Detailed Island Risk Assessment in Maldives

Volume III: Detailed Island Reports

Th. Vilufushi – Part 1

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Table of contents

1. Geographic background

1.1 Location

Vilufushi Island is located at the bottom of the two chains of atolls in central Maldives, at approximately 73° 18' 30"E and 2° 30' 11" N. It is located 187 km from the nation's capital, Male', and 75km from the nearest airport, Laamu Kadhdhoo (Figure 1.1). The island forms part of the Kolhumadulu Atoll (Thaa Atoll). The Atoll Capital is located 42km southwest of Vilufushi. It's nearest inhabited islands are Madifushi (17 km), Dhiyamigili (18.5 km), Guraidhoo (20 km) and Buruni (22 km). Vilufushi is in a strategic location due to its access to fishing grounds of the eastern coastline of Maldives. Thaa Atoll is located approximately 30 km inside the eastern line of atolls and is more aligned with the western line of atolls.

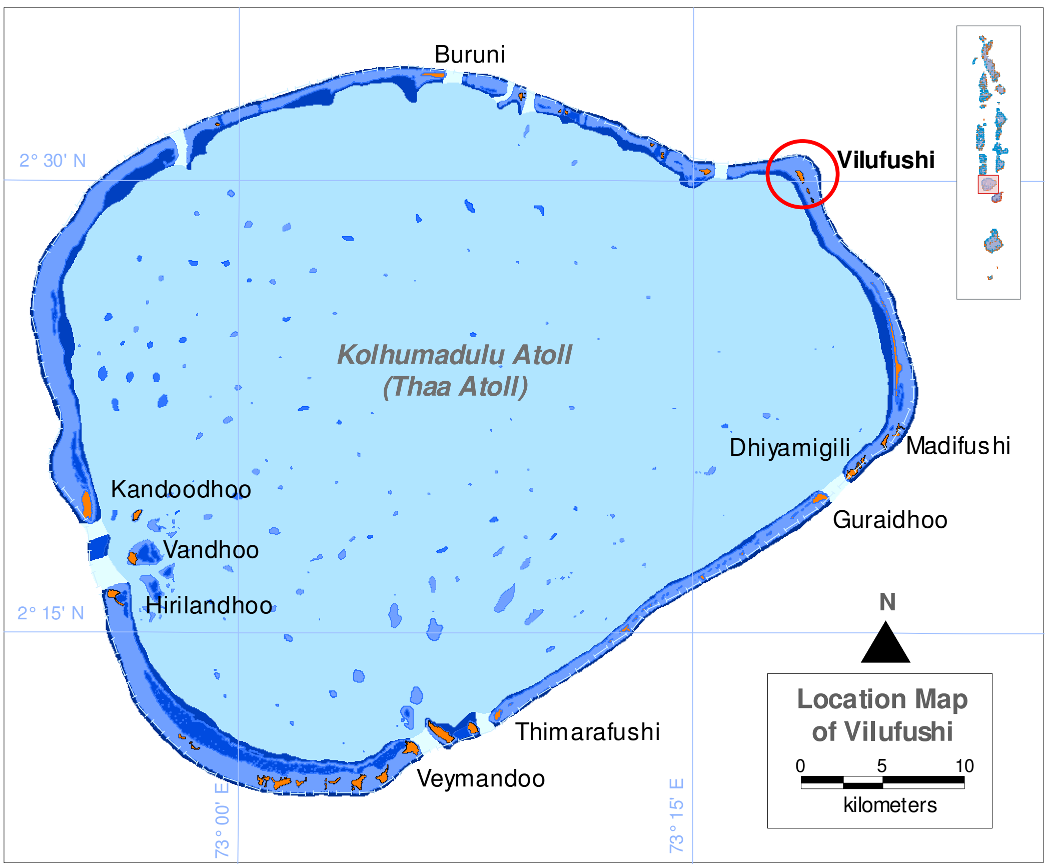

Figure 1.1 Location map of Vilufushi.

1.2 Physical Environment

The original Vilufushi Island was a small island with a length of 800 m and a width of 270 m at its widest points. The total surface area of the island was 15 Ha (0.15 km^2) and the reef surface area comprised of 3558 Ha (35.6 km^2). The reef also hosts nine other islands; out of which two are inhabited islands (Madifushi and Dhiyamigili), one is presently being developed as tourist resort (Kalhufahalafushi) and the remaining are uninhabited islands. The original island was located a fair distance away from the oceanward reef edge (800m) but close to the lagoonward reef edge (300m). The depth of the reef flat is quite shallow averaging less than -1m MSL. The original island had an elevation ranging from +0.8 to +1.5m MSL (EDC, 2006). The island is located on an east west orientation and is located on the eastern rim of Thaa Atoll.

The original Vilufushi Island was heavily urbanised with a population density of over 100 persons per Ha, making it one of the most overcrowded islands in Maldives. The settlement had expanded to the edges of coastline and new plots were being developed with ad hoc land reclamation. The island only had thin layer of depleted coastal vegetation.

Since the tsunami of 2004, all the existing structures on the original island has been removed and new land has been reclaimed to make Vilufushi four times its original size. The new land area is 61 ha (0.61 km^2) and with a length of 1260m and a width of over 550m. The entire island has been levelled to +1.4m above MSL.

Vilufushi is the first island developed to the specification of the safe island concept. It contains a coastal protection zone of 20m which comprise of a boulder based revetment +2.4m above MSL, an artificial ridge extending a further 12m and a low area (drainage zone) of 20m. Currently there is very little vegetation on the island, much of which is the narrow stretch of coastal vegetation around the original island. The revetment extends right around the island except for 2 small zones on the western side of the island. A new harbour has been dredged on the eastern side and is protected by boulders based breakwaters. No further developments have been made on the island at the time of this study, but a complete rebuilding of the island has been planned. The development will be highlighted in latter sections.

Vilufushi Island environment is now essentially an artificial environment. It's natural coastal environment has been replaced completely with revetments and a harbour. It terrestrial environment will have to be entirely re-developed due to the extensive reclamation and vegetation removal.

2. Natural hazards

This section provides the assessment of natural hazard exposure in Th.Vilufushi 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.

The island was completely devastated by the Indian Ocean tsunami of December 2004 and the inhabitants haves been relocated to neighbouring islands. Since then the island has been completely rebuilt including extensive land reclamation, topographic levelling and construction of wave barriers. The island was under reconstruction at the time of the survey. It was therefore impractical to base the hazard exposure on existing physical environment and hence assessment was based on existing development plans.

2.1 Historic events

The assessment of historic events had to rely on the records for the old island prior to the extensive developments. The specific exposure of the island due to prevailing physical environment of the time may not be entirely applicable to the present island. However, the events assessment will highlight the types of hazards facing the island even though their impacts are irrelevant.

According to the available historic records and field interviews, Vilufushi has been exposed to multiple hazards in the past although its exposure has been very limited and the intensity negligible in most cases (Table 1.1). There were no records of prior swell wave related flooding in Vilufushi and neither was their any record for nearby islands such as Madifushi, Dhiyamigili and Buruni. There were occasional records for Udha related incidents, but their intensity was very limited an effected the first 10-20m of the coastline. Although the island received high amounts of rainfall in the past, rainfall related flooding has not been an issue due the arc shaped topography and narrow width of the island. The only event with a high frequency and intensity was reported as wind storms, where structural and vegetation damage was reported on a few occasions. The Indian Ocean tsunami of 2004 was reported as the only major event on the island, but this specific event destroyed the entire settlement and recorded the highest single island fatalities for a natural disaster event in Maldives.

Table 2.1 Known historic hazard events of Vilufushi.

Metrological hazard	Dates of the recorded events	Impacts
Flooding caused by Heavy rainfall	none	Impacts were non-existent due to the narrow width of the island and subsequent good drainage on the island.
Flooding caused by swell surges	none	None reported.
Flooding caused by udha	Annually	Effects are limited to within 10-20m of coastline. Few houses built within 5m of the southeast coastline report occasional flooding due to udha. Its impacts are limited to damages to personal belongings
Windstorms	• *No dates identified*	Damage to vegetation and property. Most damage limited to roof displacements and structural damage from falling trees.
Droughts	none	No major event have been reported
Earthquake	none	No major event have been reported
Tsunami	26th Dec 2004	Entire island was flooded. Flood heights were reported at 2.0m (maximum). Flood heights and their distances are as follows. ☞ 2.0m – at a distance of 30m from shoreline ☞ 1.5m at a distance of 100m from shoreline ☞ 1.0m at a distance of 150m from shoreline ☞ less than 0.5m – at the western coastline The primary reasons for complete inundation may be related to the low ridge and the narrow width of the island.

We faced two main difficulties while interviewing the locals, which affected the final findings. First the inhabitants were grateful for the intensive assistance given by the government to rebuild the island amidst a public concern over the amount of financial resources spent on rebuilding a very ‘vulnerable settlement’. Hence, the answers they provided during the interviews were biased towards making Vilufushi appear a very safe island in the past. They might have feared the findings from this study may be used in arguing against rebuilding the island. Second, the intensity of the tsunami had painted a picture of flooding hazard in their minds. All other incidents were being compared with the tsunami events and in their minds were irrelevant.

2.2 Major hazards

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

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

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2.2.1 Swell Waves and Wind Waves

The location of Vilufushi makes the island relatively sheltered from possible swell waves approaching from the Southern Indian Ocean. Studies undertaken 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)). The location on the NE corner of the atoll shelter the island to these swell waves. The shape of the atoll, and the atoll's location close to the western line of atolls in the archipelago, also tends to protect the island from swell waves approaching from a south easterly direction (See Figure 2.1). However, there is a probability that waves refracting around the north eastern tip of Laamu Atoll to cause swell waves to reach the reef edge of Vilufushi. The effects of any such remnants could further be reduced due to the large width of reef flat, which could absorb the waves. The possible lack of strong waves can also be partially backed by the geomorphological findings from the study. Hence, it is high plausible that the absence of any reported historical flood event is actually due to the relative protection Vilufushi island enjoys against southern swell waves. For example, the swell waves that originated from the south eastern Indian Ocean affecting most islands on the eastern rim of the central Maldives during April 1987 (Goda, 1998), did not impact Vilufushi.

