	MPND/Housing/MCPI/MHUD	received
13	Any other reclamation plans	MPND	
14	Physical Studies	MPND/Housing/MCPI/MHUD	All available data & reports collected
15	Hithadhoo topographic survey	MCPI	Covers wetland area only
16	Hithadhoo Marine protected area	MEEW	
17	Island Development Plans	MOAD	6 islands

4.3.2 Field Surveys

Field surveys were carried out in the nine islands between 5 and 29 January 2007. These surveys concentrated on collecting the information outlined in Table 4.1. The table below highlights the main surveys, data collection procedures, the parameters assessed and resources required.

Table 3: Field surveys conducted and their details.

Survey	Survey Process	Resources Required	Parameters observed
Topographic Surveys - Beach profiles - Section profile - Ground water depth	- Identify survey sites - Conduct leveling survey for atleast two sections and/or alteast two beach profiles. - Measure ground water depth in wells around the survey lines. - Derive elevations and section topography using data - For other areas, interview locals to identify low areas where water drains during rainfall. - Identify reclaimed areas though interviews, official documents and comparing historical aerial images	Survey equipment : 1 level, finder, tripod, compass, differential GPS. Other Info: Aerial Photographs, Base map (2004). 1-2 support staff	- Island elevation - Topographic variations, coastal ridge(s) height, presence of depression and wetlands - remnant geomorphic features (presence of storm ridges, beach rock) - Drainage patterns - Depth to ground water lens - Topographic alterations: wetland reclamation, drainage alteration, coastal reclamation, road leveling, sand mining
Vegetation Mapping	- Pre-identify major vegetation patches and distribution from aerial images - Identify sample survey locations - Classify vegetation based on ground truthing data - Record specific characteristics of	Historical and current aerial photographs, false colour satellite images (if available), Camera, GPS	- Spatial distribution - Proportion and distribution of salt-intolerant species, proportion of non wind resistant species and cover within settlement, - proportion of salt tolerant species in coastal vegetation.

Survey	Survey Process	Resources Required	Parameters observed
	coastal vegetation - Identify sample locations of vulnerable species using GPS. - Document and photograph key vegetation species and specific locations for later reference		- Coastal vegetation belt width, density, composition, relative age, proportion of vegetation cover - Vegetation alteration: deforestation, reclamation, introduced species, level of clearing in coastal vegetation
Identify physical evidence of hazard exposure	- Pre-identify coastal changes using historical aerial images - Survey specified locations for beach composition, evidence of shoreline change (beach rock, multiple ridges), storm activity and sea level change (ridges, micro atolls, historic waterlines)	Survey equipment: 1 level, finder, tripod, compass, differential GPS. Other Info: Historical Aerial Photographs, Base map (2004). 1-2 support staff	- remnant geomorphic features (presence of storm ridges, beach rock), biological features (micro atolls, mangroves, wetlands, young coastal vegetation)
Reconstruct natural disaster and severe weather event history of island and past impacts on natural & human environment	- Identify events from historical records - Conduct interviews with locals (erosion, flooding and wind related damages) - Get recent event information from island office - Explore field evidence, where available. (shoreline change, vegetation change, storm rubble on	Historical event records, interview questionnaires, GPS, basemap and landuse maps.	- List of historical hazard events - List high impact events - Damages form historic events - Extent of past event impacts (eg flood extents) - Field evidence of historical impacts

Survey	Survey Process	Resources Required	Parameters observed
	reef) - Identify impact extents and frequently impacted locations, especially floods, using GPS - Cross check event information form publications and interviews with one another.		
Assess the status of existing environment	- Coastal Environment: Identify erosion and accretion zones, general variation in geomorphology around the island (beach composition, width height), coastal vegetation characteristics, environmental change (coastal developments, effects of alteration, beach pollution) - Terrestrial Environment: Assess ground water quality, Vegetation distribution and composition, wetlands, and their conditions, general soil conditions, identify habitats of significance, environmental change and its impacts	Historical Aerial Photographs, Base map (2004), current aerial photograph, portable water quality testing kits, Camera, GPS, vegetation species guide, Underwater camera, water proof paper	- Ground Water: quality (saltiness and contamination), size and width of island, topography (presence of depressions, wetlands) - Geomorphology: Historical beach stability, beach material composition on oceanward and lagoonward side, shape of island, beach width and length, beach ridge height, historical evidence of hazard exposure (beach rock, ridges) - Coral Reefs: Approximate live coral cover, general fish abundance, proximity to island beachline - historical erosion and accretion rate, relative changes to reef quality over the last 50 years

Survey	Survey Process	Resources Required	Parameters observed
	(deforestation, reclamations, ground water) - Marine environment: Broadly assess reef quality, reef and lagoon characteristics and alterations to Marine environment (dredging, reclamation, coral/sand mining)		- Extent of coastal environment alteration (from harbour construction, dredging, land reclamation, erosion mitigation, waste disposal or sand mining), terrestrial environment alteration (wetland reclamation, drainage alteration, deforestation, ground water over-extraction, introduced species, effects of improper land use), and marine environment alteration (sand and coral mining, and over-sedimentation due to coastal development activities)

4.4 Result interpretation and presentation

This part of the assessment corresponds to the risk assessment and risk mitigation components identified in the methodological framework (see figure 1). The environmental assessment was broadly based on the following formula:

Predicted hazard impacts x Historical hazard impacts x Existing Geophysical Features x Environmental Change = Island Physical Environment Exposure

Data interpretation was done using a range of methods. The bulk of the assessment was done using a Geographic Information System (GIS). Quantitative and qualitative data collected in-house and in field visits were fed into the GIS and overlaid on the basemap to establish a broader view of the hazards and their interaction with the environmental features. Spatial data parameters such as geographic location (relative location within archipelago, atoll and reef system) and geometric features (island shape, size, orientation and width) were solely derived from the GIS.

The following procedures were followed during the GIS based data interpretation process:

Firstly basemaps were compiled within the GIS using data provided by MPND and JCU (see table 2). Missing data were added by digitising ortho-rectified images. A number correction s to the existing basemaps was also made using recent images.

Secondly, additional layers were created which provided data on previous surveys and land use plans. Land use plans were only provided in PDF format and had to be geocoded into the GIS as a raster image.

Thirdly, data collected during field visits were entered into the GIS system as layers. The most important of these layers include historical hazard extents, estimated topographic variations, vegetation distribution, coastlines, coastal features and newly reclaimed land. In fact all the major features identified in qualitative model (see figure 2) were input as layers where ever possible.

Fourthly, predicted hazard scenarios were input as three probable intensities: high, medium and low.

Finally, the historical hazard data, existing geophysical characteristics and predicted hazard scenarios were used to analyse a range of impacts. These include:

- identification of hazard zones (eg. rainfall hazard based on topography drainage pattern and predicted maximum rainfall, coastal flooding hazard based on ridge height, vegetation and drainage)
- Impact of geophysical characteristics on historical hazards (eg. Overtopping thresholds for ridge heights, role of drainage patterns in rainfall and coastal flood risks, relationship between of topography, vegetation and reef characteristics in flood run-up)

- Impacts of environmental change on increased or decreased hazard exposure (eg. comparison of erosion patterns before and after developments, using historical data)
- Role of natural adaptation (eg comparison of hazard exposure and geophysical responses across the 9 islands)

Other methods used in the interpretations include comparison of topographic section data against flood heights to establish relationship between topography, flood run-up, intensity and height. Correlation methods were also used assess the relationship between geophysical features past flood run-up including island width, location, orientation and shape.

- It has to be noted that while we used GIS for this analysis we were unable to tap its true potential in risk assessment due to lack of data. The geophysical data available for these islands are limited and the time and resources available for this study does not allow collection of high resolution data. For example key information such as high resolution topographic and bathymetric data was unavailable. Using such data it would be possible to model flood extents based on specific hazard intensities. Such assessments could be conducted in the future or as part of new island assessments as highlighted in the methodological framework in Figure 4.1. Some such potential studies are highlighted below:

- Quantitative modelling of island shoreline response to sea level rise. A possible approach would be to use Shoreline Translation Model as developed by Kench and Cowell (2001).

- Quantitative modelling reef characteristics in wave energy and height propagation over the reef flat.

- Drainage modelling for flood thresholds based on topographic variations.

- Detailed assessments of impacts from land reclamation and coastal engineering.

The approach in presenting the findings has taken into account the end users of the document. Since this report is targeted for policy makers and planners, the presentation style follows a simple descriptive format rather than a scientific document format. Much of the scientific working shave been left out and only the results are described. In any case, the methodology used in this assessment is not complex when compared to the risk assessment field and has been geared for rapid assessment of islands.

4.5 Limitations

1. The primary limitation is lack of data. This study could be considerably enhanced if the following data were available.
    a. Topographic data of island at 0.5m resolution
    b. Bathymetry data of surrounding lagoon at 1m resolution
    c. Coral reef conditions data of the 'house reef' including live coral cover, fish abundance and coral growth rates.
    d. Sediment budget data
    e. At least an years data on island coastal processes including sediment movement patterns, shoreline changes, current data and wave data.
    f. Island or atoll level meteorological data.
2. Lack of time to do a detailed quantitative analysis. The following were some of the methods considered, but sacrificed due to time and to some extent, data limitations.
    a. Quantitative physical assessments
    b. Coastal change modeling
    c. Flood risk and climate change risk modeling using GIS
    d. Quantitative hydrological impact assessment
    e. Coral reef surveys
3. Lack of scientific studies on the following areas
    a. How the coral islands of Maldives naturally interact and respond to severe weather events and climate change?

   b. Coastal processes of coral islands especially in response to general climatic conditions, especially monsoon.
   c. Interaction between island ground water and ocean.
   d. How island water tables respond to heavy rainfall?
   e. Response of coral reefs to climate change and reef growth rates.

4. There is a time scale mismatch between environmental changes and socio-economic developments. While we project environmental changes for the next 100 years, the longest period that a detailed socio-economic scenario is credible is about 10 years.
5. Uncertainties in climatic predictions, especially those related Sea Level Rise and Sea Surface Temperature increases. It is predicted that intensity and frequency of storms will increase in the India Ocean with the predicted climate change, but the extent is unclear. The predictions that can be used in this study are based on specific assumptions which may or may not be realized.

This document is intended both as a guide to the methodology used in the study as well as a guiding document follow-up assessments. It is also intended to serve as hands-on guide for replicating and extending risk assessment for other safe islands.

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Appendix A – Survey Procedures

Pre-field assessment:

1. Analyze aerial photographs and identify key natural and built environment characteristics as information sheet and on a map.
2. Analyze existing natural environment form maps/aerial photographs and natural environment changes brought in the new plans.
3. Identify key coastal modifications.
4. Identify planned survey points, lines and zones on a map/aerial photograph
5. Prepare and print an aerial photograph for coastal environment assessment.
6. Prepare worksheet for coastal environment assessment
7. Prepare basemap in a GIS with existing biophysical characteristics available from literature.
8. Identify key historic natural events in the island, based on literature
9. Prepare and test survey equipments.

Field work

Day 1:

Activity	**Estimated Time**
1. Survey a cross-section of the island based on predefined locations	60 minutes
2. Survey beach profiles based on predefined location	60 minutes
3. Survey ground water levels at selected points across the island both during high tide and low tide.	30 minutes
4. Conduct interviews with locals on the natural history of the island and past natural events. Delineate effected zones where ever possible.	45 minutes
5. Survey status of existing environment a. Map and document key geophysical features and processes b. Identify coastal erosion patterns and zones c. Observe impacts of coastal infrastructure and modifications d. Observe surrounding lagoon conditions e. Observe Ground Water Quality f. Survey present status of coastal ecosystems g. Identify present coastal problems h. Identify human influences on coastal environment i. Coastal land use and historical changes in coastal land use	6 hours

j. Coastal vegetation mapping. k. Evidence of sea level change, shoreline change and other aspects of geologic history	
6. Plot and analyse island section and beach profiles	60 minutes
7. Summarize existing environment conditions on a map	60 minutes

Day 2:

Activity	**Estimated Time**
1. Undertake further assessment of existing environment (if required)	2 hours
2. Assess the modifications proposed to the exiting environment in the new land use plan	60 minutes
3. Assess the potential impacts on natural environment process and elements from the predicted hazards, based on new land use plan (preliminary field assessment)	4 hours
4. Identify hazard zones for each hazard (but not each scenario)	60 minutes
5. Develop env impacts and hazard zone report for socio-economic group	2 hours

Appendix B:

Survey Form1: Topographic Survey form

Atoll and Island Name:____
Date Surveyed:__________________ Profile Location/ID:________________
Surveyor(s):____

Point ID	Height	Distance	Comment

Note: This form is for an electronic level

Survey Form 2: Historical Event Interview Form

Name of Person:
Oragnization/Address:
Age:
Experience in island historical events:

Date of Event (s):_______________________
Event Name (s) :____
Type of Event: *Udha ; Tidal Wave ; heavy rainfall ; earthquake ; tsunami ; Storm ; erosion ; temperature rise*
Description of Event (How it unfolded, direction of approach, flood height):

Damage caused by the event:

Extent of impact: *Note: Mark on Map as well*

Other Notes:

Chapter 5 Structural Vulnerability Assessment

By Dr. Jianping Yan

5.1 Introduction

5.1.1 The concept of structural vulnerability

5.1.2 Dimensions of structural vulnerability

5.2 Assessment methodology

5.2.1 Overview of methodologies

5.2.2 Methodology used in the project

5.3 Data needs and requirements

5.3.1 Data required

5.3.2 Data availability

5.3.2 Data gaps

5.4 Working procedure in the field

5.5 Result presentation

5.5.1 House vulnerability

5.5.2 Houses at risk

5.5.3 Critical facilities at risk

5.5.4 Functioning impacts

5.6 Recommendations for risk reduction

5.1 Introduction

5.1.1 The concept of structural vulnerability

Structural vulnerability, also called physical vulnerability, refers to the potential impacts of hazard events on the built environment, infrastructure, and lifelines. This type of vulnerability is perhaps the easiest to quantify because it depends directly on the physical impact of a hazard event. The best developed vulnerability models have focused on the behaviour of building stock as the most significant component of the built environment. In general, such models are in need of development and validation using both empirical data from post-disaster reconnaissance, laboratory testing such as from shake tables and wind tunnels, as well as computer simulation techniques. Much information can be take from other areas (e.g., US, Europe), but differences in building techniques, standards and materials in different regions, significant model calibration and testing under local conditions is still required. Casualty models have been developed based primarily on assumptions lied to the likelihood of occupants being injured or killed in the event of building damage or failure. These models draw on the well developed HAZUS risk assessment model used throughout the USA to determine risk from earthquake. The vulnerability of lifelines and other critical infrastructure has been studied internationally using past disasters as case studies. However, there are limitations to the value of this knowledge applied to any specific infrastructure system because it is often the complex network or systems interactions that dictate the extent of impact and duration of recovery.

5.1.2 Dimensions of structural vulnerability

The vulnerability of structural elements such as buildings, bridges, roads, etc., can be determined by their foundation, structural design, shape, materials used, construction techniques, maintenance and proximity of these structural elements to other objects. The weight attached to each of these factors will vary according to the type of hazards encountered. Different hazards produce different forces affecting these structures. In general, structural vulnerability of a building can be assessed from 6 dimensions: foundation, structure, material, maintenance or age, protection, and location (Fig. 5.1). These 6 indicators can be divided into two groups: structural and non-structural indicators group. The structural group, including foundation, structure, and material, is the primary factors of the structural vulnerability; the non-structural group comprised of maintenance, protection, and location, is the secondary factors of the structural vulnerability, which are generally used to weight the primary factors to build the total vulnerability index.

Each primary indicator can be further described by a series of sub-indicators. For example,

- **Foundation:** It is a key factor of structural vulnerability. The strength of a foundation depends on its type, burial depth, and its surrounding soil conditions. In the Maldives, two types of building foundations are identified: spread footing (traditional) and isolated footing with tie beam.

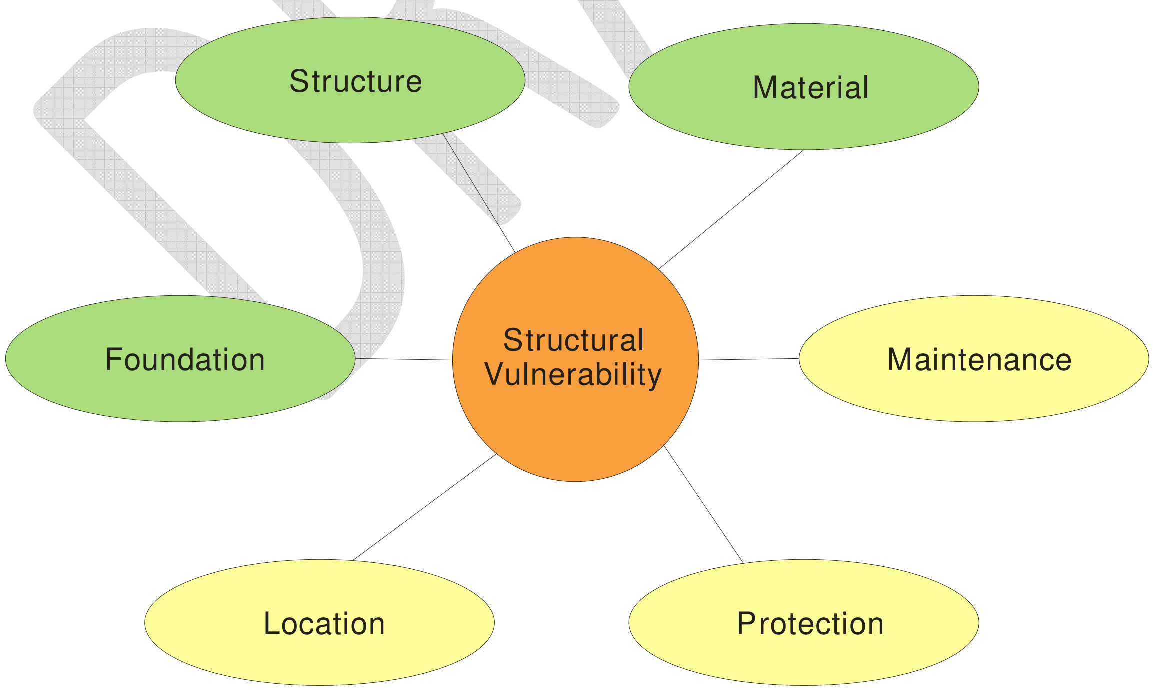


Fig. 5.1 Dimensions of structural vulnerability.

- **Structure:** It generally refers to the frame of building body**,** wall thickness, and bonding. In the Maldives, coral stone walls are generally 15 - 20cm thick whereas cement block/brick more than 20 cm. For the vulnerability of the roof, slope, material, bonding, and anchorage are some of the important factors to inspect.
- **Material:** Most building walls in the Maldives are made from coral stone or cement brick/block. Whole concrete walls are rare; Roof material is generally CGI and CG.
- **Maintenance or age**
- **Protection**: In the Maldives, there are three protection measures against ocean-originated floods: boundary wall, coastal vegetation, and natural ridge. Boundary wall, a unique phenomenon in the Maldives, can serve as a good protection measure against ocean-originated floods.
- **Location:** It refers to the relative position to flow path or the plinth level to road surface.

5.2 Assessment methodology

5.2.1 Overview of methodologies

There are three methods to assess the vulnerability of structural elements:

5.2.1.1 Empirical vulnerability ranking

Empirical vulnerability ranking is a qualitative approach that is largely based on historic damage records and the knowledge and experience of vulnerability analysts. The results of assessment are therefore subjective.

The vulnerability of a structural element is assessed in terms of its overall conditions or the extent of damage and ranked by 5 classes as shown in Table

5.1. The extent of damage is defined in terms of the spatial area of the asset affected. For example, the vulnerability of a house immediately at the shoreline which a tsunami wave may occur is clearly higher than for a house at a distance of 100 m from the shoreline because the depth and velocity of flow are much less. Given a particular facility type and the probable water/flow depth at the facility location, the appropriate vulnerability factor (the extent of damage) may be assessed systematically by expert judgment.

Table 5.1 The ranking of structural vulnerability in terms of the extent of damage (adapted from OECS, 2003).

Class	Rank	Criteria
Extremely vulnerable	4	More that 75% of the element is damaged or completely destroyed due to one or more of the following factors: its location, foundation, design, material, maintenance, age, and protection.
Highly vulnerable	3	More that 50% of the element is damaged due to one or more of the following factors: its location, foundation, design, material, maintenance, age, and protection.
Moderate vulnerable	2	25-50% of the element is damaged due to one or more of the following factors: its foundation, design, material, maintenance, age, and protection.
Probably vulnerable	1	10-25% of the element is damaged due to one or more of the following factors: its foundation, design, material, maintenance, age, and protection.
Not particular vulnerable	0	Less than 10 % of the element is damaged due to one or more of the following factors: its foundation, design, material, maintenance, age, and protection.

OECS, 2003: Technical manual for post-disaster rapid environment assessment, Volume 1 & 2, OECS – Environment & Sustainable Development Unit, Organization of Eastern Caribbean Countries (http://www.oecs.org/esdu/)

The purpose of the above table is to provide a format for listing specific facilities and then scoring them in each community. The total of these scores will provide a “vulnerability score” that can be used to identify facilities with higher than average vulnerabilities, and then allow the owner/operator to evaluate the facility for potential mitigative actions that can reduce that vulnerability. This number will reflect the sum of the scores in the row corresponding to each facility. The overall score will help identify areas of vulnerability that need to be addresses and give an indication as to the types of mitigation initiatives that need to be recommended for the facility in question. Overall scores of all submitted facilities would be ranked and prioritized for further evaluation. The higher the score, the more closely the facility would be studied for mitigation initiatives.

5.2.1.2 Vulnerability Indicator Matrix

An alternative option based on the statistics of historic records is the vulnerability matrix method proposed by Leone et al. (1996). This method is flexible and can cater for a wide range of situations and can, to a certain degree, reduce subjectivity, compared with the methods mentioned above. With this method, the vulnerability of structural elements at risk depends on the characteristics of hazards and the technical resistance of the building, such as the type, nature, age, etc. for instance**,** Fig. 5.2 gives a correlation, in terms of vulnerability, between exposed elements and the characteristics of landslides. The applicability of this method, like other methods, also requires statistical analysis of detailed records on landslides and their consequences.

Landslide characteristics	Buildings at risk: S	L	M	H
T				
M				
V				
S				
R				

S - Squatter
L - Low-rise building
M - Multi-storey building
H - High-rise building

T - Type of failure
M - Mechanism of failure
V - Volume
S - Speed
R - Runout distance

Vulnerability		Distance to slide (m)			Nature					
		< 10	10-50	> 50						
Volume (m^3)	$< 10^2$	0.3	0.2	0.1						
	10^2-10^3	0.4	0.3	0.2						
	10^3-10^4	0.6	0.5	0.4						
	$> 10^4$	1.0	0.9	0.8						

Fig. 5.2 An example of structural vulnerability matrix (from Leone et al., 1996).

5.2.1.3 Vulnerability Function / curve

A more quantitative approach to assessing the vulnerability of structural elements is to build its vulnerability function or curve (Mehta and Khanduri, 1999). The function relates mean damage potential of a particular class of buildings to hazard intensity. A typical vulnerability function is shown for the case of cyclones (Fig. 5.3).

However, many uncertainties involved in defining the vulnerability of structural elements make the task of developing vulnerability curves very complex. The three prerequisites for developing vulnerability curves are the economic loss data, the hazard for which the environment was subjected to, and inventory of structural elements. In addition to the above, information on the structural damage statistics, knowledge of hazard-structure interaction, building and its code information and a knowledge of the socio-economic conditions of the regions all contribute to the development of a sound vulnerability function.

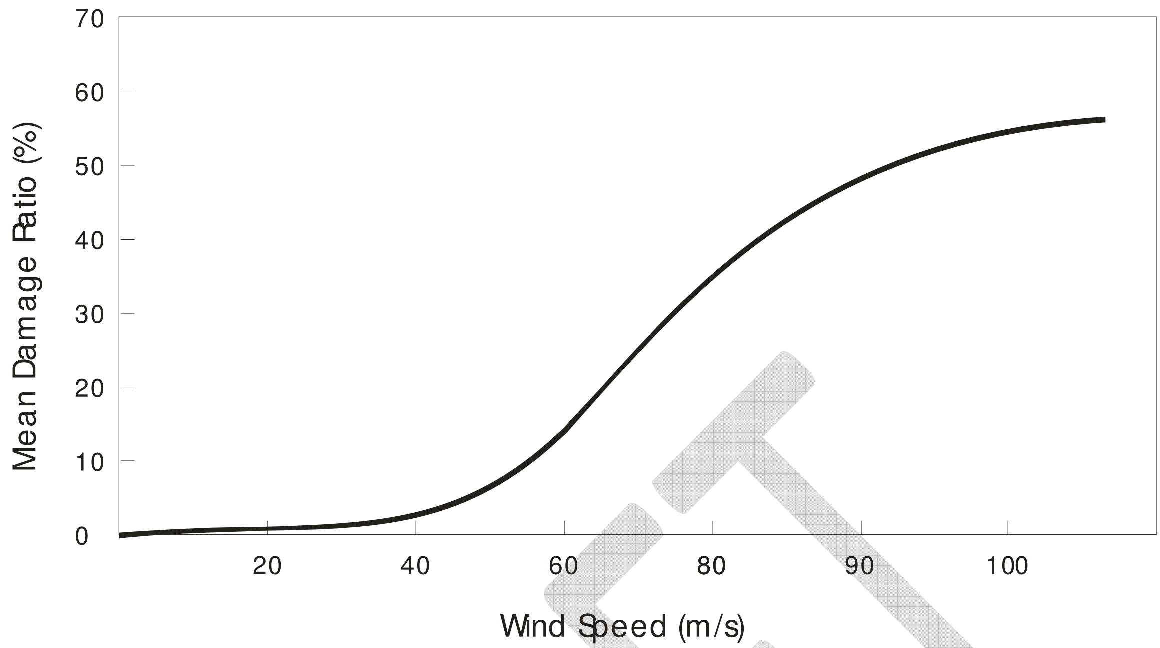


Fig. 5.3 The vulnerability curve or function for cyclones (Mehta and Khanduri, 1999).

5.2.2 Methodology used in the project

5.2.2.1 Vulnerability assessment

Due to lack of the time and man power available, this project assesses structural vulnerability using the empirical vulnerability ranking approach, and associated worksheets criteria are listed in Annex.

However, if a structural vulnerability indicator database is available, the semi-quantitative approach is strongly recommended, using the following structural vulnerability matrix (Fig. 5.4 and Table 5.2).

		Building at risk	
		Single-storey	Multi-storey
Flood Intensity	Water depth		
	Flow velocity		
	Duration		

Description:

Vulnerability		Foundation			Structure			Material			Protection			Location		
Intensity																

Fig. 5.4 Proposed structural vulnerability matrix for flood hazard.

Table 5.2 Proposed weighting for structural vulnerability factors.

Indicators	**Weigh factor**
Foundation	
Structure	
Material	
Maintenance	
Protection	
Location	

5.2.2.2 Functioning impact assessment

The functioning impact of a critical facility can be described by the duration of its failure to operation, impact extent, and recovery capacity. This module needs to be further developed based on the proposed worksheets.

5.3 Data needs and requirements

5.3.1 Data required

The number of people, buildings and infrastructure within an area influences the total risk. This exposure data is essential to any risk assessment. Analysis of risk to a community requires the development of extensive data-sets that define the most vulnerable components of the communities. Key databases of interest are the following:

- Basemaps, such as satellite images, DEMs
- Building construction classifications and distributions
- Building codes, construction practices and costs.
- Critical infrastructure (roads, water, power, sewerage, emergency facilities, hospitals, etc…).
- Cadastre (land boundaries and ownership).
- Census data (population distribution, income, and other statistics such as age, occupation, disability, education).
- Economic data (business sectors, industrial production, exports, imports, etc).
- Emergency management arrangements for disaster response and recovery.
-

These data provide the basis for vulnerability assessments, which allows us to ultimately determine the potential impact of an event.

5.3.2 Data availability

At the time when the survey starts, the following datasets are available:

- **Base maps**, including satellite images and land use maps, are available at the Ministry of Planning and National Development. Some of the maps, e.g. land use maps, need to be georeferenced.
- **Historic event records:** Available at island offices, but might be not complete and systematic.
- **Building data,** available at various sources**.**

5.3.3 Data gap

At the time when the survey starts, the following datasets are not available and need to be collected in the field:

- **Hazard zoning maps:** to be delivered by hazard assessment during the field survey.
- **Risk receptor datasets:** For this study, these datasets include house and critical facilities. In the future study, datasets such as commercial, industry, and infrastructure should be included into the risk receptor database. The risk receptor datasets are not available at the time when the survey starts and need to be compiled from various sources, such as digitized from the satellite images and land use maps available.
- **Vulnerability data,** including vulnerable houses and structural components, need to be identified in the field in terms of physical structure, protection, and the relative elevation of the plinth to the adjacent road surface.

5.4 Working process in the field

Structural vulnerability assessment in the field is a 6-step process as follows:

Step 1: Preparation

Before going to the field, check to see the following maps and worksheets are ready:

- A1/10,000 base map for inventory of elements at risk. The base map can be a satellite/ aerial image or a mostly updated land-use map;
- Hazard zoning maps and associate event scenarios (**Worksheets 5.1 and 5.2**);
- Worksheets for inventory and vulnerability assessment of critical facilities (**Worksheets 5.3, 5.4, 5.5**);
- Worksheets for functioning impact assessment (**Worksheets 5.6-8**);

Step 2: Inventory of vulnerable houses

Identify vulnerable houses by walking through all the streets or roads of the targeted island in terms of the criteria defined in ***Worksheet 5.3***, and mark the vulnerable house identified on the base map using the symbols defined in the worksheet.

Step 3: Inventory of critical facilities

Mark all the critical facilities identified onto the base map. The critical facilities in the Maldives include governmental institutions (island office, atoll office, court, NSS, fire station), schools of various kinds, hospitals, mosques, communication system (antenna of Dhiraagu and Wataniya, Cable TV), power house and its oil tank, waste disposal site, and so on. For each critical facility identified, use ***Worksheet 5.4*** to collect information on its foundation, wall structure and material, roof structure and material, age, its boundary wall, and measure the heights of its boundary wall, entrance and plinth floor above the ground. Take pictures of it from different perspectives.

Step 4: Vulnerability assessment of critical facilities

After completing ***Worksheet 5.4***, assess and rank its vulnerability to different hazards of pre-defined intensity using ***Worksheet 5.5***, in terms of its foundation, design, material, maintenance, protection and age, as well as its distance to shoreline.

Step 5: Functioning impacts assessment

Use **Worksheets 5.6, 5.7, 5.8** to investigate the functioning of the targeted facilities in terms of different hazard scenarios.

Step 6: Preliminary data processing and analysis

After completing the above 5 tasks,

- Count the number of vulnerable houses from the base map in terms of their types and put the number into ***Worksheet 5.3***;
- Give IDs to the pictures taken and put the IDs into ***Worksheet 5.4***;
- Identify and analyze critical facilities at risk, using ***Table 1***, ***Worksheet 5.4***, and the event scenarios and hazard zoning maps from hazard assessment.

5.5 Result presentation

5.5.1 House vulnerability

This section aims to discuss the characteristics of house vulnerability and the distribution of vulnerable houses and explore the reasons on the house vulnerability of the targeted islands, based on the facts on the vulnerable houses identified, which are summarized in Fig. 5.5 and 5.6.

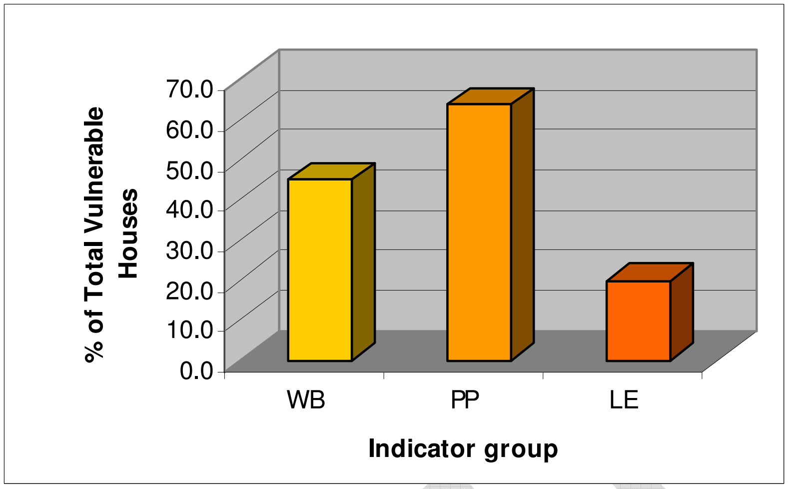


Fig. 5.5 The type of house vulnerability.

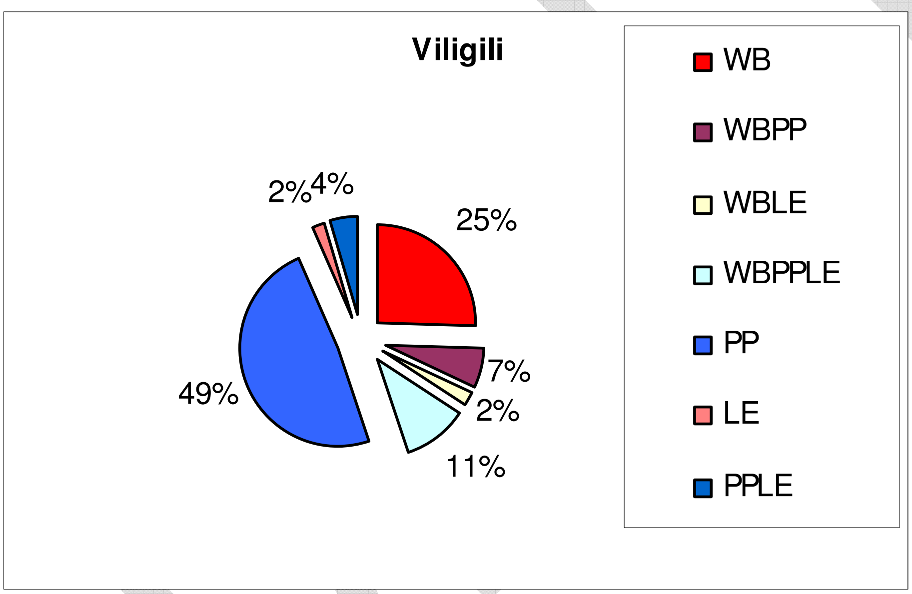


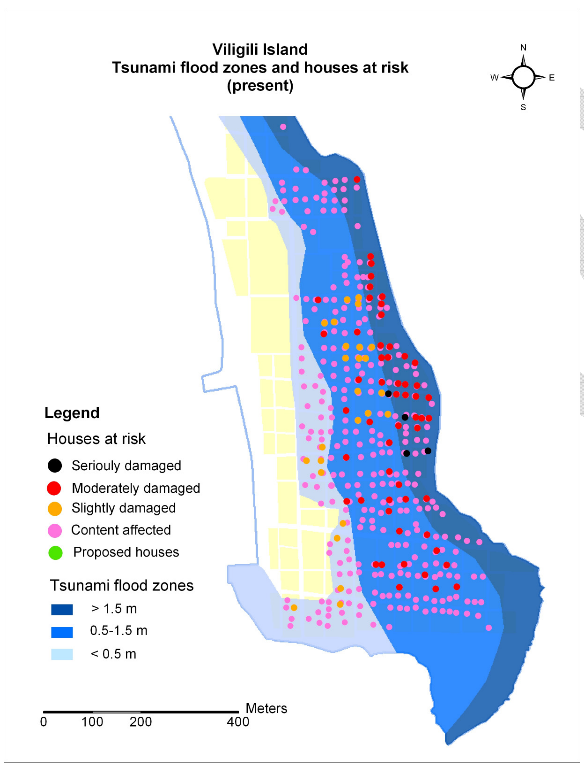
Fig. 5.6 The distribution of vulnerable houses.

5.5.2 Houses at risk

This section aims to examine the exposure and potential damage of the existing houses on the targeted island, in terms of the hazard zoning maps. The results of analysis are summarized in Table 5.3 and shown in Fig. 5.7.

Table 5.3 houses at risk.

Hazard type		Exposed houses		Vulnerable houses		Potential Damage							
						Serious		Moderate		Slight		Content	
		#	%	#	%	#	%	#	%	#	%	#	%
Flood	***TS(p)***	317	80.1	85	21.7	4	1.3	55	*17.4*	*25*	*7.9*	*233*	*73.5*
	TS(f)	124	31.6	27	21.8	0	0	5	*4.0*	*14*	*11.3*	*105*	*84.7*
	W/S	54	13.8	23	42.6	0	0	0	0	5	9.3	49	*90.1*
	RF	141	36.0	32	22.7	0	0	0	0	5	3.5	136	*96.5*
Earthquake		*392*	*100*	41	10.5								
Wind		*392*	*100*	*41*	*10.5*	-	-	-	-	-	-	-	-
Erosion													



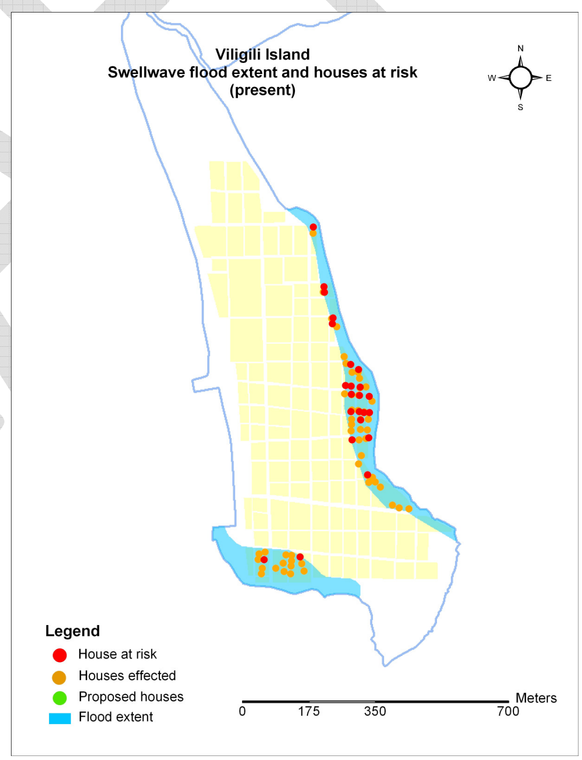


Fig. 5.7 Houses at risk associated with tsunami (left) and swell wave (right).

5.5.3 Critical facilities at risk

This section aims to examine the exposure and potential damage of critical facilities on the targeted island, in terms of the hazard zoning maps. The results of analysis are summarized in Table 5.4 and shown in Fig. 5.8.

Table 5.4 Critical facilities at risk.

Hazard type		**Critical facilities**		**Potential damage/loss**	
		Exposed	Vulnerable	Physical damage	Monetary value
Flood	Tsunami (prior to reclamation)	Hospital, power house, Atholhuge Dhiraagu and Wataniya sites, waste site	Hospital, power house, waste site	Slight to moderate	
	Tsunami (after reclamation)	Hospital, Dhiraagu and Wataniya sites, Atholhuge	Hospital	Slight to moderate	
	Wave/surge	Oil storage, hospital	None	no	
	Rainfall	1 mosque, 1 Atholhuge, hospital, wataniya site	None		
Earthquake		All facilities	None	No	
Wind		-	-	-	-
Erosion		-	-	-	-

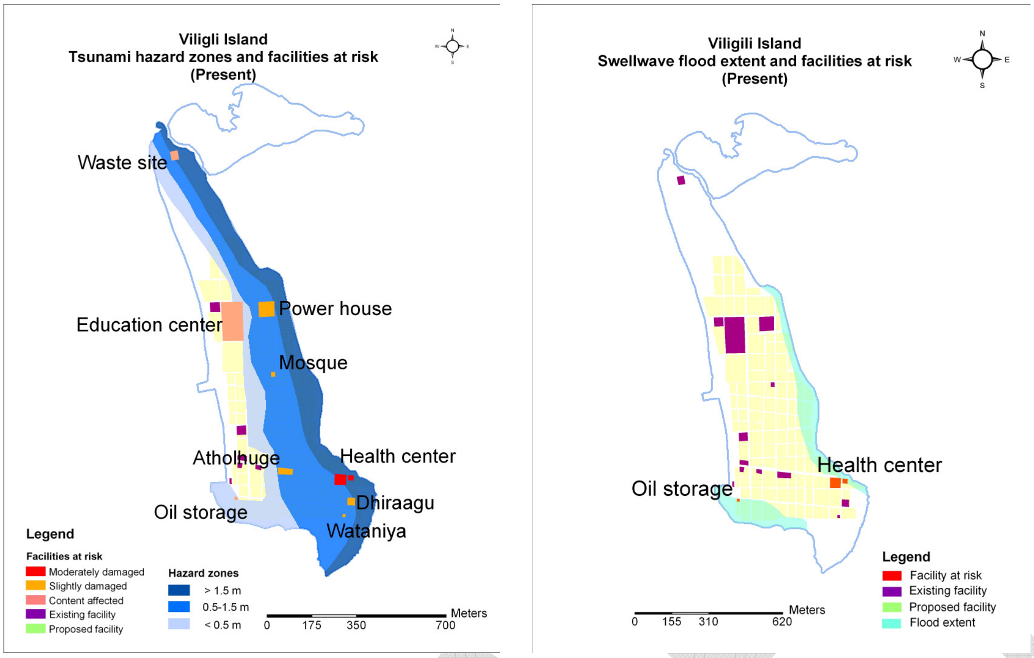


Fig. 5.8 Critical at risk associated with tsunami (left) and swell wave/surge (right).

5.5.4 Functioning impacts

This section is designed to assess potential impacts on the functioning of the critical facilities that are subjected to physical damage or content affected. The results of analysis are summarized in Table 5.5.

Table 5.5 Potential functioning disruption matrix

Function	Flood			Earth-quake	Wind
	Tsunami	Swell wave	Rainfall		
Administration[1)]					
Health care	a few weeks	days			
Education					
Religion					

Sanitation[3)]			3-5 days, island-wide		
Water supply					
Power supply	A week, island-wise				
Transportation					
Communication[2)]					

Note: 1) Administration including routine community management, police, court, fire fighting; 2) Communication refers to telecommunication and TV; 3) Sanitation issues caused by failure of sewerage system and waste disposal.

5.6 Recommendations for risk reduction

Some options for risk reduction specific to the Maldives are identified as follows:

- **Location of key critical facilities (Land use planning):** Avoid locating key critical facilities, such as hospital, power house, waste site, and 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. In particular, waste disposal sites are generally of poor standard and household wastes are dumped on the shoreline or on designated places on the islands itself. Coastal flooding may carry these wastes to other places of the island or contaminate the groundwater systems.

- **Enhancement of building codes:** The enhancement differs from hazard to hazard. 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. On the other hand, option for rainfall floods is strong foundation with proper height in terms of potential sea level rise.

- **Modification 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. **In** proper leveling of the ground may cause unexpected flooding to other areas that are not affected before. Two of the typical examples are road maintenance applied on south islands of the Maldives and harbour construction. The former has resulted in localized flooding in its adjacent households and the latter has made the loading and unloading area subjected to flooding due to the blockage of natural groundwater flow systems.

- **Hazard mitigation**: Under circumstances, hazard mitigation might be a cost/effective option for risk reduction, in comparison with 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. 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 flooding is not due to the natural reasons, rather than because of improper human activities-preventing road flooding by raising road surface. It has been a dilemma to mitigate such a flood type.

References

Leone, F., Aste, J.P., Leroi, E., 1996. Vulnerability assessment of elements exposed to mass-moving: Working toward a better risk perception. In: Senneset, K. (Ed.), Landslides. Balkema, Rotterdam, pp.263-269.

Mehta, R. and Khanduri, A., 1999. Defining building vulnerability and inventory for coastal India with regard to cyclones. Proceedings of National Conference on Wind Engineering, pp.203-208.