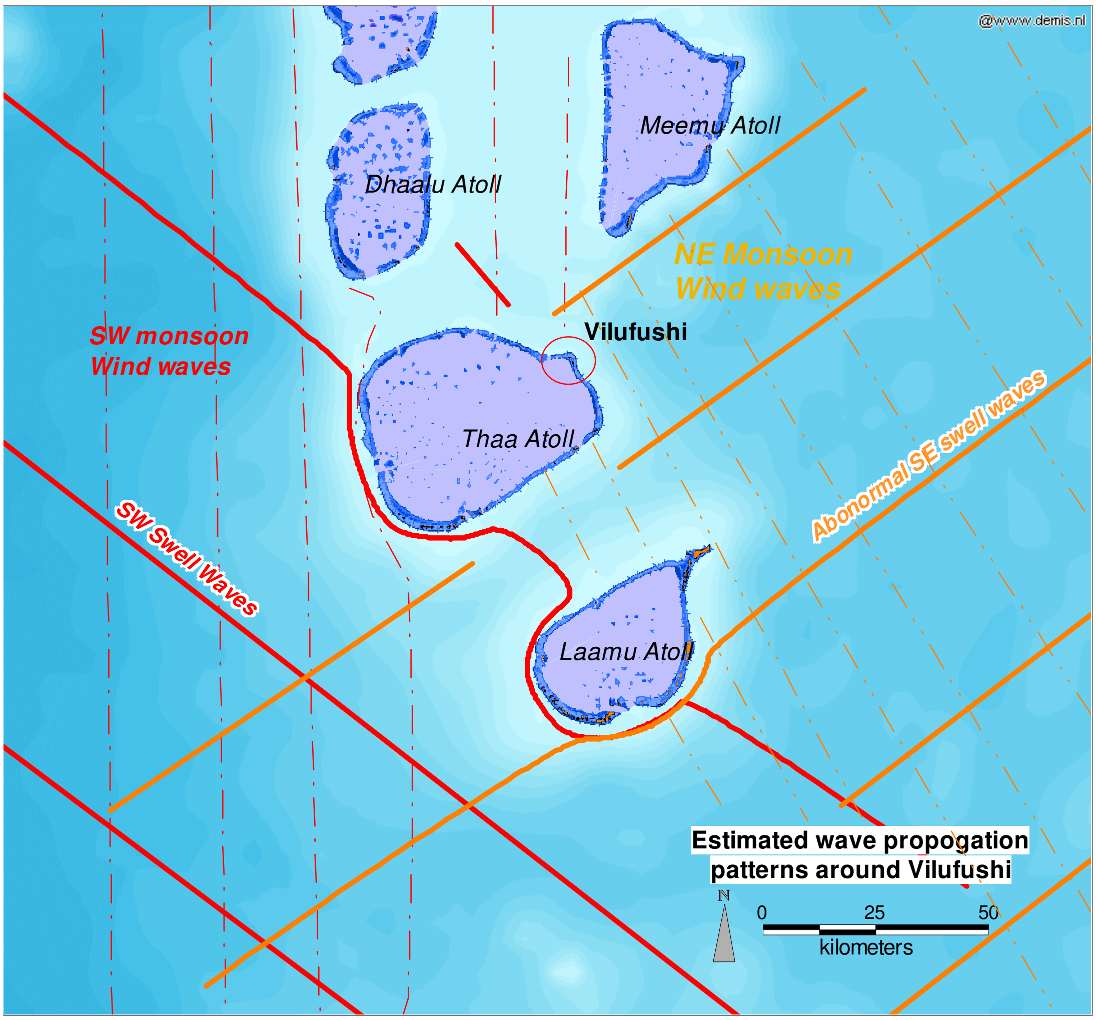

Figure 2.1 Estimated (predominant) wave propagation patterns around Vilufushi: the island enjoys protection from southern swell waves due to its location, atoll shape and line-up of atolls.

There is probability that swell waves could penetrate through the 4 km wide western reef pass and propagate to the western shoreline of Vilufushi (based on Kench et al.,(2006)). However the impacts of such waves are expected to be minimal due to the narrow channel width and presence of patch reefs within the atolls.

Vilufushi is more likely to be exposed to wind waves during both the NE and SW monsoon. During SW monsoon, strong wind and the 35-45 km fetch area within the atoll may generate wave less than 0.5 m. During the NE monsoon, wind waves could reach significant heights (at open ocean) of 1.5-2.0 m between December and February (EDC, 2006). Hence, the reports of annual low levels of flooding during the *Udha* season are well founded and predicted to continue effecting Vilufushi.

The Disaster Risk Assessment report of 2006 (UNDP, 2006), reported that Vilufushi was located in a moderate storm surge hazard zone with probable maximum event reaching 0.6m above MSL or 1.53 m with a storm tide. The combined historical records of nearby islands in Meemu, Thaa and Laamu Atoll does not show any flooding caused by a storm surge. The occurrence of any abnormal swell waves or surge on Vilufushi 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. 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.

The island has now undergone major transformation of its coastline and has coastal protection developed at a height of 2.4 m above MSL. Based on the predicted maximum storm surge scenario of 1.53 m storm tide of and a probable maximum swell wave height of 2.0 m above MSL, the island is unlikely to be flooded from its eastern side. There is a small probability that wave refraction around the island may cause low levels of inundation on the unprotected areas of the western coastline.

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 2.2). The average rainfall at S Gan is approximately 481mm more than that at HDh Hanimadhoo.

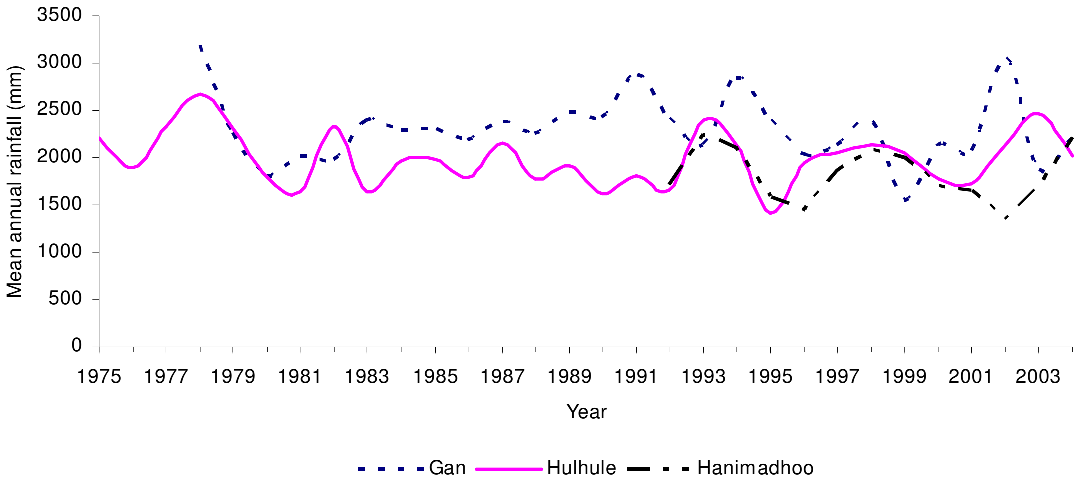

Figure 2.2 Map showing the mean annual rainfall across the Maldives archipelago.

The closest meteorological station to L.Vilufushi is Kadhoo airport which became operational in 1986. Unfortunately this study does not have access to Kadhoo data. Moreover, Kadhoo data may be limited for long term trend observation due smaller number of detailed observation years. Hence, to resolve the issue, data from Hulhule' has been used. It is recommended that further assessment be made once Kadhoo data becomes available.

The mean annual rainfall of Hulhule' is 1991.5 mm with a Standard Deviation of 316.4 mm and the mean monthly rainfall is 191.6 mm. Rainfall varies throughout the year with mean highest rainfall during October, December and May and lowest between February and April (See Figure 2.3). Limited severe weather reports shows that Kadhoo received a maximum precipitation of 110.8 mm for a 24 hour period on 21th November 2004 (DoM, 2005). Based on interviews with locals, this event did not cause any flooding on the island.

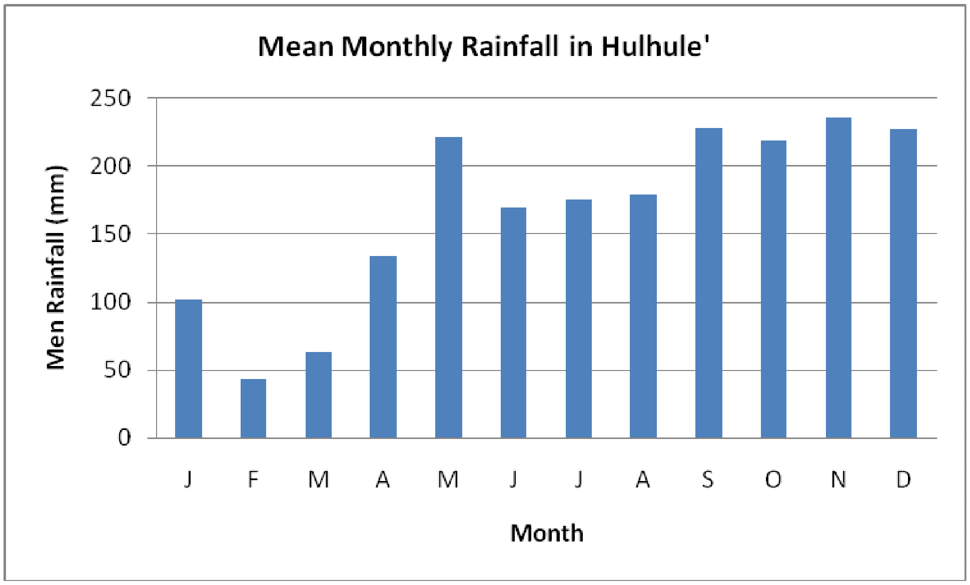

Figure 2.3 Mean Monthly Rainfall in Hulhule'(1975-2004).

Historic records show that Vilufushi is not affected by rainfall related flooding. As noted earlier, this is most likely due to the well established natural drainage system on the island. Due to the arc shape and narrow width of the island, water drains quickly towards the sea. If the rainfall is higher the surface runoff is increased, often creating small gullies along the east-west roads.

The redevelopment of Vilufushi through extensive reclamation and topographic profiling would change the rainfall related hazard exposure in the island. At present, it is impossible to undertake a detailed assessment of rainfall hazard zones and the reclamation and profiling has only been completed recently. According to the reclamation and settlement master plan, a natural drainage system was to be established where the old island coastline meets the new reclaimed land. Unfortunately, this plan was overlooked during the implementation and the entire island was reported to have been levelled to 1.4m MSL. It is unclear how this would affect the future drainage system of the island. It is well known that newly reclaimed areas undergo settlement over time and could develop topographic variations, especially in coral island environments due to the increased compressibility of the carbonate sand (based on Chang et al., (2006)). It is also now understood that the hydraulic conductivity of newly reclaimed land could be lower than a naturally developed soil system (Guo and

Jiao, 2007). No specific tests have been done in Maldives to date, but if the current findings on carbonate sand elsewhere hold true, it could increase the flooding intensity in Vilufushi.

The proposed drainage zone within the Environment Protection one could also attract surface runoff during heavy rainfall. However, it remains unclear how the drainage zone would function given the proposed topographic profiling of a 0.1 m lower than the island height, without any graduated contouring.

The probable maximum precipitations predicted for Hulhule' and S.Gan by UNDP (2006) are shown in Table 2.2:

Table 2.2 Probable Maximum Precipitation for various Return periods in Hulhule' and Gan.

Station	**Return Period**			
	50 year	100 year	200 year	500 year
Hulhule'	187.4	203.6	219.8	241.1
Gan	218.1	238.1	258.1	284.4

Given the high variations in rainfall in Kadhoo, these figures may vary. Based on the field observations in other islands and correlations with severe weather reports from Department of Meteorology ((DoM, 2005) the following threshold levels were identified for flooding (Table 2.3). These figures must be revised once site specific daily rainfall data becomes available and once a comprehensive topographic survey has been undertaken. This assessment also does not take into account any artificial drainage systems that may be established on the island.

***Table 2.3 Threshold levels for rainfall related flooding in Vilufushi*.**

Threshold level (daily rainfall)	**Impact**
50mm	Puddles on road, flooding in low houses, occasional minor damage to household goods in most vulnerable locations, disruption to businesses and primary school in low areas.
100mm	Moderate flooding in low houses; all low lying roads flooded; moderate damage to household items especially in the backyard areas
150mm	Widespread flooding on roads and low lying

	houses. Moderate to major damage to household goods, School closure.
200mm	Widespread flooding on roads and houses. Major damages to household goods, sewerage network, backyard crops, School closure, gullies created along shoreline, possible damage to road infrastructure.
230+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, sewerage network and quay wall.

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 the table.

2.2.3 Wind storms and cyclones

Maldives being located within the equatorial region of the Indian Ocean is generally free from cyclonic activity (Fig. 2.4). There have only been a few cyclonic strength depressions that have tracked through the Maldives, all which occurred in the northern and north central regions. According to the hazard risk assessment report (UNDP, 2006) Gan falls within the second least hazardous zone for cyclone related hazards and has a maximum predicted cyclonic wind speeds of 56 Kts (see figure below). There are no such records for the southern region, although a number of gale force winds have been recorded due to low depressions in the region. Winds exceeding 35 knots (gale to strong gale winds) were reported as individual events in Kadhoo annually between 2002 and 2006, all caused by known low pressure systems near Maldives rather than the monsoon (DoM, 2005). The maximum wind speed in Kadhoo during this period was approximately 46 kts.

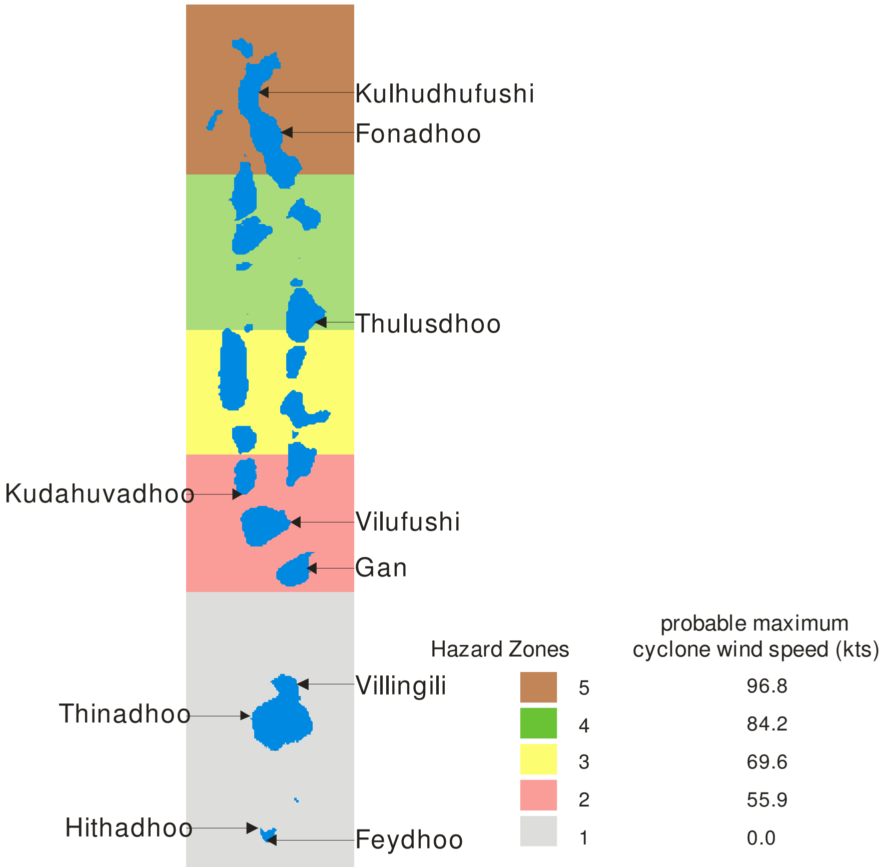

Figure 2.4 Cyclone hazard zones of the Maldives as defined by UNDP (2006).

Historic records for Vilufushi have indicated that near gale force winds (see Table 3.6) have caused minor damage to property and trees on the island. Hence during the high winds between 2002 and 2005, a number of minor to moderate damages were reported to vegetation and property. Vilufushi Island is sparsely vegetated due to the high population density which could aid in increasing the intensity on structures.

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 2.4 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 are predicted based on interviews with locals and housing structural assessments provided by risk assessment report (UNDP, 2006), as shown in Table 2.5

Table 2.5 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 vegetation
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

The thresholds provided here could change based on the development undertaken on Vilufushi. At present there is no planned re-vegetation programme which could eventually lead to continued exposure of structures to direct impacts of strong wind during SW monsoon and localised storm events.

2.2.4 Tsunami

UNDP (2006) reported the region where Vilufushi is geographically located to be a very high tsunami hazard zone. The tsunami of December 2004 had devastated a number of islands in the eastern rim of Thaa atoll. Vilufushi was amongst the worst effected islands in Maldives. According to the official estimates, the entire island was flooded during this event. Flood waters travelled from coast to coast with little loss of intensity. Wave heights were reported at 2.0m on the eastern coastline and 0.5 m on the western coastline. There were extensive damage to majority of the properties on the island and also incurred the heaviest casualties and fatalities in Maldives. The severest damage to the houses and structures were 100m from the coastline eastern. The decay of the flood water for this tsunami showed a logarithmic decay function.

Comparatively higher exposure of Laamu Atoll may be partially due to the refraction of the wave caused by the Indian Ocean bathymetry as it travelled westwards Maldives (Ali, 2005). The Indian Ocean bathymetry (Fig 2.5) shows shallower water depths extended far offshore at around the central region of the Maldives (at around the atolls of Laamu – Meemu). This shallower area caused the wave to bend away from the southern atolls and became focused towards the central region of the country. It is likely that a similar pattern may persist in any future event if the waves originate from the northern Sundra trench.

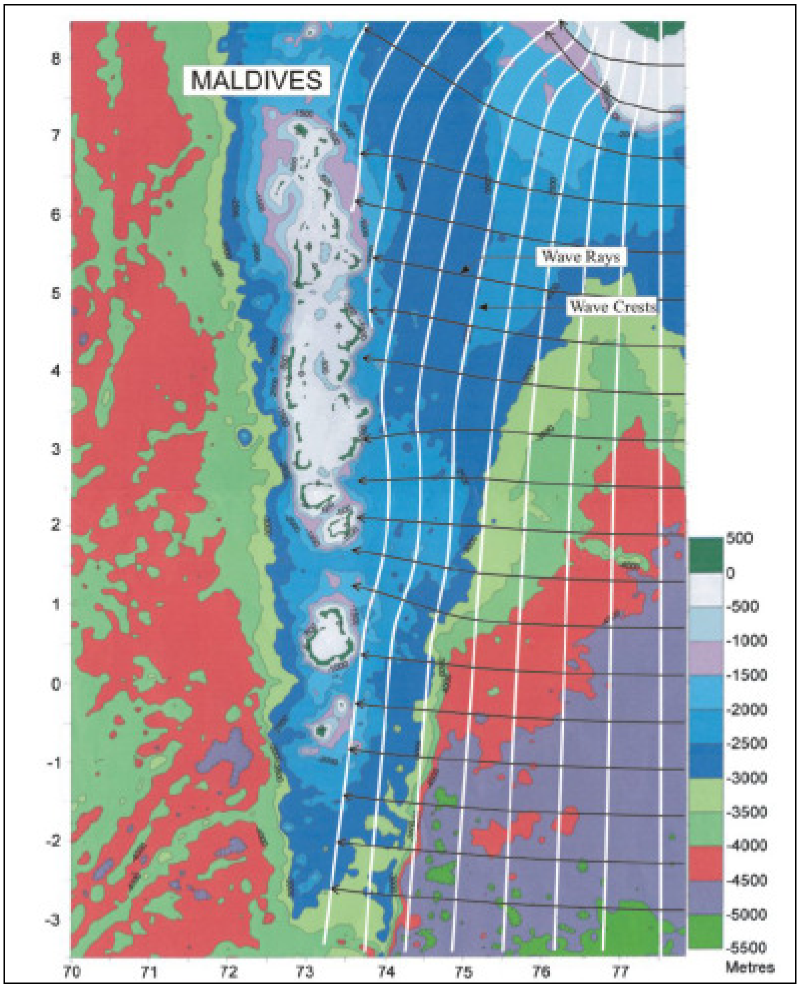

Figure 2.5 Submarine topography around Maldives archipelago and modelled wave refraction for the December 2004 tsunami (source: Ali (2005)).

The predicted probable maximum tsunami wave height for the area where Vilufushi is located is 3.2 – 4.5 m (UNDP, 2006). Examination of the flooding that will be caused by a wave run-up of 4.5m for the newly developed island indicates that such a magnitude wave will flood the eastern half of the island. The first 150-200 m from the shoreline will be a severely destructive zone (Figure 2.6). 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.

It also 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. This could cause flooding of the island from the lagoonward side of the island, if the water level rises above the height of the island. The maximum tsunami wave induced water level height predicted for the atoll lagoon near Vilufushi is 1.7m. This could flood the western half of the island up to 0.3m from the lagoonward side. Hence, there is high likelihood that the entire island will be flooded.

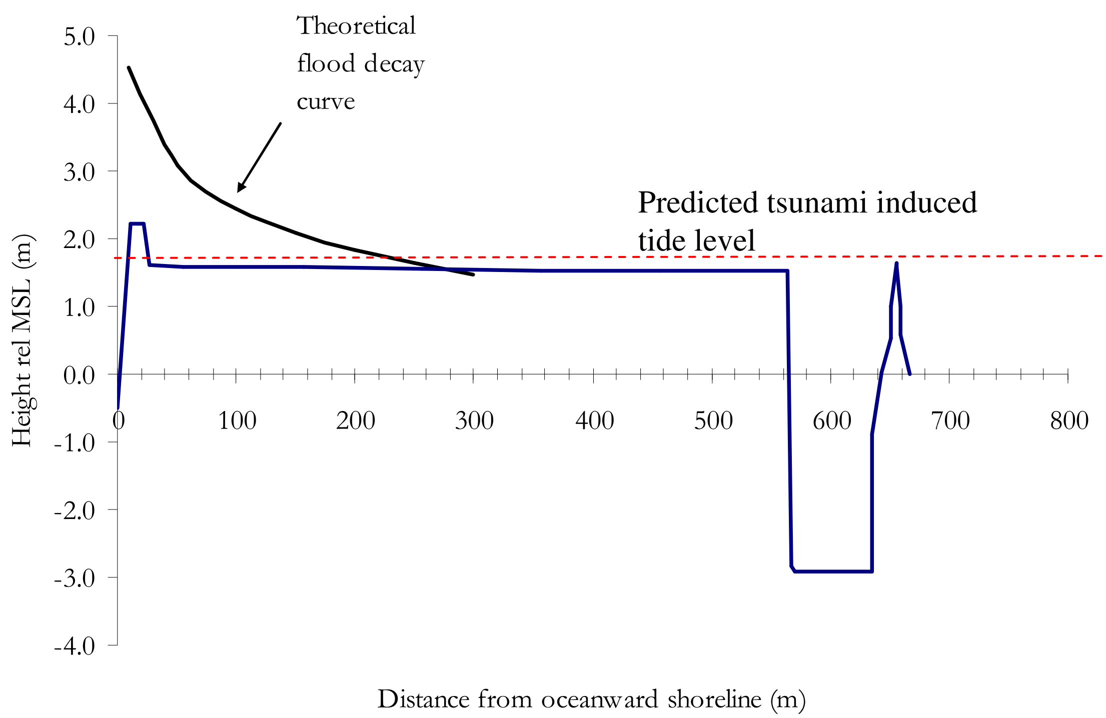

Figure 2.6 Tsunami related flooding predicted for Vilufushi based upon theoretical flood decay curve and the newly reclaimed islands cross-sectional profile.

2.2.5 Earthquakes

There hasn't been any major earthquake related incident recorded in the history of Vilufushi 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 Thaa 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 Vilufushi is located has a value less than 0.04 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 2.6). The MMI is a measure of the local damage potential of the earthquake. See Table 2.7 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 Vilufushi Island as time was limited for such a detailed assessment. Instead, the findings of UNDP (2006) were used.

Table 2.6 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 2.7 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

According to these findings it is unlikely that Vilufushi 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

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

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, 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 <u>increasing annual MTL at Gan of 3.9 mm/year.</u> 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 <u>MTL at Gan by 2100 will be nearly 0.4m above the present day MTL</u>.

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. Although no specific studies have been done for Thaa Atoll, the findings from Addu Atoll could be used as a guide to predicted changes.

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 southern Atolls.

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 Gan 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 2.7).