Worksheet 5.1: Potential maximum hazard intensity for the targeted islands **DIRAM UNDP MALDIVES**

Island	Potential Max. Hazard Intensity				
	Earthquake (PGA)	Windstorm (m/s)	Tsunami (m.a.s.l.)	Storm surge (m.a.s.l.)	Rainfall (mm/24 hours)
Kulhudhuffushi	0.04	58	4.5	2.30	140-180
Funadhoo	0.04	58	4.5	2.30	
Thulusdhoo	0.04	42	4.5	1.50	190-240
Kudahuvadhoo	0.04	29	3.2-4.5	1.40	
Villufushi	0.04	29	4.5	1.5	
L. Gan	0.05	29	4.5	1.5	220-290
Villigilli	0.07	<29	3.2-4.5	<1.5	
Thinadhoo	0.07	<29	2.5	<1.5	
Hithadhoo	0.32	<29	2.5	<1.5	

Worksheet 5.2 Hazard event scenarios

Hazard		Event scenarios			Historic records of functioning impacts, if available
		Intensity	Frequency	Probability	
Flood	Tsunami				
	Wave/surge				
	Rainfall				
Wind					
Drought					
Earthquake					
Erosion					

Worksheet 5.3: Inventory of vulnerable houses

DIRAM UNDP MALDIVES

Island: **Survey Date:** **Assessor:**

House Type	Combination of Vul. indicators	Criteria for vulnerable houses	Code	Symbol on map	# of houses	Remarks
A	Physical condition	• Weak foundation • Poorly structured and cracked wall with aged coral stones • Weak roof – rusty roof, weak attachment to the wall	WB			
B	Physical condition + protection	• Weak foundation • Poorly structured and cracked wall with aged coral stones • Weak roof – rusty roof, weak attachment to the wall • Poor protection with respect to ocean-originated floods	WBPP			
	Physical condition + Plinth level	• Weak foundation • Poorly structured and cracked wall with aged coral stones • Weak roof – rusty roof, weak attachment to the wall • Plinth is lower than the adjacent road surface	WBLP			
	Physical condition, protection, plinth level	• Weak foundation • Poorly structured and cracked wall with aged coral stones • Weak roof – rusty roof, weak attachment to the wall • Poor protection with respect to ocean-originated floods • Plinth is lower than the adjacent road surface	WBPPLP			
C	Protection	• Poor protection with respect to ocean-originated floods	PP			
	Plinth level	• Plinth is lower than its adjacent road surface	LP			
	Protection + plinth level	• Poor protection with respect to ocean-originated floods • Plinth is lower than the adjacent road surface	PPLP			

Note: Protection is evaluated in terms of the distance to shore line (within the ocean-originated flood-prone area), the physical conditions of boundary wall, coastal vegetation and ridge. Protection can be considered as poor if one of the following cases is met: Houses located within a distance of 20 meters from shoreline; Houses located within a distance of 20-50 meters from shoreline, with a poorly structured boundary wall of less than 1.5 meters high; or houses are poorly structured or their foundations area weak; or no coastal vegetation or protection structure on shoreline; Houses located within a distance of 50-100 meters from shoreline, and their boundary walls are less than 1.0 meter high and poorly structured; Houses located within a distance of 100-200 meters, and their boundary walls are less than 0.5 meter and poorly structured.

Worksheet 5.4: Inventory of critical facilities

DIRAM UNDP MALDIVES

Island: **Survey Date:** **Assessor:**

No.[1]	Facility Name	Foundation	Wall	Roof	Boundary wall	Age	Location	Height above ground (m)			# of pictures & IDs	Remarks
								Boundary wall	Entrance	Plinth level		

Notes: 1) Get the number from landuse map. If no landuse map available, give a number and mark it on the map.

Island: **Survey Date:** **Assessor:**

No.[1]	Element at risk	Hazard scenarios															Remarks
		Earthquake (PGA)			Windstorm (m/s)			Flood									
								Tsunami[2] (m)			Wave/surge[2] (m)			Rainfall (ft)			
		0.1	0.2	0.3	40	50	60	0.5	1.0	1.5	0.5	1.0	1.5	1	2	3	

4. extremely vulnerable: More that 75% of the element is damaged due to one or more of the following factors: its location, foundation, design, material, maintenance, and protection.

3. Highly vulnerable: 50-75% of the element is damaged due to one or more of the following factors: its location, foundation, design, material, maintenance, and protection.

2. Moderately vulnerable: 25-50% of the element is damaged due to one or more of the following factors: its foundation, design, material, maintenance, and protection.

1. Probably vulnerable: 10-25% of the element is damaged due to one or more of the following factors: its foundation, design, material, maintenance, and protection.

0. Not particularly vulnerable: Less than 10% of the element is damaged due to one or more of the following factors: its foundation, design, material, maintenance, and protection.

1) Get the number from landuse map. If no landuse map available, give a number and mark it on the map.

2) Wave height at the shoreline (high tidal level)

Island: **Facility Name:**

Survey Date: **Assessor:**

Hazard type:	**Occurrence date:**
Event description:	

Component	**Physical damage**	**Functioning impacts**	**Relative importance**
Building			
Equipment			
Documents			
Personnel			

Island: **Power Facility Name:**

Survey Date: **Assessor:**

Hazard type:	**Occurrence date:**
Description:	

Component	Physical damage	Functioning impacts	Relative importance
Building			
Generator			
Distribution network			
Oil storage			

Island: **Transportation:**

Survey Date: **Assessor:**

Hazard type:	**Occurrence date:**
Description:	

Component	**Physical damage**	**Functioning impacts**	**Relative importance**
Harbour			
Jetty			
Boats			
Boat repair services			

Chapter 6 Economic Vulnerability Assessment

By Rob Mukiza

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6.2 Assessment Methodology

6.3 Data needs and requirements

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- 6.3.2 Data availability
- 6.3.3 Data gaps

6.4 Working procedure

- 6.4.1 Field survey
- 6.4.2 In-house analysis

6.5 Result presentation and interpretation

6.6 Limitations and recommendations

Chapter 7 Social Vulnerability Assessment

By Bob Alexander

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Chapter **8 Risk profiling and mapping**

By Dr. Jianping Yan

8.1 Risk ranking

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8.1.2 Risk classification

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8.1 Risk ranking

There are many techniques for estimating or 'modeling' risk. The simplest of these are based on the statistics of past events and their impacts. For example, risk from flooding is normally determined based on an assumption that future floods will follow a pattern similar to the past. Thus, given enough data from past events, the risk can easily be determined. However, many natural hazards have no or limited historical-event precedents upon which we can properly assess the risk, particularly for rare or extreme events that can have the largest impact on society.

Ideally, risk profiling integrates information about past events with social models of our communities, economic models and the physics of earth processes to estimate the probabilities and impacts of future events. Capturing the risk requires modeling the probability of many events and their impacts. Thus, thousands of scenarios are developed through computational simulations in which sophisticated computing techniques are used to capture the interaction of hazard phenomena with the elements at risk and their associated vulnerabilities.

8.1.1 Risk matrix

The practice of risk management permits decision-makers to anticipate losses and to evaluate potential impacts to facilitate effective planning and management. It requires recognition of risks, evaluation of the frequency of those events and the related severity of consequences or potential losses, and determination of appropriate measures for prevention or reduction of these risks from a cost/benefit point of view (Long and John, 1993).

A simple solution to the risk model presented in Section 1.1 is risk matrix. The risk matrix shown in Fig. 7.1, widely used in risk analysis, is modified from the one proposed by Long and John (1993). In this toolkit, the frequency axis in

Long's risk matrix has been replaced by probability because of the reasons mentioned before. The matrix method gives a qualitative measure that permits the prioritization of risk among multiple hazards and multiple risk takers. It enables risk reduction planners to classify various types of hazards into different categories of priority by locating them on a two-dimensional grid based on their probability and loss or impacts.

The ranking of each cell is subjective and would vary from one region to another. The definitions of Characters A-E are presented in Table 7.1. The ranking depends on the probability of a hazardous event and the potential loss it might cause. The classification of probability and severity shown in Section 7.2 might guide you to build the risk profiles for a community.

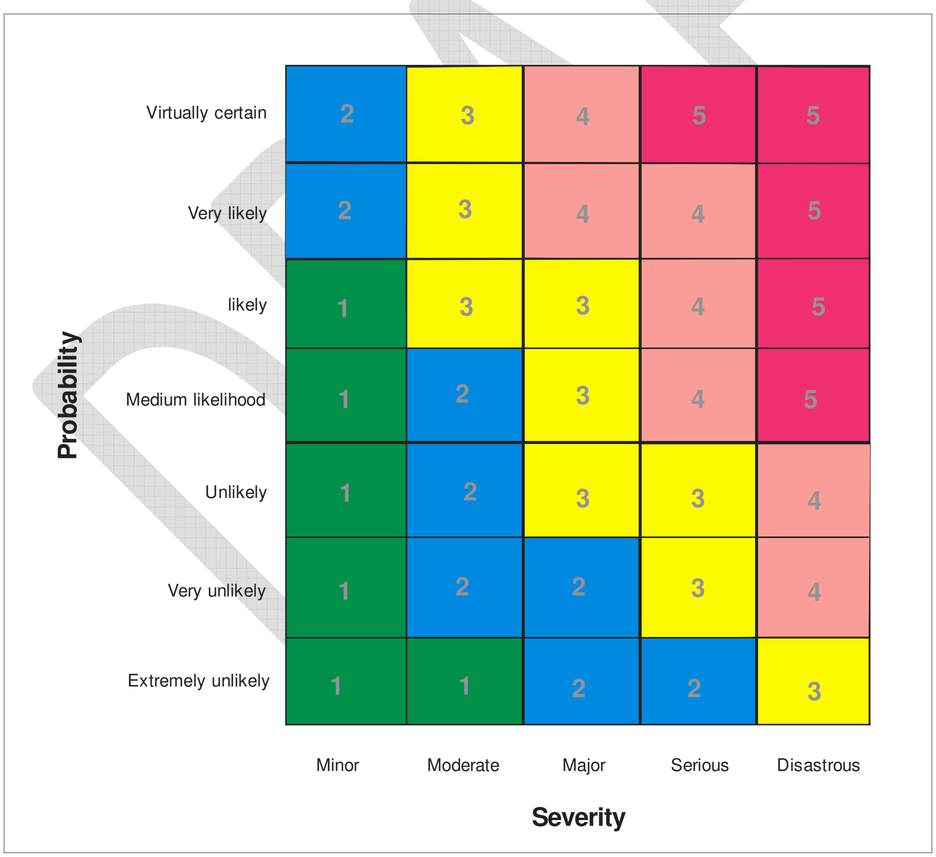

Fig. 8.1 Risk matrix.

8.1.2 Risk classification

The cells of the risk matrix can be grouped into five levels (A-E) in terms of the potential severity of a hazardous event and its probability within a specific time scale (Table 7.1). For the sake of risk mapping, each risk level is assigned a number (1-5) and a color (red, orange, yellow, blue and green, respectively). It has to be pointed out that the definitions of risk classes (example of losses) may be quite different from region to region, depending on the acceptance of risk.

Table 8.1 Classification of risk.

Class	Score	Example of losses	Action level	Color
Very high	**5**	-Massive death or fatal injury; -Complete shutdown of facilities and critical services for more than one month; -More than 75 percent of the property located in the affected area is severely damaged.	**Urgent action** - Very high - risk condition with highest priority for reduction & contingency planning	**Red**
high	**4**	Death or fatal injury; -Complete shutdown of facilities and critical services for more than one month; -More than 50 percent of the property located in the affected area is severely damaged.	**Immediate action -** High risk condition with high priority for reduction & contingency planning	**Orange**
Moderate	**3**	-Permanent disability, severe injury or illness; -Complete shutdown of facilities and critical services for more than two weeks; -More than 25 percent of the property located in the affected area is severely damaged.	**Prompt action –** Moderate to high-risk condition with risk addressed by reduction & contingency planning	**Yellow**
Low	**2**	-Injury or illness not resulting in disability; -Complete shutdown of facilities and	**Planned action** – Risk condition sufficiently high to give consideration for further reduction & contingency	**Blue**

		critical services for more than one week; -More than 10 percent of the property located in the affected area is severely damaged.	planning	
Very low	**1**	-Treatable first aid injury; -Complete shutdown of facilities and critical services for more than 24 hours; -No more than 1 percent of property located in the affected area is severely damaged.	**Advisory in nature –** Low risk condition with additional reduction & contingency planning	**Green**

8.1.3 Severity classification

The classification of loss/impact severity is a dynamic ***socio-political*** process that relates to the socio-economic situation of the area investigated. What one society considers severe may not be considered to be severe in another socity. For example, in the densely populated areas, thousands of people affected may be considered to be minor in impact severity, whilst in less-populated mountainous environments or marine islands the population of most of the villages is seldom more than a thousand, a loss of tens of lives is considered to be disastrous. On the other hand, the criteria of loss/impact severity may change over time when a society's economic development or value system may change significantly. In this context, the acceptability or tolerance of risk is a dynamic socio-political process, as well.

Assessing the severity of a risk scenario and its probability requires the application of a consistent method of measurement. There may be multiple impacts for a hazardous event. After you rank the severity of each applicable consequence, you will need to input the "overall" severity rank into a Scenario Matrix form. If the highest consequence severity rank was "high" for any of the types of impacts, then choose this rank as the overall severity. The probability can be calculated from the frequency of occurrence or recurrence interval of this hazard scenario and the given time frame by using the formula shown in Section 1.2, or by consulting the lookup table of Probability-AEP-Timeframe. After that, rank the probability by consulting Table 7.3 (a table for probability classification).

It has pointed out that the intensity of a hazard event has to be described before its probability is ranked because the more intense a hazard scenario, the less likely it is to occur. On the other hand, the severity of impact of a hazard event depends on the exposure of elements at risk, their vulnerabilities, and the response capabilities of the population being threatened.

Table 8.2 Criteria for ranking impact severity (derived from Tsunami_Maldives_Layout.pdf)

Class	Rank	Criteria							
		Value Loss (m.$)	Property damage	Population displacement	Critical Facility closed	Critical Infrastruct. interrupted	Economic impact	Social impact	Environmental impact
Disastrous	5		>50%	>50%	Long-term	Long-term			Long-term & widespread
Serious	4		20-50%	20-50%	A few month	A few month			Extended & widespread
Major	3		10-25%	10-25%	A few week	A few week			Long & widespread
Moderate	2		1-10%	1-10%	A few days	A few days			Temporary & moderate
Minor	1		<1%	<1%	Temporary	Temporary			Temporary & localized

Table 8.3 Criteria for ranking probability (after IPCC, 2001a)

Class	**Rank**	**Probability**
Virtually certain	7	>99%
Very high	6	90-99%
High	5	66-90%
Moderate	4	33-66%
Low	3	10-33%
Very low	2	1-10%
Extremely unlikely	1	<1%

If difficult to calculate the probability of occurrence of an event, the frequency of occurrence can be used as an alternative solution. Criteria for ranking frequency are proposed for the Maldivian islands as shown in Table 7.4.

Extremely frequent: Events occur at least once every year.

Very frequent: Events usually have a high number of recorded incidents or anecdotal evidence. For example, rainfall-induced floods might occur once or so every ten years.

Frequent: Hazards also have a historical record but occur with a frequency of 10 to 25 years.

Moderate means events are those that occur infrequently. There may be little recorded historical evidence and a return interval of 25 to 50 years is possible.

Rare refers to hazards that are not expected to occur more frequently than once every 50 to 100 years. There may be no historical incidents in the community.

Very rare are very unlikely and have a return period of More than 100 years. For example, a "one hundred year flood."

Extremely rare: Events extremely unlikely occur within a given timeframe.

Table 8.4 Criteria for ranking frequency

Class	Rank	Frequency
Extremely frequent	7	<1/1
Very frequent	6	1/1-1/10
Frequent	5	1/10-1/25
Moderate	4	1/25-1/50
Rare	3	1/50-1/100
Very rare	2	1/100-1/500
Extremely rare	1	>1/500

8.2 Risk profiling

8.2.1 Scenario Analysis

Scenario analysis is useful either when it is applied to a limited situation in great detail and worked through systematically and comprehensively. In this case, it can act as a useful reality check, as a means of testing operational capacity against a likely event that is understood in some detail. The other situation where scenario analysis is useful is when it is applied as a mind clearing exercise or as reconnaissance activity. In this case the purpose is to identify the boundaries of the problem and the most prominent features of typology.

The risk scenarios can provide a capacity to model and forecast impact consequences so that the response phase can be managed more effectively. The same modeling is also appropriate for rehearsing and planning for the recovery phase. There are examples in the literature of GIS being used to model the impact of a damaging earthquake and to forecast the requirements for short term and long term post-event shelter. Similarly it is possible to model the physical damage to lifelines and the impacts of their loss on the community.

Use of the scenario analysis technique develops ‘future memory’; i.e. disaster responders develop an understanding of what will happen when such an eventuality occurs so that their actions are based on ‘experience’ when it eventually does happen. This process could be reinforced by the development of role-play simulation ‘games’.

To build risk scenarios, three factors should be taken into account: the intensity of hazardous events, the vulnerability of elements at risk to that event intensity, and the time frame of risk assessment. Worksheet 8.1 and 8.2 shows scenarios built based on the three factors mentioned above.

8.2.2 Risk scenario profiling

After completing risk matrix, a community risk profile for a specific time scale can be created by plotting Worksheet 8.3.

8.3 Risk mapping

8.3.1 Map contents

The contents to be inserted in a hazard risk map are the following, though it is unnecessary to include all items, which are selectable for each purpose:

- Base map including topographic and photographic (orthophotos) maps: The topographic map is more effective to understand the information for a hazard risk map than orthophotos. Sometimes, a photographic map contains too much information to interpret it.
- The mechanism and knowledge of natural events and their consequences.
- Disaster preparedness information: It is very important information that should be disseminated to the vulnerable population. Mainly, the vulnerability of the area to disaster should be included and the past disaster records can also be included on demand.
- Evacuation-related information: The sites/spots for shelter and evacuating routes to be used in case of a disaster are shown in the map. Residents

should know their evacuating route and places of shelter from the hazard map. In addition, the system and procedure for transmitting accurate inform about the warnings on an impending disaster and evacuation to residents should also form part of the map, for example, a forecasting siren or a warning siren.

8.3.2 Map types

Risk maps can be classified into two groups in terms of their objectives:

- **Resident-educating Type** – This type of maps has the objectives to inform the residents living within the hazard-prone area of the risk of danger. The information on spots of danger or places of safety and the basic knowledge on disaster prevention are given to residents. Therefore, it is important that such information is represented in an understandable and very simple language.
- **Administrative Information Type** – This type of maps is used as the basic materials that the administrative agencies utilize to conduct landuse planning, disaster preparedness, and mitigation service. The hazard risk maps are used to strengthen the warning and evacuation systems, as well as for proper land use regulations and introduction of building codes. These can also be used in preventive works.

Depending on map content and methods used in data collection and data processing, three types of hazard risk maps can be distinguished:

- **Hazard registration maps** – Maps containing historically known hazardous events compiled from literature and documents, interviews and field work.

- **Hazard extent maps** – Maps containing information of hazard-prone areas identified by geomorphologic investigations in the field and by the use of topographic maps and air photos.
- **Hazard zoning maps** – Maps that define hazard intensity areas compiled on the basis of known historic events and geomorphologic investigations.

8.3.3 Mapping Procedure

The procedure of creating a hazard risk map can be divided into the following processes:

- Collecting the hazard-related information to be inserted in the hazard risk map;
- Creating disaster record map: Profiling the past history of disasters before creating a hazard risk map. Also, the measured data such as rainfall should be arranged so as to ensure statistical analysis. The topographic and geological studies to trace the evidences of disasters should be made in the field as necessary;
- Creating risk factor map (e.g. landform map): The landform map is an important information source. Flood plains, alluvial fan, mountains and valleys are formed through past floods, earthquakes and volcanic activities. Even if you cannot produce a quantitative hazard zoning map, a landform map is helpful. If you use aerial photos (satellite data), you can produce a landform map easily even though no topographic map is available.
- Forecasting a range of hazards: To define the subject phenomenon and its scale and forecast the range of hazard events using digital simulation technology;
- Publishing the maps by distributing directly to people or through Internet or by any other means. Then, the disaster prevention activity and land use planning can be facilitated using the hazard risk map.

Hazard Severity Analysis	Island	
	Atoll	
	Assessor	
	Date	

No.	HazID	ScID	HazIntensity Rank	Exposure	Potential Damage/loss	Severity Rank
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						

Remarks:

Hazard Likelihood Analysis				**Island**					
				Atoll					
				Assessor					
				Date					
No.	**HazID**	**ScID**	**Recurrence Interval (yr)**	**Occurrence Date last time**	**Likelihood (%)**				
					Times pan (yr)	**5**	**10**	**25**	**50**
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Remarks:

Island Risk Profiling		
	Island	
	Atoll	
	Timespan	
	Assessor	
	Date	

Probability	Minor	Moderate	Major	Serious	Disastrous
Virtually certain	2	3	4	5	5
Very likely	2	3	4	4	5
likely	1	3	3	4	5
Medium likelihood	1	2	3	4	5
Unlikely	1	2	3	3	4
Very unlikely	1	2	2	3	4
Extremely unlikely	1	1	2	2	3

Severity

Remarks:

Detailed Island Risk Assessment in Maldives

Volume III: Detailed Island Reports

S. Feydhoo – Part 1

DIRAM team
Disaster Risk Management Programme
UNDP Maldives

December 2007

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1. Geographic Background

1.1 Location

Feydhoo Island is located on the western rim of Addu atoll, at approximately 73° 08' 00"E and 0° 40' 52" S, about 542 km from the nations capital Male' and 2 km from the nearest airport, Gan (Fig. 1.1). It is the southernmost inhabited island in Maldives. Feydhoo is one of the few inhabited islands facing the western Indian Ocean and exposed to the south west monsoon related wave action. Feydhoo is one of the six inhabited islands in the atoll and it's nearest inhabited islands are Maradhoo Feydhoo and Maradhoo. Feydhoo forms part of a stretch of 5 islands connected though causeways and bridges and is the second largest group of islands connected in this manner. Addu Atoll is the southern most atoll of Maldives and is located south of the equator. It sits along the southern half of the laccadive-chagos ridge, exposing the entire atoll to direct wave action from Indian Ocean.

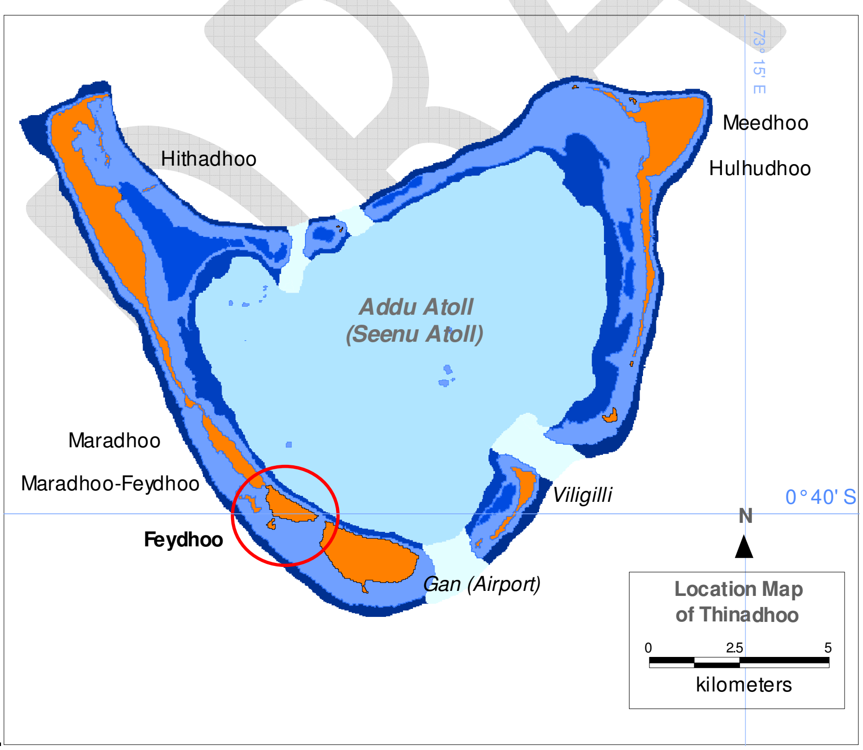

Figure 1.1 Location map of Feydhoo.

1.2 Physical Environment

Feydhoo is a fairly large island with a length of 1600 m and a width of 550 m at its widest point. The total surface area of the island is 62.5 Ha (0.62 km^2). It is the 4^{th} largest island in Addu atoll amongst six inhabited islands. The reef of Feydhoo is large with a surface area of 4152 Ha (41.5 km^2) and cover the entire western rim of Addu Atoll, stretching to approximately 18km. The reef also hosts 3 large inhabited islands and the Airport island (Gan), totalling a 1011ha (10.1 km^2) of land. It is one of the largest concentrations of land in a single reef. The reef and the islands on them are is oriented in a northwest-southeast direction. Feydhoo is located on the southern half of the reef system, approximately 700m from the oceanward coastline and 255 m from the lagoonward coastline.

There are a group of small uninhabited islands located on the oceanward reef flat of Feydhoo. They could be effectively considered barrier islands for Feydhoo Island, although the relatively small size and dispersed nature would probably mean that they do not necessarily perform the functions of a barrier island.

Feydhoo is a highly urbanised settlement with a registered population over 4000 inhabitants, which is considered large in Maldivian context. The high level of urbanization also meant that the natural environment of the island is highly modified to meet the development requirements of the settlement. Majority of the present population of Feydhoo Island consist of the inhabitants from Gan Island, who migrated to Feydhoo in 1950's during the development of Gan as an airbase for British Royal Air force. It should be noted that the vegetation cover in Feydhoo is quite substantial compared to other islands with similar population densities. At first glance, this appears to be due to the effectives of settlement planning, large plot sizes and possibly due to the high rainfall. Almost all islands have a substantial backyard area with a concentration of large trees.

A number of infrastructure development and coastal modification activities has been undertaken in the island over the last 60 years resulting in substantial changes to the island environment. These include reclamation activities, coastal protection, beach replenishment and modifications to coastline resulting from the linking of nearby islands using causeways and bridges. Environmental issues associate with urbanisation are being experienced by its inhabitants including, ground water contamination, improper waste disposal, degradation of coastal areas, depletion of vegetation and coastal erosion. The island is currently facing a shortage of land for further development activities and residential development.

Feydhoo has a high incidence of historical natural hazards and the present environmental characteristics in the island have a number of weaknesses which may expose the island to future hazards.

2. Natural hazards

This section provides the assessment of natural hazard exposure in Feydhoo Island. A severe event history is reconstructed and the main natural hazards are discussed in detail. The final two sections provide the hazard scenarios and hazard zone maps which are used by the other components of this study as a major input.

2.1 Historic events

The island of Feydhoo has been exposed to multiple hazards in the past. A natural hazard event history was reconstructed for Feydhoo based on known historical events. As highlighted in methodology section, this was achieved using field interviews and historical records review. Table 2.1 below lists the known events and a summary of their impacts on the island.

The historic hazard events for Feydhoo showed that the island faced the following multiple hazards: 1) flooding caused by heavy rainfall and 2) swell surges, 3) windstorms and 4) earthquakes. Impacts caused by these events and frequency of occurrence of the events vary significantly. Flooding caused by rainfall and swell surges are the most commonly occurring hazard events, which however, can only traced back 15-20 years, beyond which no reports of serious events are available. Windstorms have also been reported as frequent especially during the southwest monsoon. Since the elderly in the island cannot recall events beyond 1984, it is highly plausible that severe events came to the attention of inhabitants only with the rapid expansion of settlement especially towards the hazard prone western coastline of the island. Feydhoo is also one of the very few islands which have a recorded damage caused by an earthquake, although the damage was insignificant.

Table 2.1 Known historic hazardous events of Feydhoo.

Natural hazard	Dates of the recorded events	Impacts
Flooding caused by Heavy rainfall	• 27th June 1997 • 3rd May 2004 • 4th September	Damage from rainfall related flooding was mostly limited to household goods and backyard crops. These events are

	2005	reported to cause flooding almost across the entire island. Flooding of the houses is increased by raised roads that drain the water from the roads into the houses alongside the roads. Rain related flooding on the island is reported to reach up to 0.4m from ground level. Measured values on walls showed 0.3m. Major impacts of these flooding are: Blocking of the sewerage networks within the flooded zones Severe damages to the backyard crops such as bananas, chillies etc. Damages to house furniture and other household goods. Reduction in mobility around the island leading to short term closure of economic and social institutions
• Flooding caused by swell surges	• 8th May 1993 • 5th June 1993 • 6th & 7th April 1984 • 6th November 1994 • 15th October 1985 • 2nd & 3rd June 1987 • 20th July 2001 • 3rd May 2004 • 18thSeptember 2005 • 4thSeptember 2006 • 30thNovember 2006	The island is reported to experience frequent (once every few years) flooding caused by wave surges and sometimes large swell waves generated far offshore from the costs of the Maldives. These events are also reported to occur during mid SW monsoon. Surge waters often reaches up to 200m inland along much of the length of southern shoreline. These surge waters have flooded the impact zone (Figure 3.10) up to a height of 0.3m. The major impact of these events is damages to the backyard crops within the impact zone.
• Windstorms	• 17th October 1995 • 20th May 2000 • 20th July 2003 • 3rd May 2004 • 30thNovember 2006	Rare incidents of strong winds have also been reported for the island. The recorded event of strong winds and rain affected caused damages to the roofs of some houses were blown off and trees such as papaw, banana, coconut palms, etc. The effect of this event was felt across the entire island.
Droughts		No major event have been reported
Earthquake	16th July 2003 (1:25	The only earthquake that has been

	– 1:30am)	recorded to have caused damages to the island was in 2003. This earthquake cracked some buildings and houses on the island. These included Feydhoo School and Feydhoo Office but the damage was minimal and there was no functional loss at any of these two facilities
Tsunami	26th Dec 2004	There have been one noticed event but this event did not flood the island of Feydhoo.

2.2 Major hazards

Based on the historical records, meteorological records, field assessment and Risk Assessment Report of Maldives (UNDP, 2006) the following meteorological, oceanic and geological hazards have been identified for Feydhoo.

- Swell waves and wind waves
- Heavy rainfall (flooding)
- Windstorms
- Tsunami
- Earthquakes
- Climate Change

2.2.1 Swell Waves and Wind Waves

<u>Origins and Occurrence of waves in Feydhoo</u>

The wave regime around Maldives, especially around the western line of atolls is partially influenced by swell waves originating from the Southern Indian Ocean (Kench et. al (2006), Young (1999), DHI(1999) and Binnie Black & Veatch (2000)). The Southern Indian Ocean is notorious for developing the most intense storms found anywhere on earth which are capable of generating swell waves throughout the year. Abnormal storm events in this regional could generate waves capable of causing flooding in the low lying islands of Maldives.

Feydhoo Island is the southernmost inhabited island of Maldives. Its proximity to the southern Indian Ocean combined with the location on the southwest corner of

Addu Atoll exposes the island to southern swell waves. The presence of swell waves around the region was confirmed by DHI(1999) during a wave study in the neighbouring Fuvahmulah Island (see Table 2.2).

The occurrence of abnormal swell waves on Feydhoo reef flat is dependent on a number of factors such as the wave height, location of the original storm event with in the South Indian Ocean, tide levels and reef geometry. It is often difficult to predict occurrence of such abnormal events as there is only a small probability, even within storm events of similar magnitude, to produce waves capable of flooding islands.

Table 2.3 shows major flooding events in Feydhoo and concurrent major storm events in South Indian Ocean.

Table 2.2 Wave regimes in neighbouring Fuvahmulah Atoll.

Season	Total	Long Period	Short Period
NE - Monsoon	Predominantly from E-S. High Waves from W	From S-SW	Mainly E-NE. High waves from W
Transition Period 1	Mainly from SE-E	From S-SW	Mainly from NE-SE
SW - Monsoon	From SE-SW. Mainly from S. High Waves also from W	From S-SW	Mainly from SE-S. High waves from West
Transition Period 2	As SW monsoon	From S-SW	From SE-W. Higher waves from West

Table 2.3 Historical flood events and possible links with storm events.

Flooding event	Cyclone Name	Date of Storm Event	Maximum Category	Distance	Direction	Tide Level
9 July 1971	9/07/1971	9-Jul-71	NA	1300	SSW	NA
27 August 1980	unknown					NA
6th & 7th April 1984	7/03/1984	4 Apr – 14 April 1984	3	1300km	WSW-S	Data not available

Flooding event	Cyclone Name	Date of Storm Event	Maximum Category	Distance	Direction	Tide Level
15th October 1985	unknown					Data not available
2nd & 3rd June 1987	unknown					Median tide
9-10 September 1987	unknown					NA
8th May 1993	Konita	29 Apr - 07 May 1993	3	1200km	SSW	High – 2 days after Peak tide of May
5th June 1993	unknown					Peak tide of June
26th November 1994	Albertine	21 Nov – 1 Dec 1994	4	1200km	SSW-S	Medium Tide
20th July 2001	unknown					Peak tide
4thSeptember 2006	unknown					Data not available
30thNovember 2006	Anita	29 Nov - 02 Dec 2006	1	3700	WSW	Data not available
15 - 17 May 2007	Unknown	13 -19 May 2007	Extra tropical Depression	5630	SW	Peak tide of the month

Not all flooding events could be linked to the storm events but 3 events appear to be a direct result of category 3 or larger cyclones within 1500km radius of Feydhoo. The event of November 2006 does not appear to be linked to the storm event in spite of their concurrent occurrence. The most striking feature of past swell wave incidents are that the two known severest events (April 1987 and May 2007) events did not originate from cyclonic events but rather from the extremely low winter depressions. The flood events identified in the table but not associated with the cyclonic events are also likely have originated from such depressions. The common factor in all these flood events is that they occurred during or close to peak tide of the month.

Based on these findings all storms within 1500 km of Feydhoo above category 3 were analysed against tide and reported flood events (see Table 2.4). There are no clear patterns evident from the data, suggesting a number of other factors controlling the development and propagation of abnormal swell waves. Detailed assessment using synoptic charts of the South Indian Ocean corresponding to major flooding events are required to delineate any specific trends and exposure thresholds for Feydhoo. Unfortunately this study does not have the resources and time to undertake such an assessment but is strongly recommended for any future detailed assessments.

Table 2.4 Cyclones within 1500km of Feydhoo and of category 3 strength (source: Unisys and JTWC (2004) and University of Hawaii Tide Data).

Cyclone Name	Date	Wind Speed (knots)	Longitude	Tide Level (monthly)	Flooding reported
1963-01-09	12/01/1963	70	70.4	NA	No
1971-07-09	09/07/1971	NA	72.0	NA	Yes
1979-11-25	29/11/1979	100	73.7	NA	No
1979-12-10	18/12/1979	110	79.9	NA	No
1982-01-06	12/01/1982	115	76.5	NA	No
1982-04-23	29/04/1982	100	77.9	NA	No
1984-04-03	5/04/1984	75	69.5	NA	Yes
1986-01-07	9/01/1986	80	81.6	NA	No
1987-03-02	9/03/1987	75	73.7	NA	No
1988-10-30	2/11/1988	75	77.3	low	No
1988-11-05	14/11/1988	100	80.5	High	No
1989-03-26	1/04/1989	100	70.0	Highest	No
1990-01-30	3/02/1990	65	69.7	NA	No
1991-03-20	26/03/1991	90	81.2	NA	No
1993-01-16	24/01/1993	110	70.0	Low	No
1993-04-29	4/05/1993	90	68.8	High	Yes
1994-03-26	4/04/1994	70	79.2	Highest	No
1994-11-21	26/11/1994	115	72.7	Medium	Yes
1995-01-31	6/02/1995	65	71.0	Low-medium	No

Cyclone Name	Date	Wind Speed (knots)	Longitude	Tide Level (monthly)	Flooding reported
1995-03-28	1/04/1995	95	70.5	Medium - High	No
1996-04-06	13/04/1996	135	64.8	Medium-High	No
1996-10-15	18/10/1996	65	79.7	Low	No
1996-10-28	6/11/1996	125	81.0	Medium - High	No
1996-11-20	26/11/1996	65	80.5	Medium	No
2001-01-06	12/01/2001	100	69.1	Medium - High	No
DINA	18/01/2002	70	71.2	High	No
IKALA	26/03/2002	65	73.2	Medium	No
BOURA	17/11/2002	75	69.2	High	No
KALUNDE	8/03/2003	140	71.7	Low	No
BENI	12/11/2003	105	74.5	Low	No
AROLA	9/11/2004	75	77.1	NA	No
BENTO	23/11/2004	140	76.5	NA	No

Flooding is also known to be caused in Feydhoo by a gravity wave phenomenon known as *Udha*. These events are common throughout Maldives and especially the southern atolls of Maldives. No specific research has been published on the phenomenon and has locally been accepted as resulting from local wind waves generated during the onset of southwest monsoon season. The relationship has probably been derived due to the annual occurrence of the events during the months of May or June.

The origins of the *udha* waves as yet remain scientifically untested. It is highly probable that waves originate as swell waves from the Southern Indian Ocean and is further fuelled by the onset of southwest monsoon during May. The timing of these events coincides as May marks the beginning of southern winter and the onset of southwest monsoon. The concurrent existence of these two forms of gravity waves during the southwest monsoon is confirmed by Kench et. al (2006) and DHI(1999). It is also questionable whether the southwest monsoon winds waves alone could cause flooding in islands since the peak tide levels on average are low during May, June and July. Furthermore the strongest mean wind speeds in Gan has been observed for November and is more consistent during October to November than during May and June period (Naseer, 2003).

This issue needs to be further explored based on long term wave and climatological data of the Indian Ocean before any specific conclusions can be made. However if the relationship does exists, this phenomena could prove to be a major hazard in the face of climate change since the intensity of southern Indian Ocean winter storms is expected to increase.

Processes controlling water levels around Feydhoo

Waves undergo extreme and rapid transformations as they interact with reef crest, which control the character of hydrodynamic processes on adjacent reef flat. One of the products of such transformations is the water level setup created at the reef edge and currents generated by the wave setup. Current records made for various studied over reef flats (Aslam, 2004) have shown low frequency oscillations in the current speed. These oscillations have been attributed to surf beat, edge wave and shear waves.

The degree to which wave energy is transformed or "filtered" by the process of wave breaking on the reef depends on several factors, including overall reef geometry, water depth at the reef crest, uniformity of depth along and across the reef, width of the reef flat and depth of the reef flat (Gourlay, 1994, Gourlay, 1996).

Strong winds can cause higher incident waves to break on the reef and the sea-level can rise locally due to shear force of wind on the water surface. The rise in water level due the shear force of winds and the wave setup created as a result of breaking waves on the reef edge can produce high water level set up on the reef flat. Similarly surges or swell waves beyond significant wave heights of 9m on open ocean can cause water levels to rise 3.0m on the reef flat of Feydhoo (based on (Department of Meteorology, 2007)). When such rises in water level are combined with high tide levels there could be strong surges of water across the reef flat. Due to the low elevation of Feydhoo Island coastline, such waves have the potential to create flooding.

Kench and Brander (2006) reported a relationship between wave energy propagation across a reef flat and, reef width and depth. Using their proposed

Reef Energy Window Index, the percentage of occurrence of gravity wave energy at Feydhoo reef flat is approximately 30%.

Historical surge related flood impacts

The oceanward coastline has been identified as the main flood zone on Feydhoo Island for surges (Figure 2.1). The inland extent of flooding is greatest along shorelines facing the embayment between Gan and Feydhoo and embayment between Feydhoo & Maradhoo. The reason for this pattern could be attributed to the focusing of flow into the topographically lower embayment areas. In addition, the presence of a small island on the oceanward side causes wave refraction and the islands closeness to Feydhoo could partially explain the generally smaller distance of flooding in the corresponding area of Feydhoo. The northern side of the island have not experienced flooding since the atoll is fairly protected on the eastern side. There was also no possibility of wave diffraction around the island corners due to the presence of largely solid causeways.

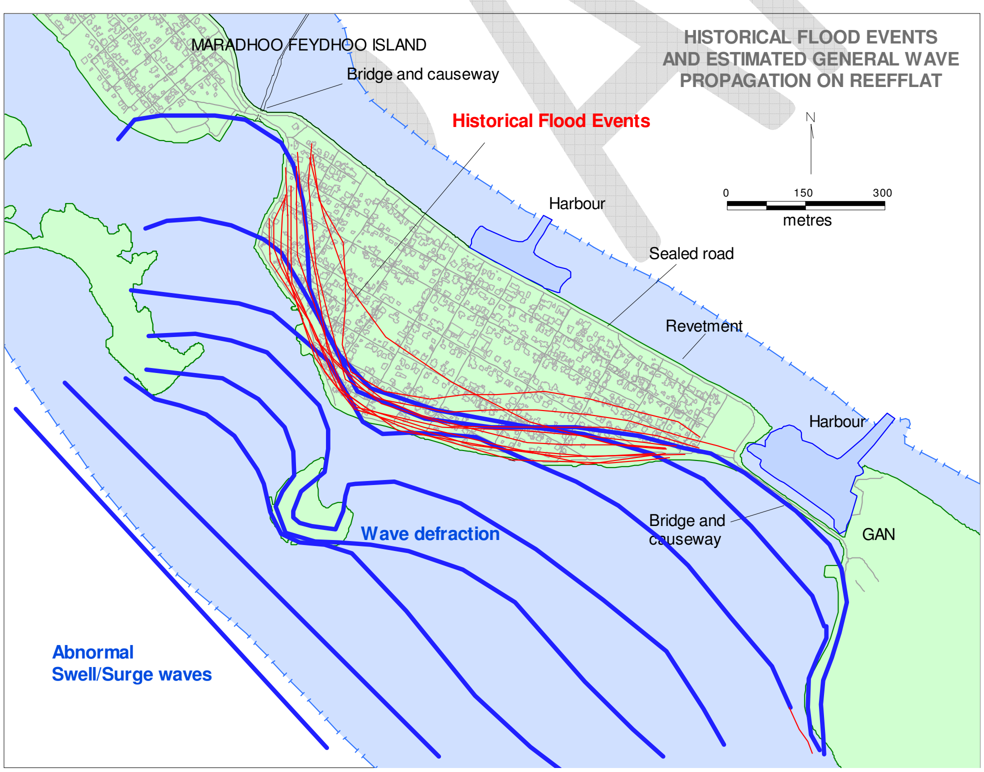

Figure 2.1 Historical flood events and probable wave propagation patterns in Feydhoo and its reef flat.

The highest wave height reported on the island during flooding events was 1.0m. This height is consistent with flood heights reported from swell or surge related waves in Maldives. It was reported that over topping during flood events were controlled on the north-western part of the island due to the erection of a 1.5m ridge. During the flooding event of May 1007, flood waters failed to overtop this ridge where as areas with natural beach heights were flooded.

Future event prediction

It is known that Feydhoo is exposed to abnormal swell waves originating from the Southern Indian Ocean. Due to its location, this should be considered the most serious hazard for Feydhoo. Feydhoo Island is expected to be exposed to storm waves mainly from south and west south west as shown in Figure 2.2. Events beyond this arch may not influence Feydhoo due to the protection offered the eastern rim of the atoll. However it is still probable that waves could diffract around the southern end of Addu Atoll and cause flooding in Feydhoo. Effects of such events are considered to be smaller.

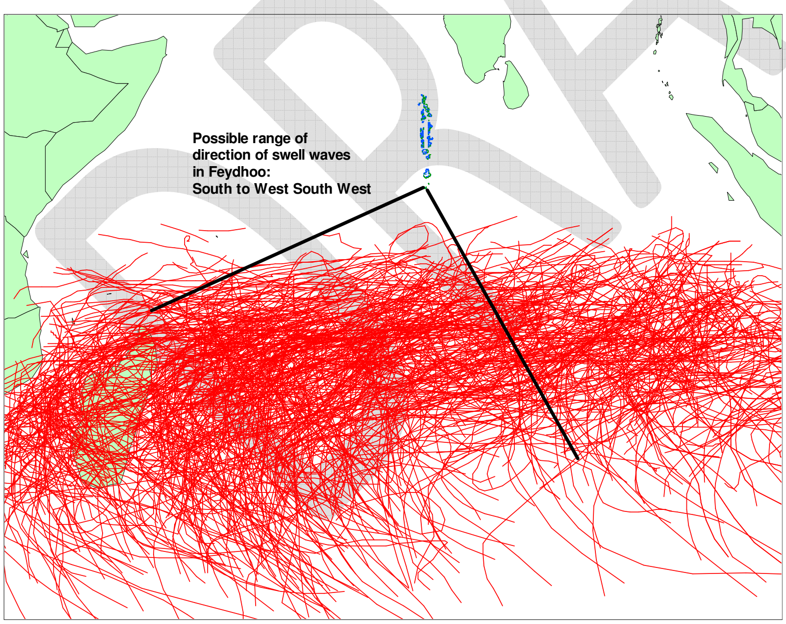

Figure 2.2 Historical storm tracks (1945-2007) and possible direction of swell waves for Feydhoo Island.