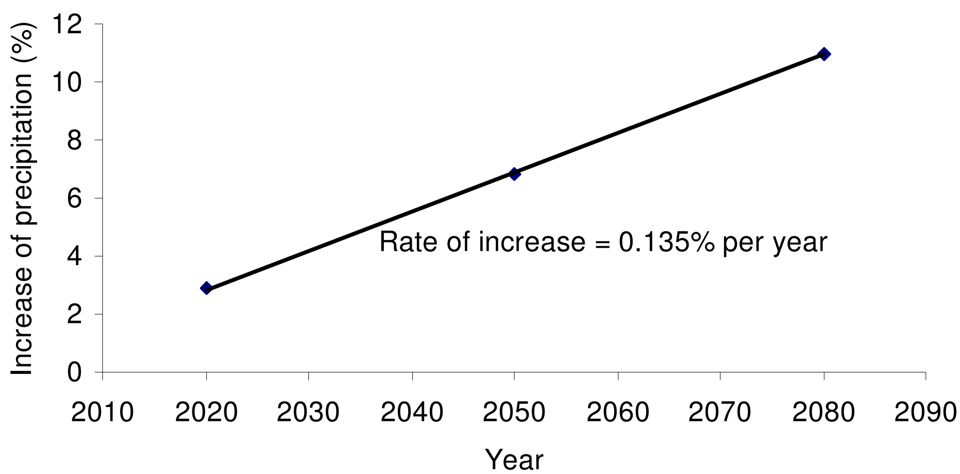

Fig 2.7 Graph showing the rate of increase of averaged annual mean precipitation in tropical south Asia (Adger et al., 2004).

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 Vilufushi 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 Vilufushi and surrounding region is summarised below. 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 2.8 Summary of climate change related parameters for various hazards.

Element	**Predicted rate of change**	**Predicted change (overall rise)**		**Possible impacts on Hazards in Gan**
		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°C / decade	Yr 2050: +1.72° Yr 2100: +3.72°		
SST	0.3°C / 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 effect 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 Vilufushi Island (Table 2.9, 2.10 and 2.11).

Table 2.9 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 +3.2 above reef flat)*	NA	< 3.5m	> 3.5m	> 4.0m	Moderate	Very Low	Unlikely
Storm Surges	1.53m	< 3.5m	> 3.5m	> 4.0m	Low	Unlikely	Unlikely
Tsunami *(wave heights on reef flat)*	4.5m	< 3.5m	> 3.5m	> 4.0m	Moderate	Low	Very low
SW/NE monsoon high seas	1.5m	< 3.5m 1.0.1.	> 3.5m	> 4.0m	High	Unlikely	Unlikely
Heavy Rainfall *(For a 24 hour period)*	284mm	<75mm	> 75mm	>175mm	High	Moderate	Low

Table 2.10 Slow onset flooding hazards (medium term scenario – year 2050)

Hazard	Impact thresholds			Probability of Occurrence		
	Low	**Moderate**	**Severe**	**Low**	**Moderate**	**Severe**
SLR: Tidal Flooding	< 2.5m	> 2.5m	> 3.5m	Moderate	Very Low	Very Low
SLR: Swell Waves	< 3.5m	> 3.5m	> 4.0m	Very high	Low	unlikely
SLR: Heavy Rainfall	<75mm	>75mm	>175mm	Very High	Moderate	Low

2.11 ther rapid onset events

Hazard	Max Prediction	Impact thresholds			Probability of Occurrence		
		Low	Moderate	Severe	Low	Moderate	1.0.2. Severe
Wind storm	NA	<30 knts	> 30 knts	> 45Knts	Very High	High	1.0.3. Moderate
Earthquake (MMI value[2])	I	< IV	> IV	> VI	Very Low	Unlikely	Unlikely

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

Swell waves and storm surges are unlikely to have an impact on the island given its present coastal protection structures remain intact (Figure 2.8). The threshold level for flooding on the island from the eastern side is wave heights of 3.2 m above reef flat. Smaller events may not affect the island while the probability of events higher than this

[2] Refer to earthquake section above

height is very low or unlikely. Similarly, the predicted storm surges are smaller than the ridge height.

The western side of the island is exposed to SW wind waves but their intensity is predicted to be low. Moreover, swell waves or surges could refract around the island or cause a rise in tide level which could flood the western coastal areas. The intensity of such events is expected to be moderate to low.

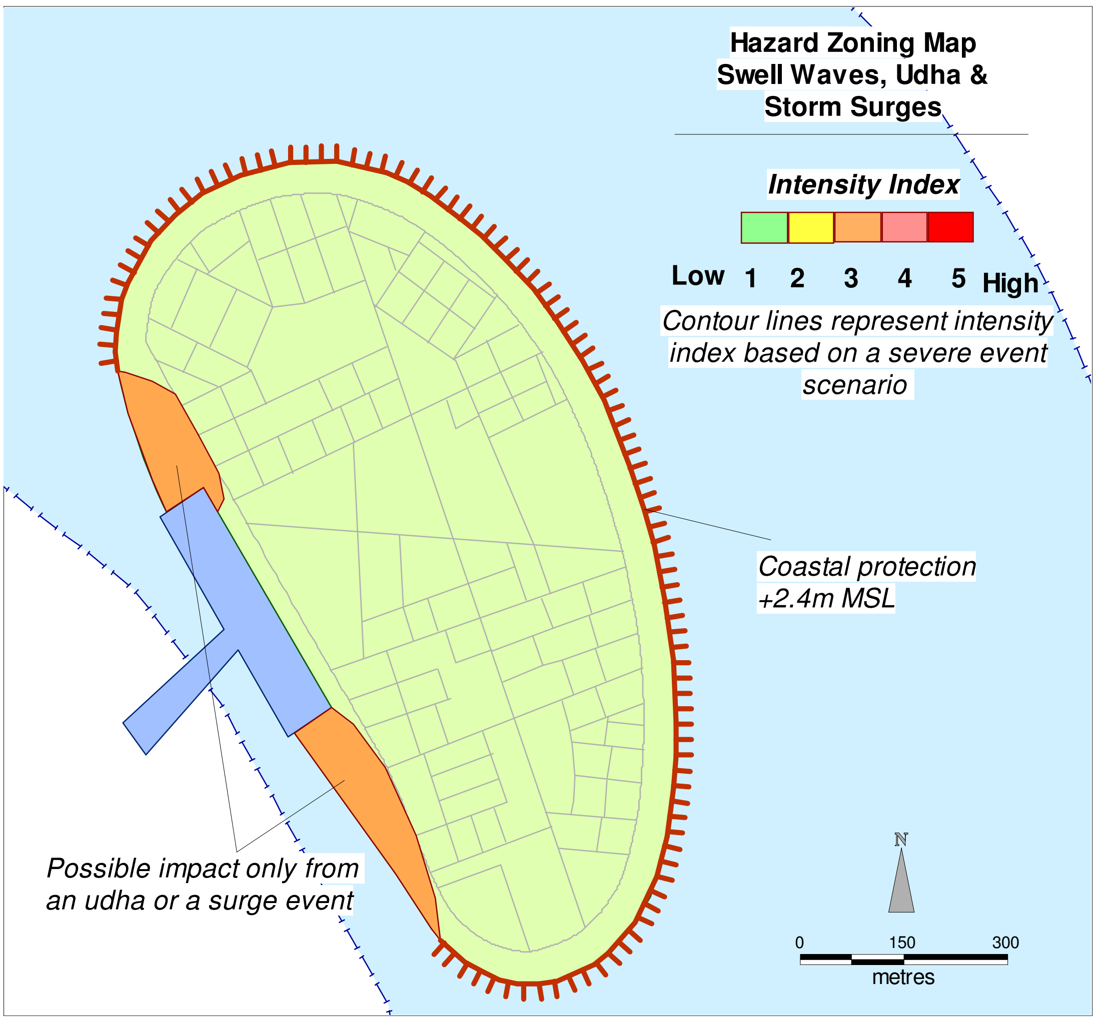

Figure 2.8 Hazard zoning map for swell wave, storm surges and southwest monsoon high seas.

2.4.2 Tsunamis

When a severe threshold of tsunami hazard (>4.0 m on reef flat) is considered, the entire island predicted to be effected (Figure 2.9). If the waves reach beyond 4.0 m on reef flat the entire island is highly likely to be flooded due the combined effects of rushing water from the eastern side and rise in tide levels from the lagoon ward side. The first 100m from the eastern coastline are expected to have the highest intensity capable of extensive destruction. Intensity of rushing water is predicted to be high to almost half of the island from the oceanward coastline based on the theoretical flood decay curve described earlier in this section.

The effected zone is dependent on the distance from coastline and minor variations in topography as it advances inland. This assessment is based on a flat topography and no obstructions. When developments do take place, there may be changes to the described hazard zones. 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 only predicted area for low impact is the artificially raised 'high ground' for emergency evacuation. Works on elevation had not started at the time of this study. The planned drainage zone proposed within the Environment Protection Zone (EPZ) is unlikely to have any influence on the run-up of a tsunami due the mere -0.1m variation proposed for the zone.

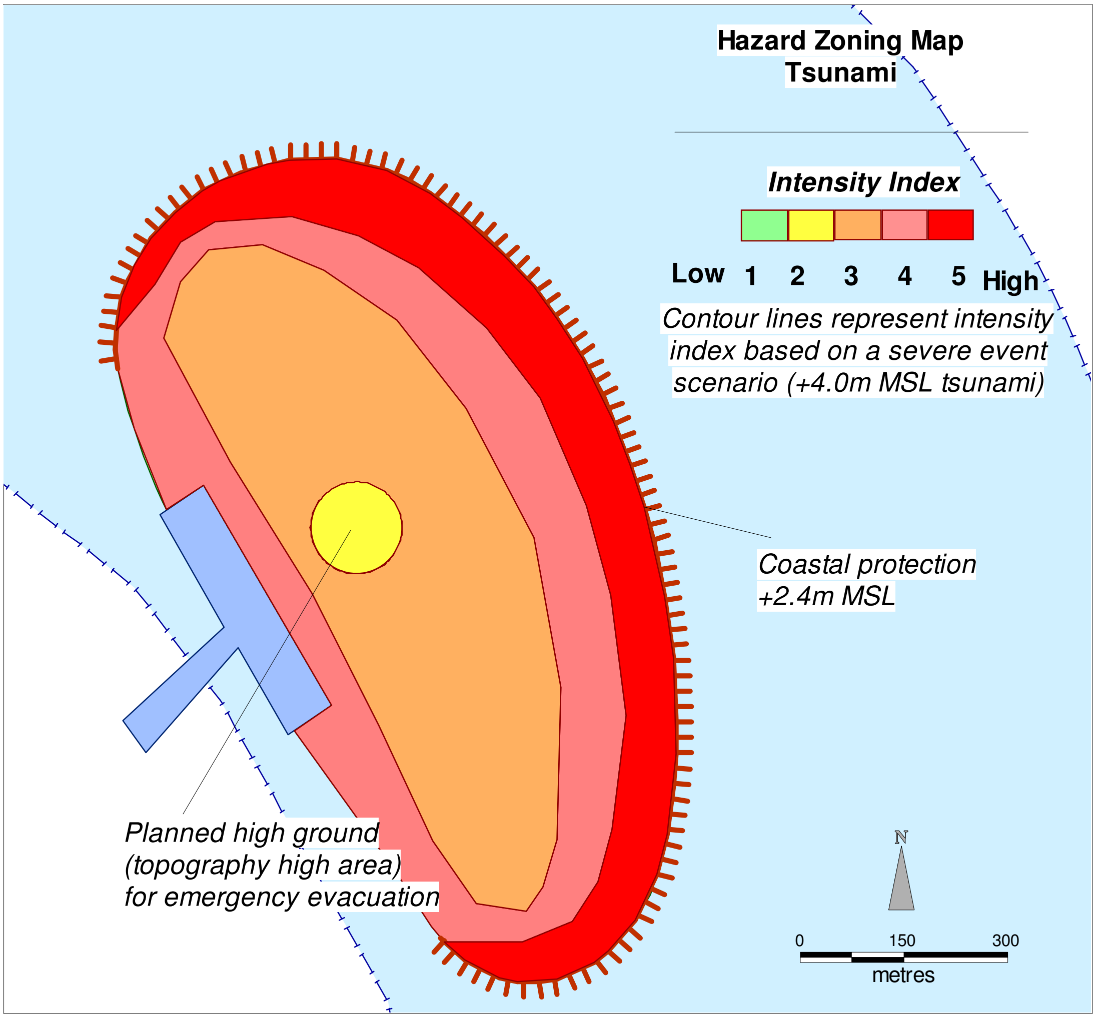

Figure 2.9 Hazard zoning map for tsunami flooding.