At present, it is very difficult to forecast the exact probability of swell hazard event and their intensities due to the unpredictability of swell events and lack of research into their impacts on Maldives. However, since the hazard exposure scenario is critical for this study a tentative exposure scenario has been developed based on the historical events. In this regard there is a probability of major swell events occurring every 5 years in Feydhoo with probable water heights of 1.0 m and every 3 years with probable water heights of 0.5-0.75 m. Events with water heights less than 0.5m and greater than 0.2m are likely to occur annually. A flooding probability of 40% was also observed from the tide data when the monthly peak tide reaches 2.3 m or more. There were only 7 events above this threshold between 1987 and 2003, 3 of which involved flooding in Feydhoo. These tides usually occur in March, April, October or November. Tides alone may not have caused the flooding but its occurrence with swell waves would have triggered the events.

The timing of swell events is expected to be predominantly between November and June, based on historic events and storm event patterns (see Table 2.5).

Table 2.5 Variation of Severe storm events in South Indian Ocean between 1999 & 2003 (source: (Buckley and Leslie (2004)).

	Severe wind event variation	
Longitude band	**Winter**	**Summer**
30 °E to 39 °E	12.5	17
40 °E to 49 °E	7.5	10
50 °E to 59 °E	7.5	26
60 °E to 69 °E	6	14
70 °E to 79 °E	6	6
80 °E to 89 °E	12	6
90 °E to 99 °E	12	8
100 °E to 109 °E	8	3
110 °E to 119 °E	15	7
120 °E to 130 °E	13.5	2

The reclamation plans for Feydhoo shows that the reef flat width will be reduced to approximately 380m. This reduction in the reef flat width will increase the percentage of occurrence of gravity wave energy on this reef flat to approximately 43% and therefore increasing the probability of flooding caused by surges by 13%. Similarly the impact of flooding will increase relative to encroachment of settlement to coastal areas, even if the probability of flood events remains constant. Potential increase in frequency and intensity of flood events are also probable with climate change and is addressed in a latter section.

2.2.2 Heavy Rainfall

The rainfall pattern in the Maldives is largely controlled by the Indian Ocean monsoons. Generally the NE monsoon is dryer than the SW monsoon. Rainfall data from the three main meteorological stations, HDh Hanimaadhoo, K. Hulhule and S. Gan shows an increasing average rainfall from the northern regions to the southern regions of the country (Figure 2.3). The average rainfall at S. Gan is approximately 481mm more than that at HDh. Hanimadhoo.

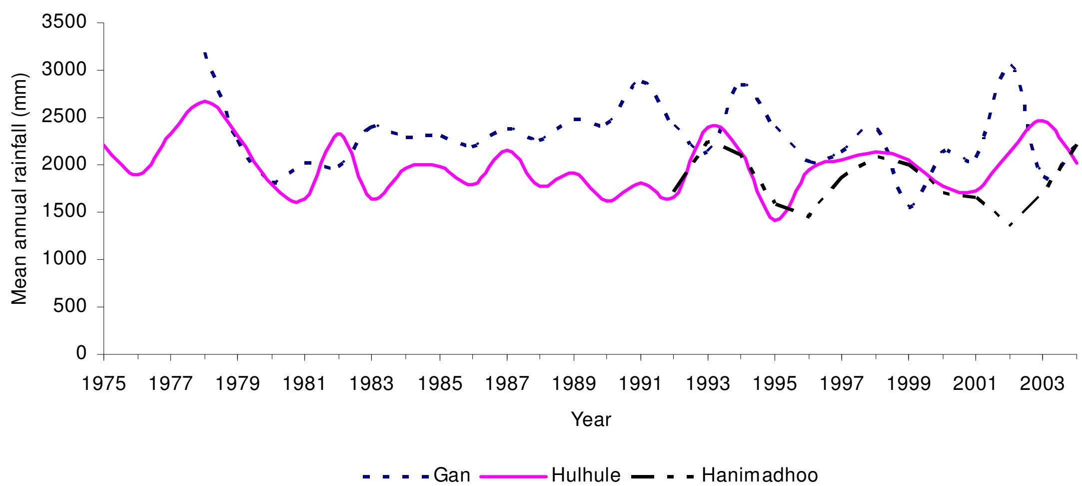

Figure 2.3 Mean annual rainfall across the Maldives archipelago.

The mean annual rainfall of Gan is 2299.3 mm with a Standard Deviation of 364.8 mm and the mean monthly rainfall is 191.6mm. Rainfall varies throughout the year with mean highest rainfall during October, December and May and lowest between February and April (See Figure 2.4).

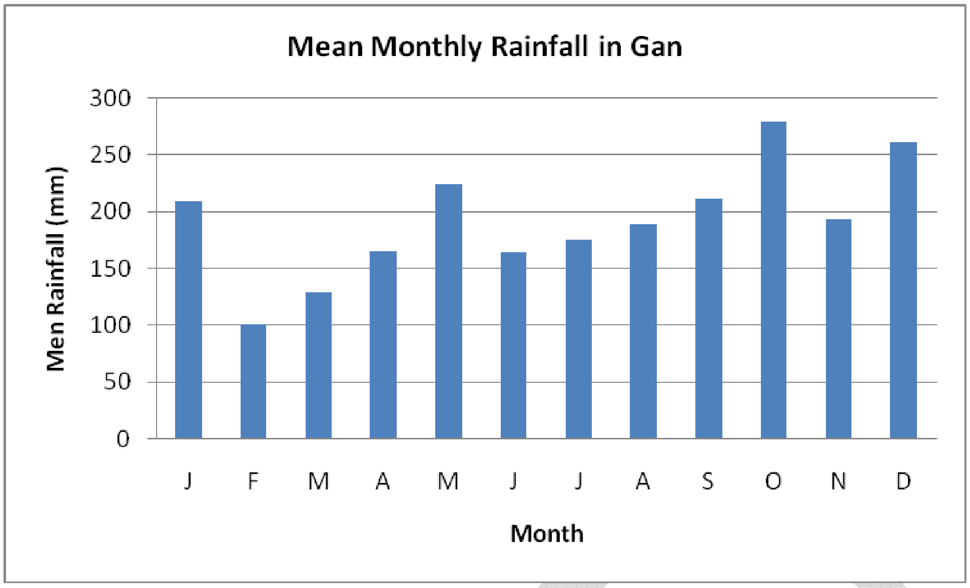

Figure 2.4 Mean Monthly Rainfall (1978-2004).

Historic records of rainfall related flooding on the island of Feydhoo indicates that this island is often flooded (Figure 2.5). Records for all incidents have not been kept but interviews with locals and research into newspaper reports show that localised levels of flooding within areas of Feydhoo has been experienced dating back to 1970's. The main events recorded in historical documents and island office correlates positively with abnormal departure of rainfall from mean values. As figure below shows, there have been 4 specific years where rainfall have deviated over 20% of the mean values. These variations are often caused by significant rainfall events rather than an equally distributed increase in monthly rainfall. Out of the 4 events, 3 are known to have caused significant flooding on the island. Flooding caused by rainfall on the island of Feydhoo has been reported to reach up to 0.4 m above the ground level.

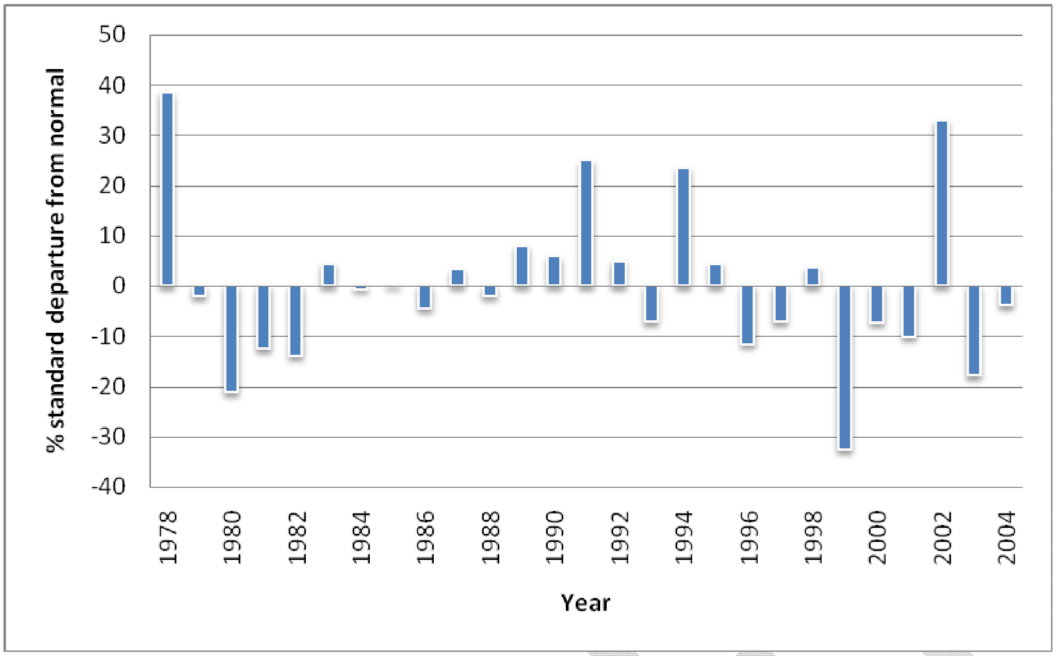

Figure 2.5 Standard departure of rainfall from normal levels.

It would be possible to identify threshold levels for heavy rainfall for a single day that could cause flooding in Feydhoo, through observation of daily rainfall data. Unfortunately, we were unable to acquire daily historical data from the Department of Meteorology due to the newly introduced user-pays-policy and lack of resources to acquire them.

Feydhoo Islands' exposure to flooding is further enhanced by human activities. Since the 1960s, taro pits were dug across almost all the housing plots in the islands. These activities have left low elevations across the island, specifically inside the backyards, leading to heavy rainfall related flooding, Introduction of vehicles and extensive use of roads led to the top soil to be hardened, creating puddles and occasionally wide scale retention of water in the lower roads. As a remedy, roads were maintained by levelling, re-levelling and infilling using extra sand. Over the years, roads have been raised and now stand higher than the surrounding houses. Heights of about 0.4m were observed in some roads. To add to the problem, the old taro pits further serves as a drainage area from the roads. Majority of the taro pits have since been refilled, although most the refilled areas are still lower than the surrounding roads. This setup of an artificial topography guarantees flooding during heavy rainfall.

The probable maximum precipitations predicted for Gan by UNDP (2006) are shown in Table 2.6.

The maximum precipitation for 24 hour period in Maldives has been recorded as 219.8 mm in Kaadedhoo airport 133 km north of Gan. Based on the field observations and correlations with severe weather reports from Department of Meteorology (DoM, 2005) the following threshold levels were identified for flooding. These figures must be revised once historical daily rainfall data becomes available (Table 2.7).

Quite often heavy rainfall is associated with multiple hazards especially strong winds and possible swell waves. It is therefore likely that a major rainfall event could inflict far more damage than those identified in the table.

Table 2.6 Probable Maximum Precipitation for various Return periods in Gan.

Return Period			
50 year	100 year	200 year	500 year
218.1	238.1	258.1	284.4

Table 2.7 Threshold levels for rainfall related flooding in Feydhoo.

Threshold level (daily rainfall)	**Impact**
50mm	Puddles on road, flooding in low houses.
100mm	Flooding in low houses; a number of roads flooded; minor damage to household items especially in the backyard areas
150mm	Widespread flooding on roads and low lying houses. Minor to moderate damage to household goods, possible school closure.
200mm	Widespread flooding on roads and houses. Moderate to major damages to household goods, possible school closure, damage to crops, gullies created along shoreline, possible damage to road infrastructure.
250+mm	Widespread flooding around the island. Major damages to household goods and housing structure, schools closed, businesses closed, damage to crops, damage to road infrastructure,

2.2.3 Wind storms and cyclones

Maldives being located within the equatorial region of the Indian Ocean is generally free from cyclonic activity. There have only been a few cyclonic strength depressions that have tracked through the Maldives, all of which occurred in the northern and central regions. According to the hazard risk assessment report (UNDP, 2006), Feydhoo falls within the least hazardous zone for cyclone related hazards. There are no records cyclones in the southern region, although a number of gale force winds have been recorded due to low depressions in the region.

Historic records for Feydhoo have indicated that even strong breeze – near gale force winds (Table 2.8) have caused significant damage to property and trees on the island. One such event that is observed in the available meteorological records (records for the years 2002 and 2003) was the strong breeze that occurred on the 20th of July 2003. This event was recorded to have attained an average wind speed of 23 knots.

In order to perform a probability analysis of strong wind and threshold levels for damage, daily wind data is crucial. However, such data was unavailable for this study. Estimates have therefore been made using the only available data: 2002 and 2003.

Analysis of all the wind speed data for the years 2002 and 2003 indicates that the probability of occurrence of wind speeds greater than 23 knots is 1.3 days (0.36%) in a year (Table 2.9). The analysis also indicated that highest winds blow from SSW – W (Figure 2.6).

The threshold levels for damage are predicted based on interviews with locals and housing structural assessments provided by risk assessment report (UNDP, 2006), as shown Table 2.10.

Table 2.8 Beaufort scale and the categorisation of wind speeds.

Beau- fort No	Description	Cyclone category	Average wind speed (Knots)	Average wind speed (kilometres per hour)	Specifications for estimating speed over land
0	Calm		Less than 1	less than 1	Calm, smoke rises vertically.
1	Light Air		1 -3	1 - 5	Direction of wind shown by smoke drift, but not by wind vanes.
2	Light breeze		4 - 6	6 - 11	Wind felt on face; leaves rustle; ordinary wind vane moved by wind.
3	Gentle breeze		7 - 10	12 - 19	Leaves and small twigs in constant motion; wind extends light flag.
4	Moderate breeze		11 - 16	20 - 28	Raises dust and loose paper; small branches moved.
5	Fresh breeze		17 -21	29 - 38	Small trees in leaf begin to sway; crested wavelets form on inland waters.
6	Strong breeze		22 - 27	39 - 49	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.
7	Near gale		28 - 33	50 - 61	Whole trees in motion; inconvenience felt when walking against the wind.
8	Gale	Category 1	34 - 40	62 - 74	Breaks twigs off trees; generally impedes progress.
9	Strong gale	Category 1	41 - 47	75 - 88	Slight structural damage occurs (chimney pots and slates removed).
10	Storm	Category 2	48 - 55	89 - 102	Seldom experienced inland; trees uprooted; considerable structural damage occurs.
11	Violent storm	Category 2	56 - 63	103 - 117	Very rarely experienced; accompanied by widespread damage.
12	Hurricane	Category 3,4,5	64 and over	118 and over	Severe and extensive damage.

Table 2.9 Probability of occurrence of wind at different speeds in Addu Atoll (based on hourly records for the years 2002 and 2003).

Direction	Probability of occurance Speed range			
	<=10 kts	>10 - 20kts	>20 - 30kts	>30kts
0 - 22.5	0.0881	0.0002		
22.5 - 45	0.0529	0.0007		
45 - 67.5	0.0278	0.0002		
67.5 - 90	0.0304	0.0003		
90 - 112.5	0.0216	0.0011		
112.5 - 135	0.0253	0.0024		
135 - 157.5	0.0246	0.0011		
157.5 - 180	0.0419	0.0015		
180 - 202.5	0.0615	0.0027		
202.5 - 225	0.0655	0.0149	0.0002	0.0001
225 - 247.5	0.0645	0.0343	0.0002	
247.5 - 270	0.1407	0.0838	0.0031	
270 - 292.5	0.0769	0.0088		
292.5 - 315	0.0619	0.0034		
315 - 337.5	0.0545	0.0027		
337.5 - 360				
Total	**0.8381**	**0.1583**	**0.0035**	**0.0001**

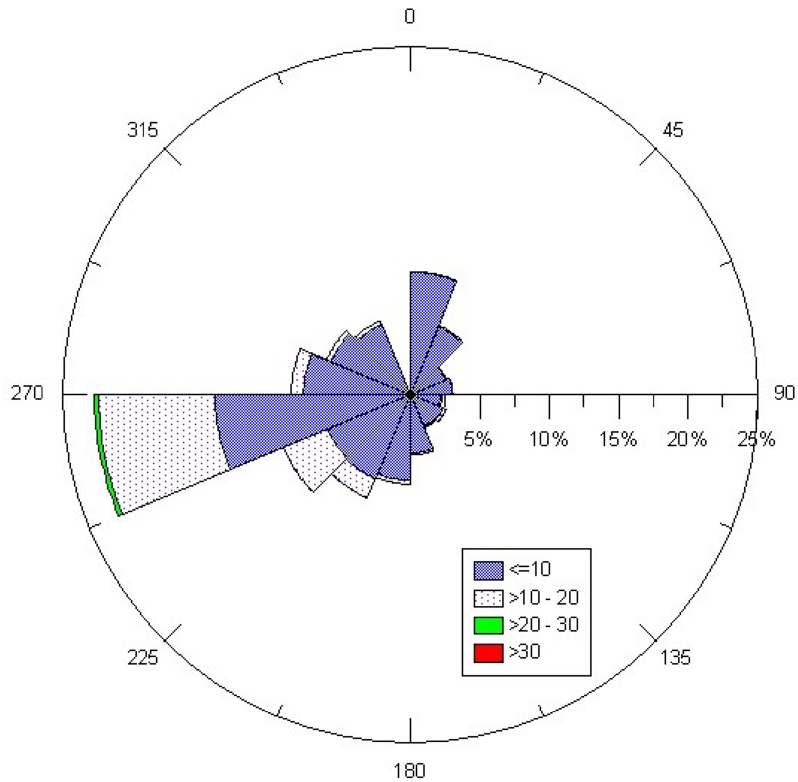

Figure 2.6 Windrose chart for Gan, Addu Atoll, using the hourly data for years 2002 and 2003.

Table 2.10 Threshold levels for wind damage based on interviews with locals and available meteorological data.

Wind speeds	Impact
1-10 knots	No Damage
11 – 16 knots	No Damage
17 – 21 knots	Light damage to trees and crops
22 – 28 knots	Breaking branches and minor damage to open crops, some weak roofs damaged
28 – 33 knots	Minor damage to open crops and houses
34 - 40 knots	Minor to Moderate to major damage to houses, crops and trees
40+ Knots	Moderate to Major damage to houses, trees falling, crops damaged

2.2.4 Tsunami

UNDP (2006) reported the region where Feydhoo is geographically located to be a moderate tsunami hazard zone. The tsunami of December 2004 had no impact on Feydhoo. There was no reported flooding of the island from this event. The tide gauge at Gan in Addu Atoll recorded the tsunami of December 2004 as a wave of height 1.4 m within the atoll lagoon (Figure 2.7). Plotting the maximum water level recorded at Gan tide gauge (0.8 m +MSL) over the cross-sectional profile of Feydhoo clearly shows that the tsunami wave of December 2004 was just a few centimetres lower than the average ground level of Feydhoo (Figure 2.8). Comparatively lower wave height recorded at Gan is partly due to the refraction of the wave caused by the Indian Ocean bathymetry as it travelled westwards Maldives and due the relative distance for the earthquake epicentre which triggered the tsunami.

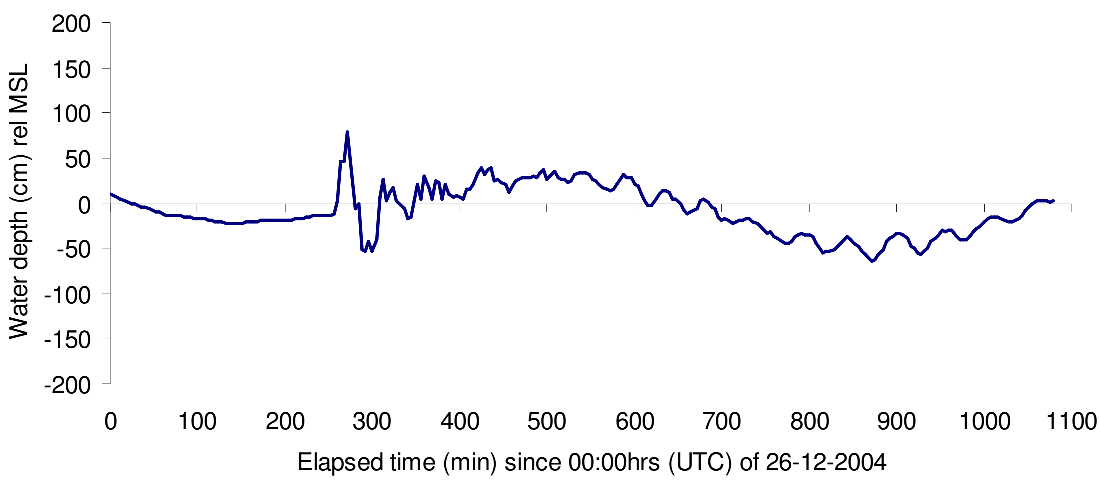

Figure 2.7 Water level recordings from the tide gauge at Gan, Addu Atoll indicating the wave height of tsunami 2004.

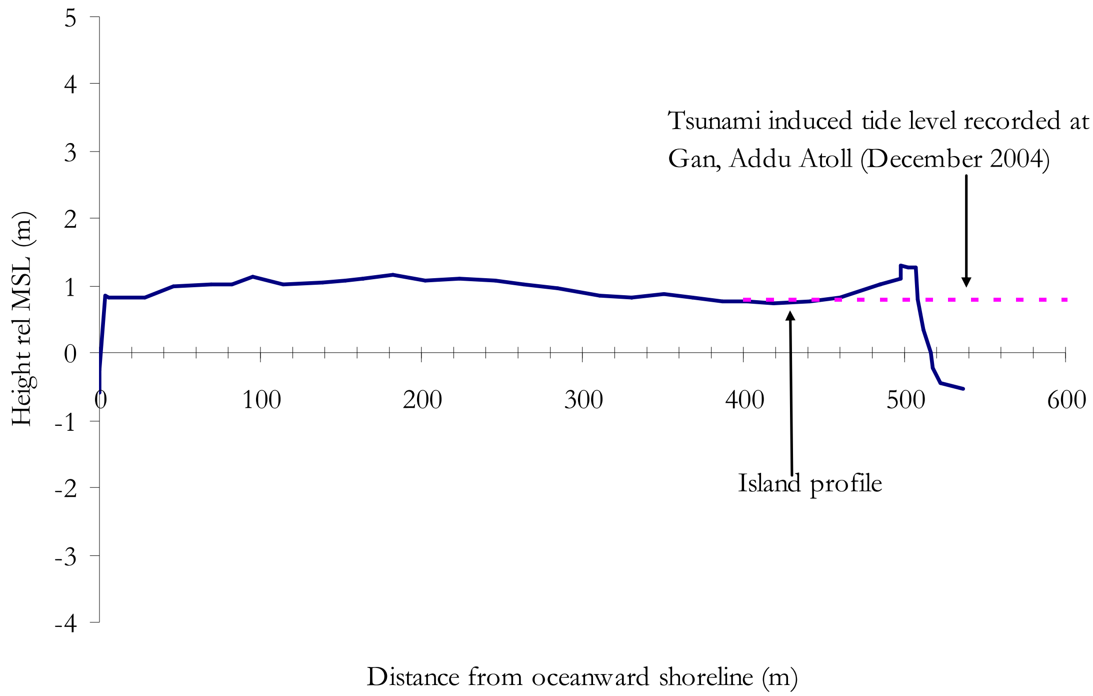

Figure 2.8 Maximum water level caused by tsunami of December 2004 plotted across the island profile of Feydhoo evidently showing the reason why the island did not get flooded by this event.

The absence of impact during the 2004 tsunami doesn't mean that the island is not exposed to tsunamis. The predicted probable maximum tsunami wave height for Feydhoo is 0.8 – 2.5 m (based on UNDP (2006)). Examination of the flooding that will be caused by a wave run-up of 2.5 m for the island of Feydhoo indicates that such a magnitude wave will flood at least up to 100 m inland and that the first 10 – 20 m from the shoreline will be a moderately destructive zone. The main advantage for Feydhoo against tsunamis is that it is located on western coastline of Addu Atoll and that no major atoll passes exist directly east of the atoll. The main source of tsunamis for Maldives is Sumatran trench on the eastern side.

However, it is well understood that the tsunami waves will also diffract into the atoll lagoon through atoll passes which will cause the water level within the atoll lagoon to rise. The atoll passes on the northern and south eastern end of the atoll will lead to diffraction and possible flooding if water level rises above the height of the island. The tsunami of December 2004 which raised the water level within the atoll lagoon by approximately 0.8 m above MSL was just below the average island elevation. The ration between maximum tide level (MSL) to maximum wave height for the tsunami of 2004 is 0.57. When this ratio is applied to the maximum tsunami wave height predicted within the lagoon for this region of the country results in a 1.8 m water level rise within the atoll lagoon. This would flood the island of Feydhoo not just from the lagoonward side but also from the oceanward side and the entire island could be flooded due its narrow width.

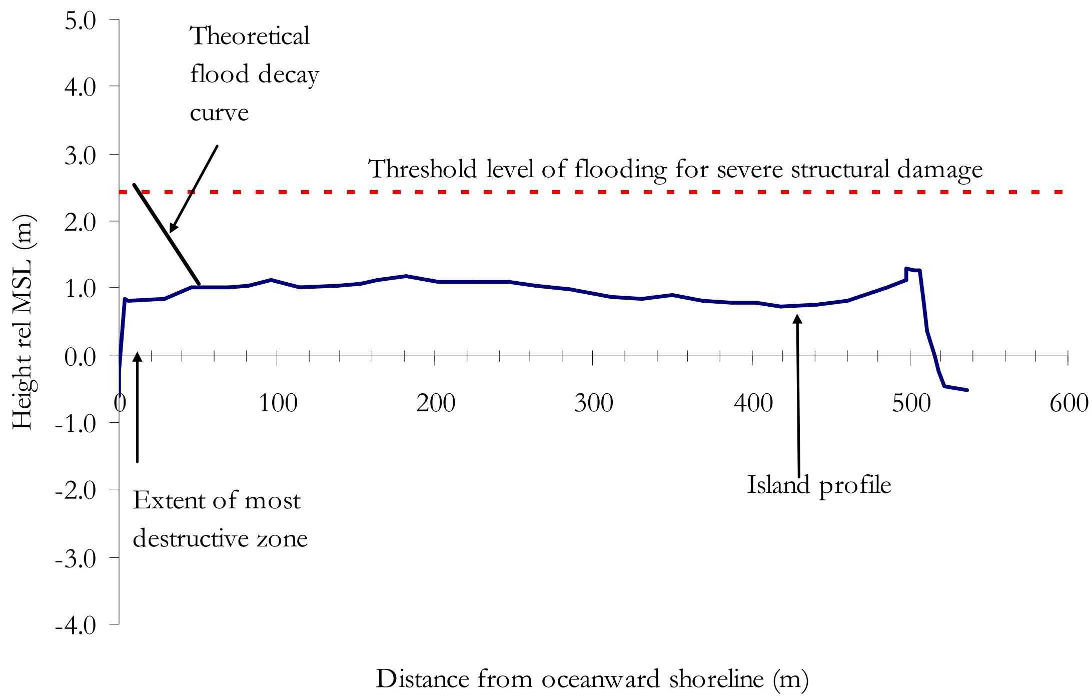

Figure 2.9 Probable tsunami related flooding for Feydhoo based on a theoretical flood decay curve and the maximum probable tsunami wave height.

2.2.5 Earthquakes

There hasn't been any major earthquake related incident recorded in the history of Feydhoo or even Madives. However, Feydhoo does have one of the very few records of an earthquake related tremor and associated damage. During 16th July 2003 an earthquake of unknown (but possibly of very small magnitude) caused tremors in Feydhoo creating cracks in some buildings especially Feydhoo School. No other event of significance is recorded.

However, the Disaster Risk Assessment Report (UNDP 2006) highlighted that Addu Atoll is geographically located in the highest seismic hazard zone of the Maldives. According to the report the rate of decay of peak ground acceleration (PGA) for the zone 5 in which Feydhoo is located has a value less than 0.32 for a 475 years return period (see table below). PGA values provided in the report have been converted to Modified Mercalli Intensity (MMI) scale (see column 'MMI' in Table 2.11). The MMI is a measure of the local damage potential of the earthquake. See Table 2.12 for the range of damages for specific MMI values. Limited studies have been performed to determine the correlation between structural damage and ground motion in the region. The conversion used here is based on United States Geological Survey findings. No attempt has been made to individually model the exposure of Feydhoo Island as time was limited for such a detailed assessment. Instead, the findings of UNDP (2006) were used.

Table 2.11 Probable maximum PGA values in each seismic hazard zone of Maldives (modified from UNDP, 2006).

Seismic hazard zone	PGA values for 475yrs return period	MMI[1]
1	< 0.04	I
2	0.04 – 0.05	I
3	0.05 – 0.07	I
4	0.07 – 0.18	I-II
5	**0.18 – 0.32**	**II-III**

Table 2.12 Modified Mercalli Intensity description (Richter, 1958).

MMI Value	Shaking Severity	Description of Damage
I	Low	Not felt. Marginal and long period effects of large earthquakes.
II	Low	Felt by persons at rest, on upper floors, or favourably placed.
III	Low	Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.
IV	Low	Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the

[1] Based on KATZFEY, J. J. & MCINNES, K. L. (1996) GCM simulation of eastern Australian cutoff lows. *Journal of Climate*, 2337-2355.

		walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV, wooden walls and frame creak.
V	Low	Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.
VI-XII	Light - Catastrophe	Light to total destruction

According to these findings the threshold for damage is very limited even in a 475 year return earthquake. It should however be noted that the actual damage may be different in Maldives since the masonry and structural stability factors have not been considered at local level for the MMI values presented here. Usually such adjustments can only be accurately made using historical events, which is almost nonexistent in Maldives. If an indicator from the 2003 earthquake can be derived, an earthquake of an MMI value of III could create cracks in structures especially those with poor masonry. If high rise buildings like Feydhoo School are constructed more often, such buildings could experience damage.

2.2.6 Climate Change

The debate on climate change, especially Sea Level Rise (SLR) is far from complete. Questions have been raised about SLR itself (Morner et al., 2004, Morner, 2004) and the potential for coral island environments to naturally adapt (Kench et al., 2005, Woodroffe, 1993). However the majority view of the scientific community is that climate is changing and that these changes are more likely to have far reaching consequences for Maldives. For a country like Maldives, who are most at risk from any climate change impacts, it is important to consider a cautious approach in planning by considering worst case scenarios. The findings presented in this section are based on existing literature. No attempt has been made to undertake detailed modelling of climate change impacts specifically on the island due to time limitations. Hence, the projection could change with new findings and should be constantly reviewed.

The most critical driver for future hazard exposure in Maldives is the predicted sea level rise and Sea Surface Temperature (SST) rise. Khan et al. (2002, Woodroffe, 1993) analysis of tidal data for Gan, Addu Atoll shows the overall trend of Mean Tidal Level (MTL) is increasing in the southern atolls of Maldives. Their analysis shows an increasing annual MTL at Gan of 3.9 mm/year. These findings have also been backed by a slightly higher increase reported for Diego Garcia south of Addu Atoll (Sheppard, 2002). These calculations are higher than the average annual rate of 5.0 mm forecasted by IPCC (2001), but IPCC does predict a likely acceleration as time passes. Hence, this indicates that the MTL at Feydhoo by 2100 will be nearly 0.4m above the present day MTL.

Similarly, Khan et al. (2002) reported air temperature at Addu Atoll is expected to rise at a rate of 0.4C per year, while the rate of rise in SST is 0.3C.

Predicted changes in extreme wind gusts related to climate change assumes that maximum wind gusts will increase by 2.5, 5 and 10 per cent per degree of global warming (Hay, 2006). Application of the rate of rise of SST to the best case assumption indicates a 15% increase in the maximum wind gusts by the year 2010 in Addu Atoll where Feydhoo is located.

The global circulation models predict an enhanced hydrological cycle and an increase in the mean rainfall over most of the Asia It is therefore evident that the probability of occurrence and intensity of rainfall related flood hazards for the island of Feydhoo will be increased in the future. It has also been reported that a warmer future climate as predicted by the climate change scenarios will cause a greater variability in the Indian monsoon, thus increasing the chances of extreme dry and wet monsoon seasons (Giorgi and Francisco, 2000). Global circulation models have predicted average precipitation in tropical south Asia, where the Maldives archipelago lies, to increase at a rate of 0.14% per year (Figure 2.10).

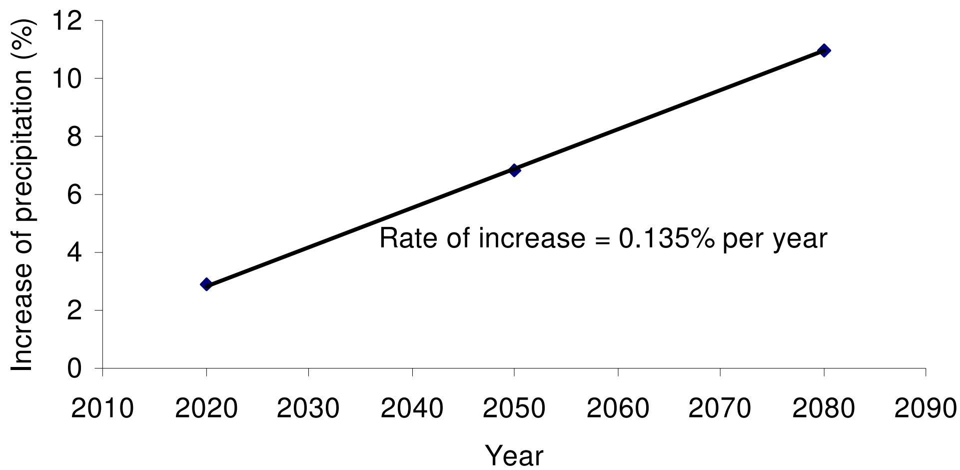

Figure 2.10 Graph showing the rate of increase of averaged annual mean precipitation in tropical south Asia (Adger et al., 2004).

There are no conclusive agreements over the increase in frequency and intensity of Southern Indian Ocean Storms. However, some researchers have reported a possible increase in intensity and even a northward migration of the southern hemisphere storm belt (Kitoh et al., 1997) due rise in Sea Surface Temperatures (SST) and Sea Level Rise. If this is to happen in the Southern Indian Ocean, the frequency of and intensity of storms reaching Feydhoo Island coastline will increase and thereby exposing the island more frequent damages from swell waves. The increase in sea level rise will also cause the storms to be more intense with higher flood heights.

The above discussed predicted climate changes for Feydhoo and surrounding region is summarised below. It should be cautioned that the values are estimates based on most recent available literature on Gan which themselves have a number of uncertainties and possible errors. Hence, the values should only be taken as guide as it existed in 2006 and should be constantly reviewed. The first three elements are based climate change drivers while the bottom three are climatological consequences.

Table 2.13 Summary of climate change related parameters for various hazards.

Element	Predicted rate of change	Predicted change (overall rise)		Possible impacts on Hazards in Feydhoo
		Best Case	Worst Case	
SLR	3.9-5.0mm /yr	Yr 2050: +0.2m Yr 2100: +0.4m	Yr 2050: +0.4m Yr 2100: +0.88m	Tidal flooding, increase in swell wave flooding, reef drowning
Air Temp	0.4℃ / decade	Yr 2050: +1.72° Yr 2100: +3.72°		
SST	0.3℃ / decade	Yr 2050: +1.29° Yr 2100: +2.79°		Increase in storm surges and swell wave related flooding, Coral bleaching & reduction in coral defences
Rainfall	+0.14% / yr (or +32mm/yr)	Yr 2050: +1384mm Yr 2100: +2993mm		Increased flooding, could affect coral reef growth
Wind gusts	5% and 10% / degree of warming	Yr 2050: +3.8 Knots Yr 2100: +8.3 Knots	Yr 2050: +7.7Knots Yr 2100: +16.7 Knots	Increased windstorms, Increase in swell wave related flooding.
Swell Waves	Frequency expected to change. Wave height in reef expected to be high			Increase in swell wave related flooding.

2.3 Event Scenarios

Based on the discussion provided in section 2.2 above, the following event scenarios have been estimated for Feydhoo Island (Table 2.14, 2.15, and 2.16).

Table 2.14 Rapid onset flooding hazards

Hazard	Max Prediction	Impact thresholds			Probability of Occurrence		
		Low	Moderate	Severe	Low Impact	Moderate Impact	Severe Impact
Swell Waves *(wave heights on reef flat – Average Island ridge height +1.8m above reef flat)*	NA	< 2.0m	> 2.0m[2]	> 3.0m	High	Low	Very Low
Tsunami *(wave heights on reef flat)*	3.0m	< 2.0m	> 2.0m[3]	> 3.0m	Moderate	Low	Very low
SW monsoon high seas	2.0m	< 2.0m	> 2.0m	> 3.0m	Very High	Very low	Unlikely
Heavy Rainfall *(For a 24 hour period)*	284mm	<75mm	>75mm	>175mm	High	Moderate	Low

Table 2.15 Slow onset flooding hazards (medium term scenario – year 2050)

Hazard	Impact thresholds			Probability of Occurrence		
	Low	Moderate	Severe	Low	Moderate	Severe
SLR: Tidal Flooding	< 2.0m	> 2.0m	> 3.0m	Moderate	Very Low	Very Low
SLR: Swell Waves	< 2.0m	> 2.0m	> 3.0m	Very high	Moderate	Low
SLR: Heavy Rainfall	<75mm	>75mm	>175mm	Very High	Moderate	Low

[2] Impact on southern half of island will be severe if floods higher than 1.5m. The northern half has an artificial high ridge.
[3] If tsunami approaches from within the atoll lagoon impact can be severe beyond 2.5m.

Table 2.16 Other rapid onset events

Hazard	Max Prediction	Impact thresholds			Probability of Occurrence		
		Low	**Moderate**	**Severe**	**Low**	**Moderate**	**Severe**
Wind storm	NA	<28 knts	> 28 knts	> 40Knts	Very High	Moderate	Low
Earthquake (MMI value[4])	III	< IV	> IV	> VI	Low	Unlikely	none

2.4 Hazard zones

Hazard zones have been developed using a hazard intensity index. The index is based on a number of variables, namely historical records, topography, reef geomorphology, vegetation characteristics, existing mitigation measures and hazard impact threshold levels. The index ranges from 0 to 5 where 0 is considered as no impact and 5 is considered as very severe. In order to standardise the hazard zone for use in other components of this study only events above the severe threshold were considered. Hence, the hazard zones should be interpreted with reference to the hazard scenarios identified above.

2.4.1 Swell waves and SW monsoon high Waves

The intensity of swell waves and SW monsoon *udha* is predicted to be highest 100m from the coastline on the ocean ward side (see Figure 2.11). Swell waves higher than 3.0m on reef flat are predicted to penetrate inner island up to or beyond 200m from coastline. The runoff on to the island is facilitated by the low topography.

The south western half of the island is predicted to experience more frequent and intense flooding since the ridge height is just 1.0m above MSL. The north western half is has an artificial ridge protecting the island form waves up to 2.5 m on the reef flat. Hence the more compact contours in the region. The lagoonward

[4] Refer to earthquake section above

side is relatively safe form swell related flooding due to the protection provided by the atoll rim and the revetment protecting the shoreline. There is a small probability of swell waves propagating through the south western reef pass if the waves are oriented parallel to the pass.

SW monsoon high waves (*udha*) are not expected to have an impact beyond 100m of the coastline.

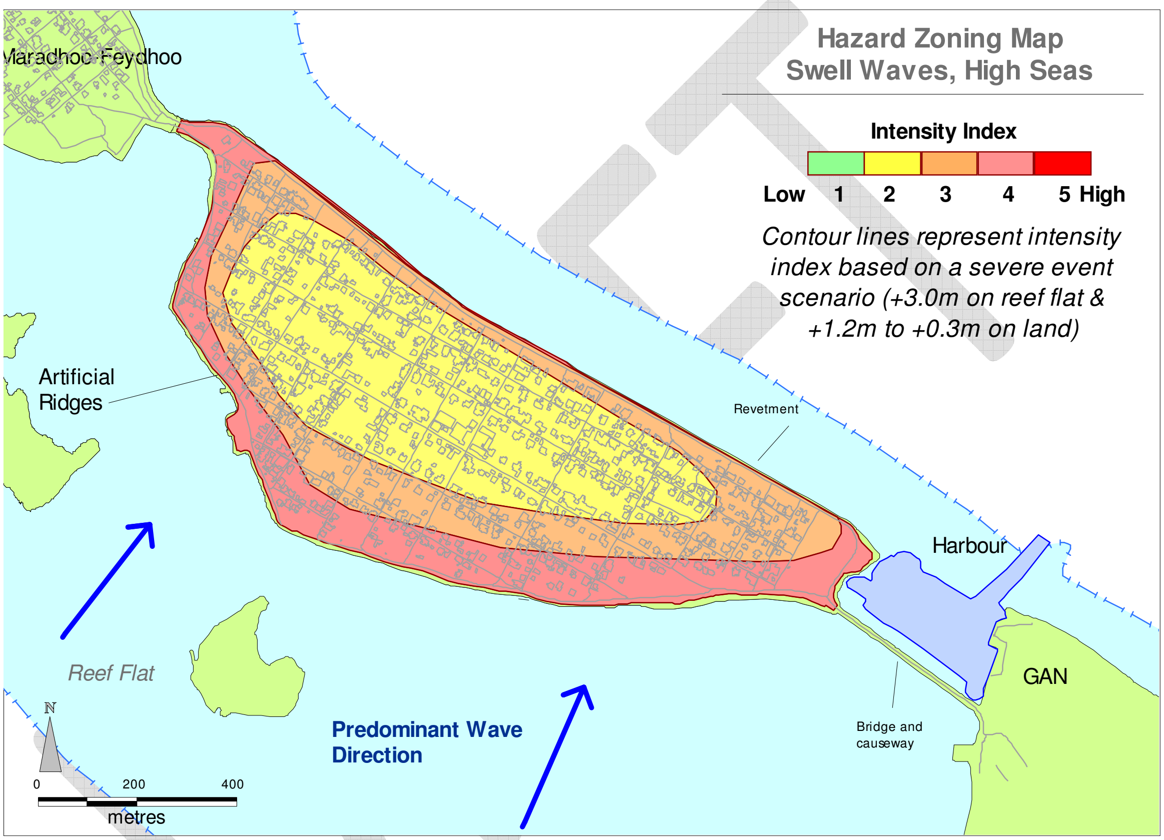

Figure 2.11 Hazard zoning map for swell waves and southwest monsoon high seas.

2.4.2 Tsunamis

When a severe threshold of tsunami hazard (>3.0 m on reef flat) is considered the southern half of the island is predicted to receive the highest intensity (Figure 2.12). This is due to the low elevation of coastline in south and possible wave refraction off Gan Island or diffraction through the south east atoll pass. The presence of solid causeways is also expected to increase flood intensity on both ends of the island. Wave height around the island will vary based on the original tsunami wave height, but the areas marked as low intensity is predicted to have proportionally lower heights compared to the coastline. Even in the worst case scenarios the tsunami wave intensity is expected to be low in Feydhoo as it is not located in the direct path of any predicted tsunamis.

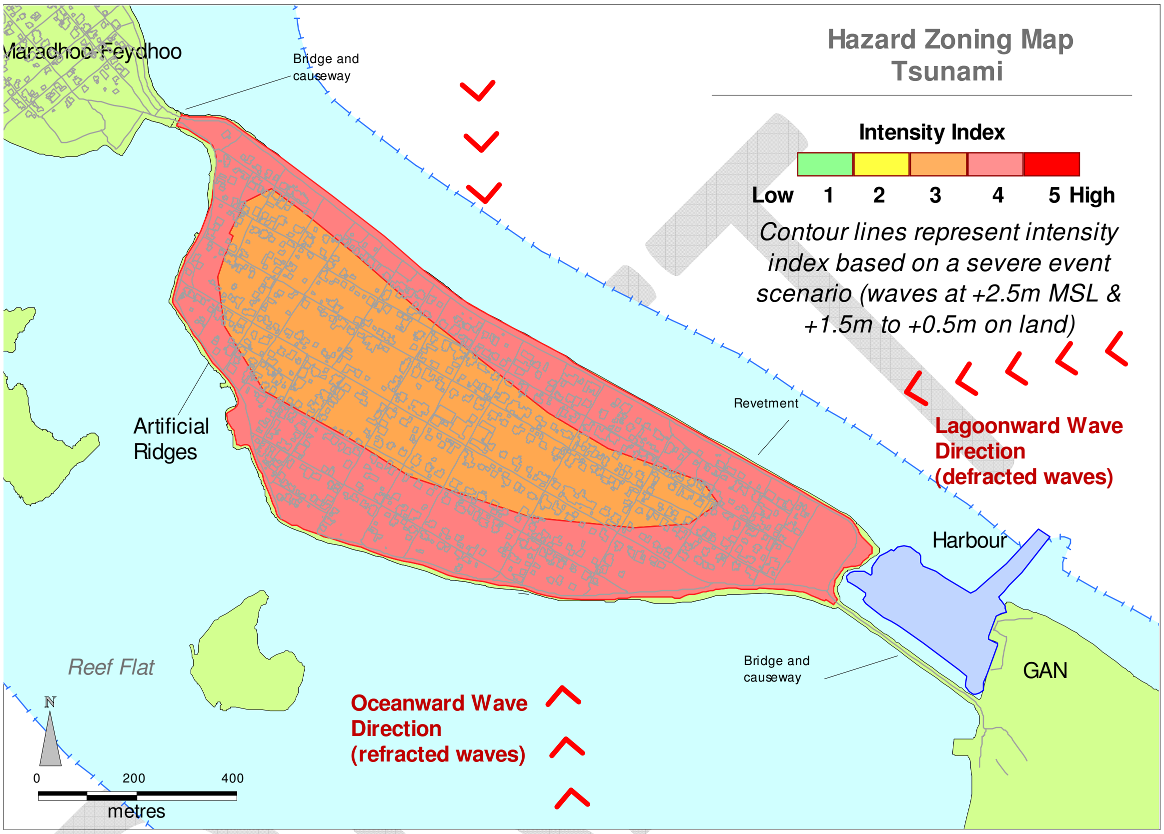

Figure 2.12 Hazard zoning map for tsunami flooding.

2.4.3 Heavy Rainfall

Heavy rainfall above the severe threshold is expected to flood most parts of the island except close to the oceanward shoreline (Figure 2.13). The area around the Addu Link Road is most susceptible to the drainage due the blockage of surface runoff towards the sea. At present the drainage system is reported to function poorly due to high levels of sedimentation and lack of arrangement within the community and authorities to regularly clean them. The inner zone with the intensity rating of four is a result of low topography, close proximity to water table, remnants of taro pits and improper road maintenance activities. The rainfall hazard zones are approximate and based on the extrapolation of topographic data collected during field visits. A comprehensive topographic survey is required before these hazard zones could be accurately established.

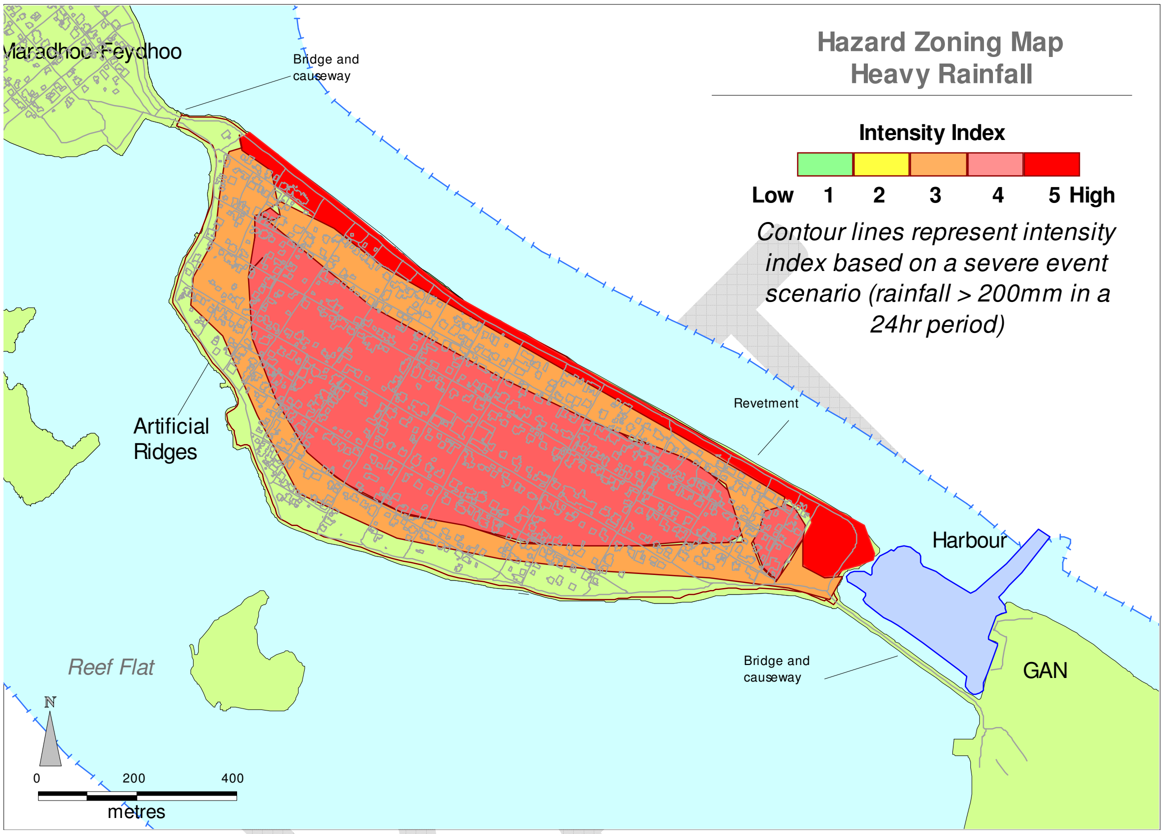

Figure 2.13 Hazard zoning map for heavy rainfall related flooding.

2.4.4 Strong Wind

The coastal areas of the western shoreline are predicted to receive the strongest winds (Figure 2.14). The eastern half of the island is expected to be slightly protected due to the vegetation cover on the western side. However, only a slight change in intensity is predicted. The western coastline is particularly exposed to the predicted strong wind direction of W to NW. Much of the impact on the eastern half of the island could be from secondary impacts such as falling trees.

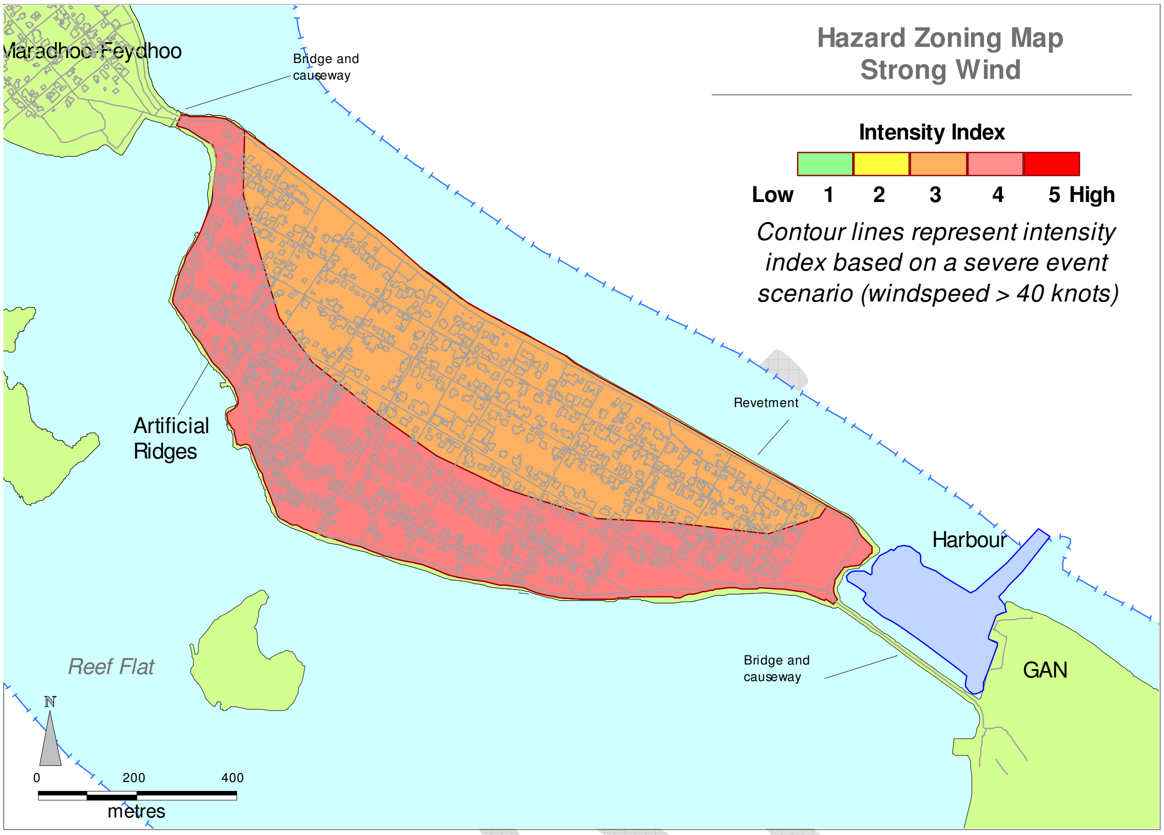

Figure 2.14 Hazard zoning map for strong wind.

2.4.5 Earthquakes

The entire island is a hazard zone with an intensity of 2.

2.4.6 Climate Change

Establishing hazard zones specifically for climate change is impractical at this stage due to the lack of topographic and bathymetric data. However, the predicted impact patterns and hazard zones described above are expected to be prevalent with climate change as well, although the intensity is likely to slightly increase.

2.4.7 Composite Hazard Zones

A composite hazard zone map was produced using a GIS based on the above hazard zoning and intensity index (Figure 2.15). The coastal zone approximately 100m on the oceanward coastline and 50m from lagoonward coastline is predicted to have the highest intensity of hazard events. The inner part of the island is also exposed to multiple hazards although at a small scale. This pattern of exposure is expected due to the small size of the island and due to the use of severest threshold for exposure.

2.5 Limitations and recommendation for future study

The main limitation for this study is the incompleteness of the historic data for different hazardous events. The island authorities do not collect and record the impacts and dates of these events in a systematic manner. There is no systematic and consistent format for keeping the records. In addition to the lack of complete historic records there is no monitoring of coastal and environmental changes caused by anthropogenic activities such as road maintenance, beach replenishment, causeway building and reclamation works. It was noted that the island offices do not have the technical capacity to carry out such monitoring and record keeping exercises. It is therefore evident that there is an urgent need to increase the capacity of the island offices to collect and maintain records of hazardous events in a systematic manner.

The second major limitation was the inaccessibility to long-term meteorological data from the region. Historical meteorological datasets at least as daily records are critical in predicting trends and calculating the return periods of events specific to the site. The inaccessibility was caused by lack of resources to access them after the Department of Meteorology levied a substantial charge for acquiring the data. The lack of data has been compensated by borrowing data from alternate internet based resources such as University of Hawaii Tidal data. A more comprehensive assessment is thus recommended especially for wind storms and heavy rainfall once high resolution meteorological data is available.

The future development plans for the island are not finalised. Furthermore the existing drafts do not have proper documentations explaining the rationale and design criteria's and prevailing environmental factors based on which the plan should have been drawn up. It was hence, impractical to access the future hazard exposure of the island based on a draft concept plan. It is recommended that this study be extended to include the impacts of new developments, especially land reclamations, once the plans are finalised.

The meteorological records in Maldives are based on 5 major stations and not at atoll level or island level. Hence all hazard predictions for Feydhoo are based on regional data rather than localised data. Often the datasets available are short for accurate long term prediction. Hence, it should be noted that there would be a high degree of estimation and the actual hazard events could vary from what is described in this report. However, the findings are the closest approximation possible based on available data and time, and does represent a detailed although not a comprehensive picture of hazard exposure in Feydhoo.

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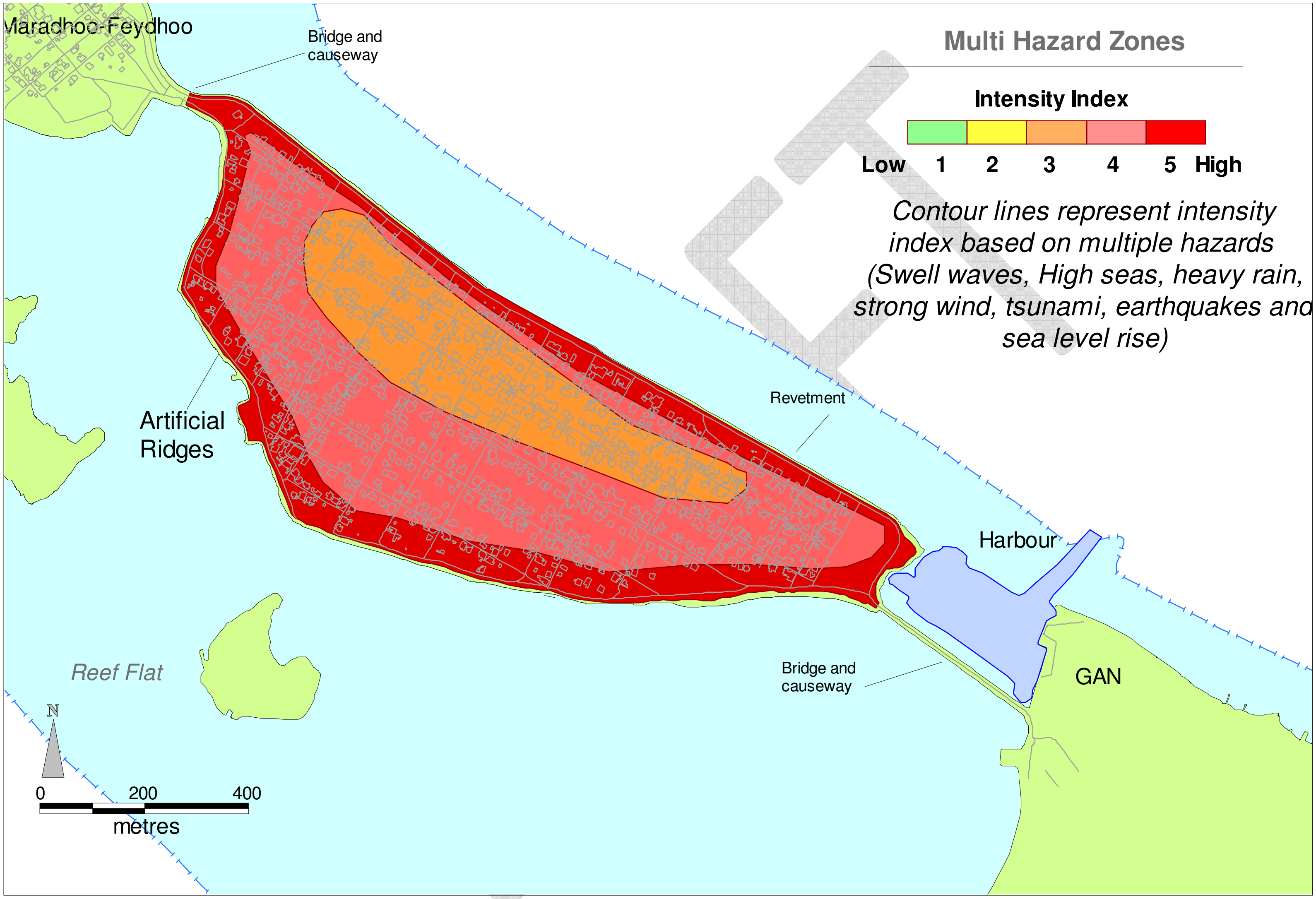

Figure 2.15 Composite hazard zone map.

3. Environment Setting and Vulnerabilities

3.1 General environment Conditions

3.1.1 Terrestrial Environment

<u>Topography</u>

The topography of Feydhoo was assessed using three island profiles (see Figure 3.1). Given below are the general findings from this assessment.

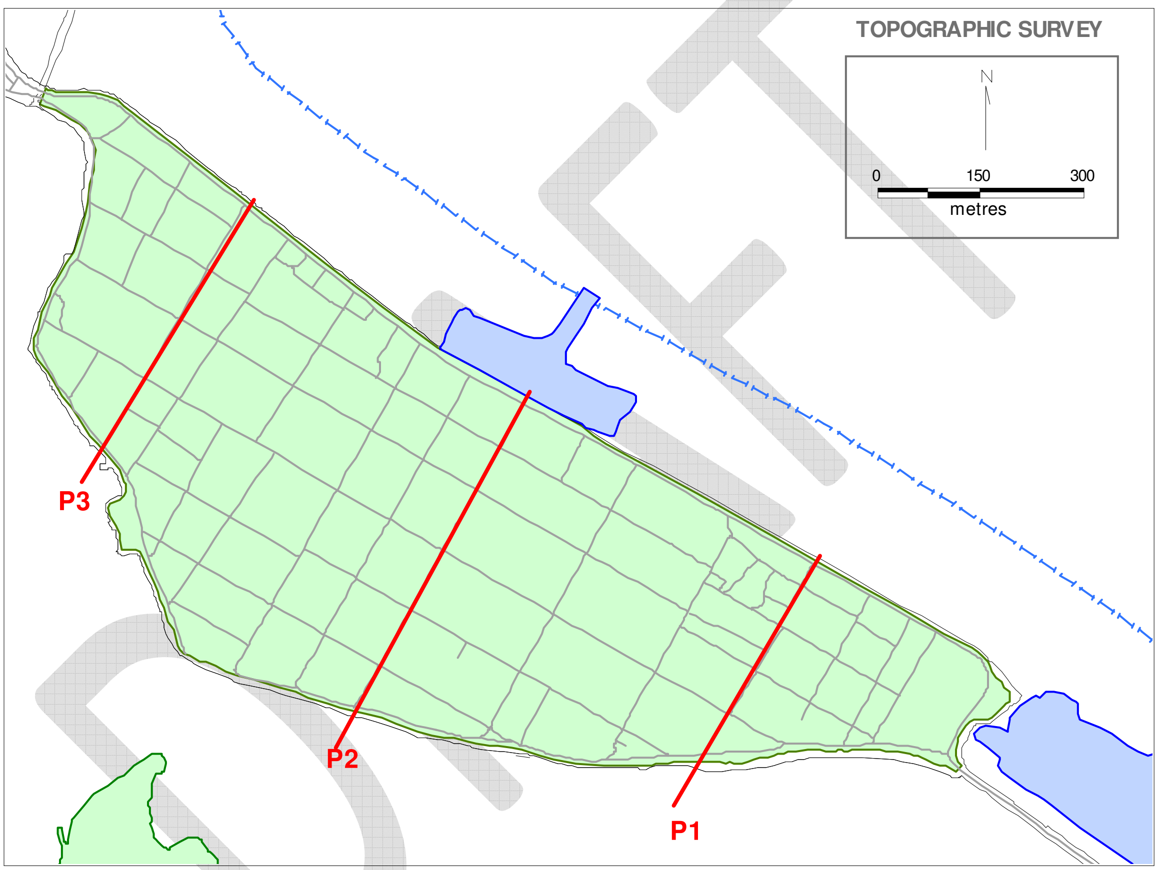

Figure 3.1 Topographic survey locations.

The island is generally low lying with an average elevation of +1.0 m MSL along the surveyed island profiles (see Figures 3.2-4). This finding was reconfirmed from the shallow depths of ground water table around the island. As characteristic of large islands, considerable variations in topography were observed in Feydhoo. Unfortunately, the roads around Feydhoo have been modified as part of the road maintenance programme. As a result they may not represent the true topography of the island. The road maintenance programme does not modify the surrounding houses and as a result a large number of houses were lower than the road. Actual height of the islands was obtained using these original heights (see Figure 3.3-4).

The main topographic feature on the island is the low elevation of most houses compared to the surrounding roads. Over the years, residents have coped with this variation and associated rainfall flooding by raising the elevation of the plots itself. Feydhoo Island is well known to have large areas of low lying areas due to the high number of houses on the western side of the island having semi-wet areas known as “olhu”. Much of these areas have now been levelled by the inhabitants and at present there are only a few remnants.

In general, the northern half of the island is slightly higher than the south. It is unclear whether this variation is due to road development activities as substantial low elevations were noted in the houses around the topographic survey line. A detailed topographic survey is required to confirm this general trend in topographic variation.

Topographic modifications have been made to the northwestern area of the island during beach replenishment and reclamation activities following severe coastal erosion in the region. An artificial ridge has been developed and the coastline has been extended to mitigate erosion. The artificial ridge ranges from +1.5 m MSL (Figure 3.3) to +2.0 m MSL (Figure 3.4).

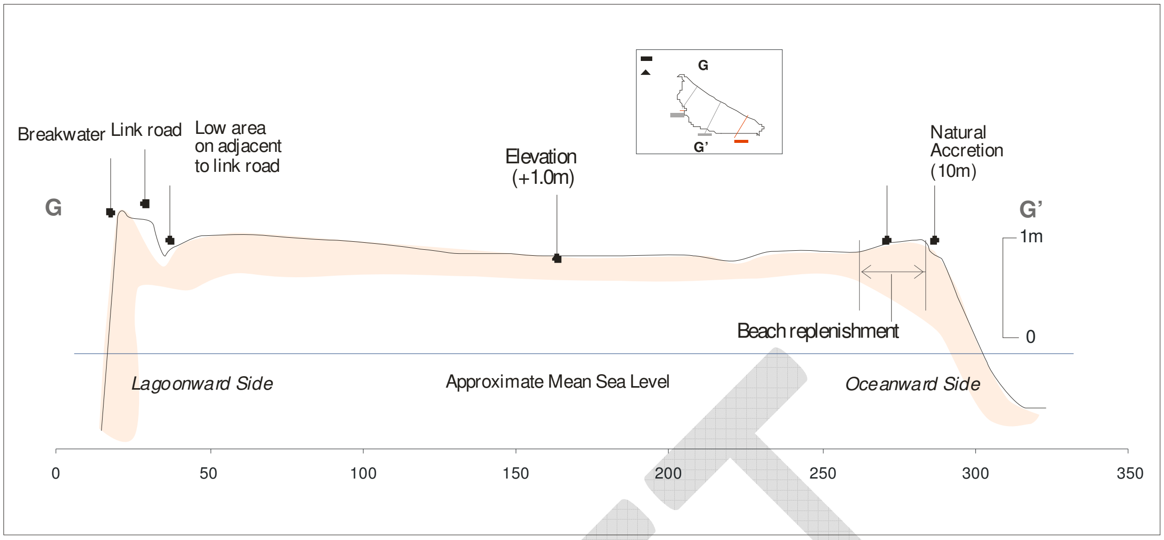

Figure 3.2 Topographic profile 1.

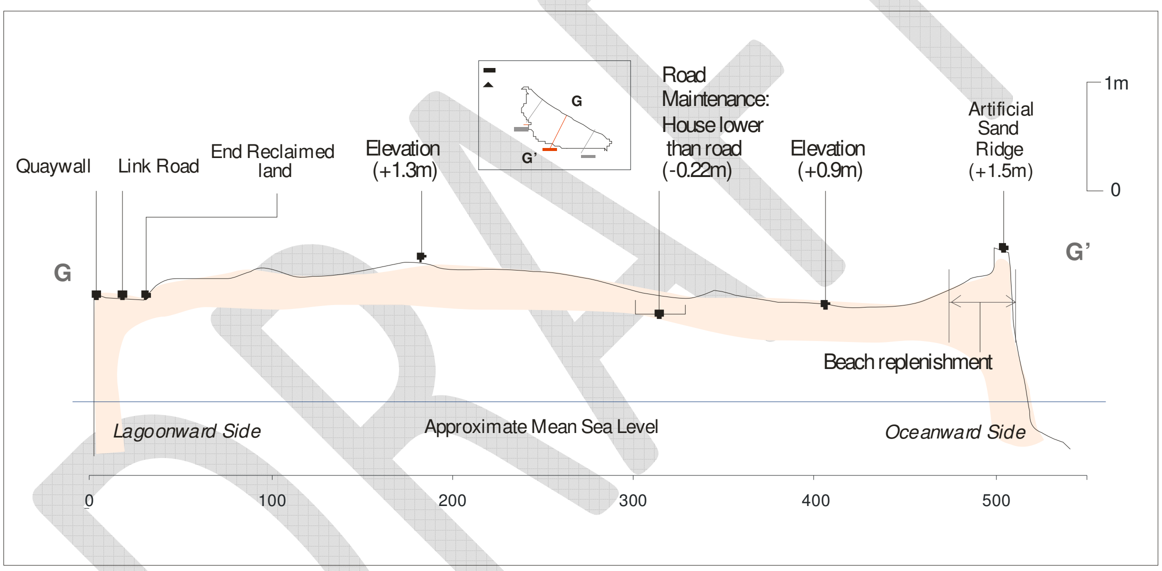

Figure 3.3 Topographic profile 2.

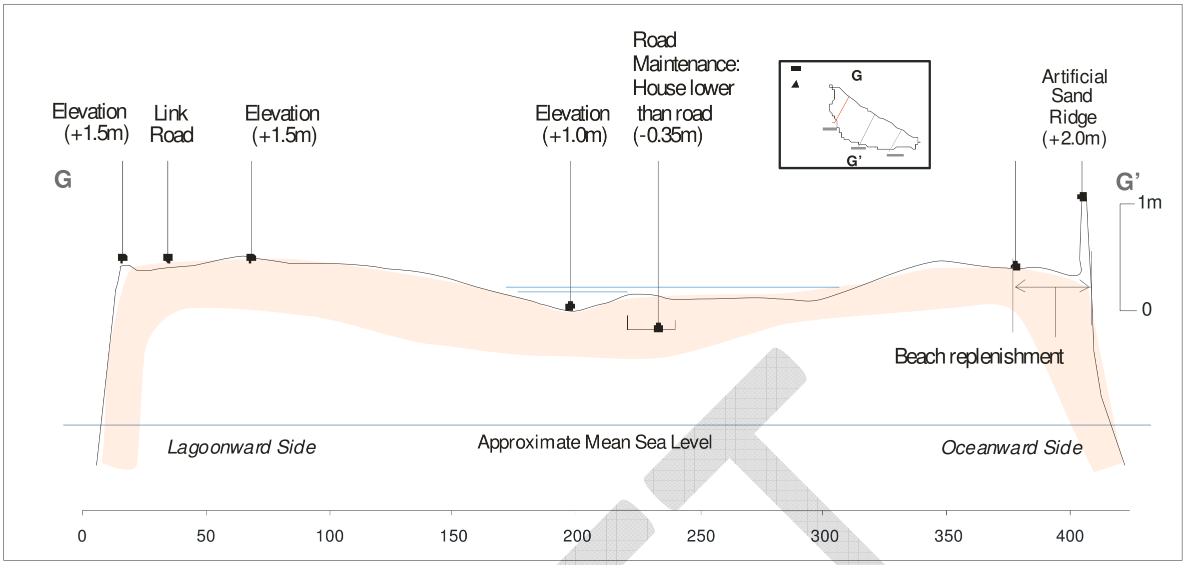

Figure 3.4 Topographic profile 3.

Vegetation

One of the most striking features of Feydhoo terrestrial environment is the relatively high vegetation cover compared to islands with similar population densities. Much of this vegetation is interestingly located in the backyards of the houses. Figure 3.5 shows the changing vegetation cover of Feydhoo over the last 55 years. It is apparent that the settlement planning and the considerations given to retention of the vegetation cover during the resettlement project played a significant role in maintaining the vegetation cover to date. Specific considerations in the project appears to include provision of backyard in all plots, retention of major vegetation during construction activities that did not fall in to the construction foot print and re-vegetation activities. Today, the plan seems to have worked very efficiently. This may be good example for resettlement projects being carried out elsewhere in the country, such as Shaviyani Atoll Funadhoo, which seems to have undergone substantial vegetation losses due to current construction practices. The reasonably strong vegetation cover may also have been assisted due to the high rainfall and low elevation in most of the backyards across the island.

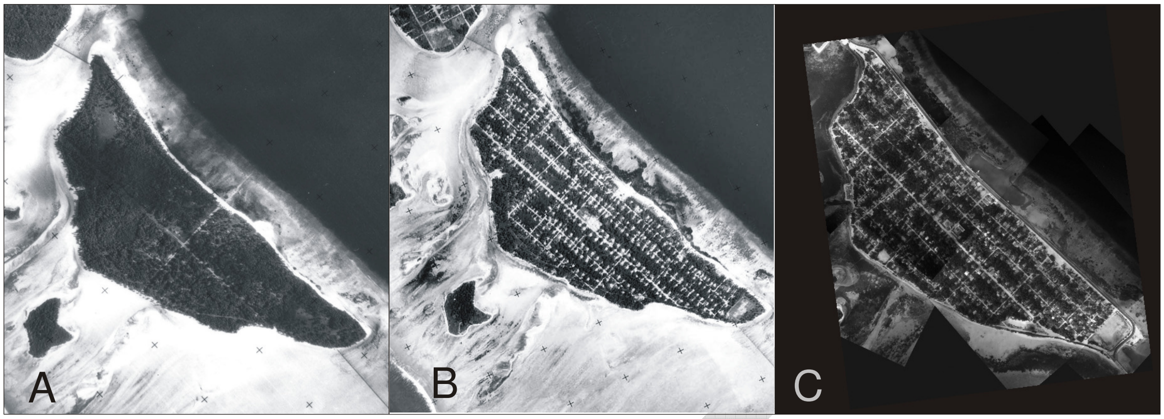

Figure 3.5 Changes in Feydhoo vegetation Cover - (A) 1958, prior to resettlement from Gan (B) 1969, after resettlement and construction activities, (c) 2004, present day.

The coastal vegetation on the island is very narrow and non-existent in some locations, especially along the southern coastline. The eastern coastline does not have any coastal vegetation as the Addu Link Road is developed along the shoreline. The western shoreline has undergone beach replenishment and small reclamation activities in the past leading to removal of coastal vegetation. New vegetation appears have been planted across the western shoreline, but appears to be inadequate in terms of its composition and width.

Ground Water and Soil

Feydhoo Island is expected to have a substantial layer of fresh water. Water lens depth varies across the island based on topography. Generally the water table could be reached with less than 1m at median tide. This could decrease to 0.5m during spring high tides or more during heavy rainfall.

Feydhoo's ground water was reported to be in generally in good quality although traces of salinisation and contamination were reported in random locations around the island. This finding was based on interviews with households during field survey and represented water quality over a year. Considering the high density of the island, it is surprising to find that the islanders did not consider groundwater quality as a problem. There are two possible reasons for this: 1) the rainfall in the region keeps the ground water recharged constantly compared to other parts of the country and, 2) the population density is based on registered population while in reality half of inhabitants have migrated out. The inhabitants reported no shortages of drinking water in the past due to the good quality of ground water and high rainfall.

The soil conditions appeared to be good throughout the island although levelling activities in the recent past and present is causing minor changes to the soil profiles around the island. The use of backyards as major agricultural areas in the past shows the fertility of the soil.

3.1.2 Coastal Environment

Beach and Beach Erosion

The islanders reported coastal erosion as a major problem on the island. Analysis using historical aerial photographs shows that the island coastline has been relatively stable compared to the island size (Figure 3.7). There have been areas of erosion on both the eastern and western sides, some loosing up to 20 m. There have also been areas of accretion reaching up 20 m. The construction of solid bridge preventing the flow of sediments around the island caused major changes to the erosion and accretion patterns. On average Feydhoo has lost about 300 m^2 of land annually between 1958 and 1969, and lost about 500 m^2 of land annually between 1969 and 2000. The loss has been associated with gains in other areas and the net erosion rate remained insignificant.

The modification of coastline, especially beach replenishment activities prevents assessment of erosion against historical data. The present erosion and accretion patterns are shown in Figure 3.8. At present the northwestern shoreline undergoes periodic erosion, especially during SW monsoon. This process may have been enhanced since the development of the bridge between Feydhoo and Maradhoo-Feydhoo due to sudden increase in the current flow. The process is most likely to stabilise in the long-run.

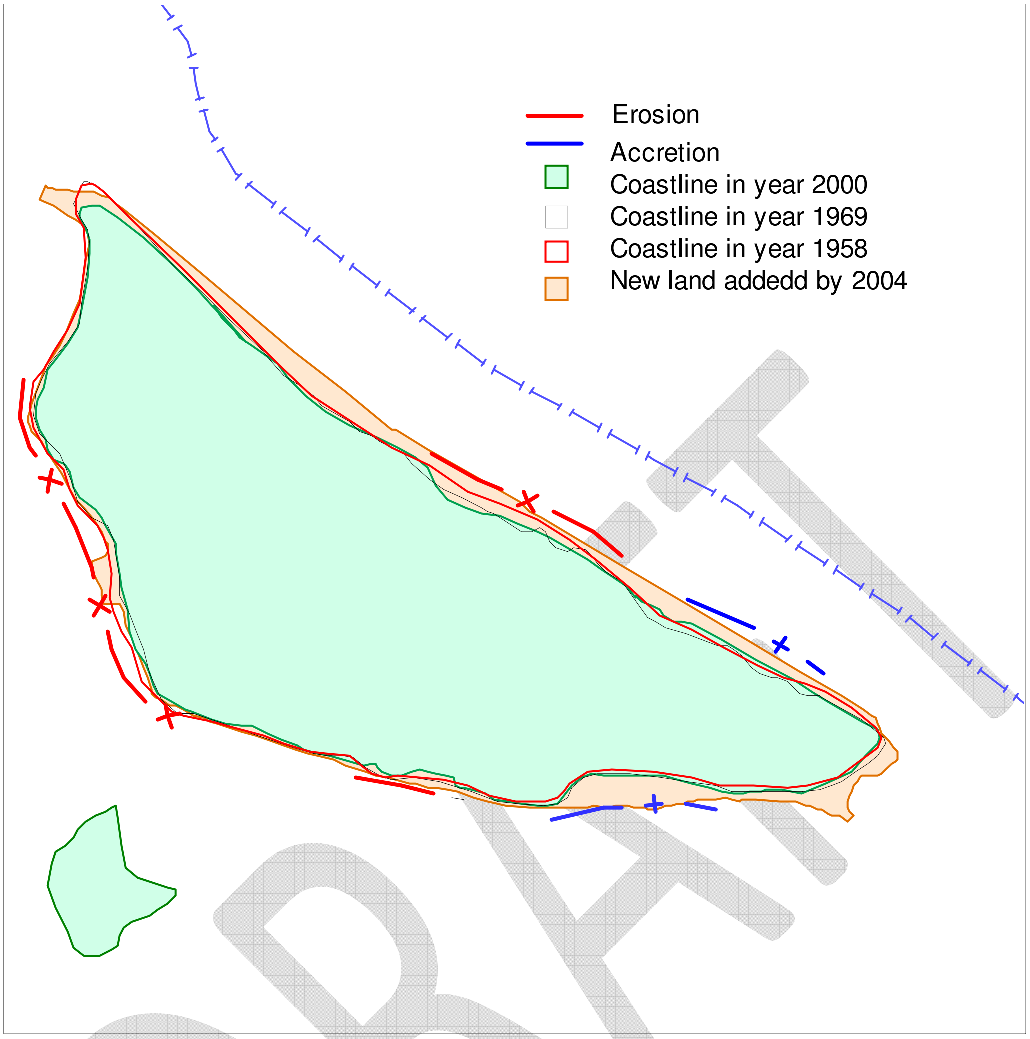

Figure 3.7 Historical erosion patterns.

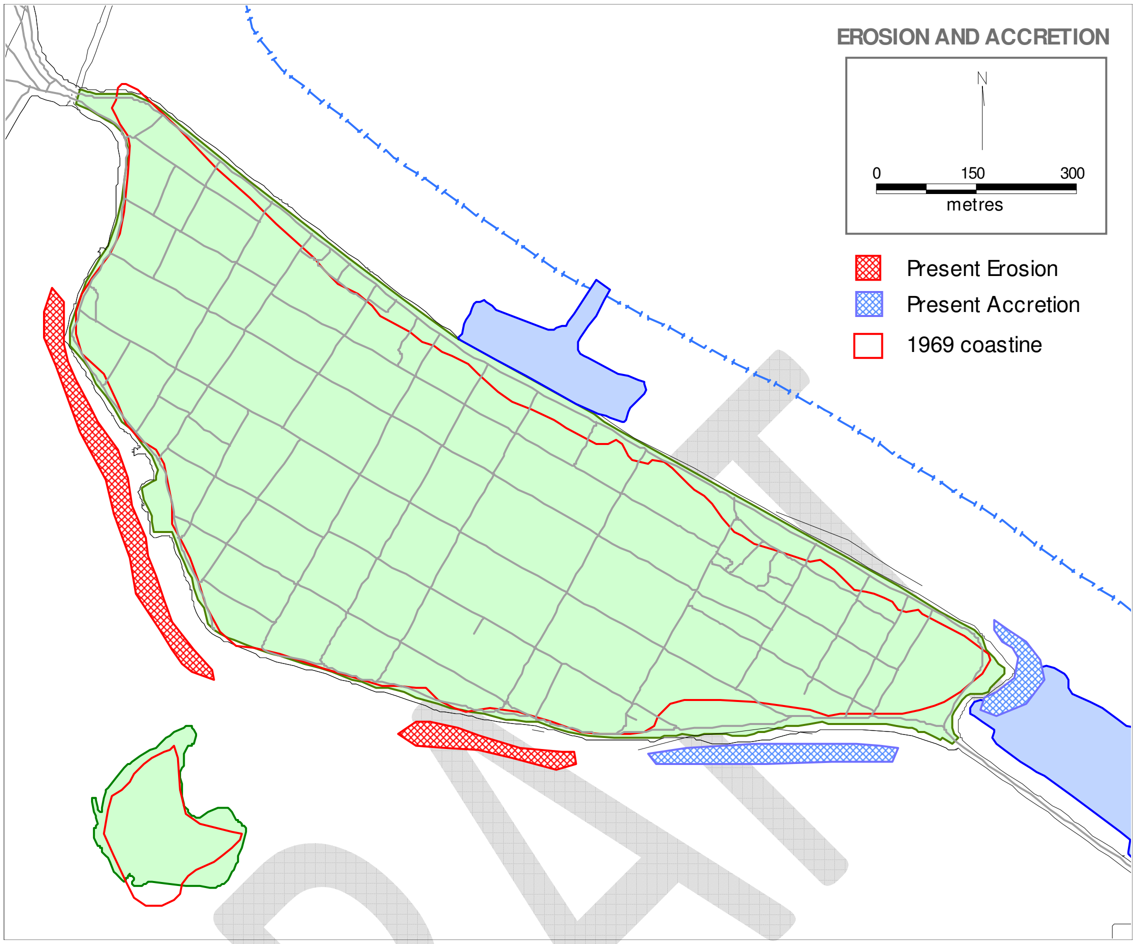

Figure 3.8 Present coastal erosion

3.1.3 Marine environment

General Reef Conditions

General historical changes to reef conditions were assessed anecdotally, through interviews with a number of fishermen. The general agreement amongst the interviewees was that the quality of reef areas on the lagoonward declined considerably over the past 50 years following the construction of causeways between Gan, Feydhoo and Maradhoo-Feydhoo. During this period lowering of coral cover and reduction in fish numbers, were reported. Since the causeways were replaced by bridges, fish abundance was reported to be increasing dramatically. Reef conditions on the oceanward reef line were reported to be in relatively good condition.

Patches of seagrass can be found around the island and has been prevalent since the 1960's. The construction of causeways in the 1960's caused the currents on the western reef flat to slow down, which favoured further growth of segrass. During the field survey a 0.5 m layer of seagrass was observed in the area of which 0.4 m comprised of dead matter.

3.1.4 Modifications to Natural Environment

Coastal Modifications

- Coastal infrastructure has been developed around Feydhoo Island. These include a harbour on the northeastern side (including dredged areas, breakwater and quay walls), causeways with bridges on both ends of the island and coastal protection along the entire lagoonward shoreline to protect the Addu Link Road. The road itself runs along the length of lagoonward shoreline.
- Land reclamation has been carried out around the island to create additional land for Addu Link Road development and to mitigate erosion. The entire lagoonward shoreline has been reclaimed to approximately 50m form the original shoreline. The western shoreline was replenished with sand following severe erosion in the north western and southwestern areas.
- Much of the sand used for the reclamation and the construction of the causeways were obtained from the lagoon between Gan and Feydhoo. Approximately 4.8ha of lagoon area was dredged up to 3m deep.
- Due to these changes to the coastal environment, there appears to be no alongshore transport on the lagoonward side of the island. There are seasonal changes to beach line on the oceanward coastline.

Terrestrial Modifications

- The terrestrial environment of the island has been considerably modified to the settlement expansion across the entire island.

- The coastal vegetation of the island has been all but removed, except for a thin strip of vegetation, which may not perform the functions of a coastal vegetation system against natural hazards.

- The vegetation on the island has been reduced considerably, but the loss of vegetation cover is considerably low compared to the other islands with similar population densities. The retention of vegetation can be partly owed to the settlement design and consideration given to the retention of major vegetation during housing construction project in the 1960's.

- The increase in rainfall related flooding on the low areas of the island prompted the authorities to undertake road maintenance activities, which primarily involved levelling and raising roads. This has led to some houses in the island to be lower than the road, especially in the low lying areas, causing flooding in these houses during heavy rainfall.

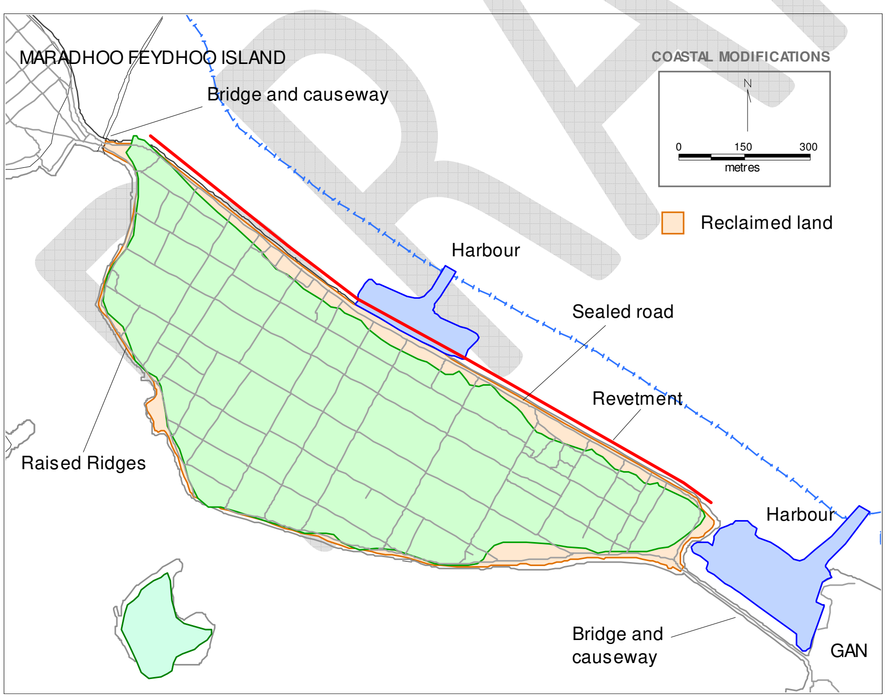

Figure 3.9 Coastal Modifications in Feydhoo.

3.2 Environmental mitigation against historical hazard events.

3.2.1 Natural Adaptation

It is difficult to ascertain past adaptation due to the intense modification brought to the island. It is highly likely that the natural adaptation process of the island was substantially altered due to the numerous development activities. The limitations continue to be a problem today and artificial adaptation is highly likely in the future.