2.*4.3 Heavy Rainfall*

As noted earlier it is difficult to predict the rainfall hazards due the early stage of development in the island (Figure 2.10). However, an attempt has been made to forecast the potential hazard areas based on the planned topographic variations and assuming no artificial drainage systems will be established.

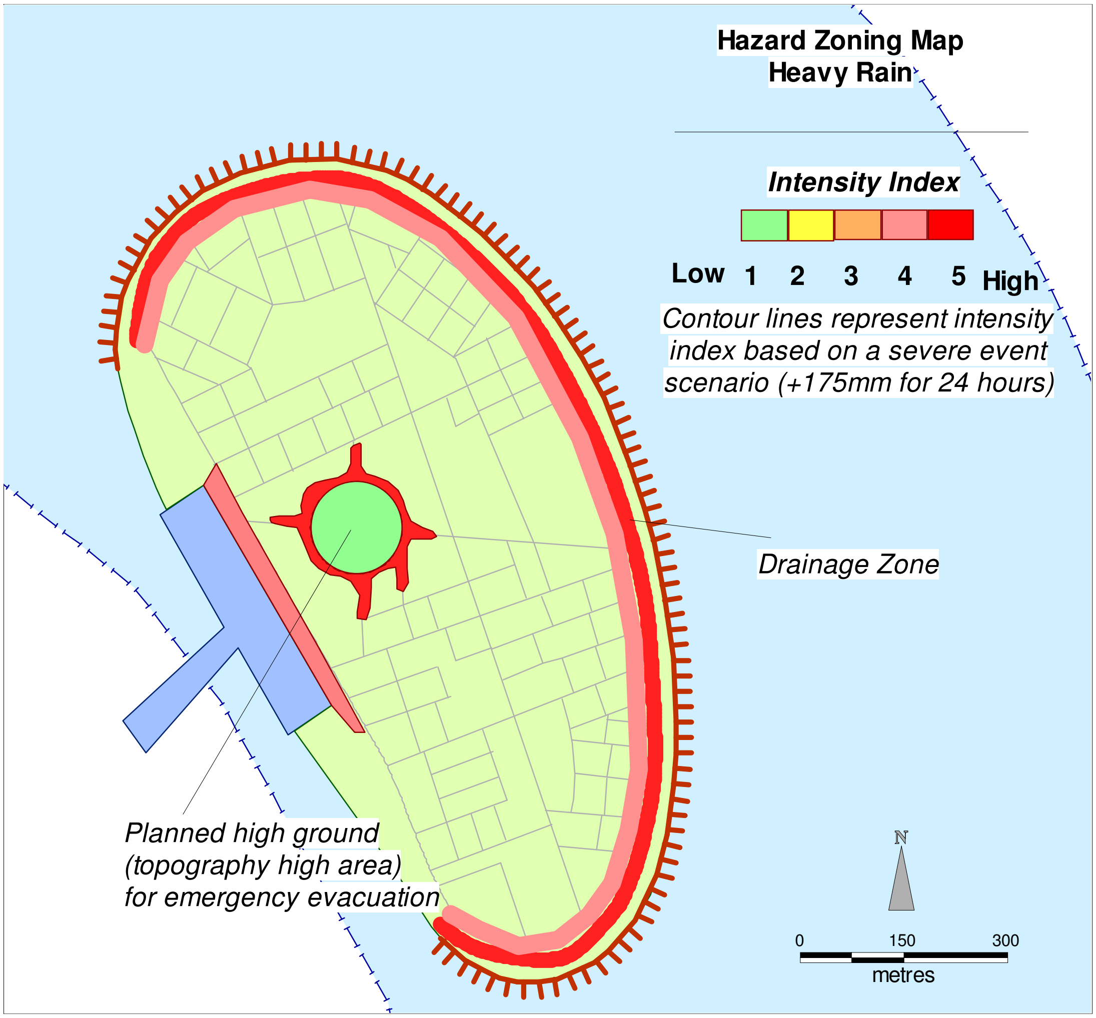

Figure 2.10 Hazard zoning map for heavy rainfall related flooding.

In this regard, the areas predicted for maximum intensity are the areas surrounding the 'high ground' and EPZ drainage zone. Areas close to the harbour is also likely to be exposed due the presence of the 'high ground' and any blockages caused by quay wall.

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. The entire island, except has been assigned an intensity index of 4 for strong winds during a severe event. The high ground area is expected to receive slightly higher intensity than what is experienced on the island due to its high elevation. Similarly the structures behind the area could experience a reduced intensity.

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.

2.4.7 Composite Hazard Zones

A composite hazard zone map was produced using a GIS based on the above hazard zoning and intensity index (Figure 2.11). The tsunami hazard dominates the multiple hazard indexes, since it is the only hazard that could occur with damaging intensity.

The coastal zone approximately 200m from the oceanward coastline is predicted to be the most intense regions for multiple hazards. The eastern side is particularly highlighted as a hazard zone.

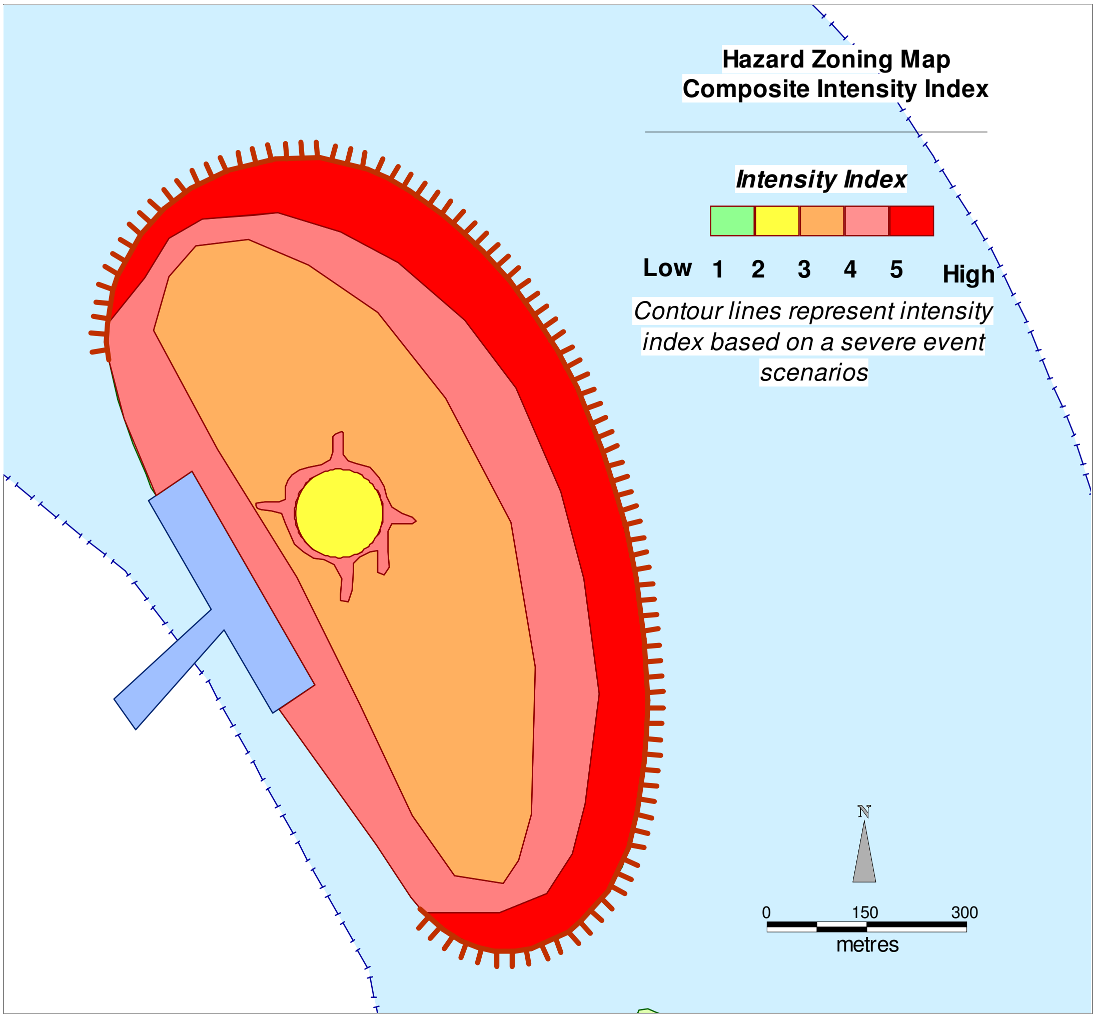

Figure 2.11 Composite hazard zone map.

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 Vilufushi 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 Vilufushi.

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3. Environment Vulnerabilities and Impacts

3.1 Environment Settings

3.1.1 Terrestrial Environment

Topography

Vilufushi Island has been entirely levelled to +1.4 m above MSL as part of the safe island development concept. The original island topography varied from +0.8 m to +1.5 m above MSL. Although much of the island is now raised, the height +1.4 m above MSL still makes Vilufushi a low lying island in terms of exposure to hazards. To mitigate the effects of low elevation, an artificial ridge has been developed around the island except on the western shoreline where a harbour is being developed. The ridge forms part of the Environment Protection Zone (EPZ) proposed under the safe island concept. EPZ includes a coastal protection zone of 20 m with a boulder based revetment +2.4 m above MSL, an artificial ridge extending a further 12 m and a low area (drainage zone) of 20 m. The existing profile of the island is shown in Figure 3.1 below and details of the environment protection zone in presented in Figure 3.2.

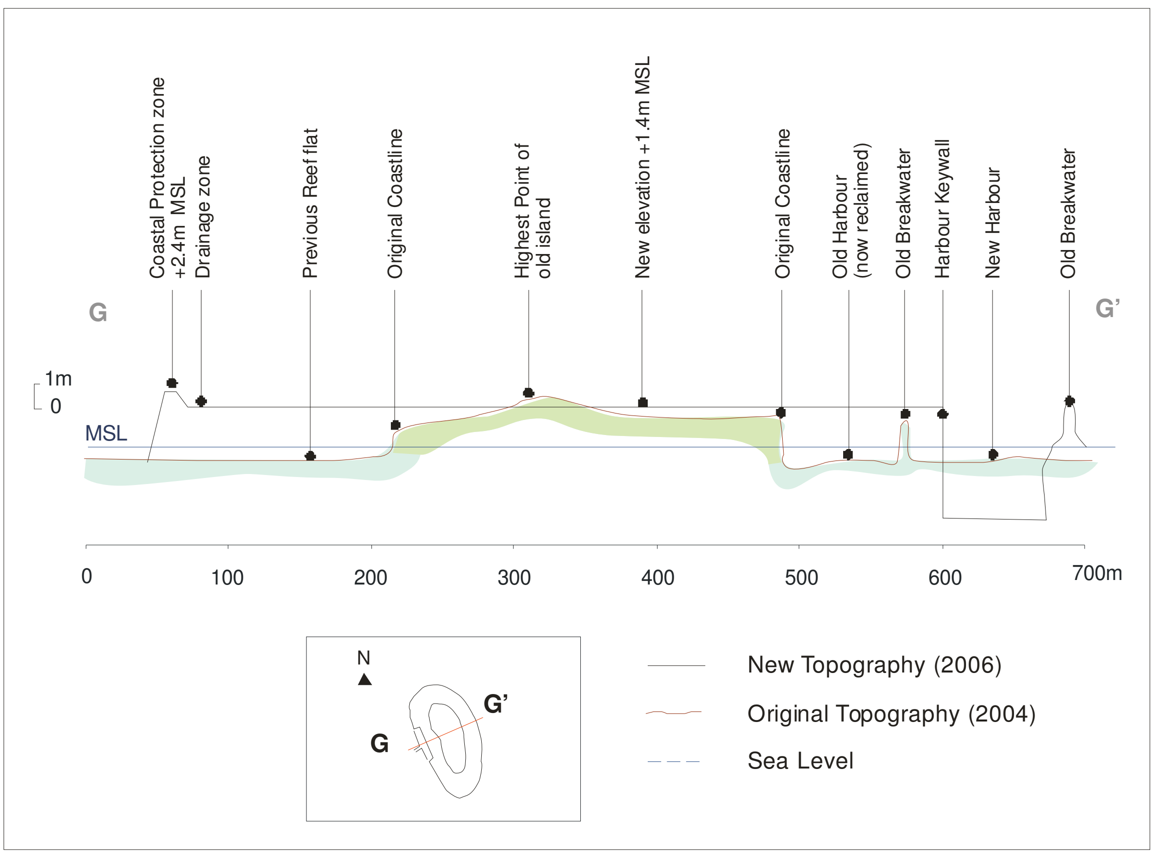

Figure 3.1 Topography of original island and newly reclaimed land.