3.2.1 Human Adaptation

Feydhoo Island has a number of mitigation measures undertaken to prevent impacts from natural hazards. The main measures on the lagoonward side include a foreshore breakwater to protect the Addu Link Road and nearshore breakwaters to protect harbour. The foreshore breakwaters were constructed specifically to mitigate potential coastal erosion hazards. A number of measures have also been undertaken to prevent rainfall related flooding. These include raising the roads and housing plots to prevent flooding, and construction of an artificial drainage system around the Addu Link Road to mitigate impacts of potential rainfall related flooding on the road. Mitigation measures on the oceanward side include beach replenishment and artificial ridges to prevent erosion and flooding.

3.3 Environmental vulnerabilities to natural hazards

3.3.1 Natural Vulnerabilities

Natural Vulnerabilities

- The low elevation generally makes the island susceptible to swell waves from the west and predicted sea level rise. In the past, parts of the island used to have low wetland areas known as *olhu* distributed across the island. This is believed to be a result of the low elevation and subsequent proximity to water table of the island. Today most houses have been raised with sand fills but the variations in topography remains.

- North-south orientation exposes the majority of the island's western coastline to flooding Hazards.
- Narrow width in southern half of Feydhoo exposes the area to flooding impacts compared to the rest of the island.
- Feydhoo Island is exposed to swell waves and monsoon generated waves from South West Indian Ocean (Naseer 2003) due to its location on the western rim of Addu Atoll.
- Feydhoo is located in a high rainfall zone. Combined with substantial lows in topography, the island is frequently exposed to rainfall related flooding.
- Feydhoo is also located in an earthquake prone zone due to its proximity to Carlsberg Ridge (UNDP, 2005).
- Reef width appears to play an important role increasing or decreasing the impacts of ocean induced wave activity. The present distance of Feydhoo Island coastline to reef edge may increase or decrease the exposure of the island to certain sea induced Hazards. Implications of the existing distance needs to be studied further to establish a concrete relationship.

3.3.2 Human induced vulnerabilities

- Past continuous road maintenance activities on the island to mitigate rainfall flooding has caused the road to be raised higher than the surrounding housing plots. As a result flooding in houses during heavy rainfall has been a major problem.
- The western coastline (oceanward side) has been reclaimed to mitigate coastal erosion. The extent of reclamation is quite small and is more comparable to beach replenishment. The reclamation process did not consider the existing sediment composition of the region and therefore may have hindered sediment transport alongshore during the short-term.
- For more than 25 years the coastal processes around Feydhoo was drastically reduced with the construction of a solid causeway joining Gan

and Maradhoo on south and north sides of the island. These modifications had major implications for the island building process of Feydhoo by reducing the flow of sediments around the island and causing excessive loss of sediments. The causeways have now been redeveloped and fitted with bridges. However, the new mechanism for water flow does not facilitate the crucial transport of sediments around the island. Hence, the natural adaptive capacity of Feydhoo to ocean induced hazards may have been considerably reduced due to a poorly functioning coastal system.

- The eastern coastline is now an artificial environment due to dredging activities, quay walls, breakwater and reclamation activities. The island building processes no longer function properly in this region.
- Waste dumping on the coastline reduces alters the coastal processes, pollutes the lagoon and may hinder coral growth if they reach the coral reefs.

4.4 Environmental assets to hazard mitigation

1. The location of Feydhoo on western rim of Seenu Atoll and close to the equator protects the island from direct exposure to the most damaging sea induced events such as tsunamis and storm surges. The relative lack of storm activities in the region and protection offered by the eastern rim of the atoll makes Feydhoo one the least exposed islands to devastating ocean induced natural hazards. It should however be noted that the maximum predicted tsunamis of 4.5m height may still inflict damage in Feydhoo due to its low elevation.
2. Strong vegetation cover within the island due the settlement design. However, certain trees which are vulnerable to strong winds (such as breadfruit trees) pose a hazard during such events.
3. The artificial ridge placed on the northwest side to mitigate erosion could perform the function of flood mitigation, although the width and height used may not be adequate to mitigate a major flooding event.

4.5 Predicted environmental impacts from natural hazards

The natural environment of Feydhoo and islands in Maldives archipelago in general appear to be resilient to most natural hazards. The impacts on island environments from major hazard events are usually short-term and insignificant in terms of the natural or geological timeframe. Natural timeframes are measured in 100's of years which provides ample time for an island to recover from major events such as tsunamis. The recovery of island environments, especially vegetation, ground water and geomorphologic features in tsunami effected islands like Laamu Gan provides evidence of such rapid recovery. Different aspects of the natural environment may differ in their recovery. Impacts on marine environment and coastal processes may take longer to recover as their natural development processes are slow. In comparison, impacts on terrestrial environment, such as vegetation and groundwater may be more rapid. However, the speed of recovery of all these aspects will be dependent on the prevailing climatic conditions.

The resilience of coral islands to impacts from long-term events, especially predicted sea level rise is more difficult to predict. On the one hand it is generally argued that the outlook for low lying coral island is 'catastrophic' under the predicted worst case scenarios of sea level rise (IPCC 1990; IPCC 2001), with the entire Maldives predicted to disappear in 150-200 years. On the other hand new research in Maldives suggests that 'contrary to most established commentaries on the precarious nature of atoll islands Maldivian islands have existed for 5000 yr, are morphologically resilient rather than fragile systems, and are expected to persist under current scenarios of future climate change and sea-level rise' (Kench, McLean et al. 2005). A number of prominent scientists have similar views to the latter (for example, Woodroffe (1993), Morner (1994)).

In this respect, it is plausible that Feydhoo may naturally adapt to rising sea level. There are two scenarios for geological impacts on Feydhoo. 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, based on the natural history of Maldives (based on findings by Kench et. al (2005), Woodroffe (1993)). 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 and beaches of Feydhoo (based on (Yamano 2000)). 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 Feydhoo, 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 (based on Pernetta and Sestini (1989), Woodroffe (1989), Kench and Cowell (2002)).

Hithadhoo has particular vulnerability to sea level rise due to the extensive amount of changes brought around the island, especially the oceanward side. These activities would have altered the natural processes required to adapt varying climatic conditions and may not function properly. Artificial structures may be required in Feydhoo to adapt sea level rise. The low elevations within the island may also be a concern as the low 'olhu' areas may become wetland areas with rising water table.

As noted earlier, environmental impacts from natural hazards will be apparent in the short-term and will appear as a major problem in inhabited islands due to a mismatch in assessment timeframes for natural and socio-economic impacts. The following table presents the short-term impacts from hazard event scenarios predicted for Feydhoo.

Hazard Scenario	**Probability at Location**	**Potential Major Environmental Impacts**
Tsunami (maximum scenario)		
▪ 2.5m	Low	• Salt water intrusion into island water lens causing long term or permanent damage to selected inland vegetation especially common backyard species such as mango and breadfruit trees • Contamination of ground water if the sewerage system is damaged or if liquid contaminants such as diesel and chemicals

Hazard Scenario	Probability at Location	Potential Major Environmental Impacts
		are leaked. • Minor-moderate damage to backyard crops • Moderate to major damage to coastal protection and island access infrastructure such as breakwaters and quay walls. • Short-medium term loss of soil productivity
Storm Surge *(based on UNDP, (2005))*		
▪ 0.60m (1.53m storm tide)	Very Low	• Minor to moderate damage to coastal protection infrastructure • Minor geomorphologic changes in the north western shoreline and lagoon
Strong Wind		
▪ 28-33 Knots	Very High	• Minor damage to very old and young fruit trees • Debris dispersion near waste sites. • Minor damage to open field crops
▪ 34-65 Knots	Low	• Moderate damage to vegetation with falling branches and occasionally whole trees • Debris dispersion near waste sites. • Moderate-high damage to open field crops • Minor changes to coastal ridges
▪ 65+ Knots	Very Low	• Widespread damage to inland vegetation • Debris dispersion near waste sites. • Minor changes to coastal ridges • Loss of backyard crops
Heavy rainfall		
▪ 187mm	Moderate	• Minor to moderate flooding in low areas, including roads and houses.
▪ 284mm	Low	• Widespread flooding across the island • Minor damage to backyard crops
Drought	Low	• Minor damage to backyard fruit trees
Earthquake	Low	• Minor-moderate geomorphologic changes to land and reef system.
Sea Level Rise by year 2100 (effects of single flood event)		
▪ Medium (0.41m)	Moderate	• Widespread flooding during high tides and surges. • Loss of land due to erosion. • Loss of coastal vegetation • Major changes to coastal geomorphology. • Saltwater intrusion into wetland areas and salinisation of ground water leading to water shortage and loss of flora and fauna. • Minor to moderate expansion of wetland areas

3.6 Findings and Recommendations for safe island development

At the time of this study, no detailed plans have been developed for establishing Feydhoo as a safe island. Presented below are some of the considerations that need to be made in developing Feydhoo as a safe island in the future.

- Feydhoo is exposed to rainfall related flooding hazards due to improper modification of topography and low areas within the island. A proper drainage system needs to be established in the island to reduce the exposure to rainfall related flooding.
- Reclamation of the western reef flat (oceanward side of the island) should consider the local and regional implications of extending the shoreline towards reef flat.
- Appropriate studies will need to be undertaken to understand the wave conditions of the area before the extent of reclamation, shape of coastline and topographic characteristics are considered.
- The existing standard designs for elevation, ridge and Environment Protection Zone (EPZ) for safe islands may need to be reviewed for this island.
- Reclamation is highly likely to cause damage to the outer reef due to its proximity and current land reclamation practices. This would reduce the defensive capacity of the reef system and expose Feydhoo to long term climate hazards. Appropriate reclamation practices need to be considered.
- The soil composition of a reclaimed area may need to be properly established. Soil in coral islands of Maldives has specific profiles which dictate the suitability vegetation and perhaps drainage.
- The elevation of the newly reclaimed area should be inline with the existing island topography or should consider establishing a functioning drainage system to mitigate flooding hazards resulting from modified topography, especially where the new reclamation joins the existing island.

- The flat elevation of a +1.4m above MSL for the reclaimed land may not be the most efficient topography for a functioning drainage system. The costs involved in establishing and maintaining an artificial drainage system without the assistance of natural slopes may be considerably higher.
- The function of the low drainage areas in the proposed Environment Protection Zone (EPZ) needs to be reviewed. Given the limited topographic variations within the newly proposed reclaimed land, the proposed 0.1m variation and the 25m width in the drainage area may not have the desired effects on flood control. The function of a low area near the high ridges has best been performed in other islands if the width of the area is large and if an appropriate variation in height between the low area and the high areas exists. Hence it is recommended that a review of the function and characteristics of the floodway, reconsideration of the flat elevation of +1.4m for the island and reconsideration of the 0.1m variation for the floodway be undertaken.
- Based on the 9 islands studied in this project, it has been observed that strong coastal vegetation is amongst most reliable natural defences of an island at times of ocean induced flooding, strong winds and against coastal erosion. The design of EPZ zone needs to be reviewed to consider the important characteristics of coastal vegetation system that is required to be replicated in the safe island design. The width of the vegetation belt, the composition and layering of plant species and vegetation density needs to be specifically looked into, if the desired outcome from the EPZ is to replicate the coastal vegetation function of a natural system. Based on our observations, the proposed width of coastal vegetation may not be appropriate for reducing certain ocean induced hazard exposures. The timing of vegetation establishment also needs to be clearly identified in the safe island development plan. .

- A re-vegetation plan needs to be incorporated into the safe island development plan to ensure minimal exposure to strong winds and future climate change related temperature increases.
- The EPZ zones needs to be extended around the island.

3.7 Limitations and recommendations for further study

- The main limitation of this study is the lack of time to undertake more empirical and detailed assessments of the island. The consequence of the short time limit is the semi-empirical mode of assessment and the generalised nature of findings.
- The lack of existing survey data on critical characteristics of the island and reef, such as topography and bathymetry data, and the lack of long term survey data such as that of wave on current data, limits the amount of empirical assessments that could be done within the short timeframe.
- The topographic data used in this study shows the variations along three main roads of the island. Such a limited survey will not capture all the low and high areas of the island. Hence, the hazard zones identified may be incomplete due to this limitation.
- This study however is a major contribution to the risk assessment of safe islands. It has highlighted several leads in risk assessment and areas to concentrate on future more detailed assessment of safe islands. This study has also highlighted some of the limitations in existing safe island concept and possible ways to go about finding solutions to enhance the concept. In this sense, this study is the foundation for further detailed risk assessment of safe islands.
- There is a time scale mismatch between environmental changes and socio-economic developments. While we project environmental changes for the next 100 years, the longest period that a detailed socio-economic scenario is credible is about 10 years.

- Uncertainties in climatic predictions, especially those related Sea Level Rise and Sea Surface Temperature increases. It is predicted that intensity and frequency of storms will increase in the India Ocean with the predicted climate change, but the extent is unclear. The predictions that can be used in this study are based on specific assumptions which may or may not be realized.

- The following data and assessments need to be included in future detailed environmental risk assessment of safe islands.
    - A topographic and bathymetric survey for all assessment islands prior to the risk assessment. The survey should be at least at 0.5m resolution for land and 1.0m in water.
    - Coral reef conditions data of the 'house reef' including live coral cover, fish abundance and coral growth rates.
    - At least a years data on island coastal processes in selected locations of Maldives including sediment movement patterns, shoreline changes, current data and wave data.
    - Detailed GIS basemaps for the assessment islands.
    - Coastal change, flood risk and climate change risk modeling using GIS.
    - Quantitative hydrological impact assessment.
    - Coral reef surveys
    - Wave run-up modelling on reef flats and on land for gravity waves and surges.

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4. Structural vulnerability and impacts

S. Feydhoo is predominantly exposed to rainfall and swell wave/surge floods. Historically, it has experienced frequent flooding events that have caused substantial losses. In particular, a rainfall flooding event may result in minor damage to property, but its accumulative damage/impacts can be significant. In the context of accelerated sea-level rise, flooding will be further enhanced in the future. Swell wave/surge flood can penetrate inland up to 100 m inland along most of the length of eastern shoreline. The events may cause severe damages to most backyard crops in the flooding zone. More severe swell wave flooding events, with a water depth of about 0.5 m, reached up to 400 m inland was recorded prior to 1990.

4.1 House vulnerability

Around 200 houses were identified as vulnerable, which accounts for 30% of the total houses on the island. Among the vulnerable houses identified, most houses are vulnerable due to their plinth level lower than their adjacent road surface, whereas houses with poor physical conditions account for less than 10% of the total houses and houses with poor protection 5% only.

4.1.1 House vulnerability

The vulnerability of houses is dominantly attributed to non-structural factor - plinth level lower than the adjacent road surface (Fig. 4.1). Of 195 vulnerable houses identified, more than 80% are found located at an elevation lower than their adjacent road surface, which was improperly elevated to protect from road flooding on the island. In addition, a good number of houses, accounting for around 17% of the total vulnerable houses identified, are found relatively close to shoreline and without proper protection, either effective coastal vegetation or strong boundary wall. In contrast, structurally-weak houses make up to 26% of the total vulnerable houses only. Non-structural aspects of the house vulnerability may have been enhancing the intensity of rainfall flooding events, i.e. the prolonged duration and water depth of floods, over the past decades.

4.1.2 Vulnerable houses

The vulnerable houses of the targeted island can be divided into 3 major groups: houses with low plinth, weak houses with low plinth, and houses with poor protection (Fig. 4.2). As shown in Fig. 4.2, around 60% of the vulnerable houses may be exposed to rainfall flood due to their low elevation relative to their adjacent road surface. About 20% of the vulnerable houses are exposed to rainfall floods due to their low elevation and may be vulnerable due to their poor physical conditions. In addition, there are a good amount of vulnerable houses with poor protection exposed to the ocean-originated floods on the southeastern coast of the island, accounting for 15% of the total vulnerable houses. Coastal vegetation on the southwestern coast is relatively sparse and hardly plays a role in mitigating ocean-originated hazards.

Purely physically-weak houses account for 5% only and the houses that are poorly protected and with a low elevation and poor physical conditions are found to be 3% of the total vulnerable houses.

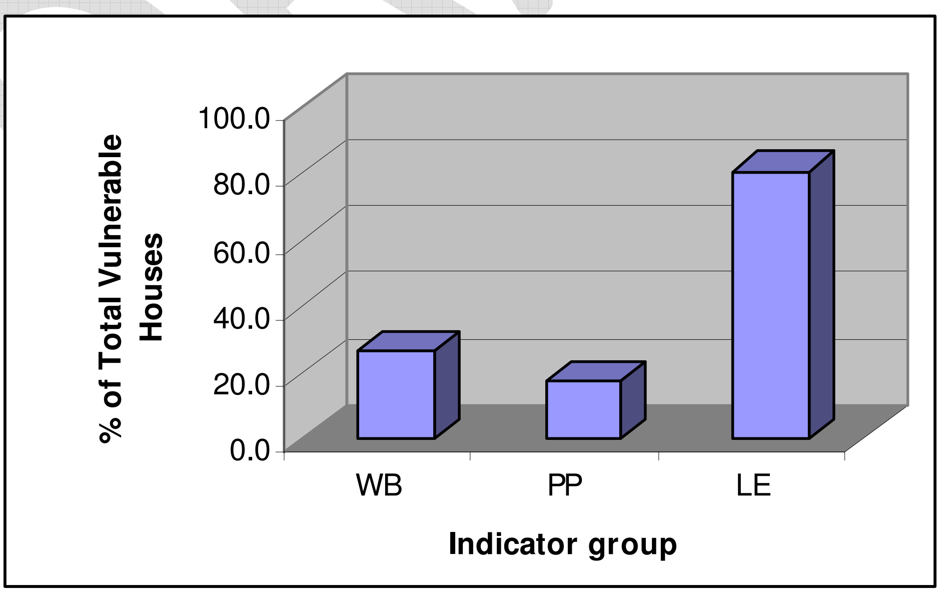

Fig. 4.1 Type of house vulnerability.

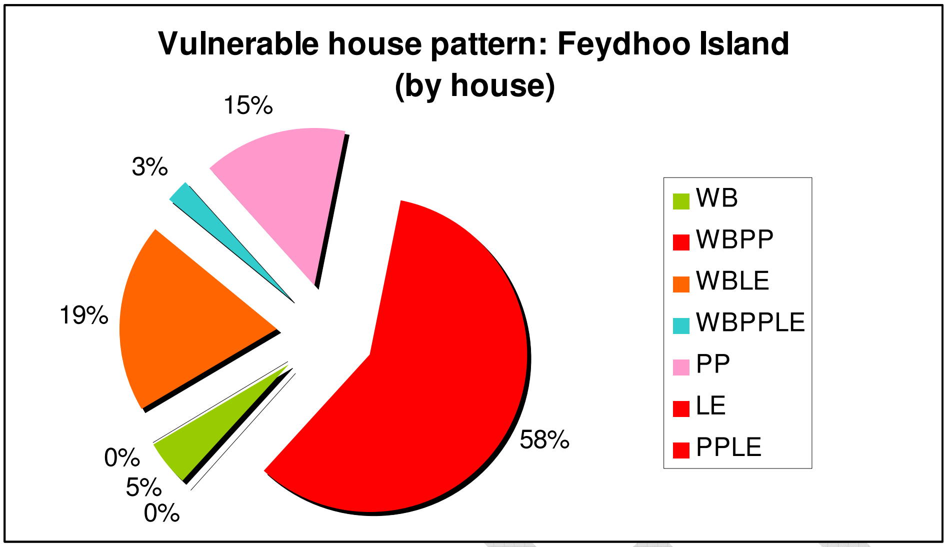

Fig. 4.2 Distribution of vulnerable houses.

4.2 Houses at risk

4.2.1 Rainfall flood

More than 50% of the island's populated area is subjected to rainfall floods (**Fig. 4.3, left**). Water depth can be up to 0.4 m and last up to 3 – 5 days. As shown in Table 4.1, more than 340 houses are exposed to rainfall floods, of which 117 are vulnerable due to their poor physical conditions and low plinth. During flooding, around 31 vulnerable houses may be subjected to slight damage and 86 houses will have their contents affected. In addition**,** backyard crops, such as bananas, chillies etc., may be subjected to severe damage as well.

4.2.2 Swell wave/surge flood

As shown in **Fig. 4.3 right**, around 190 houses are exposed to swell wave floods in total, of which 70 are vulnerable due to their poor physical conditions, proximity to shoreline and poor protection. Given a inundation of 0.5 m, around 20 vulnerable houses may be subjected to slight damage and 50 houses will have their contents affected.

4.2.3 Earthquake

Feydhoo Island is located in Seismic Hazard Zone 5 and exposed to a GPA of 0.18-0.32, according to RMSI (2006). In case an earthquake occurs, around 52 houses may be subjected to a slight to moderate damage. In worse case, some houses may be completely destroyed during an earthquake.

Table 4.1 Houses at risk on S. Feydhoo.

Hazard Type		Exposed houses		Vulnerable Houses		Potential Damage							
						Serious		Moderate		Slight		Content	
		#	%	#	%	#	%	#	%	#	%	#	%
Flood	***TS***	-	-	-	-	-	-	-	-	-	-	-	-
	W/S	192	34.4%	70	36.5%	0	0	0	0	19	9.9%	173	90.1%
	RF	341	61.1%	117	34.3%	0	0	0	0	31	9.1%	310	90.9%
Earthquake		***558***	***100***	52	9.3%								
Wind		-	-	-	-	-	-	-	-	-	-	-	-
Erosion													

4.3 Critical facilities at risk

Most critical facilities of the targeted island, such as schools, mosques, and island office, are located in the rainfall flood-prone area, whereas only a few in the ocean-originated flood-prone area (Table 4.2, Fig. 4.4 and 4.5). Physically, most buildings of critical facilities are not vulnerable to any flood hazards prevailing on the island and subjected to little damage during flooding, given the water depth of 0.5. All facility buildings have strong foundations and are well structured, with an age of less than 10 years. However, contents of some critical facility buildings may be affected and subjected to some degree of damage or loss, due to the low elevation relative to their adjacent roads. For example, the plinth level of schools, i.e. KPS pre-school and Feydhoo school, is just 10-30 cm above their adjacent road surface and entrances just at road level. A moderate heavy rainfall can cause flooding in school yards and disturb school activities. Under some circumstances, schools may be closed for days. Located in the northeastern low-lying area of the island, on the other hand, buildings of Cable TV and power distribution stations may be subjected to frequent floods with the plinths at road level. However, most mosques on the island may not be affected by most flooding events because of their high plinth level up to 40-60 cm, except for some that are relatively close to southwestern shoreline and subjected to higher floods.

Therefore, critical facilities on Feydhoo Island are at low risk, although located in hazard-prone areas.

Table 4.2 Critical facilities at risk on S. Feydhoo Island.

Hazard type		**Critical facilities**		**Potential damage/loss**	
		Exposed	Vulnerable	Physical damage	Monetary value
Flood	Tsunami	-	-	-	-
	Wave/Surge	2 mosques, 1 wataniya site	None	Content-affected	n.a.
	Rainfall	3 mosques, 2 schools, 1 island office, 1 hospital, and 1 media center	None	Content-affected	n.a.
Earthquake		All facilities	n.a.	n.a.	n.a.
Wind		-	-	-	-
Erosion		-	-	-	-

4.4 Functioning impacts

Although causing no physical damage to most critical facility buildings, major flooding events may impact the functioning of some critical facilities. Some potential functional impacts are summarized in Table 4.3. As one of the serious functioning impacts, the sewerage system on the island may fail to operate days during flooding, whereas school activities may be interrupted. In addition, the short circuit of distribution stations may lead to a widespread disruption of power distribution.

4.5 Recommendations for risk reduction

According to the physical vulnerability and impacts in the previous sections, the following options are recommended for risk reduction of S. Feydhoo:

- Retrofit the vulnerable houses identified by raising their plinth to a proper level or improving their drainage systems.
- Avoid maintaining the roads of the island by raising their surface.
- Both major flooding hazards prevailing on the island are mitigatable. Rainfall floods can be reduced by improving the drainage systems of the island. The building of the road on the north coast might block the island's groundwater flow system and have enhanced rainfall flooding. On the other hand, setting up an EPZ with a ridge of proper height on the south coast can mitigate flooding induced by swell wave/surge significantly.

Table 4.3 Potential functioning impact matrix

Function	Flood			Earthquake	Wind
	Tsunami	Wave/surge	Rainfall		

Administration[1)]					
Health care					
Education			A few days		
Religion					
Sanitation[3)]		Island-wise, 3 -5 days			
Water supply					
Power supply		days			
Transportation					
Communication[2)]					

Note: 1) Administration including routine community management, police, court, fire fighting; 2) Communication refers to telecommunication and TV; 3) Sanitation issues caused by failure of sewerage system and waste disposal.

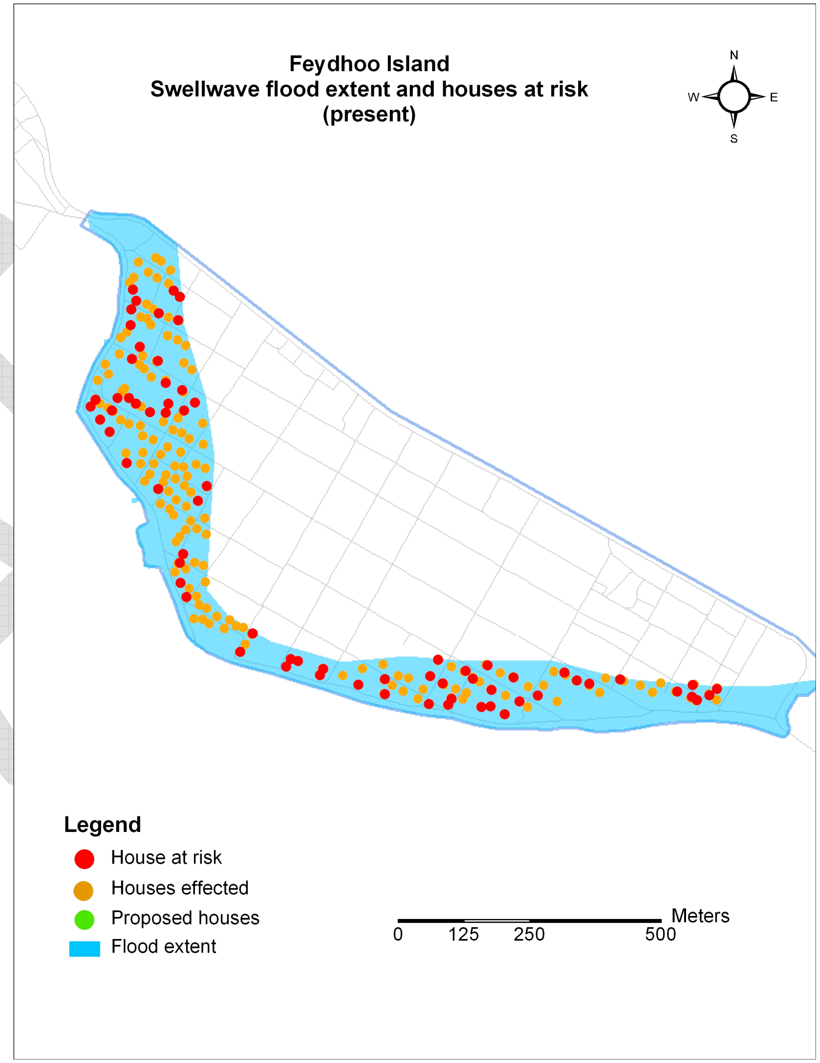

Fig. 4.3 Houses at risk associated with rainfall floods (left) and swell wave/surge floods (right).

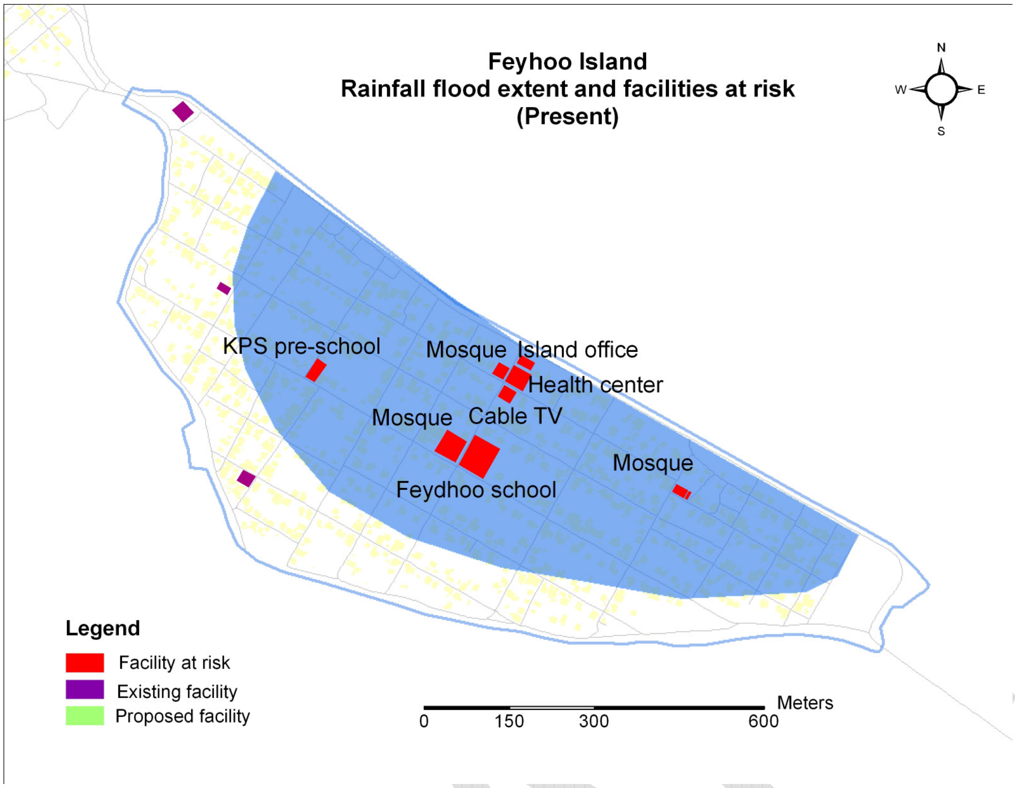

Fig.45.4 Critical facilities at risk associated with rainfall floods.

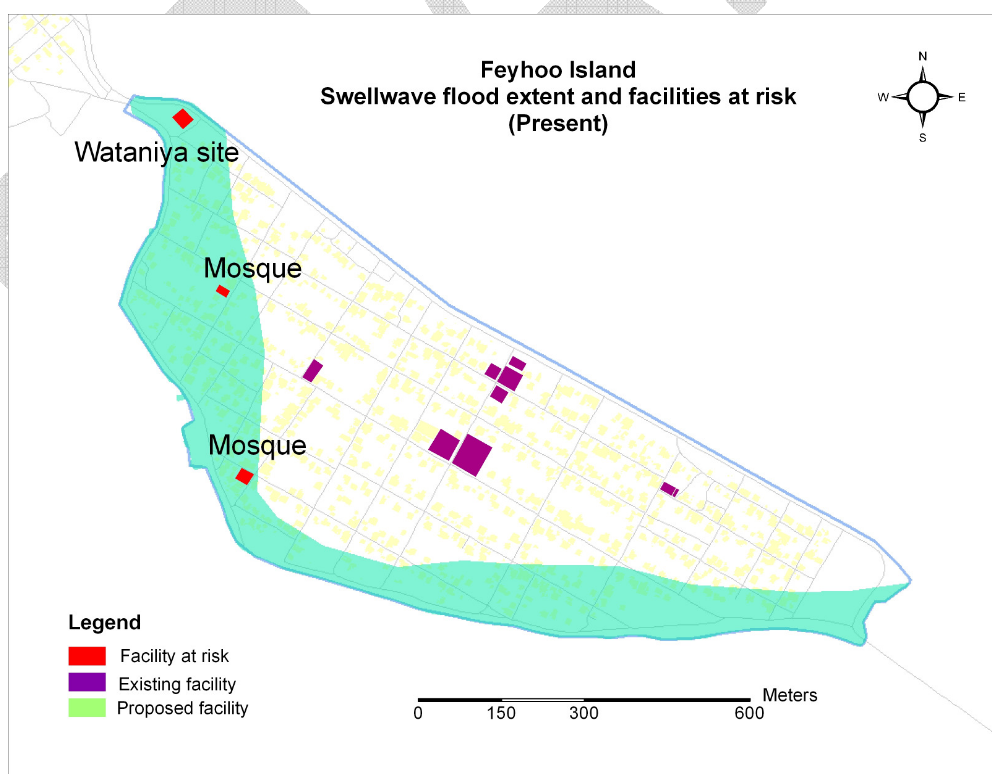

Fig. 4.5 Critical facilities at risk associated with swell wave/surge floods.

Detailed Island Risk Assessment in Maldives

Volume III: Detailed Island Reports

Sh. Funadhoo – Part 1

DIRAM team
Disaster Risk Management Programme
UNDP Maldives

December 2007

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1. Geographic background

1.1 Location

Funadhoo is located on the eastern rim of Thiladhunmathi Atoll, at approximately 73° 17' 26"E and 6° 09' 08" N, about 220 km from the nations capital Male' and 68 km from the nearest airport, Hanimaadhoo (Fig. 1.1). Funadhoo is the Atoll Capital of Shaviyani Atoll, amongst a group of 15 inhabited islands. It's nearest inhabited islands are Lhaimagu (4 km), Maaungoodhoo (12 km), and Milandhoo (16 km). Due to its location on the eastern rim and the higher latitude, Funadhoo is exposed to NE monsoon generated winds and waves, and occasional storm activities originating from the cyclone belt of Indian Ocean (UNDP, 2005).

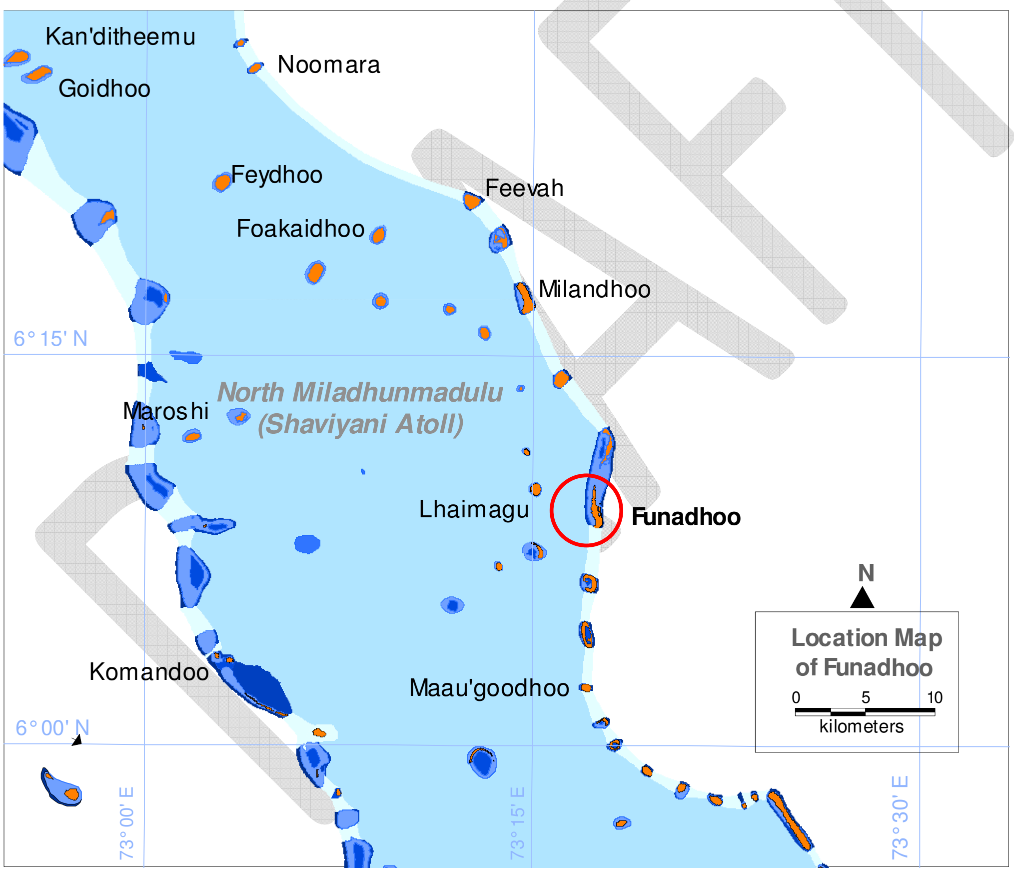

Fig. 1.1 Location map of Funadhoo.

1.2 Physical environment

Funadhoo is a fairly large island with a length of 3000m and a width of 585 m at its widest point. The total surface area of the island is 84.5 Ha (0.85 km^2). The reef of Funadhoo Island medium sized with a surface area of 992 Ha (9.92 km^2) stretching to 7 km. However, it is the largest reef system within a good stretch of 120 km along the eastern rim of Thiladhunmathi Atoll. The reef also hosts the uninhabited island of Farukolhufushi. Both the islands are located on either ends of the reef system, with Funadhoo being located at the southern end. The island distance to oceanward reef edge varies from 50 m to 640 m. The lagoonward reef edge distance varies from 320 m to 520 m. The settlement is located approximately 300 m from the oceanward reef line.

Funadhoo Island appears to be a relatively stable and constantly growing island. During the last 50 years the island has grown in size including the natural merging of a separate island north of the Funadhoo. The island continues to grow northward, probably due to the abundant supply of sediments from both the oceanward and lagoonward lagoon. Funadhoo seems to be exposed to wave action from both the oceanward side and to a smaller extent on the lagoonward side. This may be due to the relative strength of waves generated within the atoll during SW monsoon owing to the fetch distance and lack of obstruction for wave activity. The lagoonward reef flat showed features similar to an oceanward reef flat including presence of a small algal ridge and sediment grooves. Hence, it is highly likely that the island building and stabilisation processes operate during both seasons as opposed to a single season found in some islands of Maldives (base on Ali (2000)).

Funadhoo coastal environment features a strip of vegetated land close to the coastline followed by a lagoon area between the main island. The lagoon area has become a mangrove habitat over the years. The strip of land functions similar to that of a barrier island absorbing wave energy reaching over the eastern reef line, protecting the shoreline of the main island. This feature is also a crucial defence against sea induced natural hazards, including tsunamis. Funadhoo Island and the region in general are known to be exposed to severe storm activities. Remnants of such events can be seen on the oceanward reef flat where large block of reef have been over turned. The coastal geomorphology of the narrow strip of land gives further evidence of a high energy zone. Due to the history of storm activity in the region, it is highly likely that the strip of land is also a result of series of such events. Hence, the exposure of the southern half of the island to ocean induced natural hazard seems to comparatively much lower than the northern half. Fortunately majority of the present settlement is protected by the existing natural defence systems.

The natural environment of Funadhoo is in relatively good condition perhaps owing to the recentness of human settlement on the island and the low population density. Much of the northern and southern half of the island is in a good natural condition and coastal modifications have so far been limited to a single area on the western coastline. The terrestrial environment has however had a number of changes brought to them including significant reduction in the vegetation cover in the settlement area and continued modification to key vegetation areas around the island for settlement purposes. The mangrove areas and other wetland areas in the island also appear to be under increasing stress from the need for settlement expansion.

2. Natural hazards

This section provides the assessment of natural hazard exposure in Sh.Funadhoo Island. A severe event history is reconstructed and the main natural hazards are discussed in detail. The final two sections provide the hazard scenarios and hazard zone maps which are used by the other components of this study as a major input.

2.1 Historic events

Analysis of historic events in Funadhoo was limited due the unavailability of historical records prior to 1990's. Moreover, the island was officially inhabited only during 1968, making Funadhoo one of the newest inhabited islands in Maldives. Settlement did not begin until the 1980's and 1990's and even then population site was relatively small. Hence, we found it difficult to find elderly on the island with adequate historical knowledge on Fundhoo.

The incomplete records show that Funadhoo has exposure to natural hazards has been very limited. An attempt at reconstructing the natural hazard event history was made. As highlighted in methodology section, this was achieved using field interviews and historical records review. Specific attention was given to evaluating events in neighbouring inhabited islands to identify large scale events which could have affected Funadhoo. Table 2.1 below lists the known events and a summary of their impacts on the island.

The historic hazardous events for Funadhoo showed that the island faced the following multiple hazards: 1) windstorms, 2) swell surges, 3) storm surges 4) Udha, and 5) tsunami. Impacts and frequency of these events vary significantly. Flooding caused by rainfall and udha events is the most commonly occurring hazard events. Windstorms have also been reported as frequent especially during the southwest monsoon. Swell surges have been reported but very infrequent and as having little impact.

Table 2.1 Known historic hazard events of Funadhoo.

Metrological hazard	Impacts	Dates of the recorded events
Flooding caused by Heavy rainfall	There have been no records of any rain related major flooding event on the island.	
Flooding caused by swell surges	There have been no records of wave surge related flooding on the island. Nonetheless, geormorphic evidence on the	

	southern end of the island suggests that there have been occasions of wave overwash events in the past at the southern end of the island. However, flooding caused by these events are not expected to have reached beyond 50 – 100m from the shoreline.	
Windstorms	No major events recorded, but frequent low intensity events reported by elders.	
Droughts	No major event have been reported	
Earthquake	No major event have been reported	
Tsunami	There has been only one known event. This event flooded the northeren end of the island that is unprotected by the barrier island like mangrove spit extending from the southern end of the island to almost halfway to the north of the island. The tsunami was reported to have a runup height of approximately 1.5m from the ground level. This event however did not cause major damage to any of the houses on the island. There was some damage caused to the harbour quaywall. The flood waters killed backyard crops in the flooded areas.	26^{th} Dec 2004

2.2 Major hazards

Based on the historical records, meteorological records, field assessment and Risk Assessment Report of Maldives (UNDP, 2006) the following meteorological, oceanic and geological hazards have been identified for Funadhoo.

- Windstorms
- Swell waves and udha
- Storm Surges
- Tsunami
- Heavy rainfall (flooding)
- Earthquakes
- Climate Change

2.2.1 Swell waves and udha

Studies on wave patterns around the country reports a predominantly southwest to a southerly direction for swell waves (Kench et. al (2006), Young (1999), DHI(1999) and Binnie Black & Veatch (2000)). Being located on the eastern rim of Thiladhunmathi Atoll, and on the eastern line of atolls with the archipelago, Funadhoo is relatively protected from predominant swell waves in the region. However, the island is still exposed to abnormal swell waves originating from intense storms in the southern hemisphere between 73°E and 130°E longitude. Waves generated from such abnormal events could travel against the predominant swell propagation patterns in the Indian Ocean (Goda, 1998), causing flooding on the eastern rim island of Maldives (Fig. 2.2).

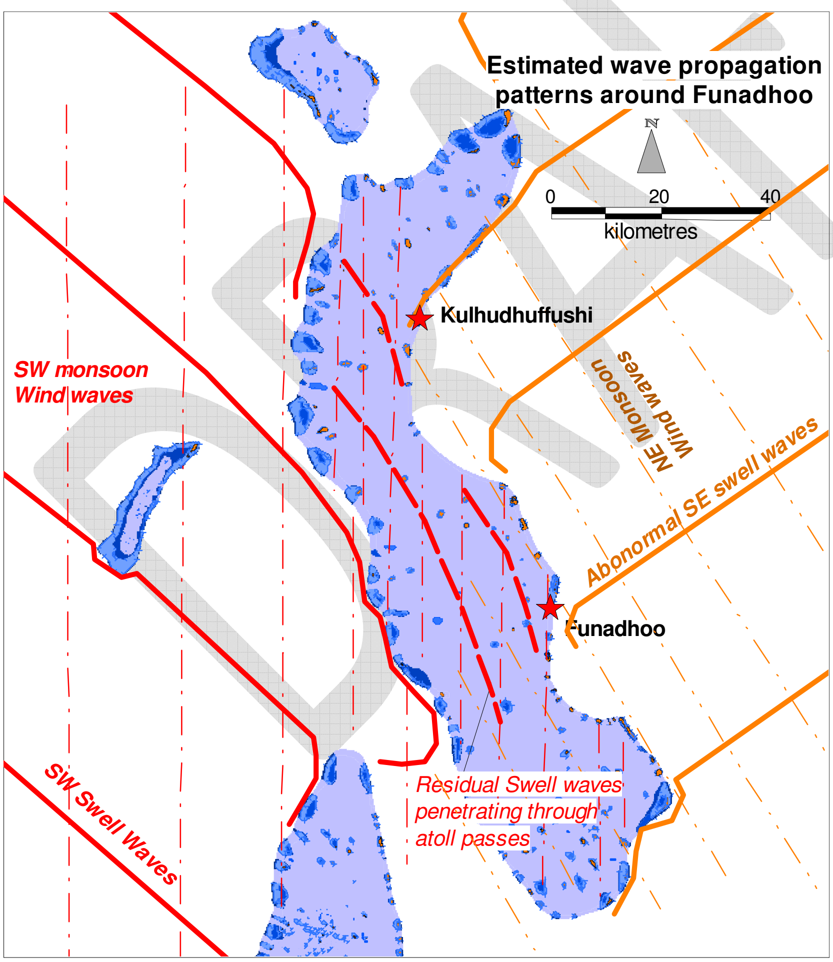

Fig. 2.2 Estimated (predominant) wave propagation patterns around Funadhoo.

It is also probable that abnormal swell waves approaching from a south westerly direction could penetrate through the western reef passes and reach the western shoreline of Funadhoo. Impact so such waves are estimated to be low due to the partial protection offered by Raa Atoll and due to the geophysical characteristics of its western coastline. The swell wave event of May 2007 which affected a number of western and eastern rim, failed to affect Funadhoo due to these characteristics.

The occurrence of abnormal swell waves on Funadhoo reef flat is dependent on a number of factors such as the wave height, location of the original storm event with in the South Indian Ocean, tide levels and reef geometry. Fig 2.3 illustrates the estimated wave propagation and behaviour patterns around Funadhoo. The orientation of the island in a N to S direction could facilitate wave run-up on the island from oceanward side. Similarly the presence of a channel south of the island may cause waves to refract around the island and flood along the southwestern shoreline.

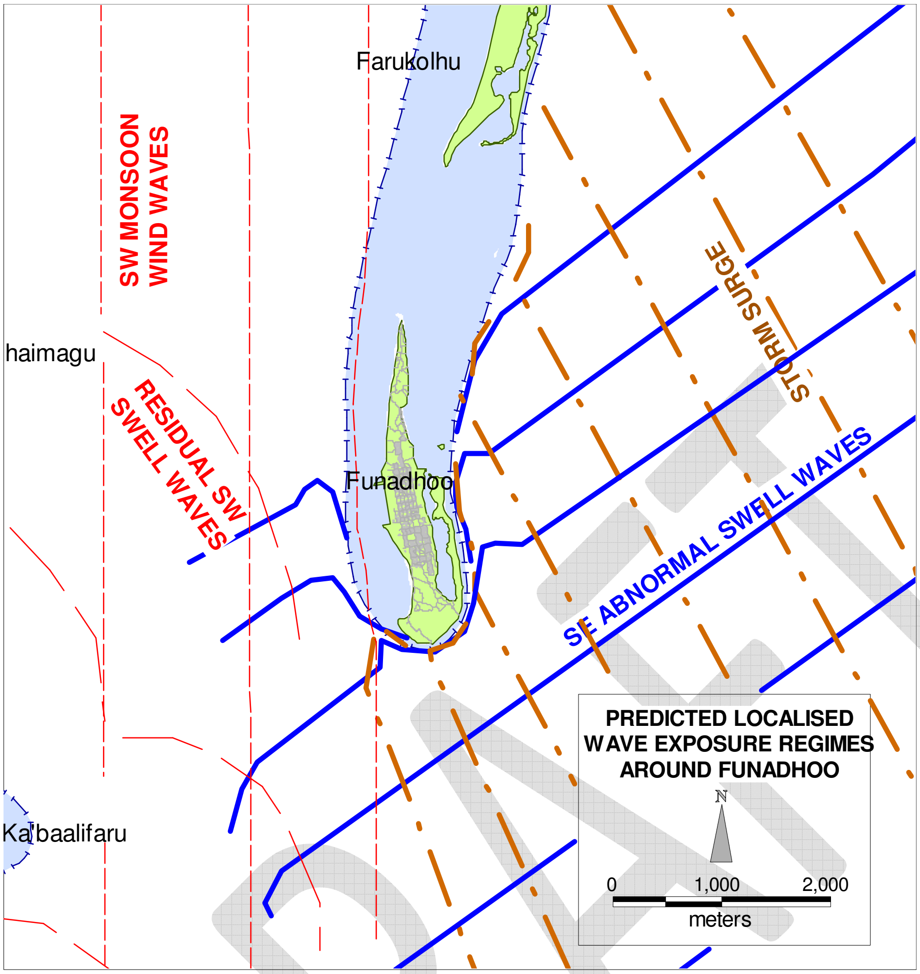

Fig. 2.3 Estimated behaviour of swell waves around Funadhoo.

It is often difficult to predict occurrence of such abnormal events as there is only a small probability, even within storm events of similar magnitude, to produce waves capable of flooding islands. Moreover, based on the current data available it is impossible to link the swell incidents to the known cyclonic events in the Indian Ocean. Detailed assessment using synoptic charts of the South Indian Ocean corresponding to major flooding events are required to delineate any specific trends and exposure thresholds for Funadhoo from southern swells. Unfortunately this study does not have the resources and time to undertake such an assessment but is strongly recommended for any future detailed assessments.

Unlike the swell waves, both the oceanward and lagoonward coastlines of Funadhoo are exposed to monsoonal wind waves. During the NE monsoon between November and March, the eastern (oceanward) coastline may receive strong waves. Wave studies done in similar settings have reported wave heights less than 2.0 m and with wave periods of 2-4 seconds. The west coast is exposed to wind generated waves during SW monsoon, originating within the atoll due to the 26 km fetch and usually with wave heights less than 0.5 m.

Udha

Flooding is also known to be caused in Funadhoo by a gravity wave phenomenon known as *Udha*. These events are common throughout Maldives and especially the southern atolls of Maldives during the SW monsoon.

The intensity and impacts of *udha* waves are usually very low with flooding occurring within 5-10m of coastline at less than 0.3m height above the ground. It is not expected to be a major hazard in the short-term. Moreover, the geophysical characteristics of the western shoreline, namely the comparatively high atoll lagoonward ridge could help prevent low intensity *udha* events.

The origins of the *udha* waves as yet remain scientifically untested. No specific research has been published on the phenomenon and has locally been accepted as resulting from local wind waves generated during the onset of southwest monsoon season. The relationship has probably been derived due to the annual occurrence of the events during the months of May or June. It is highly probable that waves originate as swell waves from the Southern Indian Ocean and is further fuelled by the onset of southwest monsoon during May. The timing of these events coincides as May marks the beginning of southern winter and the onset of southwest monsoon. The concurrent existence of these two forms of gravity waves during the southwest monsoon is confirmed by Kench et. al (2006) and DHI(1999). It is also questionable whether the southwest monsoon winds waves alone could cause flooding in islands since the peak tide levels on average are low during May, June and July. However, the strongest mean wind speeds in Hanimaadhoo has been observed for May, June and July (Naseer, 2003). This issue needs to be further explored based on long term wave and climatological data of the Indian Ocean before any specific conclusions can be made. However if the relationship does exists, this phenomena could prove to be a major hazard in the face of climate change since the intensity of southern Indian Ocean winter storms is expected to increase.

Storm Surges

The Disaster Risk Assessment report of 2006 (UNDP, 2006), reported that Funadhoo was located in a moderate storm surge hazard zone with probable maximum event reaching 0.6m above MSL or 1.53m with a storm tide. The combined historical records of nearby islands report major storms in the past which have caused extensive damages to inhabited island and changes to coastal features. The most notable events were reported as December 1918 and January 1955 events, which caused extensive damages and flooding in the northern region of Maldives. Furthermore, there is geophysical evidence on the eastern coastline of Funadhoo and nearby islands that points significant wave events, most likely caused by a single or a series of storm surges. The location of Funadhoo in the northern half of Maldives and close to the northern Indian ocean cyclone belt further increases the probability of surge events.

Similar to the swell waves, the occurrence of any storm surge on Funadhoo reef flat is dependent on a number of factors such as the wave height, location of the original storm event within the Indian Ocean, tide levels and reef geometry.

Future swell event prediction

Due to its location, abnormal swell related flooding events should be considered a serious hazard for Funadhoo. The island is expected to be exposed to storm waves mainly from south and south east as shown in the map (Fig. 2.4). Events beyond this arch may not influence the island due to the protection offered by surrounding atolls.

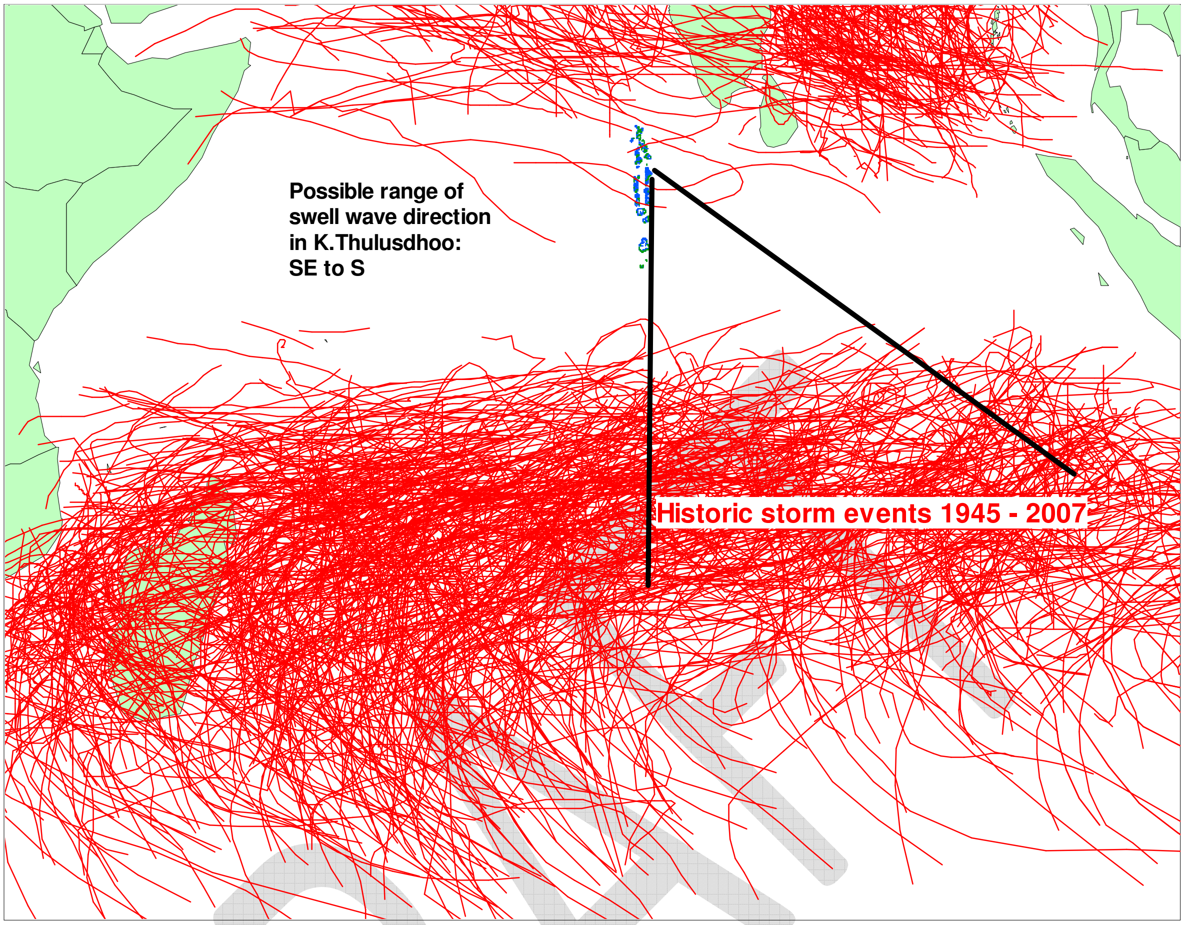

Fig. 2.4 Historical storm tracks (1945-2007) in Indian Ocean and possible direction of swell waves for Funadhoo Island.

Due to the unpredictability of these swell events and lack of research into their impacts on Maldives, right now it is impossible to forecast the probability of swell hazard event and their intensities. Assessment in Funadhoo is further limited by the lack of historical events. However, since the hazard exposure scenario is critical for this study a tentative exposure scenario has been estimated for the island. There is a probability of major swell events occurring every 15 years with probable water heights above 0.5 m and every 10 years with probable water heights of 0.3 m. Events with water heights less than 0.2 m are likely to occur annually especially as Udha.

The timing of swell events is expected to be predominantly between November and June, based on historic events and storm event patterns (see Table 2.2).

Table 2.2 Variation of Severe storm events in South Indian Ocean between 1999 & 2003 (source: (Buckley and Leslie (2004)).

	Severe wind event variation	
Longitude band	**Winter**	**Summer**
30 °E to 39 °E	12.5	17
40 °E to 49 °E	7.5	10
50 °E to 59 °E	7.5	26
60 °E to 69 °E	6	14
70 °E to 79 °E	6	6
80 °E to 89 °E	12	6
90 °E to 99 °E	12	8
100 °E to 109 °E	8	3
110 °E to 119 °E	15	7
120 °E to 130 °E	13.5	2

The probability of storm surges occurring in Funadhoo is low but should be considered to belong to the group of islands most exposed storm surges in Maldives. Fig. 2.5 shows storm tracts in the regions and potential storm surge direction for Funadhoo.

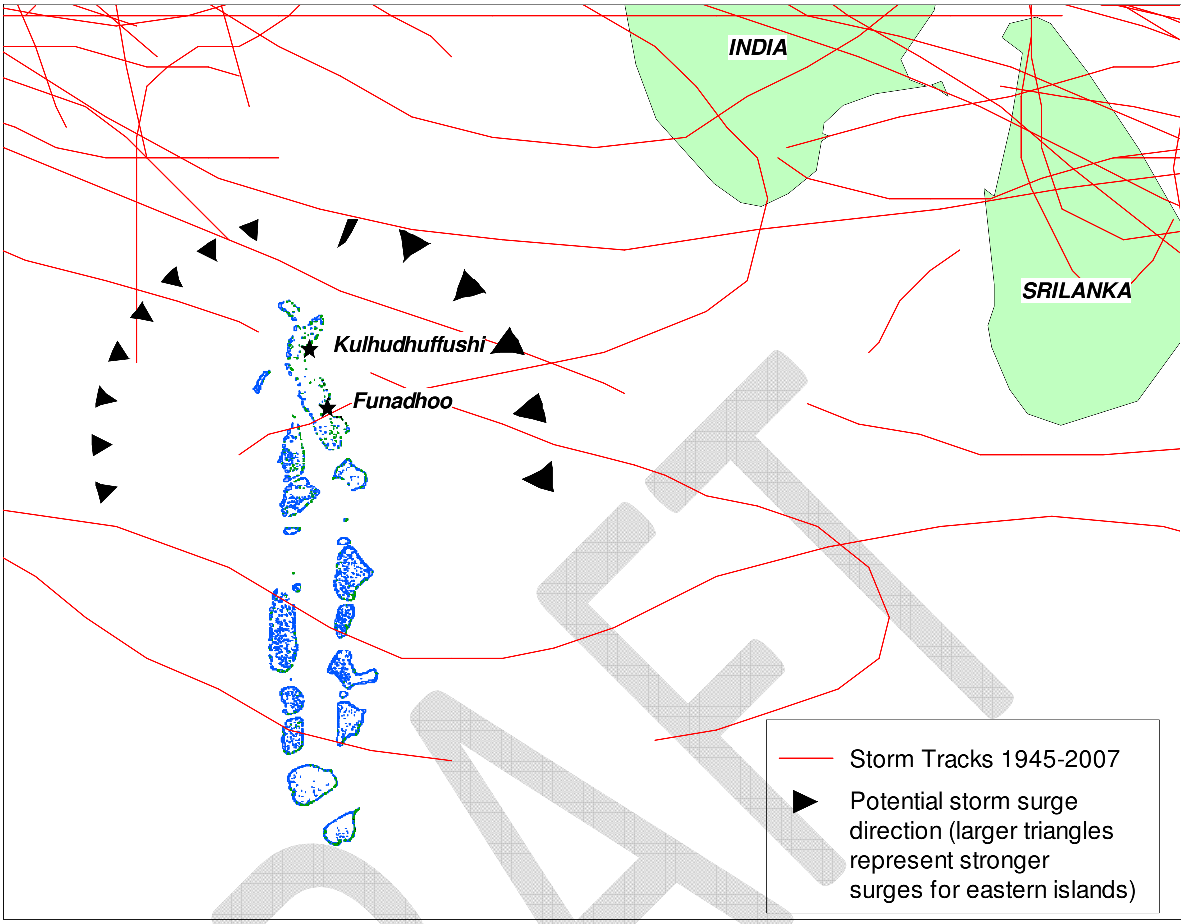

Fig. 2.5 Historical storm tracks (1945-2007) in Indian Ocean and possible direction of storm surges for Funadhoo Island

The reclamation plans for Funadhoo were incomplete at the time of this study. The existing drafts show land reclamation on the eastern half of the island. After this development the reef flat width will be reduced to approximately 250m. This reduction will increase the percentage of occurrence of gravity wave energy on the reef flat to approximately 30% and therefore increasing the probability of flooding caused by surges by 20%. Similarly the impact of flooding will increase relative to encroachment of settlement to coastal areas, even if the probability of flood events remains constant. Potential increase in frequency and intensity of flood events are also probable with climate change and is addressed in a latter section.

2.2.2 Heavy Rainfall

The rainfall pattern in the Maldives is largely controlled by the Indian Ocean monsoons. Generally the NE monsoon is dryer than the SW monsoon. Rainfall data from the three main meteorological stations, HDh Hanimaadhoo, K. Hulhule and S Gan shows an increasing average rainfall from the northern regions to the southern regions of the country (Fig. 2.6). The average rainfall at HDh Hanimadhoo is approximately 481 mm lower than that at S Gan.

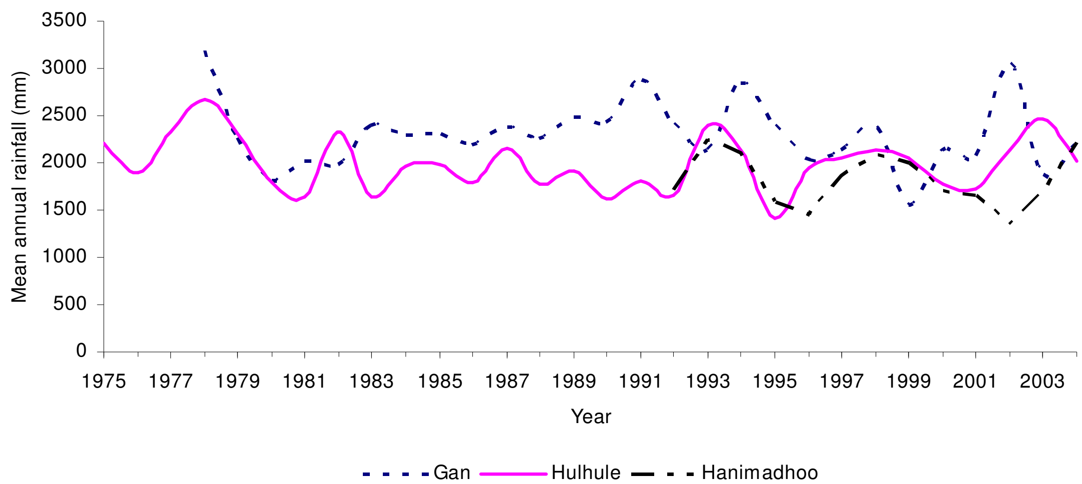

Fig 2.6 Map showing the mean annual rainfall across the Maldives archipelago.

The closest meteorological station is the Hanimadhoo Meterological Centre located 67km north of Funadho . Unfortunately this study does not have access to daily data for Hanimaadhoo.

The mean annual rainfall in Hanimaadhoo is 1818.7 mm with a Standard Deviation of 316.4 mm and the mean monthly rainfall is 151.5mm. Rainfall varies throughout the year with mean highest rainfall during May to August and lowest between January to March (See Fig. 2.7).

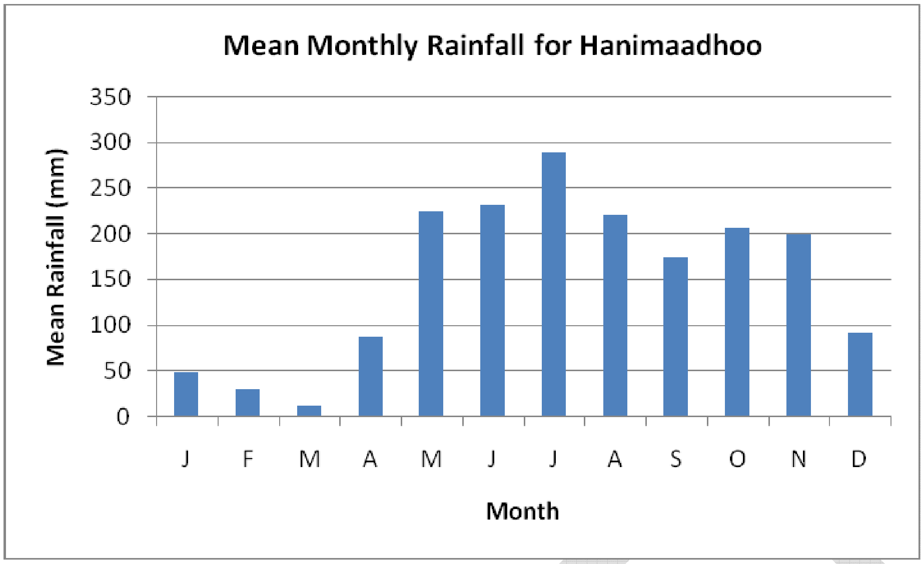

Fig 2.7 Mean Monthly Rainfall in Hanimaadhoo (1992 to 2004).

Historic records of Funadhoo indicates that this island is has not experienced any major flooding incidents in the past. However, interviews with locals revealed localised levels of flooding in sections of the island, most notably around the reclaimed harbour area, new housing areas and close to southern wetlands. These areas correspond to topographic and artificially blocked drainage areas of the island. The relatively narrow width of the island and the arch shaped topography (as opposed to saucer shaped topography) facilitates quick drainage of surface runoff into the lagoon. Minimal topographic variations were observed along the topographic survey lines (see section of physical environment), except near the mangrove and wetland areas on the east. Heavy rainfall related flooding has been reported to reach up to 0.15 m above the ground level around the harbour and southern parts of the island. The combination of low rainfall levels in the north, favourable topographic conditions and relatively less modification to terrestrial environment has so far helped to keep Funadhoo less exposed to rainfall related flooding.

It would be possible to identify threshold levels for heavy rainfall for a single day that could cause flooding in Funadhoo, through observation of historic daily rainfall data. Unfortunately, we were unable to acquire complete daily historical data from Hanimaadhoo. Available limited severe weather reports published on the Department of Meteorology website is summarised below in Table 2.3. The values shows that Hanimaadhoo received a maximum precipitation of 95mm for a 24 hour period, between 2001 and 2007, on 23 July 2007 (DoM, 2005). Based on interviews with locals none of the events listed in the table caused any significant flooding. However, they did report that events of 2002 and 2007 caused minor flooding in various parts of the island. Due to the distance between Hanimaadhoo and Funadhoo, it is plausible that rainfall variations could occur between the two sites on the given dates. Hence, unless rainfall data is collected closer or on Funadhoo Island it may difficult to identify the exact threshold levels for rainfall related flooding in Funadhoo.

Table 2.3 Maximum precipitation for 24 hour periods between 2001 and 2007 at Hanimaadhoo Weather Station

Year	Maximum Rainfall	Date
2001	89.4	13 may
2002	81.0	31 July
2003	72.9	12 June
2004	79.0	2 May
2005	62.9	29 May
2006	71.0	8 September
2007	95.0	23 July

The probable maximum precipitations predicted for Hanimaadhoo by UNDP (2006) are shown in Table 2.4.

Table 2.4 Probable Maximum Precipitation for various Return periods in Hanimaadhoo Weather Station .

Station	Return Period			
	50 year	100 year	200 year	500 year
Hanimaadhoo	141.5	151.8	162.1	175.6

Based on the field observations and correlations with severe weather reports from Department of Meteorology the following threshold levels were identified for flooding. These figures must be revised once historical daily rainfall data becomes available.

Quite often heavy rainfall is associated with multiple hazards especially strong winds and possible swell waves. It is therefore likely that a major rainfall event could inflict far more damages those identified in Table 2.5.

Table 2.5 Threshold levels for rainfall related flooding in Funadhoo

Threshold level (daily rainfall)	Impact
70mm	Puddles on road, flooding in low houses,

	occasional minor damage to household goods
110mm	Moderate flooding in low houses; minor damage to household items, damage to household crops, temporary (minor to Moderate) disruptions to socio-economic functions for less than 24 hours
150m	Widespread flooding on roads and low lying areas. Moderate damage to household goods, disruptions to socio-economic functions for more than 24 hours.
175+mm	Widespread flooding on roads, low areas and houses. Moderate damage to household goods, sewerage network, backyard crops, disruption to socio economic functions for more than 24 hours, gullies created along shoreline, possible damage to road and harbour infrastructure.

2.2.3 Wind storms and cyclones

Maldives being located within the equatorial region of the Indian Ocean is generally free from cyclonic activity. There have only been a few cyclonic strength depressions that have tracked through the Maldives (UNDP, 2006). However, Funadhoo falls within the most hazardous zone for cyclone related hazards in Maldives and has a maximum predicted cyclonic wind speeds of 96.8 Kts (see Fig. 2.8). There are no records of such high wind intensity resulting from a cyclone for the northern region in the recent past, although a number of gale force winds have been recorded due to low depressions and South west monsoon in the region. Winds exceeding 35 knots (gale to strong gale winds) were common occurrences during south west monsoon over the last 7 years. In general the wind speeds are higher in the north than the central and southern areas during SW monsoon (DoM, 2005). Peak wind speeds in Hanimaadhoo between 2006 and 2007 showed 10 events above gale to strong gale winds (above 35 Knots) and within them 6 events were above 40 knots. During the past 7 years the highest peak wind speed was recorded as 46 knots on 21 June 2007.

In addition historical records show that the northern region was hit by a number of major storms which combined high wind speeds, heavy rainfall and strong seas. As noted above, the most significant two events occurred during 1918 and 1955 both which led to extensive damage and abandonment of a number of inhabited islands.

Moreover, interviews with the locals have indicated that the island has been affected by numerous wind storms. Unfortunately records have not been kept for these events, especially their dates or its impacts. Lack of information is compounded by the fact that island was one of the youngest inhabited islands in Maldives. However events of 22 June 2003, 12 July 2003, 22 June 2006 and 21 June 2007 have been reported to have caused moderate to extensive damage to crops, vegetation and housing structures. All these events had wind speeds over 40 knots.

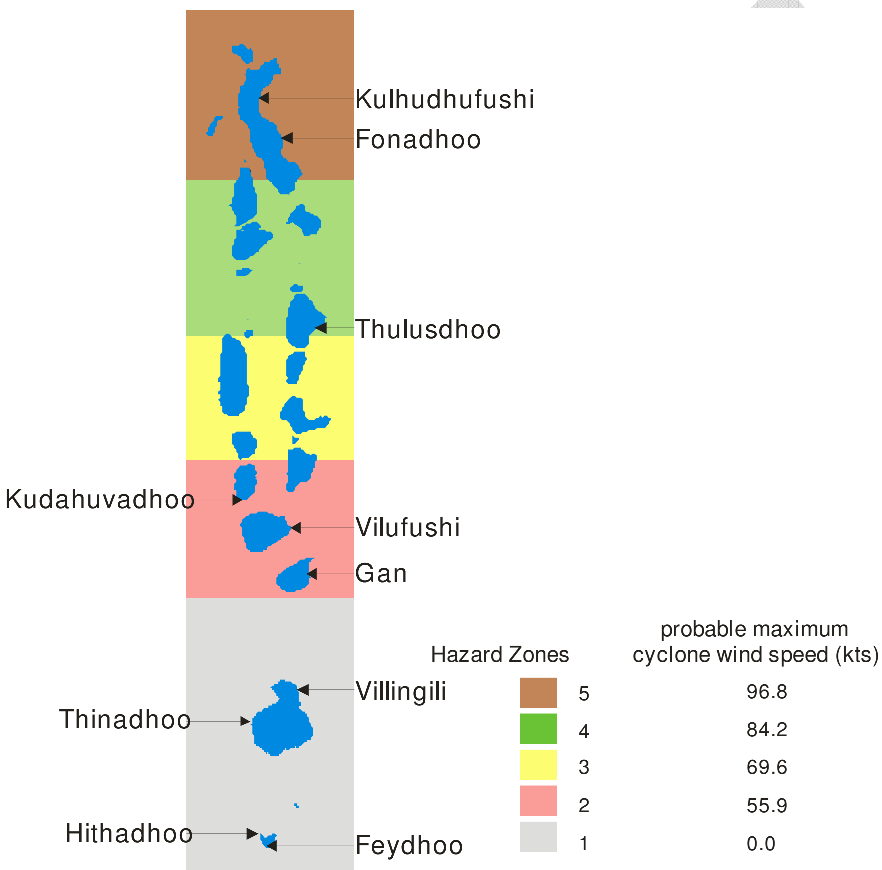

Fig 2.8 Cyclone hazard zones of the Maldives as defined by UNDP (2006).

Hence, wind speeds close to near gale winds (see Table 2.6) have caused moderate damage to property and trees on the island. The settlement area within the island is fairly sparsely vegetated owing to the recentness of the settlement and the practice of clearing entire tracts of land during housing construction undertaken by bulk contracts. During the time of survey the entire tract planned for new housing development has been cleared including mature trees. Moreover, the remaining large trees within the settlement contain a large proportion of wind vulnerable species, especially breadfruit trees *(Artocarpus altilis).*

In order to perform a probability analysis of strong wind and threshold levels for damage, daily wind data is crucial. However, such data was unavailable for this study.

Table 2.6 Beaufort scale and the categorisation of wind speeds.

Beau- fort No	Description	Cyclone category	Average wind speed (Knots)	Average wind speed (kilometres per hour)	Specifications for estimating speed over land
0	Calm		Less than 1	less than 1	Calm, smoke rises vertically.
1	Light Air		1 -3	1 - 5	Direction of wind shown by smoke drift, but not by wind vanes.
2	Light breeze		4 - 6	6 - 11	Wind felt on face; leaves rustle; ordinary wind vane moved by wind.
3	Gentle breeze		7 - 10	12 - 19	Leaves and small twigs in constant motion; wind extends light flag.
4	Moderate breeze		11 - 16	20 - 28	Raises dust and loose paper; small branches moved.
5	Fresh breeze		17 -21	29 - 38	Small trees in leaf begin to sway; crested wavelets form on inland waters.
6	Strong breeze		22 - 27	39 - 49	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.
7	Near gale		28 - 33	50 - 61	Whole trees in motion; inconvenience felt when walking against the wind.
8	Gale	Category 1	34 - 40	62 - 74	Breaks twigs off trees; generally impedes progress.
9	Strong gale	Category 1	41 - 47	75 - 88	Slight structural damage occurs (chimney pots and slates removed).
10	Storm	Category 2	48 - 55	89 - 102	Seldom experienced inland; trees uprooted; considerable structural damage occurs.
11	Violent storm	Category 2	56 - 63	103 - 117	Very rarely experienced; accompanied by widespread damage.
12	Hurricane	Category 3,4,5	64 and over	118 and over	Severe and extensive damage.

The threshold levels for damage (Table 2.7) are predicted based on interviews with locals and housing structural assessments provided by risk assessment report (UNDP, 2006).

Table 2.7 Threshold levels for wind damage based on interviews with locals and available meteorological data

Wind speeds	Impact
1-10 knots	No Damage
11 – 16 knots	No Damage
17 – 21 knots	Light damage to trees and crops
22 – 28 knots	Breaking branches and minor damage to open crops, some weak roofs damaged
28 – 33 knots	Minor damage to open crops, minor to moderate damage to vegetation, probability of damage to property due to falling trees.
34 - 40 knots	Minor to Moderate to major damage to houses, crops and trees
40+ Knots	Moderate to Major damage to houses, trees falling, crops damaged

2.2.4 Tsunami

UNDP (2006) reported the region where Funadhoo is geographically located to be a very high tsunami hazard zone. According to official reports 20% of the island was flooded during the 2004 tsunami. Flooding occurred mainly from the southern and eastern side and penetrated more than 200m inland. Flood waters also approached from the lagoonward side due to refraction and the tsunami related tide surge. However the tsunami of December 2004 did not have a major impact on Funadhoo. Flooding was very much limited to the northern end of the island, much of which remains uninhabited. The relatively little flooding in the settlement area is believed to be a result of the presence of a barrier island system on the eastern side of the main island. The nearest tide gauge at Hanimaadhoo Airport recorded the tsunami of December 2004 as a wave of height 2.5 m within the atoll lagoon (Fig. 2.9). The maximum water level recorded at Hanimaadhoo tide gauge (1.83 m +MSL) indicated the rise in water level induced by the tsunami within the atoll lagoon of the northern atolls. The flooding caused by the tsunami on the northern part of the island was not only from the island's oceanward side but there was also reports of flooding from the lagoonward side of the island.

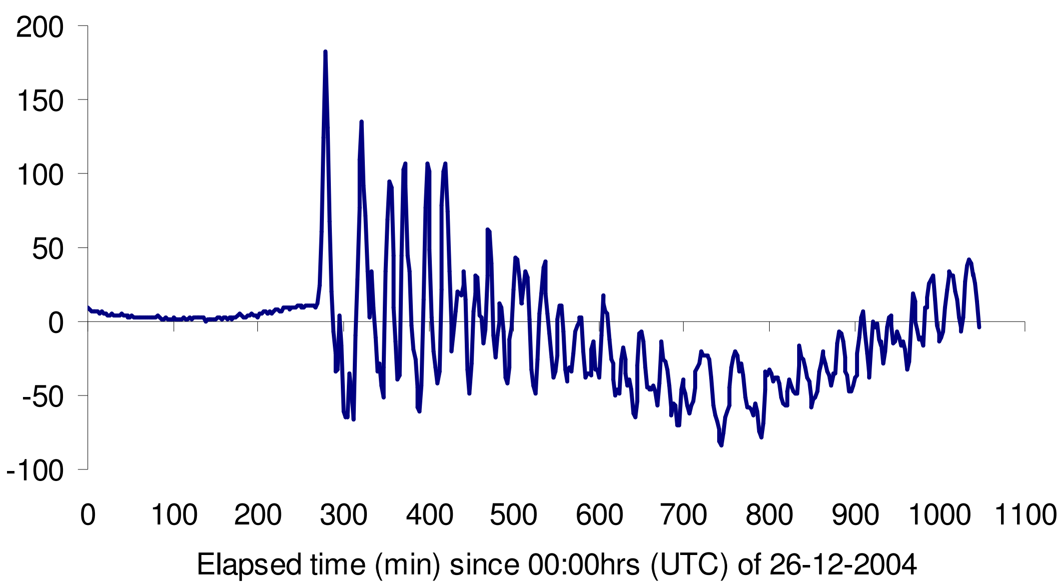

Fig 2.9 Water level recordings from the tide gauge at Hanimaadhoo indicating the wave height of tsunami 2004

There were a few structural damages close to the north eastern coastline. These range from partial damage to loss of personal property. Other damages include salinisation of groundwater for a week in the northern half, damage to vegetation, backyard crops and sewerage network.

The tsunami run-up height on the eastern shoreline was reported at 2.0 m reducing to 0.1m around 200 m inland. Tsunami induced tide levels caused flooding from within the atoll lagoon around the harbour area and along the northern half of the island. This is the result of relatively lower or absence of a coastal ridge n these area. Fig. 2.10 below shows the topographic profile in the southern part of the island where the coastal ridge is comparatively higher. Tide related Flood waters failed to reach beyond the ridges along this profile.

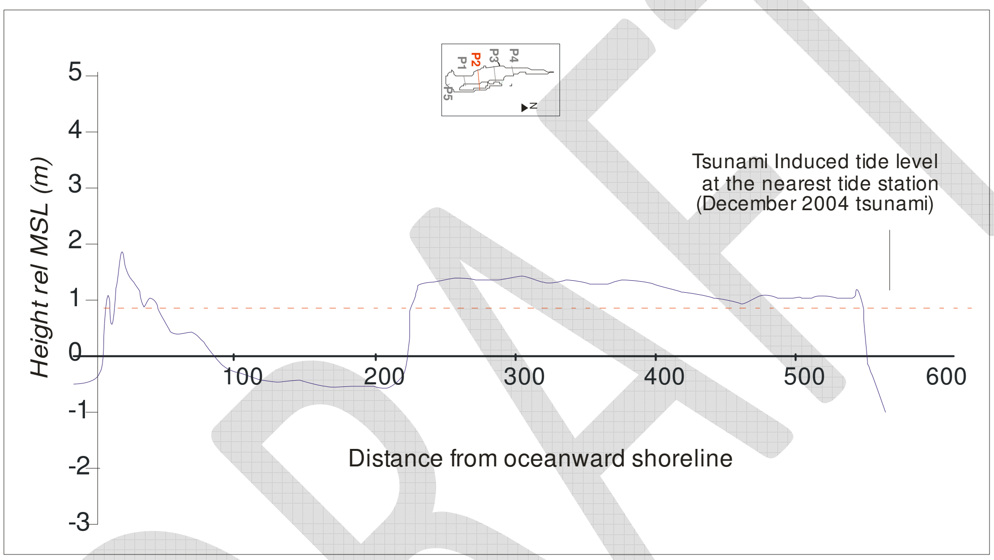

Fig. 2.10 Maximum water level within the atoll lagoon induced by tsunami of December 2004 plotted across the island profile of Funadhoo topographic profile.

The predicted probable maximum tsunami wave height for the area where Funadhoo is located is 4.5 m (UNDP, 2006). Examination of the flooding that will be caused by a wave run-up of 4.5 m for the island of Funadhoo indicates that such a magnitude wave will flood at least 300- 400 m inland from the oceanward shoreline. The first 50 – 100 m from the shoreline will be a severely destructive zone (Fig 2.11). The theoretical tsunami flood decay curve was plotted for a wave that is applied only for the direct wave from the oceanward side of the island. However, it is well understood that the tsunami wave will also travel into the atoll lagoon which will cause the water level in the atoll lagoon to rise. Rising of water level in the atoll lagoon would also cause flooding of the island from the lagoonward side of the island, if the atoll lagoon water level rises above the height of the island. Hence the entire island is predicted to be flooded with a maximum predicted tsunami.

The eastern and south eastern side of the island is characterised by the presence of a strip of land separated by a mangrove area. This strip acts as a barrier island against abnormal wave events. The geophysical characteristics of the barrier island make it capable of reducing the impacts of a severe intensity tsunamis and swell waves. However the protection is only offered to the existing settlement area and the northern area is completely exposed to such severe events.

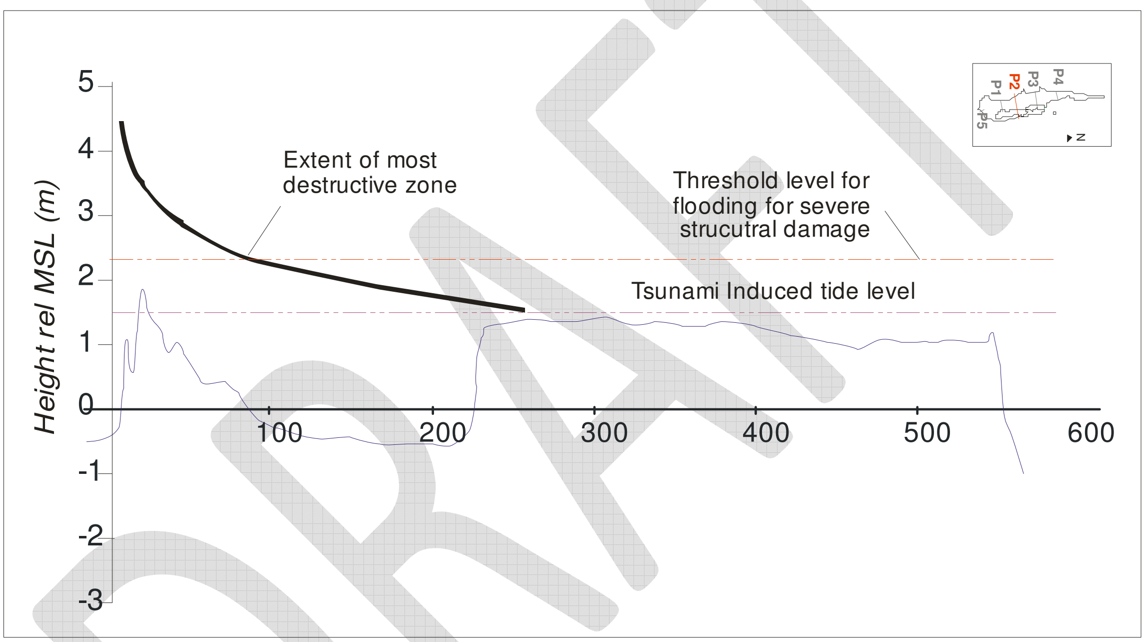

Fig 2.11 Tsunami related flooding predicted for Funadhoo based upon theoretical flood decay curve and the maximum probable tsunami wave height.

2.2.5 Earthquakes

There hasn't been any major earthquake related incident recorded in the history of Funadhoo or even Maldives. However, there have been a number of anecdotally reported tremors around the country.

The Disaster Risk Assessment Report (UNDP 2006) highlighted that Male' Atoll is geographically located in the lowest seismic hazard zone of the entire country. According to the report the rate of decay of peak ground acceleration (PGA) for the zone

1 in which Funadhoo is located has a value less than 0.04 for a 475 years return period (see Table 2.7). PGA values provided in the report have been converted to Modified Mercalli Intensity (MMI) scale (see column 'MMI' in Table 2.8). The MMI is a measure of the local damage potential of the earthquake. See Table 2.9 for the range of damages for specific MMI values. Limited studies have been performed to determine the correlation between structural damage and ground motion in the region. The conversion used here is based on United States Geological Survey findings. No attempt has been made to individually model the exposure of Funadhoo Island as time was limited for such a detailed assessment. Instead, the findings of UNDP (2006) were used.

Table 2.8 Probable maximum PGA values in each seismic hazard zone of Maldives (modified from UNDP, 2006).

Seismic hazard zone	PGA values for 475yrs return period	MMI[1]
1	**< 0.04**	**I**
2	0.04 – 0.05	I
3	0.05 – 0.07	I
4	0.07 – 0.18	I-II
5	0.18 – 0.32	II-III

Table 2.9. Modified Mercalli Intensity description (Richter, 1958).

MMI Value	Shaking Severity	Description of Damage
I	Low	Not felt. Marginal and long period effects of large earthquakes.
II	Low	Felt by persons at rest, on upper floors, or favourably placed.
III	Low	Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.
IV	Low	Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV, wooden walls and frame creak.
V	Low	Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.
VI-XII	Light - Catastrophe	Light to total destruction

[1] Based on KATZFEY, J. J. & MCINNES, K. L. (1996) GCM simulation of eastern Australian cutoff lows. *Journal of Climate*, 2337-2355.

According to these findings it is unlikely that Funadhoo will receive an earthquake capable of causing destruction. It should however be noted that the actual damage may be different in Maldives since the masonry and structural stability factors have not been considered at local level for the MMI values presented here. Usually such adjustments can only be accurately made using historical events, which is almost nonexistent in Maldives.

2.2.6 Climate Change

The debate on climate change, especially Sea Level Rise (SLR) is far from complete. Questions have been raised about SLR itself (Morner et al., 2004, Morner, 2004) and the potential for coral island environments to naturally adapt (Kench et al., 2005, Woodroffe, 1993). However the majority view of the scientific community is that climate is changing and that these changes are more likely to have far reaching consequences for Maldives. For a country like Maldives, who are most at risk from any climate change impacts, it is important to consider a cautious approach in planning by considering worst case scenarios. The findings presented in this section are based on existing literature. No attempt has been made to undertake detailed modelling of climate change impacts specifically on the island due to time limitations. Hence, the projection could change with new findings and should be constantly reviewed.