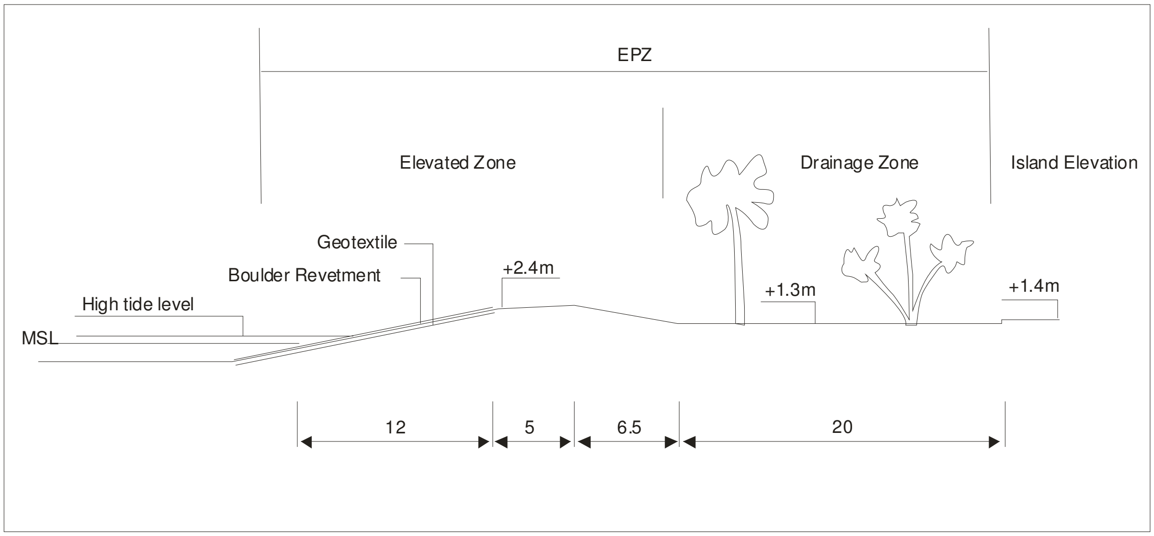

Figure 3.2 Planned Environment Protection Zone (EPZ) of Vilufushi.

Vegetation

At present Vilufushi has little vegetation cover. The only vegetation remaining on the island is the narrow strip of coastal vegetation of the old island. The undergrowth in this narrow strip has been long cleared and is further effected due to topographic levelling activities after reclamation. In the initial plans the coastal existing vegetation belt and topographic variations along it was to be retained to facilitate drainage. However, field visits to the island revealed that the entire island, including the coastal vegetation belt was levelled.

The original island itself lacked vegetation due to the heavy urbanisation. The tsunami affected much of the remaining trees and the smaller trees were cleared during the site clearing and land reclamation activities during island redevelopment. Figure 3.3 shows the vegetation cover in Vilufushi after the 2004 tsunami

Figure 3.3 Vegetation cover in Vilufushi immediately after the tsunami of 2004 (source: Google Earth)

No specific re-vegetation plan exists for the island, although a number of green areas have been identified in the proposed land use plan (see Figure 3.4). It is predicted that it'll take long time to re-vegetate the newly reclaimed land, based on experience from past reclamation activities. The reasons for slow re-growth needs to be explored further but appears to be due to the poor soil profiling and high alkalinity following reclamation.

Ground Water and Soil

The reclamation of Vilufushi will probably result in re-development of the water aquifer. No specific studies have been conducted elsewhere in the country to determine the rainwater aquifer recharge rate for a reclaimed land. Based on the general characteristics of coral island hydrology, it is estimated that a proper aquifer establishment would take a number of years and is very much dependent of amount of rainfall during the southwest monsoon. The process may be further hindered due to the extensive development planned on the island, which is likely to involve rapid discharge from the aquifer for construction activities. Furthermore, the planned urban settlement on the island and associated rapid usage of water may also hamper the recharge rate for the new land. It should be noted that these predictions needs detailed studies to establish them with any degree of certainty.

The soil in Vilufushi Island has been completely modified even on the existing island. The present solid profile doesn't represent a typical coral island soil profile. Typical profiles tend to have graded layering, generally getting coarser with depth. It also contains a considerable layer of humus in vegetated areas. The newly reclaimed land in Vilufushi doesn't contain such a graded profile and in fact no consideration was given to the soil profile during reclamation. Again, no specific studies have been undertaken in the past to determine the impact of an artificial unlayered soil profile in newly reclaimed land. It is highly likely that such land could have implications on the porosity and vegetation growth. Porosity of the reclaimed land may determine the rate of ground water recharge and extent of rainfall related flooding. Evidence from previously reclaimed islands show that vegetation re-growth has been extremely slow. It may be due to the lack of effort on re-vegetation, but it may also be due to the poor quality of soil. Hence, there is a likelihood that re-growth may be slow in Vilufushi as well, at least in the short term.

There is also a concern that newly reclaimed land may involve settlement of sediment overtime, especially following development activities. The current reclamation practices do not involve any compaction after reclamation. This may cause unplanned subtle variations in topography with implication for rainfall related flooding. It should however be noted that, no detailed studies have been undertaken on the subject in Maldives and hence the impact cannot be stated with a degree of certainty.

3.1.2 Coastal Environment

Beach and Beach Erosion

The exiting coastal environment of Vilufushi has been modified with coastal protection around 80% of the coastline. As a result, the island building coastal processes around the island has lost its function. There is essentially no beach around 80% of the island coastline. The remaining 20%, which is located on the eastern side, is exposed to severe erosion due to adjacent coastal structures. A combination of solid structures and exposed beaches often leads to seasonal erosion in and around the adjoining areas (Kench, Parnell et al. 2003).

3.1.3 Marine environment

General Reef Conditions

The reef conditions around the island were reported to be in poor to moderate condition (EDC, 2006). According to the Villigili island development EIA (EDC, 2006), the reef areas on the oceanward side were of poor quality with low levels of live coral cover and species abundance. The report goes on to state that this may have been due to the coral bleaching event of 1997 and the tsunami of 2004. Elsewhere, the reef conditions were reported to be in moderate condition. The northern area of the reef, which is comparatively less exposed to direct wave action, has moderate live coral cover and species abundance. Similarly, the lagoon ward reef areas were reported to be in moderate to good condition.

Unfortunately, the oceanward areas of the reef which requires being most resilient to climatic conditions are in a poor state. This may have implications for future natural adaptation of reefs to climatic variations and sea level rise, unless reef growth is restored to a normal level. Further studies are required to understand the decline in quality of the reef and its capacity to regenerate against varying climatic conditions.

3.1.4 Modifications to Natural Environment

Coastal Modifications

A number of coastal developments have been undertaken in Vilufushi as part of the tsunami reconstruction programme. The developments have reached to an extent where the island coastal environment is no longer in its natural state. Below are a summary of major modifications.

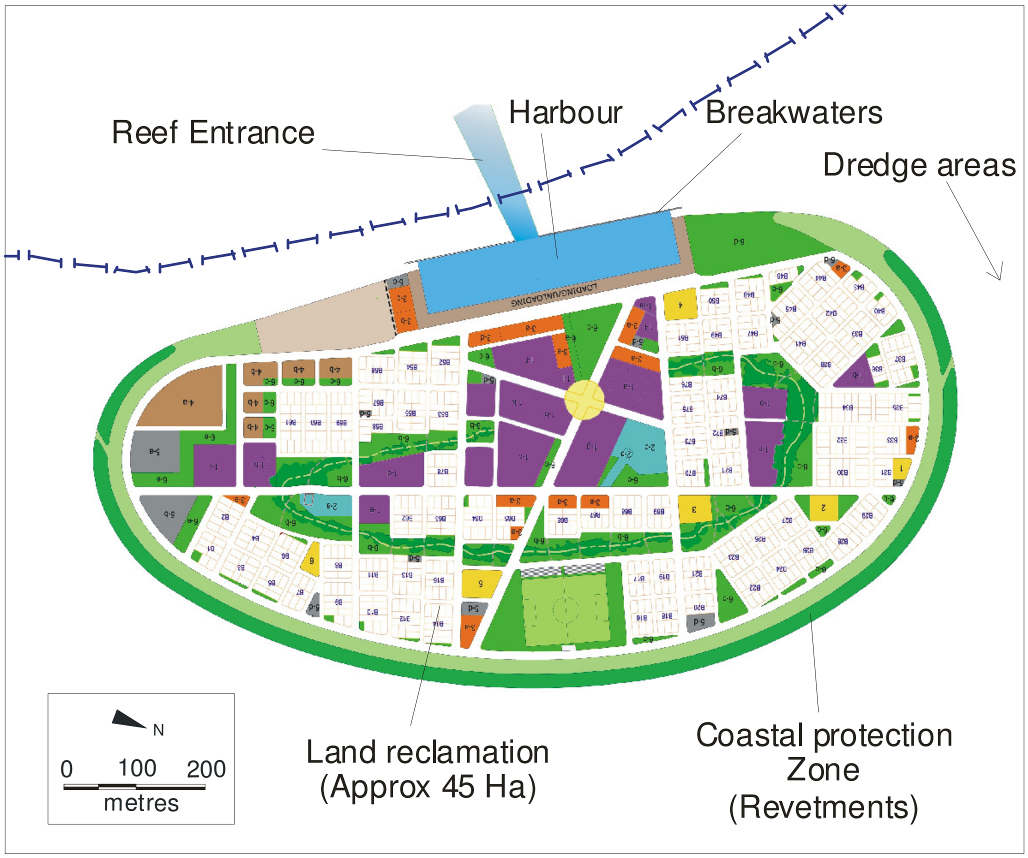

Figure 3.4 Coastal modification in Vilufushi.

- Land reclamation: Almost 45 ha of new land has been reclaimed and the coastline has been extended over 200m from the original coastline.
- Coastal protection: More than 2000m (66%) of the existing 3000m coastline has been protected by a solid (boulder based) revetment. A further 370m have been developed as a breakwater for the new harbour. Hence, only a small proportion of the coastline is exposed to the natural island building processes.
- Habour development: Harbour development activities have involved dredging of harbour and access channel, construction of break water and construction of Quay walls.
- Dredge areas: During the land reclamation, a specific area in the lagoon north of the island was designated as dredge material source. Hence, an area the size of the original island was dredged and an additional reef entrance was created to allow for the dredger to access the lagoon. These new deep areas are likely to alter the current regime and sediment distribution patterns around the island.

Terrestrial environment modifications

As discussed earlier, Vilufushi had depleted vegetation due to heavy urbanization. The tsunami of 2004, subsequent site clearing for re-development, island levelling activities and land reclamation have all contributed to further depletion of exiting vegetation. A complete re-vegetation programme is required on the island.

3.2 Environmental mitigation against historical hazard events.

3.2.1 Natural Adaptation

It is difficult to asses the historical natural adaptation due to the extensive modifications brought to the island. The minimal information on coastal topography, lagoon condition and coastal geomorphology suggested a lack of adaptive measures.

3.2.1 Human Adaptation

A number of mitigation measures against predicted natural hazards have been developed in Vilufushi Island. These measures form part of the Safe Island Development programme which aims to protect islands from predominant natural hazards, especially ocean induced hazards. Apart from the Capital Island Male', Vilufushi has the biggest investment on natural hazard mitigation measures in any island to date. Listed below are the key measures.

- An Environment Protection Zone (EPZ) around 66% of the island. EPZ includes:
    - Coastal protection structures which has specifically been designed to prevent erosion and to mitigate major flooding events such as tsunamis. These structures are also expected to play the role similar to a natural ridge system of a coral island.
    - Coastal vegetation belt which is designed to reduce the impact of ocean induced flooding and wind storms.
    - Drainage zone to reduce the impact of major flooding events such as tsunamis
- Island elevation to +1.4m MSL to reduce the impacts of ocean induced flooding.
- Elevated evacuation zone and buildings designed as an emergency evacuation measure against flooding events.

- Artificial road drainage systems to mitigate rainfall related flooding.

These measures seem to cover impacts from much of the natural hazards except earthquakes. However, it remains to be seen how these structures perform against the predicted hazards. This study has found that the current measures might have serious flaws that may reduce their effectiveness. While the inspiration to these mitigation measures appear to be the natural defensive systems established in more natural hazard resilient islands, their translation into standardised artificial features requires proper assessment of localised conditions in each island.

3.3 Environmental vulnerabilities to natural hazards

3.3.1 Natural Vulnerabilities

- Located in a high tsunami impact zone due to ocean floor topography off the eastern rim of Laamu (Shifaz, 2005).
- Islands located on the eastern rim of Maldives are more exposed to storm surges and tsunamis.

3.3.2 Human induced vulnerabilities

- Vilufushi has been reclaimed at a flat elevation of +1.4 above MSL. It is generally considered a low lying island and therefore exposed to ocean induced flooding hazards and sea level rise.
- The flat elevation would also mean that the island has no natural drainage system and is reliant on a functioning artificial drainage system to minimise rainfall flooding impacts. It is expected (although not substantiated) that the porosity of reclaimed land is generally low due to compaction and difference of grain size of dredged sand. If that's the case, then there is a probability that ground seepage during heavy rainfall will be slow, increasing the possibility of wide-spread flooding in all parts of the island. It is also predicted that the lower areas developed as floodway around the island could act as a drainage area for the outer edges. If the man-made systems fail due to siltation, it could cause flooding in the adjacent roads and houses. It is unfortunate that the planned drainage system along with the proposed green belt (coastline of original island)

was levelled. This area could have played a major role in the natural drainage of the island, reducing the cost of artificial drainage systems and their maintenance.

- Based on the findings from other islands, the proposed distance between the beach ridge and settlement area (30m) is too narrow. As a result the structures facing the eastern coastline are very likely to be exposed to potential surges and tsunami's higher than +2.4 MSL.
- The coastal vegetation proposed on the island is inadequate. The proposed 25m strip of vegetation is most likely to be sparse due the other recreational facilities planned in the zone. Findings from the 9 study islands show that at least a 50m strip of strong coastal vegetation needs to be present in order to perform its function of wave energy absorption during events such as a tsunami. In an island like Vilufushi which has a natural vulnerability to tsunami's, a narrow strip of coastal vegetation may not perform the necessary impact mitigation functions against flooding hazards. No specific plans have been found on the composition, density and layering of the vegetation belt. The function of the coastal vegetation belt of the other islands appears to be partly dependent on these three factors.
- The beach areas adjacent to the newly developed harbour are very likely to be exposed to severe erosion and accretion. It is known that beach areas are generally exposed to erosion (and accretion on one side) when a solid structure is placed perpendicular to it. With the strength of the waves reaching western coastline during southwest monsoon, it highly probable that significant erosion would occur.
- Vilufushi Island is now an artificial environment with no room for island building processes to operate. The process of engineering has removed much of the natural hazards other similar islands face but downside is that the island will have to rely on engineering solutions to adapt to varying climatic conditions and hazards. Based on recent findings on natural adaptation of coral islands to sea level variations, there is a likelihood that in the long-term Vilufushi would be worse-off than islands with a functioning coastal system, due to the potential high cost of maintaining an artificial system.
- The lack of coastal vegetation in Vilufushi would be a major concern in terms of exposure to wind storms and strong winds from south west monsoon. In the past,

natural vegetation growth has been very slow and limited in reclaimed areas around the country. It may be due the lack of effort involved in re-vegetation or due to the high alkalinity of the reclaimed soil. Re-vegetation in newly reclaimed land also involves de-vegetating part of another island. The slow process of re-vegetation either manually or naturally is a concern especially for the coastal vegetation belt which has the potential to expose the island to sea induced flooding. The effects of climate change and global warming could also be felt more strongly due to the apparent increase in temperature within the settlement area.

- The island width of just 500m and the flat elevation of +1.4m above MSL may influence the extent of inundation during a major flooding event

3.4 Environmental assets to hazard mitigation

- A large land area should generally be considered an asset against ocean induced hazards. The inundation extent during major flooding events is restrained by the limited reach of wave run-up. Hence, general terms, the large the island the smaller the proportion of flooded area. Hence, the newly reclaimed land of Vilufushi may help reduce impacts of future flooding events. It should also be noted that a number of other factors such as width of the island, elevation, topography, vegetation, structures and ridge height will also influence the extent of inundation.
- The eastern ridge of the island has been raised to +2.4m above MSL. This height represents a considerably higher ridge compared to ridges found in island with similar geographic and climatic settings. The ridge is artificial and therefore doesn't cause seasonal variations in the beach eliminating coastal erosion and accretion. The height may not be adequate against a 3.0m or higher tsunami's hazard but is expected to mitigate most ocean induced hazard scenarios predicted for the region.
- Vilufushi has a wide reef flat to absorb energy. The effects of low wave energy can be observed on the low ridges and fine beach material of the original island. Perhaps Vilifushi hasn't been exposed to major storm activities or strong wave actions. There certainly aren't any historical records of prior substantial flooding in Vilufushi. The scientific debate on the issue is inconclusive, but as has been

presented in the hazards section of this report, it is highly likely that impacts of certain types of ocean induced flooding events may be mitigated by the presence of wide reef flat. Further inquiry is required on the issue using detailed empirical research.

- Vilufushi Island is reported to have strong and healthy reef system around it (EDC, 2006), which is crucial for natural adaptation against changing wave conditions and sea level rise.

3.5 Predicted environmental impacts from natural hazards

The natural environment of Vilufushi 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)).

Unfortunately, the Vilufushi coastal environment is artificial with no room for natural coastal processes to operate. In this respect, Vilufushi will not get the benefit of natural adaptation and would require continuous human intervention to maintain the mitigation measures.

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 predicted short-term impacts from hazard event scenarios predicted for Vilufushi. The impacts are predicted to be low due to the artificial mitigation measures targeted at the specific hazards.

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 those planted in the newly reclaimed land. • Salt water intrusion into water lens causing loss of • 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 considerable period of time causing ground water shortage. If the rainwater collection facilities are destroyed, potable water shortage would be critical in the Settlement. Loss of flora and fauna may also occur amongst salt intolerant species. • Moderate to major damage to coastal protection infrastructure and environment Protection Zone in general • Short-medium term loss of soil productivity • Moderate damage to coral reefs *(based on UNEP (2005))*
Storm Surge *(based on UNDP, (2005))*		
▪ 0.60m (1.53m storm tide)	Low	• No damage
▪ 1.32m (2.30m storm tide)	Very Low	• Minor damage to coastal vegetation • Minor to moderate damage to coastal protection infrastructure • Minor-moderate geomorphologic changes in

Hazard Scenario	Probability at Location	Potential Major Environmental Impacts
		the oceanward shoreline and lagoon • Minor-moderate damage to coral reefs
Strong Wind		
▪ 28-33 Knots	Very High	• Minor damage to young fruit trees • Debris dispersion near waste sites.
▪ 34-65 Knots	Low	• Moderate damage to vegetation with falling branches and occasionally whole trees • Debris dispersion near waste sites.
▪ 65+ Knots	Very Low	• Widespread damage to inland vegetation and coastal vegetation • Debris dispersion near waste sites.
Heavy rainfall		
▪ 187mm	Moderate	• Minor to moderate flooding across the island and drainage areas along the coastline.
▪ 242mm	Low	• Widespread flooding across the island and drainage areas along the coastline.
Drought	Low	• Major damage to backyard fruit trees especially in newly reclaimed land
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	• Saltwater intrusion into the water lens causing salinisation of ground water and leading to water shortage and loss of flora and fauna.

3.6 Findings and Recommendations for safe island development plan

- A coral islands main defensive ability against frequent natural hazards is perhaps its robust natural adaptive capacity. In order to retain this ability against ocean induced hazards, a proper and functioning coastal environment is essential. It takes a number of years in term of geological time for an island to stabilise and achieve an equilibrium. Once established the island evolves and adapts to the prevailing conditions. The natural history of Maldives bears evidence to such natural adaptation, including the survival through a 2.5m rise in sea level (Kench et.al, 2004). It is perhaps the foremost reason why the coral islands of Maldives have survived thus far.

- The safe island development in Vilufushi has changed a functioning coastal environment into a more artificial environment. The implications of this change are numerous especially in the long-term. The current coastal modification reduces the exposure of the island for certain hazards and increases exposure to others. There is a high probability that the present coastal modifications would expose Vilufushi to the following ocean induced hazards.

- There could be a rapid onset of erosion in western areas where coastal protection has not been developed.
- The island does not possess any natural adaptation capacity to climate change. It may require considerable investment in the future to upgrade the coastal structures or to elevate the island through reclamation.

- Island topography and resulting drainage systems are critical features of an island in relation to exposure to natural hazards. Due to the flat reclamation, the island is now reliant on an engineered drainage system to mitigate rainfall related flooding. Artificial systems would be more effective in inhabited islands as it can eliminate impacts of rainfall hazards altogether. However, such system would involve high capital and recurrent costs and in the event of failure it could lead to a disastrous flooding event. A proper artificial drainage system needs to be installed and disaster management plans needs to be developed to mitigate a potential rainfall flooding event caused by drainage system failure.
- Based on the 9 islands studies 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 observations in other islands, the proposed width of coastal vegetation may not be appropriate for reducing certain ocean induced hazard exposures and needs to be revised. The early timing of vegetation establishment also needs to be clearly identified in the safe island development plan.
- A re-vegetation plan for the rest of the island needs to be incorporated in the Safe Island Development Plan. The plan should incorporate assessment of potential impacts of deforestation in the new vegetation source island.

- Erosion mitigation measures need to identified in advance for the western shoreline and should be incorporated in the safe island development plan.

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 bathymetry data available for Vilufushi was held by private company which undertook the EIA assessment. We were unable to collect the original dataset within the project timeframe.
- 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 methodological foundation for further detailed risk assessments 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 for a credible detailed socio-economic scenario 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 Indian 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 one year 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 modelling using GIS.
- Quantitative hydrological impact assessment of sea level rise, land reclamation and other safe island development activities
- 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

Historically, Th. Vilufushi island is exposed to rainfall floods with high frequency, swell wave/surge floods with moderate frequency, and earthquake with low frequency. Historically, it has experienced frequent flooding events that have resulted in substantial losses. In particular, a rainfall flooding event may result in minor damage to property. However, the accumulative damage/impacts can be significant. In the future, with accelerated sea-level rise, floods caused by swell wave/surge and rainfall will be dramatically enhanced.