The most critical driver for future hazard exposure in Maldives is the predicted sea level rise and Sea Surface Temperature (SST) rise. Khan et al. (2002) analysis of tidal data for Hulhule', Male' Atoll shows the overall trend of Mean Tidal Level (MTL) is increasing in the southern atolls of Maldives. Their analysis shows an increasing annual MTL at Hulhule' of 4.1 mm/year. These findings have also been backed by a slightly higher increase reported for Diego Garcia south of Addu Atoll (Sheppard, 2002). Moreover, IPCC (2001) predict a likely acceleration as time passes. Hence, this indicates that the MTL at Hulhule' by 2100 will be nearly 0.5m above the present day MTL.

Similarly, Khan et al. (2002) reported air temperature at Male' Atoll is expected to rise at a rate of 0.5°C per year, while the rate of rise in SST is 1.1°C.

Predicted changes in extreme wind gusts related to climate change assumes that maximum wind gusts will increase by 2.5, 5 and 10 per cent per degree of global warming (Hay, 2006). Application of the rate of rise of SST to the best case assumption indicates a <u>15% increase in the maximum wind gusts by the year 2010 in southern Atolls</u>.

The global circulation models predict an enhanced hydrological cycle and an increase in the mean rainfall over most of the Asia. It is therefore evident that the probability of occurrence and intensity of rainfall related flood hazards for the island of Funadhoo will be increased in the future. It has also been reported that a warmer future climate as predicted by the climate change scenarios will cause a greater variability in the Indian monsoon, thus increasing the chances of extreme dry and wet monsoon seasons (Giorgi and Francisco, 2000). Global circulation models have predicted <u>average precipitation</u> in tropical south Asia, where the Maldives archipelago lies, <u>to increase at a rate of 0.14% per year</u> (Fig. 2.12).

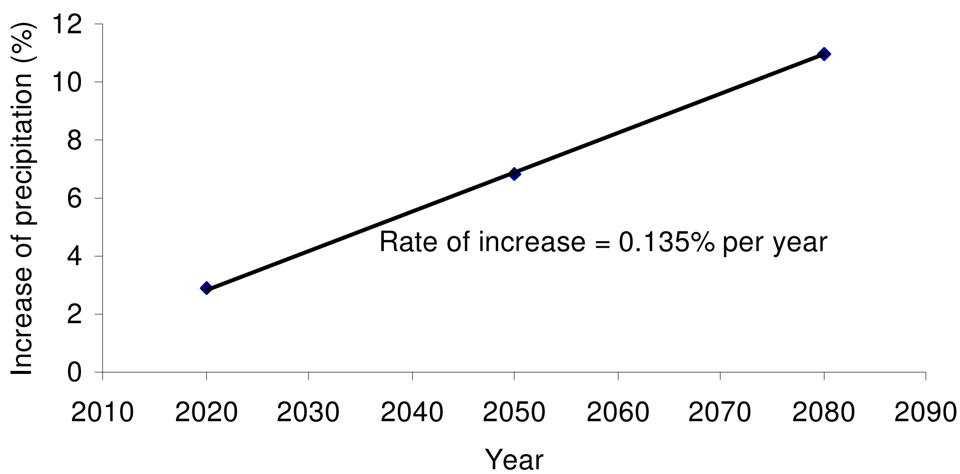

Fig. 2.12. Graph showing the rate of increase of averaged annual mean precipitation in tropical south Asia (Adger et al., 2004)

There are no conclusive agreements over the increase in frequency and intensity of Southern Indian Ocean Storms. However, some researchers have reported a possible increase in intensity and even a northward migration of the southern hemisphere storm belt (Kitoh et al., 1997) due rise in Sea Surface Temperatures (SST) and Sea Level Rise. If this is to happen in the Southern Indian Ocean, the frequency of and intensity of storms reaching Funadhoo Island coastline will increase and thereby exposing the island more frequent damages from swell waves. The increase in sea level rise will also cause the storms to be more intense with higher flood heights.

The above discussed predicted climate changes for Funadhoo and surrounding region is summarised in Table 2.10. It should be cautioned that the values are estimates based on most recent available literature on Maldives which themselves have a number of uncertainties and possible errors. Hence, the values should only be taken as guide as it existed in 2006 and should be constantly reviewed. The first three elements are based climate change drivers while the bottom three is climatological consequences.

Table 2.10. Summary of climate change related parameters for various hazards.

Element	**Predicted rate of change**	**Predicted change (overall rise)**		**Possible impacts on Hazards in Funadhoo**
		Best Case	**Worst Case**	
SLR	4.1-5.0mm /yr	Yr 2050: +0.2m Yr 2100: +0.4m	Yr 2050: +0.4m Yr 2100: +0.88m	Tidal flooding, increase in swell wave flooding, reef drowning
Air Temp	0.5℃ / decade	Yr 2050: +2.15° Yr 2100: +4.65°		
SST	1.1℃ / decade	Yr 2050: +4.73° Yr 2100: +10.3°		Increase in storm surges and swell wave related flooding, Coral bleaching & reduction in coral defences
Rainfall	+0.14% / yr (or +28mm/yr)	Yr 2050: +1204mm Yr 2100: +2604mm		Increased flooding, Could affect coral reef growth
Wind gusts	5% and 10% / degree of warming	Yr 2050: +3.8 Knots Yr 2100: +8.3 Knots	Yr 2050: +7.7Knots Yr 2100: +16.7 Knots	Increased windstorms, Increase in swell wave related flooding.
Swell Waves	Frequency expected to change. Wave height in reef expected to be high			Increase in swell wave related flooding.

2.3 Event Scenarios

Based on the discussion in section 2.2 above, the following event scenarios have been estimated for Funadhoo Island (Table 2.11).

Table 2.11 Rapid onset flooding hazards

Hazard	Max Prediction	Impact thresholds			Probability of Occurrence		
		Low	**Moderate**	**Severe**	**Low Impact**	**Moderate Impact**	**Severe Impact**
Swell Waves *(wave heights on reef flat – Average Island ridge height +2.0m above reef flat; barrier island ridge is 2.3m)*	NA	< 2.3m	> 2.3m	> 3.0m	High	Moderate	Low
Tsunami *(wave heights on reef flat)*	4.5m	< 2.3m	> 2.3m	> 3.0m	Moderate	Low	Very low
SW monsoon high seas	0.5m	< 2.3m	> 2.3m	> 3.0m	High	Very low	Unlikely
Heavy Rainfall *(For a 24 hour period)*	241mm	<60mm	> 60mm	>175mm	High	Moderate	Low

Table 2.12 Slow onset flooding hazards (medium term scenario – year 2050)

Hazard	Impact thresholds			Probability of Occurrence		
	Low	**Moderate**	**Severe**	**Low**	**Moderate**	**Severe**
SLR: Tidal Flooding	< 2.3m	> 2.3m	> 3.0m	Moderate	Very Low	Very Low
SLR: Swell Waves	< 2.3m	> 2.3m	> 3.0m	Very high	Moderate	Low

SLR: Heavy Rainfall	<70mm	>70mm	>150mm	Very High	Moderate	Low

Table 2.13 Other rapid onset events

Hazard	Max Prediction	Impact thresholds			Probability of Occurrence		
		Low	**Moderate**	**Severe**	**Low**	**Moderate**	**Severe**
Wind storm	NA	<30 knts	> 30 knts	> 45Knts	Very High	High	Moderate
Earthquake (MMI value[2])	I	< IV	> IV	> VI	Very Low	Unlikely	none

2.4 Hazard zones

Hazard zones have been developed using a Hazard Intensity Index. The index is based on a number of variables, namely historical records, topography, reef geomorphology, vegetation characteristics, existing mitigation measures (such as breakwaters) and hazard impact threshold levels. The index ranges from 0 to 5 where 0 is considered as no impact and 5 is considered as very severe. In order to standardise the hazard zone for use in other components of this study only events above the severe threshold were considered. Hence, the hazard zones should be interpreted with reference to the hazard scenarios identified above.

2.4.1 Swell waves and SW monsoon high Waves

The intensity of swell waves is predicted to be highest along the barrier island along the southern half of the south eastern half of the island and 50 m from the southern coastline (see Fig. 2.13). Swell waves higher than 3.0 m on reef flat are predicted to penetrate inner island up to or beyond 200 m from the coastline. The longest run-up would be from the oceanward coastline and on the northern half of the island. The run-up on the southern half of the island will be largely controlled by the barrier island. Waves smaller than 2.0 m MSL will be entirely mitigated by the barrier island. However, there is high

[2] Refer to earthquake section above

likelihood for the southern half to be flooded both due to direct run-up from the oceanward coastline and due to refraction.

SW monsoon *udha* events are expected to have limited impact on the island and are predicted to be confined to 10-50 m from the lagoonward coastline.

The lagoonward side is relatively safe from swell related flooding due to the protection provided by the atoll rim and island orientation. However, waves could refract around the reef system through the reef entrance south of the island. Such impacts are predicted to be limited to 10-30 m from the lagoonward coastline and their intensity is expected to remain low.

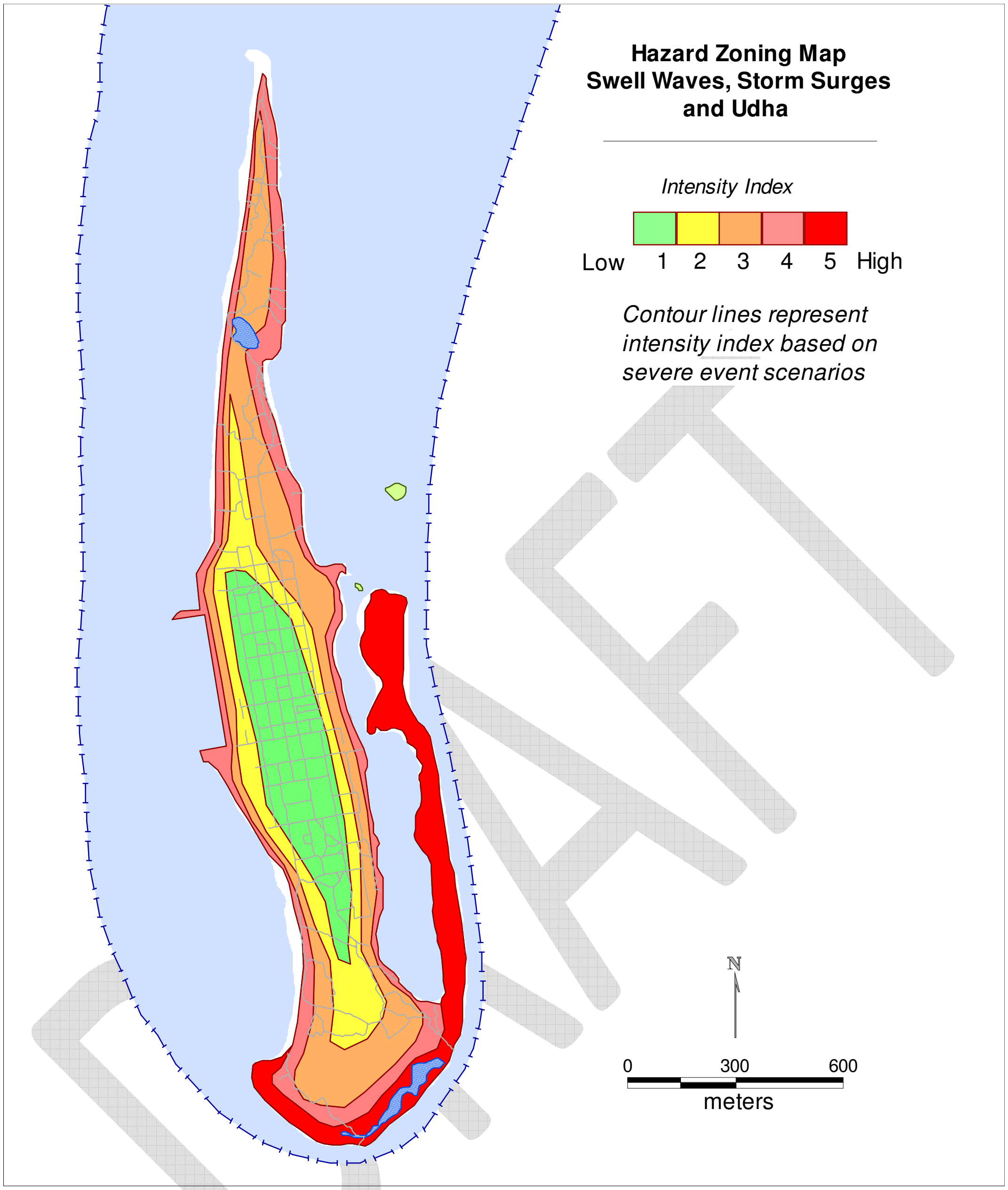

Fig. 2.13 Hazard zoning map for swell wave, storm surges and southwest monsoon high seas.

2.4.2 Tsunamis

When a severe threshold of tsunami hazard (>3.0 m on reef flat) is considered, 80% of the island is expected to be flooded (Fig. 2.14). If the waves reach beyond 4.0 m MSL the entire island is highly likely to be flooded due the prevalent tide levels. High intensity waves will flush through the island from the eastern and southern side while tide related surges will occur within the atoll lagoon, flooding from the western shoreline. The intensity of flood waters will be highest 100-150 m from the shoreline.

Wave height around the island will vary based on the original tsunami wave height, but the areas marked as low intensity is predicted to have proportionally lower heights compared to the coastline.

The presence of the barrier island on the south east will control much of the energy from a severe tsunami but may not entirely prevent flooding. The northern half is more exposed to tsunamis than southern half. In this sense the existing settlement s fairly protected in the present geophysical setting of the island

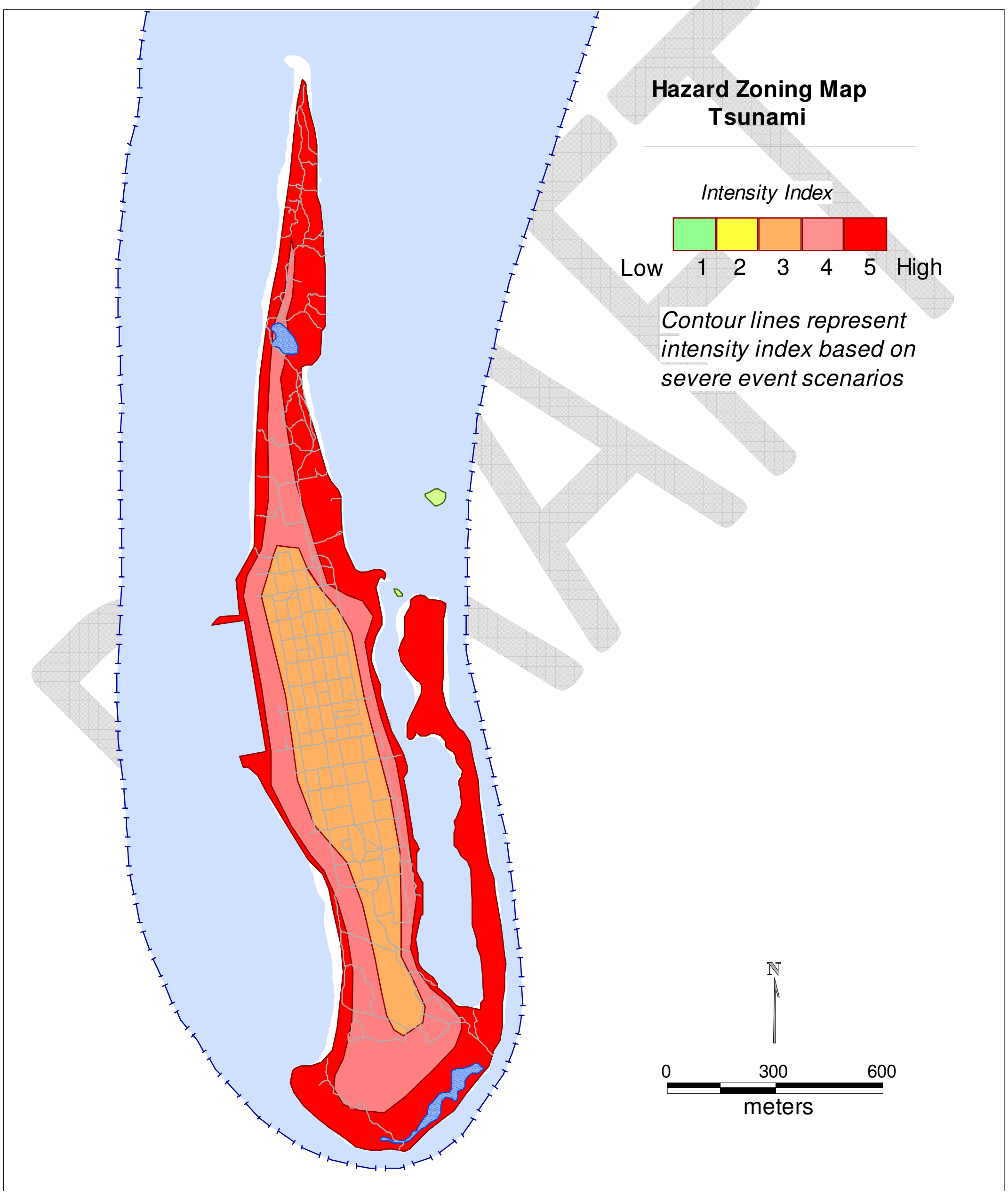

Fig. 2.14 Hazard zoning map for tsunami flooding.

2.4.3 Heavy Rainfall

Heavy rainfall above the severe threshold is expected to flood parts of the settlement (Fig. 2.15). The areas predicted for severe intensity is the topographic lows in the southern, northern and harbour area. These areas act as drainage basins for the surrounding higher areas.

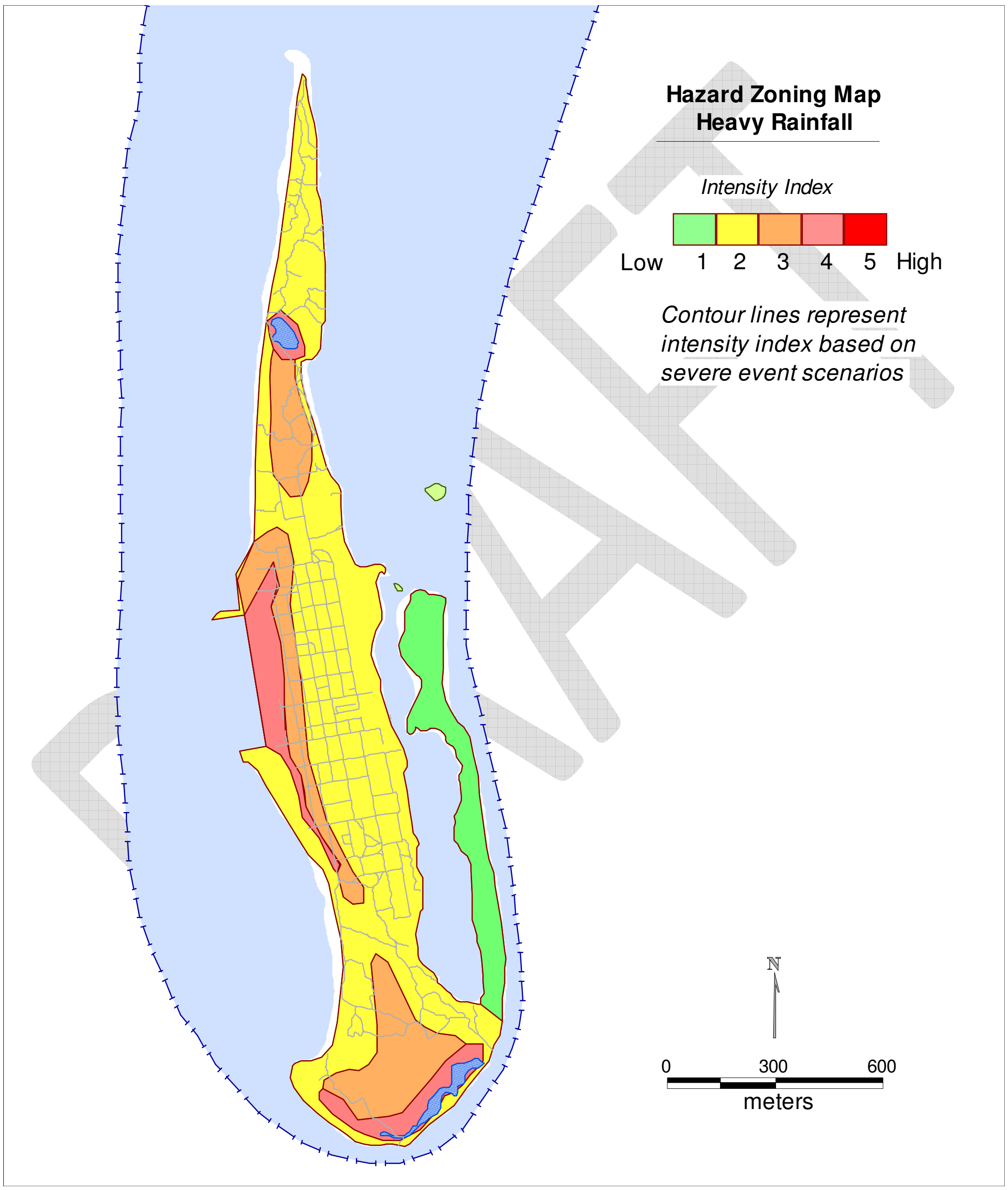

Fig. 2.15 Hazard zoning map for heavy rainfall related flooding.

The intensity is generally expected to be low in most locations. The hazard zone presented in the map below is based on limited topographic surveys done on the island.

Due to the large size of the island it was impossible to assess the topographic variation across the entire island during this project. Hence the hazard zones shown below should be considered as the most prominent zones only. More detailed assessment is required once high resolution topographic data becomes available.

2.4.4 Strong Wind

The intensity of the strong wind across the island is expected to remain fairly constant. Smaller variations may exist between the west and east side where by the west side receives higher intensity due to the predominant westerly direction of abnormally strong winds. Given the intensity of historic storm events in the region there is a real risk of severe damage during such an event. The entire island has been assigned an intensity index of 4 for strong winds during a severe event.

2.4.5 Earthquakes

The entire island is a hazard zone with equal intensity. An intensity index of 1 has been assigned.

2.4.6 Climate Change

Establishing hazard zones specifically for climate change is impractical at this stage due to the lack of topographic and bathymetric data. However, the predicted impact patterns and hazard zones described above are expected to be prevalent with climate change as well, although the intensity is likely to slightly increase.

2.4.6 Composite Hazard Zones

A composite hazard zone map was produced using a GIS based on the above hazard zoning and intensity index. The coastal zone approximately 150m from the oceanward coastline and the topographically low areas within the island are predicted to be the most intense regions for multiple hazards. The eastern side is particularly identified as a hazard zone due to the exposure to swell waves, storm surges and tsunamis.

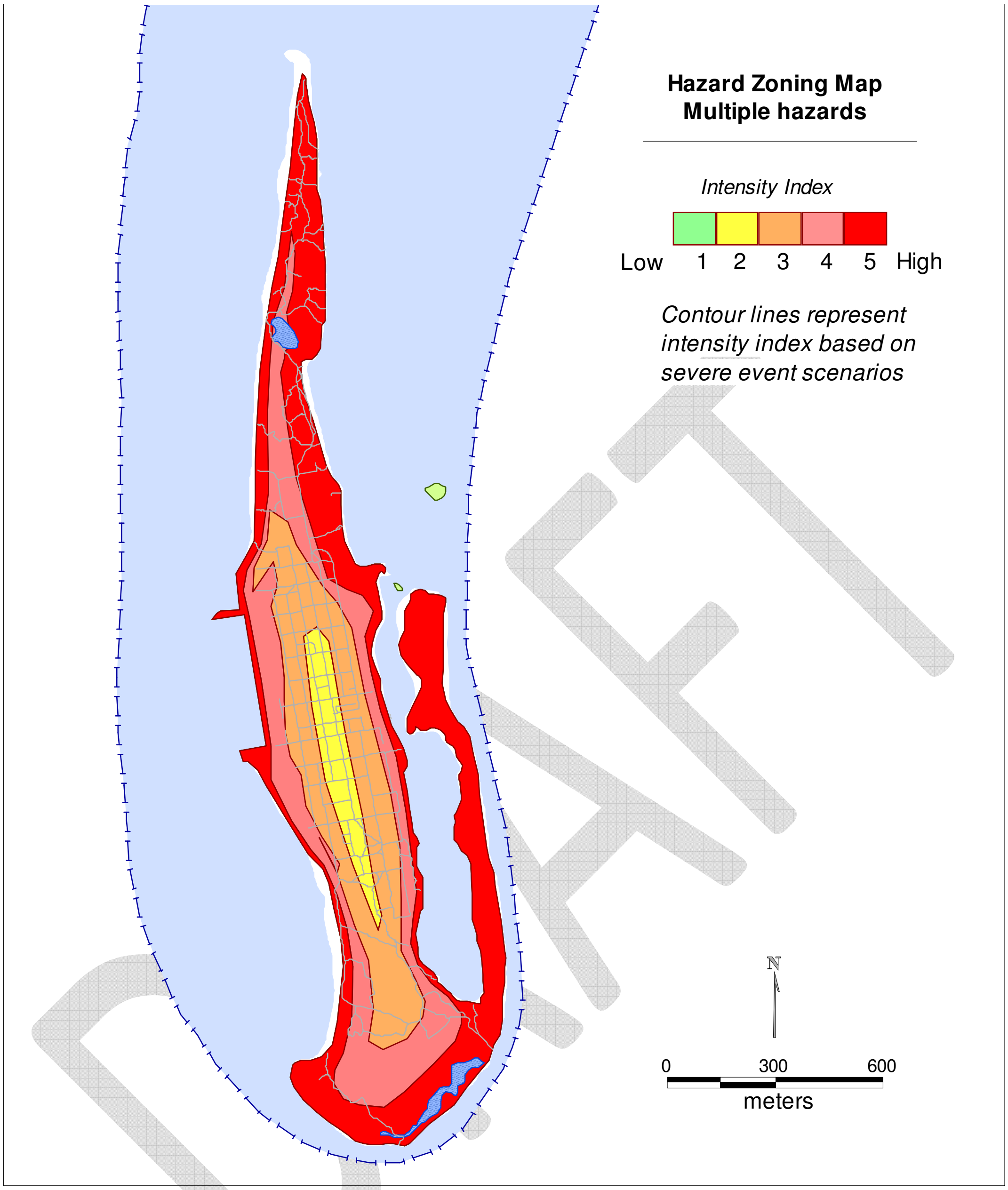

Fig 2.16. Composite hazard zone map

2.5 Limitations and recommendation for future study

The main limitation for this study is the incompleteness of the historic data for different hazardous events. The island authorities do not collect and record the impacts and dates of these events in a systematic manner. There is no systematic and consistent format for keeping the records. In addition to the lack of complete historic records there is no monitoring of coastal and environmental changes caused by anthropogenic activities such as road maintenance, beach replenishment, causeway building and reclamation works. It was noted that the island offices do not have the technical capacity to carry out such monitoring and record keeping exercises. It is therefore evident that there is an urgent need to increase the capacity of the island offices to collect and maintain records of hazardous events in a systematic manner.

The second major limitation was the inaccessibility to long-term meteorological data from the region. Historical meteorological datasets at least as daily records are critical in predicting trends and calculating the return periods of events specific to the site. The inaccessibility was caused by lack of resources to access them after the Department of Meteorology levied a substantial charge for acquiring the data. The lack of data has been compensated by borrowing data from alternate internet based resources such as University of Hawaii Tidal data. A more comprehensive assessment is thus recommended especially for wind storms and heavy rainfall once high resolution meteorological data is available.

The future development plans for the island are not finalised. Furthermore the existing drafts do not have proper documentations explaining the rationale and design criteria's and prevailing environmental factors based on which the plan should have been drawn up. It was hence, impractical to access the future hazard exposure of the island based on a draft concept plan. It is recommended that this study be extended to include the impacts of new developments, especially land reclamations, once the plans are finalised.

The meteorological records in Maldives are based on 5 major stations and not at atoll level or island level. Hence all hazard predictions for Funadhoo are based on regional data rather than localised data. Often the datasets available are short for accurate long term prediction. Hence, it should be noted that there would be a high degree of estimation and the actual hazard events could vary from what is described in this report. However, the findings are the closest approximation possible based on available data and time, and does represent a detailed although not a comprehensive picture of hazard exposure in Funadhoo.

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3. Environmental Setting and Vulnerabilities

3.1 General environmental conditions

3.1.1 Terrestrial environment

<u>Topography</u>

The topography of Funadhoo was assessed using four island profiles (see Fig. 3.1). Given below are the general findings from this assessment.

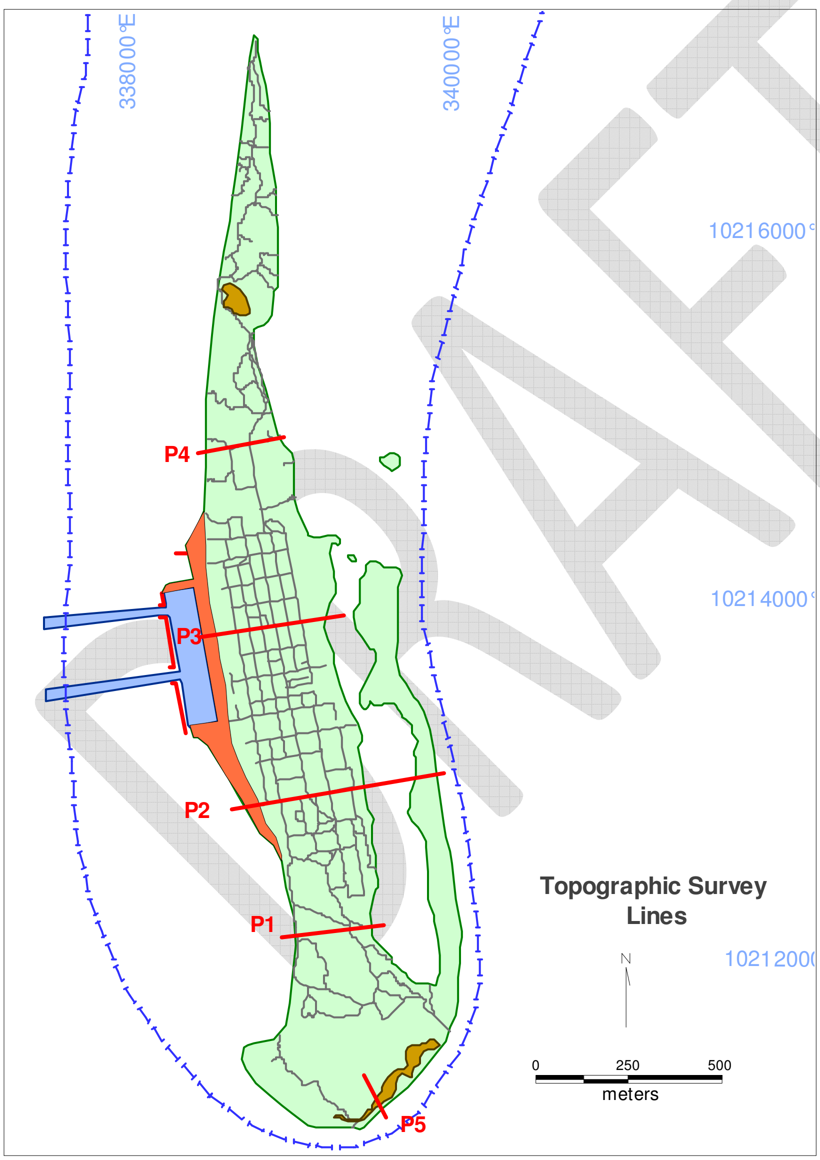

Fig. 3.1 Location of topographic profile surveys.

Funadhoo Island is generally low lying with an average elevation of +1.1 m MSL along the measured topographic profiles. The island is in general higher in the southern side and lower in the northern side. This may be due to the relatively young nature of the northern half and possibly due to the rapid growth and stabilisation of land in the area. In comparison the southern half appears to be more established and older. There are substantial topographic variations in the island caused by various stages of island development and the presence of wetland areas. The drainage system appears to be well established, partly due to the narrow width of the island and due to the presence of wetland areas. The island reported no cases of substantial rainfall related flooding and the topographic profiles revealed the absence of flood prone areas in the settlement zone (see Figs. 3.2-3.4). The new housing development in the south may however cause flooding, if the topographic variations are not considered during the development process (see Fig. 3.4).

Funadhoo is likely to be exposed to wave action from both the lagoonward and oceanward side, especially in the southern half of the island. This prediction is backed by high elevation of the coastal ridges. The elevations on the oceanward coastal ridge along the strip of 'barrier island' was recorded at +1.8 m MSL (Fig. 3.3). The ridge in this area is highest along the southwest and lowest along the southern end. This variation may be explained due to the orientation and subsequent exposure to wave action. The ridge on the atoll lagoonward side was recorded at +1.6 m MSL suggesting the strong wave activity in the area during SW monsoon (Fig. 3.2). The high ridge extends up to the northern end of the harbour, beyond which the ridge gets comparatively low. A possible reason for this variation may be the shallow depth of reef rim in the area and possible wave refraction off Lhaimagu Island, 4km west of the area in question.

In the northern half of the island, the oceanward coastal ridge increases in height to +1.4 m MSL, apart from the newly merged uninhabited island, where elevations were around +1.1 m MSL. The increase in height maybe attributed to the direct exposure to waves approaching from oceanward side.

It was not possible to assess the drainage patterns in the island in detail due to the limitations in the topographic data, but the present settlement does not appear to be exposed to rainfall induced flooding due to the drainage system.

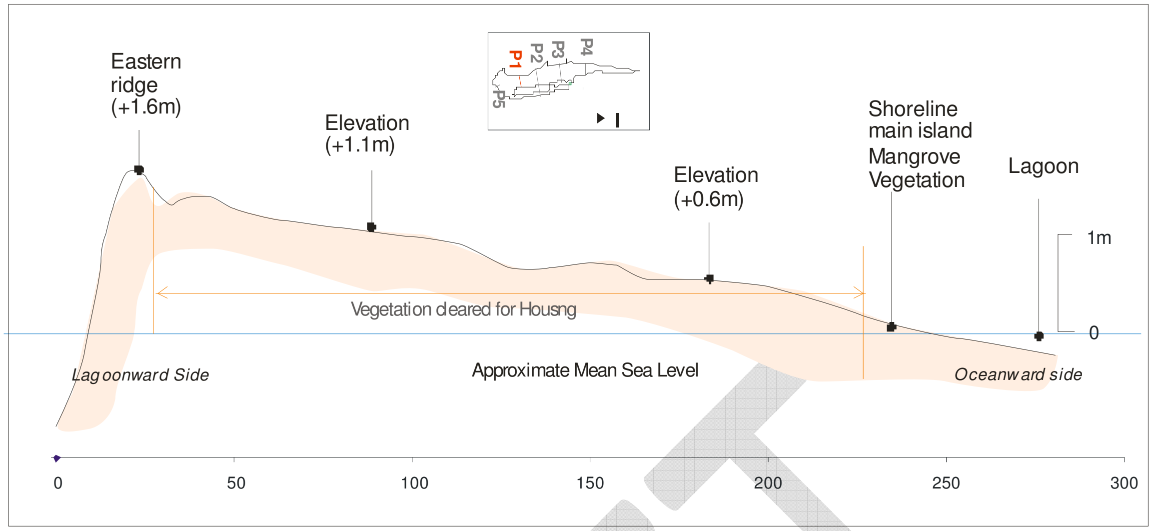

Fig. 3.2 Topographic profile P1

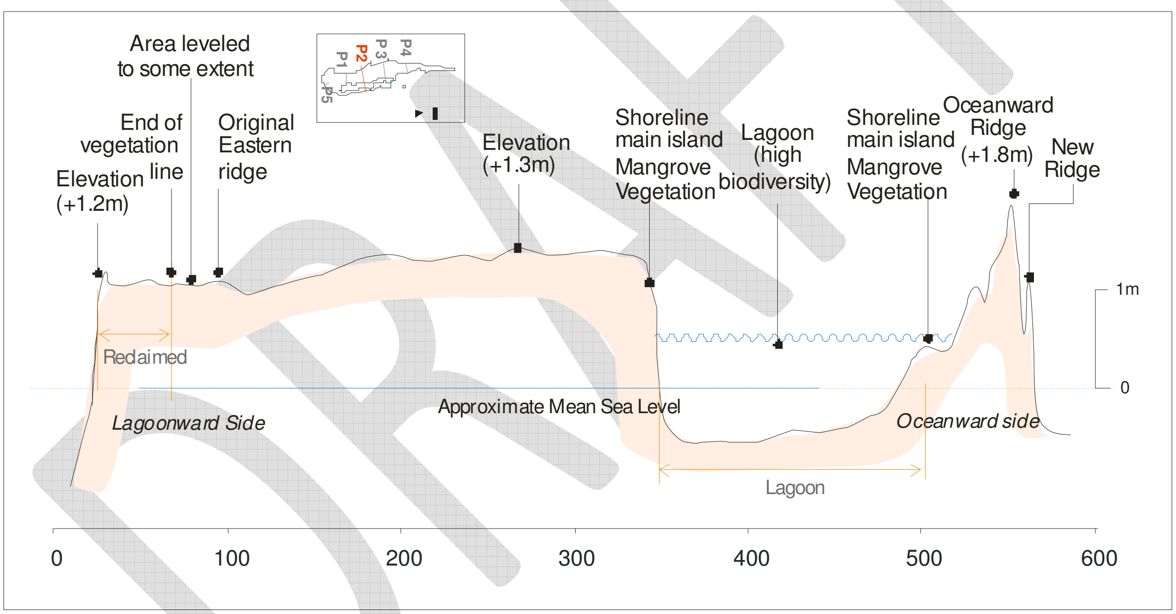

Fig. 3.3 Topographic profile P2

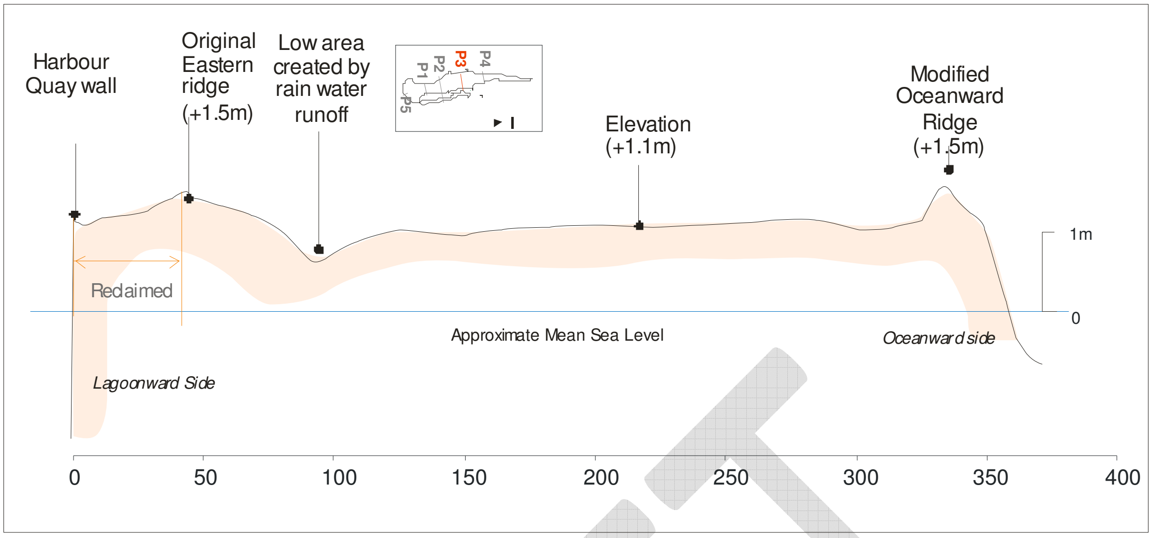

Fig. 3.4 Topographic profile P3

Vegetation

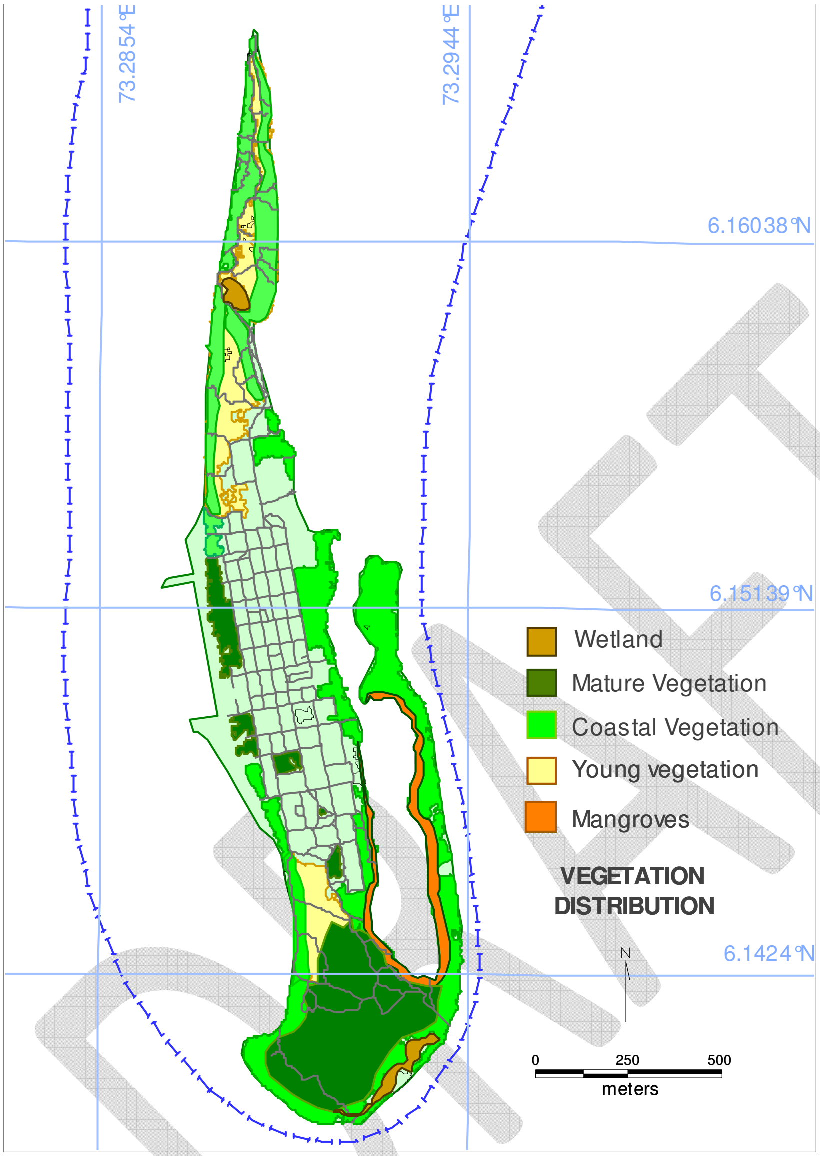

Fig. 3.5 Vegetation distribution

The vegetation cover in Funadhoo Island is generally high. Fig. 3.5 shows the dominant patterns in vegetation distribution in 2005. However, the vegetation cover within the settlement is very low. In general the southern half of the island has more mature and established vegetation while northern half has younger and smaller vegetation. The densest vegetation in the island has been cleared since the settlement. During field visits, it was observed that over 7 ha of land were cleared for new housing development. The lack of vegetation in the current settlement area may be explained by the land clearing practices in housing construction projects, which is addressed in a latter section.

There is a healthy strip of mangrove vegetation on the eastern side of the island along the ‘inland lagoon’. Much of this vegetation on the settlement side of the island is being gradually depleted. These vegetations may perform a very important role in preventing damage from major ocean induced hazards such as a tsunami by trapping debris and minimising the wave energy, if it overtops the ridge system.