4.1 House vulnerability

This section is not applicable because all the houses on the island were completely destroyed and a thorough construction is in progress.

4.2 Houses at risk

Risk analysis of housing for Th. Vilufushi is based on the land use map updated on Sept. 03, 2006 and in terms of the location of planned plots in tsunami hazard zones.

Out of 1540 plots allocated on Th. Vilufushi Island, around half of them will be located in the tsunami flood-prone area on the eastern side of the island (Fig. 4.1), of which around 66 houses may be subjected to floods of more than 1.5 meter water depth, 362 houses between 0.5 and 1.5 m water depth, and 250 in less than 0.5 meter water depth area. To estimate the physical vulnerability of and potential damage to these houses, further information on building code and protection measures are required.

Table 4.1 Houses at risk on Th. Vilufushi.

Hazard type		Exposed houses		Vulnerable houses		Potential Damage							
						Serious		Moderate		Slight		Content	
		#	%	#	%	#	%	#	%	#	%	#	%
Flood	TS	678	89.4	?	?	0	0	66	4.3	362	23.5	250	16.2
	W/S	-	-	-	-	-	-	-	-	-	-	-	-
	RF	-	-	-	-	-	-	-	-	-	-	-	-
Earthquake		1540	100	-	-	-	-	-	-	-	-	-	-
Wind		1540	100	-	-	-	-	-	-	-	-	-	-
Erosion													

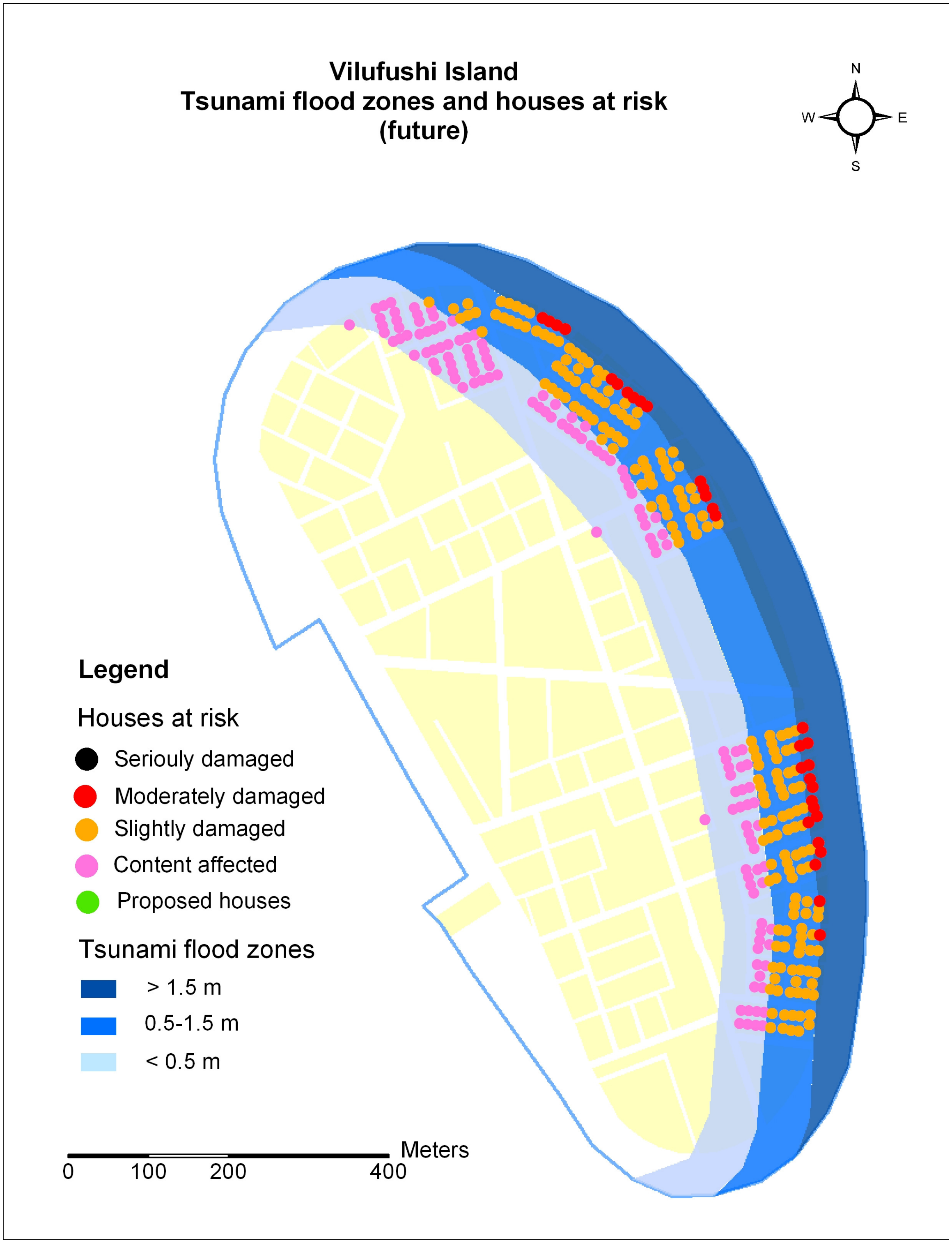

Fig. 4.1 Houses at risk associated with tsunami floods..

4.3 Critical facilities at risk

According to the land use map and hazard zoning map of the island, most critical facilities will be located on the west side of the island, far away from the tsunami flood-prone area. However, several key facilities, in particular, power house, will be found in the hazard zone and may be subjected to flooding of 0.5-1.5 m water depth. Tsunami of 4-5 m high belongs to a very infrequent hazard. If these facilities will be built with proper building codes, the risk they face should be very low. However, it would be better to relocate the power house into the western side of the island.

Table 4.2 Critical facilities at risk on Vilufushi Island.

<table>
<tr><th colspan="2" rowspan="2">Hazard type</th><th colspan="2">Critical facilities</th><th colspan="2">Potential damage/loss</th></tr>
<tr><th>Exposed</th><th>Vulnerable</th><th>Physical damage</th><th>Monetary value</th></tr>
<tr><td rowspan="3">Flood</td><td>Tsunami</td><td>1 power house, 5 transformers or pump stations, part of a waste site and a school, several shops</td><td>Not clear</td><td>Not clear</td><td>Not clear</td></tr>
<tr><td>Wave/Surge</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Rainfall</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td colspan="2">Earthquake</td><td></td><td>-</td><td>-</td><td>-</td></tr>
<tr><td colspan="2">Wind</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td colspan="2">Erosion</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
</table>

Note: “-“ means “not applicable”.

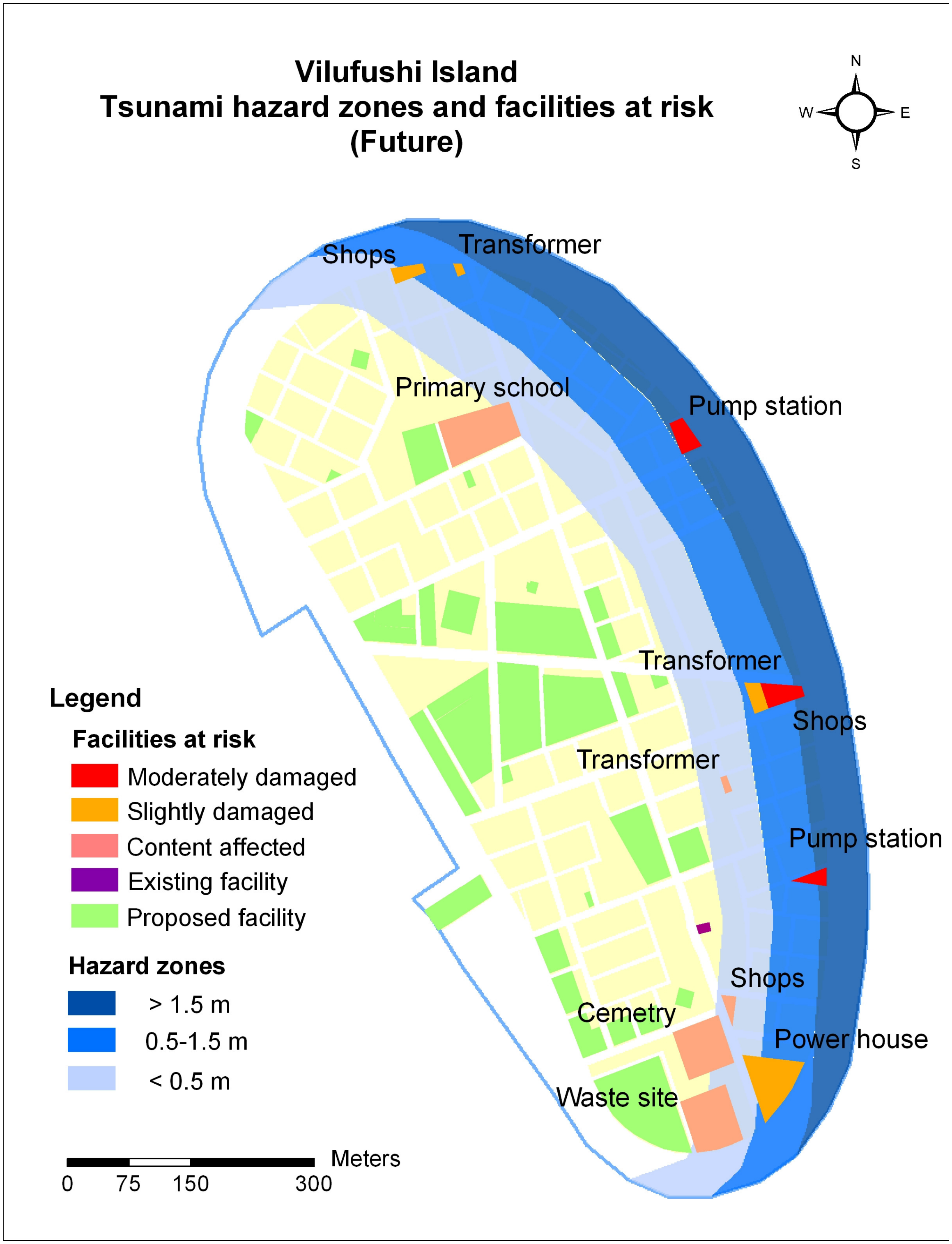

Fig. 4.2 Critical facilities at risk associated with rainfall floods.

4.4 Functional impacts

Although the power house may not be physically damaged during flooding, its functioning may be interrupted for weeks for the cleaning of generators and reinstallation of distribution network. It can further affect the functioning of the drainage systems on the island. in addition, the flooding of the waste site may cause a secondary contamination to the sensitive groundwater system of the island (Table 4.3) .

Table 4.3 Potential functional impact matrix

Function	Flood			Earthquake	Wind
	Tsunami (>4 m)	Wave/surge (>2 m)	Rainfall (1-2 ft)		
Administration[1]					
Health care					
Education					
Housing					
Sanitation[3]	Secondary contamination & drainage				
Water supply					
Power supply	Several weeks of interruption				
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 Th. Vilufushi:

- *Avoid locating key critical facilities, i.e. proposed power house and waste site, in the tsunami flood-prone area on the eastern coast.*
- *Enhance building codes in the new settlement on the eastern coast that is exposed to ocean-originated flooding. For example, strong and higher boundary walls are required and an attention should be paid to the orientation of houses. Power distribution network is designed to protect from floods of 1.5 m.*
- A standard EPZ with 2.4+ m seems to reduce tsunami hazard zones of less that 1.5 m water depth effectively. However, it is not sensitive to reduce the destructive zone of more than 1.5 m water depth. Therefore, an at least 50 m wide buffer zone between shoreline and houses is necessary.