Funadhoo has a healthy strip of coastal vegetation around the island. The south eastern and southern coastline of the island, which is the high exposure zones for regular wave activity, contains strong vegetation cover comprising of *ironwood* (*locally known as Kuredhi*). This specific species is known for its salt tolerance and effectiveness in beach stabilisation and wave impact mitigation during hazard events. Backed by a layer of mangrove vegetation, the southeastern ‘barrier island’ strip forms a strong defensive system against ocean induced hazards.

Much of the vegetation on the northern half of the island appears to be relatively young, perhaps owing to the recent accretion activities. Coastal vegetation on the western side of the island along the settlement areas are under threat due to development activities and subsequent vegetation removal.

<u>Ground Water and Soil.</u>

Funadhoo Island is expected to have a substantial layer of fresh water due to the low population density and island size. Water lens depth varies across the island based on topography. Generally the water table could be reached with less than 1.0 m at median tide in all areas. This could decrease to 0.8 m during spring high tides or more during heavy rainfall, especially in reclaimed wetland areas

Funadhoo’s ground water was reported to be in generally good condition and no cases of contamination or salinisation was reported during the field visits or in published reports. However, the present sewerage systems based on septic tanks are likely to cause contamination in the medium to long-term. Drinking water shortages have occurred in the past due to the comparatively low rainfall in the region during northeast monsoon.

The soil conditions were not assessed across the island due to time limitation. Funadhoo is expected to have comparatively good soil due to the high vegetation cover it had prior to the human settlement. The reclaimed areas from the reef have slow vegetation re-growth.

3.1.2 Coastal Environment

General environment

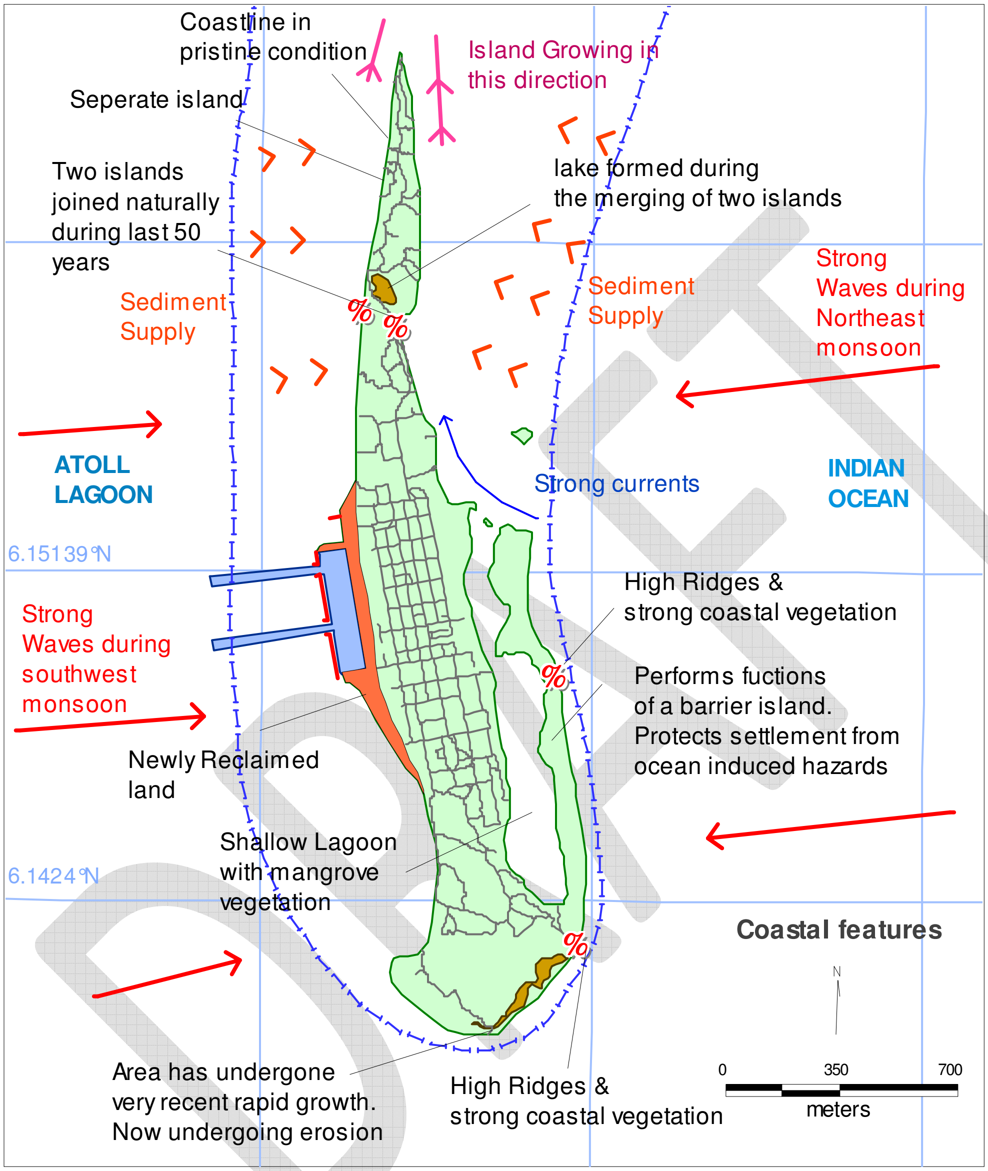

Fig. 3.6 Coastal features.

The coastal environment of Funadhoo is in relatively good condition, apart from the effects of coastal modifications along the western coastline. Some of the reasons for the present conditions include the recentness of settlement, low population density and concentrated settlement area. The relative stability and consistent supply of sediments also ensures that the coastline is well maintained naturally. At present the island continues to grow northward.

Fig. 3.6 summarises the main coastal characteristics of Funadhoo. The western shoreline, which is less exposed to natural hazards, has been modified by development activities. The coastal processes on the western shoreline have been affected by the dredging activities and breakwater. Of particular importance is the limitations caused to sediment movement along the coastline and the implications this change may have on the south eastern coastline. The north eastern side however appears to be functioning well given the huge supply of sediments in the area. As noted earlier the western coastline received strong wave activity and hence allows the island building processes to operate during SW monsoon.

The eastern shoreline has largely remained unmodified and the processes of erosion and accretion seem to adjust the coastline with varying climatic conditions. The most important feature on the eastern shoreline is the 'barrier island' (locally referred to as *Kudafunadhoo*) in the southeast of the island. The strip of land is characterised by a high ridge, strong coral rubble beach and a strong vegetation system. These characteristics, together with the presence of an inland lagoon, form a formidable natural defence system against ocean induced hazards. The evidence of its impacts was observed during the tsunami of 2004, where the impacts of the tsunami were absorbed by the natural defences leaving majority of the settlement area unscathed. The northern areas left unprotected by the barrier island suffered flooding up to 1m. A number of natural changes were brought to the ridge and vegetation system during tsunami of 2004. These include changes to the ridge topography as the waves transported existing material 5-10m inland and destruction of some of the vegetation. Two year after the incident, the area seems to have recovered with a new ridge being formed and vegetation re-establishing itself.

The eastern coastline of the island is exposed to severe storms in the past. Large numbers of over-turned reef blocks can be observed in the eastern reef flat suggesting high wave energy during storm events. Most of the overturned reef blocks can be correlated with a severe storm that hit northern Maldives during 1955. Similar, structures were observed in almost all the eastern rim islands in the region. Anecdotal information dates the appearance of these structures to a single event in 1955. Abrupt changes to coastline are possible in the future following such high energy events. It appears that such events have played a major role in helping the island grow towards the south and southwest in the past. There is evidence of rapid shoreline shift due to sudden accumulation of coral ramparts offshore. Such areas are characterised by a depression or a wetland between the original shoreline and the new coral rampart. There is evidence of 30m shift outwards in the southern zone.

Beach and Beach Erosion

Erosion and accretion in Maldivian coral islands is a natural process which is largely dictated by natural forces, especially prevailing climatic conditions. Erosion in Maldives is generally caused by natural and human alterations to coastal processes, which may be either seasonal, cyclic or long term changes (Kench 2001). Impacts of human alterations are more prominent in inhabited islands where coastal modifications have been undertaken (Kench, Parnell et al. 2003).

Funadhoo has undergone significant coastal changes over the last 40 years (see Fig. 3.7). The net effects of these changes however have been positive with the island consistently growing northward. Between 1969 and 2004, large areas of eastern coastline have been eroded, possibly due to changing current pattern in the region. Much of the lost sediment was however transported north assisting in the natural merging of the uninhabited island and further growth of the island. There is limited seasonal erosion in the northern part of the island where parts of the eastern coastline undergoes erosion during NE monsoon and deposition in the SW monsoon. The south eastern and southern coastline is relatively stable although persistent but slow erosion was observed in these areas. The relative stability may be a result of the resilient geomorphologic features in the region.

The coastal modifications on the eastern side may have major long term impacts on the erosion and accretion patterns in the southwest corner. At present, erosion in the south west corner is associated with deposition in the area adjacent to the harbour. However, the possibility of returning these sediments to their original positions is limited due to the obstructions caused by the harbour and alteration to current patterns. Hence, there may be a net loss form the southern shoreline in the future.

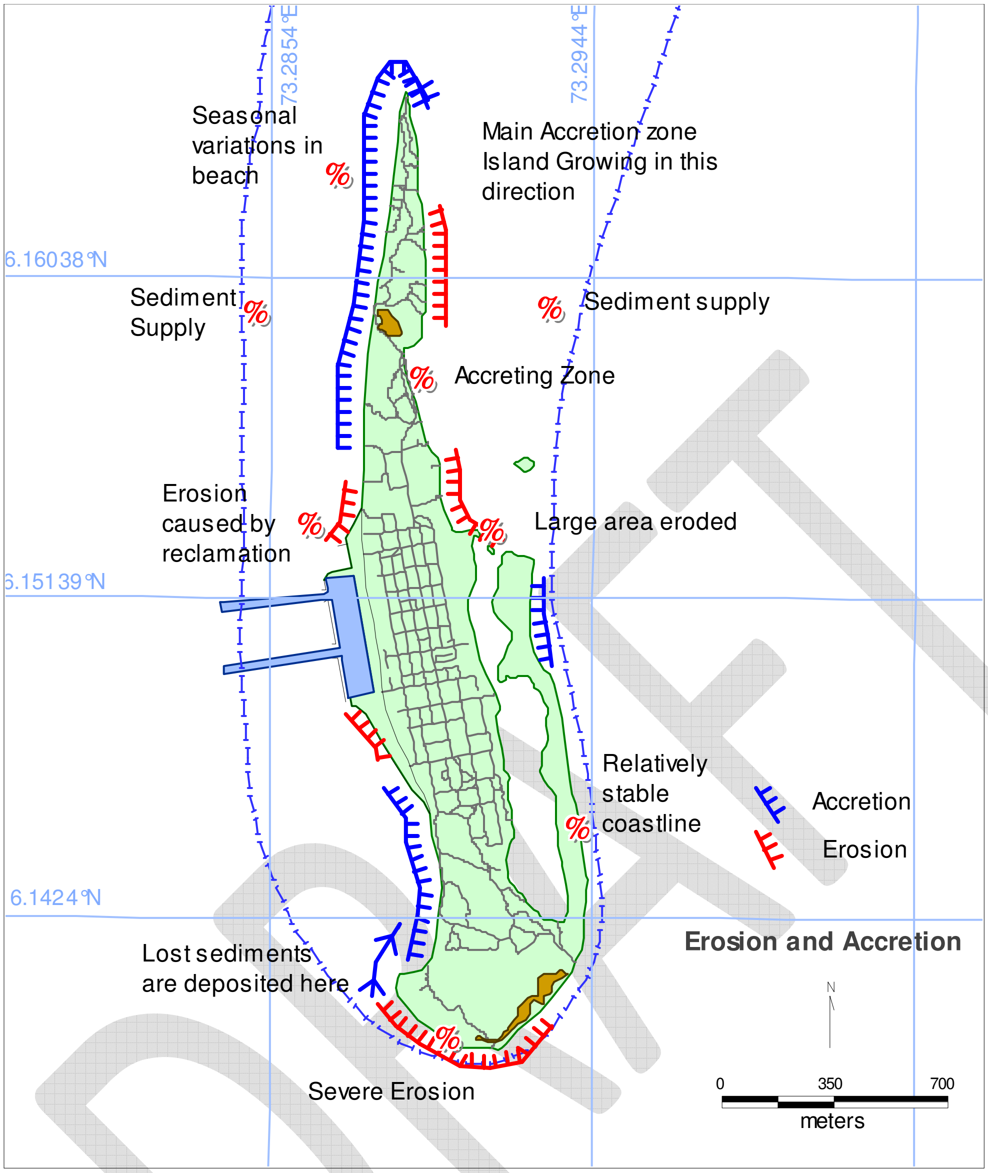

Fig. 3.7 Coastal erosion and accretion.

3.1.3 Marine environment

General Reef Conditions

General historical changes to reef conditions were assessed anecdotally, through interviews with a number of fishermen. The process was hampered by the lack of fisherman on the island and their limited knowledge on the historical changes, since most of them are new to the island. We had to rely on a few reef fishermen who frequently use the area around Funadhoo. The general agreement amongst the interviewees was that the quality of reef areas around the island was moderate. The quality of the lagoonward reef was reported to be better than the oceanward side.

3.1.4 Modifications to Natural Environment

Coastal Modifications

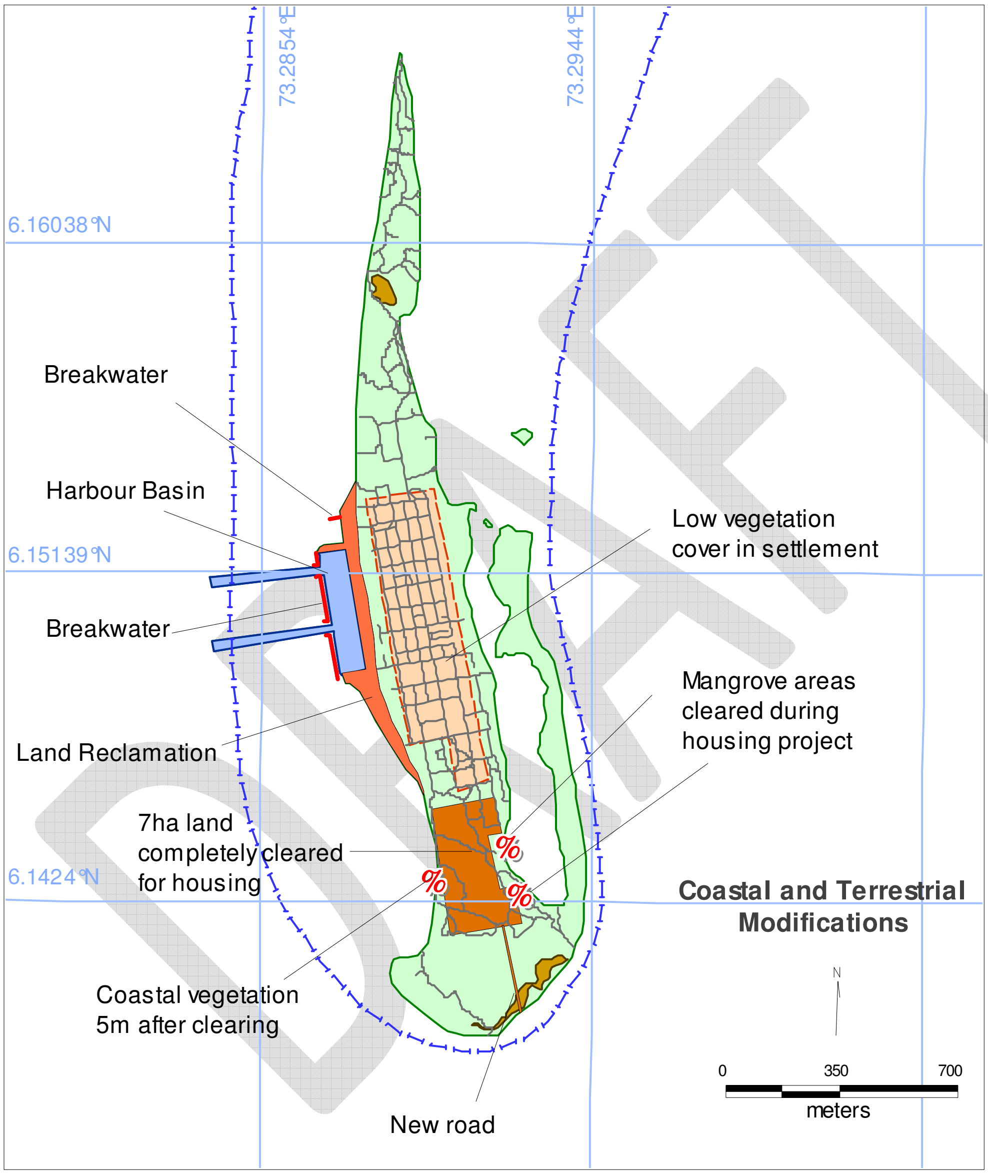

Fig. 3.8 Coastal Modifications.

Fig. 3.8 summarises the major coastal modifications in Funadhoo. Most of the modifications were undertaken are associated with the development of the local harbour. They include reef entrance dredging, harbour basin dredging, land reclamation using dredge material and breakwaters construction. These activities have affected the flow of sediments and currents along the shoreline with implication for future coastal erosion as the south western end is deprived of consistent sediment supply.

New developments being undertaken in the south appears to be encroaching on the inland lagoon system with occasional reclamation along the shoreline. Any modification to these natural defence systems may have implications for future hazard exposure.

New land reclamation on the reef has also been planned as part of the safe island development programme on Funadhoo.

Terrestrial Modifications

- The terrestrial environment of the island has been considerably modified along the settlement area. The lack of vegetation may partly be blamed on the practices during housing development activities on the island. The commercialisation of housing projects in Funadhoo and the lack environmental regulation enforcement meant that the contractors worked on construction friendly methods rather than environment friendly options. The entire area for housing development is completely stripped of vegetation as part of site setting. The large trees removed in this manner are disposed rather than replanted. There are no re-vegetation programmes following the housing project. As a result the settlement area requires a number of years for new vegetation to grow and that assuming a re-vegetation activity is undertaken. At present a 7ha area of land has been completely cleared, which could have been avoided with proper management.
- Development activities on the island are also encroaching on crucial vegetation systems on the island including removal of mangrove areas by reclaiming them. Similarly coastal vegetation in the newly cleared areas has been reduced to a mere 5m. Removing such crucial vegetation will have major implications for hazard exposure including exposure of structures to climatic hazards and coastal erosion.
- The newly reclaimed areas from the reef areas have poor vegetation cover. This pattern is typical in reclaimed reef areas across Maldives. This may be partly due to the high alkalinity of the soil following reclamation and partly due to lack of re-vegetation activities following land reclamation projects.

3.2 Environmental mitigation against historical hazard events

3.2.1 Natural Adaptation

Being located in storm hazard zone, Funadhoo Island has naturally adapted its coastal environment to adjust to the conditions. The high ridge on the oceanward side was developed most likely in response to intense storm activity but acts as a natural defence against storm activity as well as infrequent seas induced hazards such as the storm surges and tsunami. However, the protection is available to the southern part of the island only. Similar protection also exists on the southern half to the lagoonward shoreline.

3.2.2 Human Adaptation

No specific measures have been undertaken Funadhoo against natural hazards, although the retention of coastal vegetation on around this island is an indicator of concerns against natural hazards such as strong wind and flooding.

3.3 Environmental vulnerabilities to natural hazards

3.3.1 Natural Vulnerabilities

- The north-south orientation of the island coupled with narrow width and low elevation in the northern half of the island exposes these areas to sea induced flooding. The effects of the tsunami of 2004 showed these vulnerabilities.
- Funadhoo is located in a major storm hazard zone and hence is prone to strong winds and storm surges from oceanward side. Severe storm events such as the 1955 storm, which devastated much of the inhabited islands in the atoll, could still have a major impact on the island.
- The coastal ridges along southern end and northern region are not high enough to prevent the +1.82 or +2.30 m storm surges predicted for the region.

3.3.2 Human induced vulnerabilities

- Vegetation clearing for housing construction is a major concern in Funadhoo. Unlike other inhabited islands, much of Funadhoo's settlement is comprised of planned housing projects. These include selected contractors building groups of houses. This has led to large scale clearing of vegetation from the construction sites removing the more established trees as well. There is currently no planned re-vegetation programme following the completion of construction activities. This may results in houses being exposed to strong wind. Interviews with inhabitants also revealed inconveniences caused due to high temperatures, which may appear to be further exaggerated due to lack of vegetation cover. At present a large area of vegetation has been completely cleared for the construction of new houses. These new clearings have encroached on islands coastal vegetation as well, leaving barely 5m of coastal vegetation in some locations.

- The western coastline around the harbour region is now an artificial environment due to dredging activities, quay walls and reclamation activities. The island building processes has been hampered in this region. It may require continuous human intervention to mitigate natural hazards such as erosion around the harbour region. Seasonal erosion and accretion now occur around the edges of the reclaimed area. Despite the presence of the channel crossing the reef, there appears to be a continued supply of sediments around both side of the island, possibly owing to the high productive capacity of the reef or sediment availability within the lagoon.
- The new housing development on the island presently encroach the mangrove area. There are areas where mangrove vegetation has been removed and may continue to be the trend if housing plots are located too close the area. Such changes will have implications for ocean induced flooding exposure.

3.4 Environmental assets to hazard mitigation

- The narrow strip of land close to the oceanward reef edge and the mangrove area provides the first line of defence against the sea induced flooding events in the existing settlement. The narrow strip of land acts as a barrier island while adjacent mangrove area acts as a drainage zone for any overtopped water. The coastal features of the narrow strip are reminiscent of a high energy zone and have adapted well to the prevailing wave conditions. The narrow strip is also characterised by strong vegetation cover based on salt resilient species such. Hence the combined effects of a well adapted coastal geomorphology, strong coastal vegetation and the presence of a mangrove area as a drainage zone, forms the main defensive asset of Funadhoo Island against sea induced natural hazards. The uninhabited northern half, however, is not protected through this system and hence is left exposed to sea induced flooding.

- The island appears to be constantly growing northwards with a steady supply of sediments from both the oceanward side (in both monsoons) and the atoll ward side (during SW monsoon). Funadhoo has naturally merged with an exiting island and continues to grow northward. This is evidence that the coastal processes are functioning well in the northern half of the island.
- Funadhoo Island is amongst the newest inhabited islands in Maldives. Modifications to coastal environment have thus far not been restricted to harbour development on the western side. Similarly, much of terrestrial environment is still intact. It currently doesn't have the major environmental issues contributing to hazard exposure found in other inhabited islands.
- The lagoonward ridge is higher than that of most islands surveyed under this study. This may be a response to the moderately strong wave activity within the atoll during the southwest monsoon. The presence of the high ridges can prevent sea induced floods of up to 1.5 m above MSL.
- The geographic location in the archipelago has considerably reduced the exposure to earthquake hazards.
- Funadhoo has good stretch of coastal vegetation right around the island. This protects the settlement form strong winds and may minimise the impacts of potential flooding events.
- The narrow width of the island allows it to have a simple drainage system with flows towards the coastline (in northern areas) and towards the mangrove area. The drainage system is further assisted by the lack of complex variations in topography and comparatively low rainfall.
- The reef areas around the island are reported to be in moderate condition perhaps owing to the relatively late development on the island.

3.5 Predicted environmental impacts from natural hazards

The natural environment of Funadhoo and islands in Maldives archipelago in general appear to be resilient to most natural hazards. The impacts on island environments from major hazard events are usually short-term and insignificant in terms of the natural or geological timeframe. Natural timeframes are measured in 100's of years which provides ample time for an island to recover from major events such as tsunamis. The recovery of island environments, especially vegetation, ground water and geomorphologic features in tsunami effected islands like Laamu Gan provides evidence of such rapid recovery. Different aspects of the natural environment may differ in their recovery. Impacts on marine environment and coastal processes may take longer to recover as their natural development processes are slow. In comparison, impacts on terrestrial environment, such as vegetation and groundwater may be more rapid. However, the speed of recovery of all these aspects will be dependent on the prevailing climatic conditions.

The resilience of coral islands to impacts from long-term events, especially predicted sea level rise is more difficult to predict. On the one hand it is generally argued that the outlook for low lying coral island is 'catastrophic' under the predicted worst case scenarios of sea level rise (IPCC 1990; IPCC 2001), with the entire Maldives predicted to disappear in 150-200 years. On the other hand new research in Maldives suggests that 'contrary to most established commentaries on the precarious nature of atoll islands Maldivian islands have existed for 5000 yr, are morphologically resilient rather than fragile systems, and are expected to persist under current scenarios of future climate change and sea-level rise' (Kench, McLean et al. 2005). A number of prominent scientists have similar views to the latter (for example, Woodroffe (1993), Morner (1994)).

In this respect, it is plausible that Funadhoo may continue to naturally adapt to rising sea level. There are two scenarios for geological impacts on Funadhoo. 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, based on the natural history of Maldives (based on findings by Kench et. al (2005), Woodroffe (1993)). 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 and beaches of Funadhoo (based on (Yamano 2000)). 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 if the proposed coastal modifications on Funadhoo Island continue, it will face substantial challenges in adaptation (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 (based on Pernetta and Sestini (1989), Woodroffe (1989), Kench and Cowell (2002)). Alteration of coastal processes is more likely to hamper an potential natural adaptation process.

Funadhoo has a particular vulnerability to sea level rise due to the presence of an inland lagoon. Since such areas in coral islands are linked to the tide and sea level, an increase in sea level may result in increase in size of such areas and a subsequent reduction in land (Woodroffe 1989). Such enclosed areas may also not receive the benefit of natural coastal adaptation as the coastal processes are minimal due the protection form wave activity.

As noted earlier, environmental impacts from natural hazards will be apparent in the short-term and will appear as a major problem in inhabited islands due to a mismatch in assessment timeframes for natural and socio-economic impacts. The following table presents the short-term impacts from hazard event scenarios predicted for Funadhoo.

Hazard Scenario	**Probability at Location**	**Potential Major Environmental Impacts**
Tsunami (maximum scenario)		
▪ 4.5m	Low	• Widespread damage to coastal vegetation (Short-term) • Long term or permanent damage to selected inland vegetation especially common backyard species such as mango and breadfruit trees. • Salt water intrusion into island water lens causing loss of some flora and fauna. • Contamination of ground water if the sewerage system is damaged or if liquid contaminants such as diesel and chemicals are leaked. • Damage to waste management site and subsequent dispersion of debris in southern half of the island and pollution (land and ground water) • Salinisation of ground water lens to a short period of time causing ground water shortage. If the rainwater collection facilities are destroyed, potable water shortage would be critical. • Widespread damage to backyard trees (short-term) • Widespread damage to island access infrastructure such as harbours and breakwaters.

Hazard Scenario	Probability at Location	Potential Major Environmental Impacts
		• Short-medium term loss of soil productivity • Geomorphic changes to the 'barrier island' • Moderate damage to coral reefs *(based on UNEP (2005))*
Storm Surge *(based on UNDP, (2005))*		
▪ 0.60m (1.53m storm tide)	Low	• Minor damage to coastal vegetation • Minor geomorphologic changes in the eastern shoreline and lagoon
▪ 1.32m (2.30m storm tide)	Very Low	• Moderate damage to coastal vegetation especially in the north eastern region • Minor damage to selected inland vegetation especially common backyard species such as breadfruit trees. • Salt water intrusion into northern wetland areas and island water lens causing minor loss of some flora and fauna. • Contamination of ground water if the sewerage system is damaged or if liquid contaminants such as diesel and chemicals are leaked. • Salinisation of ground water lens to a short period of time causing ground water shortage in the northern part of the island. • Minor damage to waste management site and potential dispersion of debris in southern half of the island causing pollution (land and ground water) • Minor-moderate damage to coastal protection and island access infrastructure • Minor geomorphologic changes in the eastern shoreline and lagoon • Minor-moderate damage to coral reefs
Strong Wind		
▪ 28-33 Knots	Very High	• Minor damage to very old and young fruit trees • Debris dispersion near waste sites. • Minor damage to open field crops
▪ 34-65 Knots	Low	• Moderate damage to vegetation with falling branches and occasionally whole trees • Debris dispersion near waste sites. • Moderate-high damage to open field crops • Minor changes to coastal ridges
▪ 65+ Knots	Very Low	• Widespread damage to inland vegetation • Debris dispersion near waste sites. • Minor changes to coastal ridges

Hazard Scenario	**Probability at Location**	**Potential Major Environmental Impacts**
Heavy rainfall		
▪ 187mm	Moderate	• Minor flooding on roads
▪ 240mm	Very Low	• Minor-moderate flooding but restricted to low areas of the island and roads.
Drought		• Minor damage to backyard fruit trees
Earthquake		• none
Sea Level Rise by year 2100 (effects of single flood event)		
▪ Medium (0.41m)	Moderate	• Widespread flooding during high tides and storm surges. • Loss of land due to erosion. • Loss of coastal vegetation • Major changes to coastal geomorphology. • Saltwater intrusion into wetland areas and salinisation of ground water leading to water shortage and loss of flora and fauna. • Minor to moderate expansion of wetland areas

3.6 Findings and recommendations for safe island development

At the time of this study, the detailed plans for developing Funadhoo as a safe island was in the planning stage and has not been finalised. Presented below are some of the considerations that need to be made in developing Funadhoo as a safe island in the future. Assessment has also been made based on the proposed physical land use plan as of December 2006.

- Funadhoo has a well established defensive system against sea induced natural hazards on its eastern coastline. The system includes the narrow strip of land and the mangrove areas. This area needs to be preserved and should be considered an environment protection zone in their entirety. The proposed physical development plan considers delineation of a 20m zone with the narrow the strip of land and along the mangrove area. Hence, the present proposal for this zone needs to be reviewed in a safe island development plan. It should however be noted that the northern half is left exposed flooding hazards and may require artificial flood prevention measures if settlements are to expand into the area.
- At this stage, it is not recommended to deploy hard engineered structures as flood mitigation measures that may alter coastal processes. The coastal processes around much of the island are currently intact and alteration of one

area would have follow-on implications for the rest of the island and possibly exposure to coastal erosion. Instead measures may be established on land to enhance the natural ridge system and vegetation to mitigate potential sea induced flooding.

- Reclamation of the mangrove area and surrounding wetland zone should be avoided. The resent physical development plan envisages reclaiming part of the wetland area. Any such activity has a high probability to increase the exposure to flooding hazards.
- No new land reclamation has been proposed under the present physical development plan but is expected to form part of the new safe island development plan. The following points need to be considered when developing a land reclamation plan for Funadhoo.
  - ➢ Reclamation should not be considered in Funadhoo unless it is absolutely essential.
  - ➢ Reclamation is highly likely to cause damage to the outer reef due to its proximity and current land reclamation practices. This may reduce the defensive capacity of the reef system and expose Funadhoo to long term climate hazards. Proper reclamation practices need to be put in place prior to considering reclamation activities.
  - ➢ The soil composition of a reclaimed area may need to be properly established. Soil in coral islands of Maldives has specific profiles which dictate the suitability of vegetation and perhaps drainage.
  - ➢ The elevation of the newly reclaimed area should be inline with the existing island topography or should consider establishing a functioning drainage system to mitigate flooding hazards resulting from modified topography, especially where the new reclamation joins the existing island. Special consideration may need to be given to maintain the existing drainage towards the southern wetland area.
  - ➢ The elevations and desired topography for the proposed reclamation needs to be determined during the planning stage.

- A re-vegetation plan needs to be incorporated into the safe island development plan, especially to any reclaimed zone, to ensure minimal exposure to strong winds and benefits against sea induced flooding events.

- Although the western side of the island is considered the lagoonward side of the island, the openness of the atoll and prevalence of storm activity in the North Indian Ocean, may expose the eastern side of the island to moderate surges. It should be noted that the probability of a major event on the western side of the island is low but nonetheless not absent.
- A re-vegetation plan needs to be put in place to remedy the large scale clearing undertaken for housing development.

3.7 Recommendations for further study

- The main limitation of this study is the lack of time to undertake more empirical and detailed assessments of the island. The consequence of the short time limit is the semi-empirical mode of assessment and the generalised nature of findings.
- The lack of existing survey data on critical characteristics of the island and reef, such as topography and bathymetry data, and the lack of long term survey data such as that of wave on current data, limits the amount of empirical assessments that could be done within the short timeframe.
- The topographic data used in this study shows the variations along three main roads of the island. Such a limited survey will not capture all the low and high areas of the island. Hence, the hazard zones identified may be incomplete due to this limitation.
- This study however is a major contribution to the risk assessment of safe islands. It has highlighted several leads in risk assessment and areas to concentrate on future more detailed assessment of safe islands. This study has also highlighted some of the limitations in existing safe island concept and possible ways to go about finding solutions to enhance the concept. In this sense, this study is the foundation for further detailed risk assessment of safe islands.
- There is a time scale mismatch between environmental changes and socio-economic developments. While we project environmental changes for the next

100 years, the longest period that a detailed socio-economic scenario is credible is about 10 years.

- Uncertainties in climatic predictions, especially those related Sea Level Rise and Sea Surface Temperature increases. It is predicted that intensity and frequency of storms will increase in the India Ocean with the predicted climate change, but the extent is unclear. The predictions that can be used in this study are based on specific assumptions which may or may not be realized.
- The following data and assessments need to be included in future detailed environmental risk assessment of safe islands.
  - A topographic and bathymetric survey for all assessment islands prior to the risk assessment. The survey should be at least at 0.5m resolution for land and 1.0m in water.
  - Coral reef conditions data of the 'house reef' including live coral cover, fish abundance and coral growth rates.
  - At least a years data on island coastal processes in selected locations of Maldives including sediment movement patterns, shoreline changes, current data and wave data.
  - Detailed GIS basemaps for the assessment islands.
  - Coastal change, flood risk and climate change risk modeling using GIS.
  - Quantitative hydrological impact assessment.
  - Coral reef surveys
  - Wave run-up modelling on reef flats and on land for gravity waves and surges.

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4. Structural vulnerability and impacts

Funadhoo Island is exposed to ocean-originated flooding only. The barrier island on the eastern side well protects most part of the island from tsunami floods except for the northern part and southern end of the island. Swell wave/surge floods prevail in the southern end only, and the inundation extent might be very limited according to geomorphologic observations.

4.1 House vulnerability

Only 8 houses are identified as vulnerable, which account for 2% of the total houses.

The vulnerability of the houses is dominantly featured by their poor physical conditions, such as weak foundation, poorly structured wall, and weak roof. All the existing houses are located away from shoreline with a very reasonable distance. No houses are found to be lower than their adjacent road surface (Fig. 4.1).

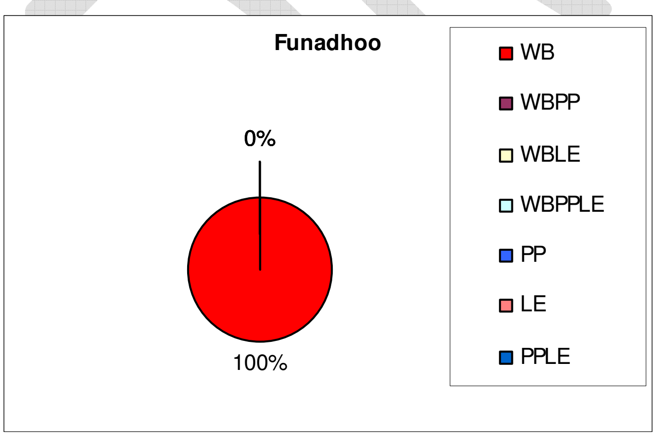

Fig. 4.1 House vulnerability by house on Funadhoo Island.

4.2 Houses at risk

Currently, around 140 houses are exposed to tsunami flooding, accounting for 35% of the total houses on the island. However, none of them are vulnerable to flooding (Table 4.1). Even the southward expansion of the settlement in the near future does not create additional exposure (Fig. 4.2).

The houses on Funadhoo Island are not vulnerable to Earthquake, either. According to RMSI (2006), Funadhoo Island is located in Seismic Hazard Zone 1 with a PGA of less than 0.04. With the current physical conditions of the houses, no damage is expected during earthquake. In worse cases, only 8 houses may be subjected to a slight damage.

Table 4.1 Houses at risk on Sh. Funadhoo.

Hazard type		**Exposed houses**		**Vulnerable houses**		**Potential Damage**							
						Serious		**Moderate**		**Slight**		**Content**	
		#	**%**	**#**	**%**	**#**	**%**	**#**	**%**	**#**	**%**	**#**	**%**
Flood	***TS***	135	35.7	0	0	0	0	0	0	0	0	0	0
	W/S	0	0	0	0	0	0	0	0	0	0	0	0
	RF	-	-	-	-	-	-	-	-	-	-	-	-
Earthquake		*378*	*100*	8	2.1	*0*	*0*	*0*	*0*	*8*	*2.1*	*0*	*0*
Wind		*378*	*100*	*8*	2.1	-	-	-	-	-	-	-	-
Erosion													

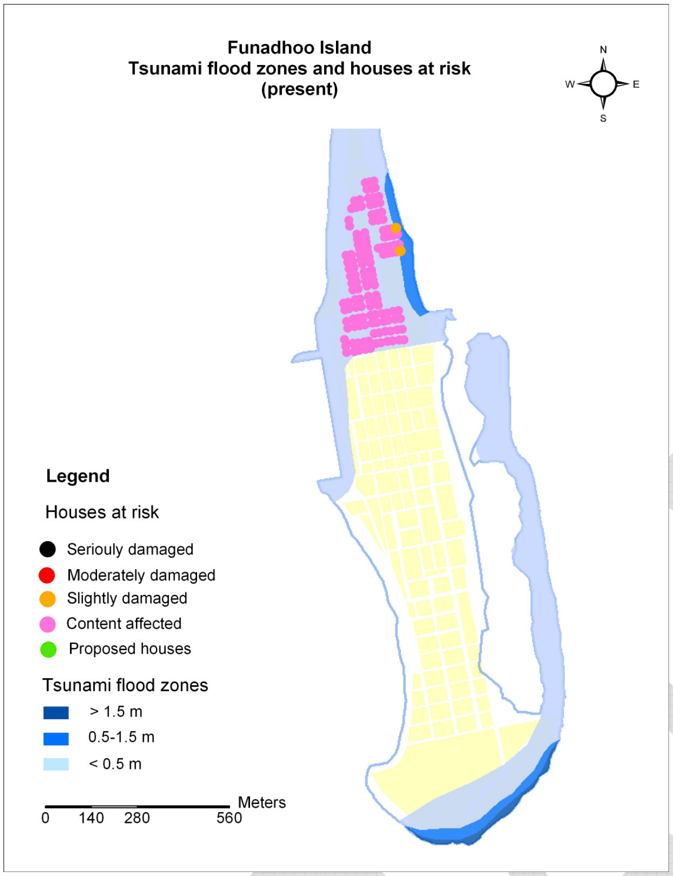

Fig. 4.2 Houses at risk associated with tsunami flooding.

4.3 Critical facilities at risk

Most of the existing critical facilities are located in the center of the island, a hazard-free area.

In the future, two key critical facilities are supposed to locate in the ocean-originated floods in the southern end of the island and will be exposed to swell wave, storm surge, and tsunami floods.

Table 4.2 Critical facilities at risk on Funadhoo Island.

Hazard type	Critical facilities		Potential damage/loss	
	Exposed	Vulnerable	Physical damage	Monetary

					value
Flood	Tsunami	Proposed waste site & power house	Both of them	Slight to moderate	
	Wave/Surge	Proposed waste site and power house	None	None	
	Rainfall	-	-	-	-
Earthquake		-	-	-	-
Wind		-	-	-	-
Erosion		-	-	-	-

4.4 Functioning impacts

Damage or impacts of the proposed power house and waste site can result in secondary contamination and disruption of power house (Table 4.3).

Table 4.3 Potential functioning impact matrix

Function	**Flood**			**Earthquake**	**Wind**
	Tsunami	**Wave/surge**	**Rainfall**		
Administration[1)]					
Health care					
Education					
Housing					
Sanitation[3)]	Secondary contamination				
Water supply					
Power supply	Disruption of power supply				
Transportation					
Communication[2)]					

Note: 1) Administration including routine community management, police, court, fire fighting; 2) Communication refers to telecommunication and TV; 3) Sanitation issues caused by failure of sewerage system and waste disposal.

4.5 Recommendations for risk reduction

According to the physical vulnerability and impacts in the previous sections, the following options are recommended for risk reduction of Sh. Funadhoo:

- *Avoid locating the key critical facilities such as power house and waste site in the flood-prone area.*

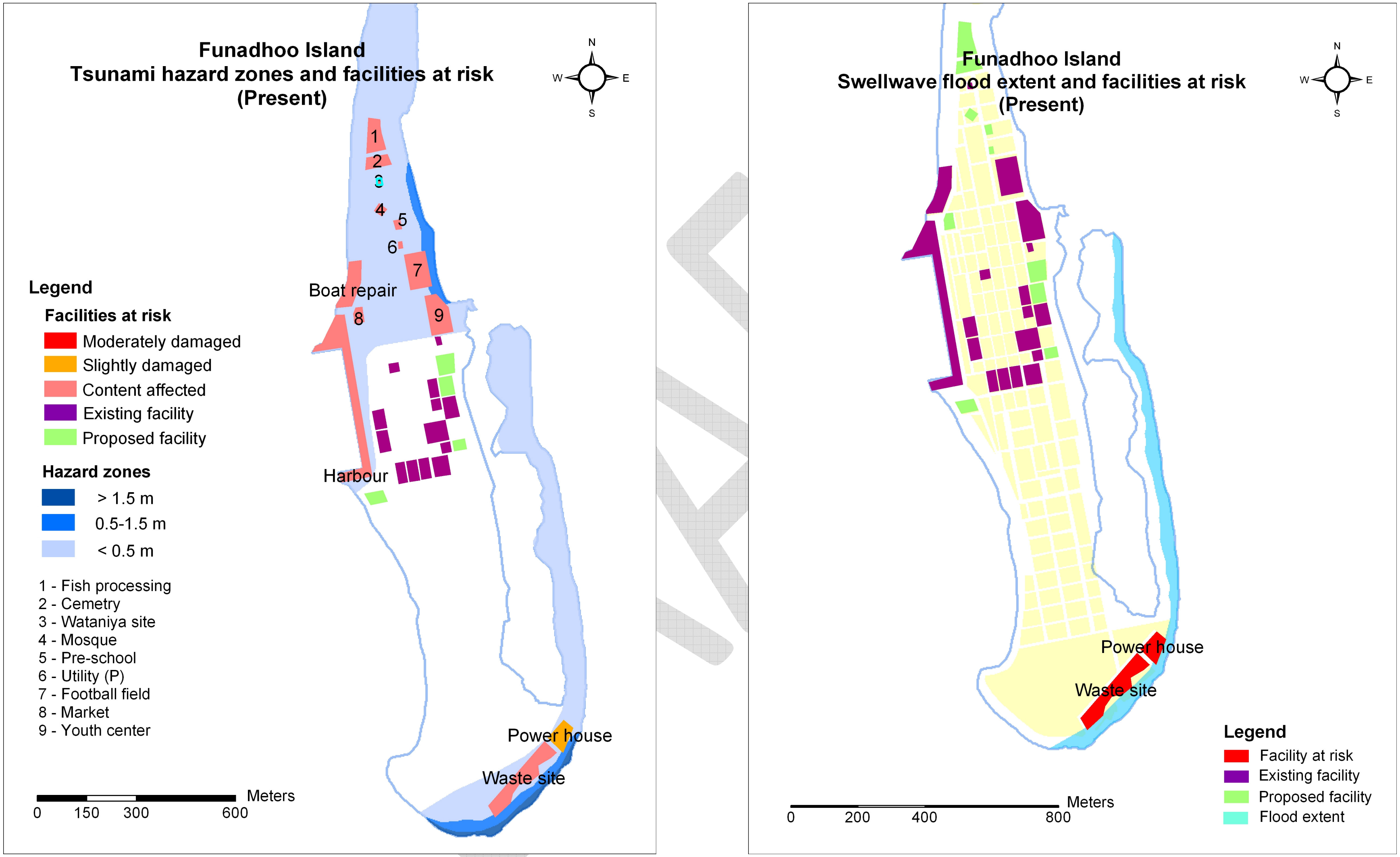

Fig. 4.4 Critical facilities at risk associated with tsunami floods (left) and wave surge floods (right).