Maldives field survey of the 2004 Indian Ocean Tsunami

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Abstract

The tsunami of 26th December 2004 severely affected the Maldives at a distance of 2500 km from the epicenter of the Magnitude 9.0 earthquake. The Maldives provides an opportunity to assess the impact of a tsunami on corral atolls. Two International Tsunami Survey Teams (ITST) surveyed a total of 13 heavily damaged islands: Dhiffushi, Huraa, Hulhule and Malé (North Malé Atoll), Embudhu Finothu (South Malé Atoll), Gan and Fonadhoo (Laamu Atoll), Vilufushi and Madifushi (Thaa Atoll) and Kolhufushi (Meemu Atoll), Kandholhudhoo (Raa Atoll), Eydhafushi (Baa Atoll) and Hinnavaru (Lhaviyani Atoll). The islands were visited by seaplane on January 14, 15, 18 and 19, 2005. We recorded flow depths up to 4 m on Vluifushi based on the location of debris in trees and watermarks on buildings. Each watermark was localized by means of global positioning systems (GPS) and photographed. Numerous eyewitness interviews were recorded on video. The significantly lower tsunami impact on the Maldives compared to Sri Lanka is largely due to the topography and bathymetry of the atoll chain.

1 Introduction

On Sunday December 26th at 00:58:53 UTC, a great earthquake with a moment magnitude of 9.0 – or possibly greater (*Stein and Okal, 2005*) – occurred offshore Northern Sumatra, Indonesia. Large tsunamis were generated and severely damaged coastal communities in countries along the Indian Ocean, including Indonesia, Thailand, Sri Lanka, India, Maldives and Somalia. The tsunami death toll is currently estimated at 300,000 – exact numbers are likely never to be determined, given that detailed pre-tsunami population census were not available in several affected regions and human remains were occasionally buried in mass graves without identification. Beyond the loss of human lives, the tsunami also destroyed livelihoods, traumatized whole populations and severely damaged habitats. In the near field of the epicenter Sumatra was hardest hit by the tsunami (Borrero, 2005). In the far field the

tsunami severely affected Sri Lanka across the Bay of Bengal at a distance of 1600 km from the epicenter (Liu et al., 2005). In East Africa the tsunami impact focused on Somalia some 5000 kilometers to the west of the earthquake epicenter (Fritz and Borrero, in prep.).

The tsunami severely affected the Maldives at a distance of 2500 km from the epicenter or at half way point between Sumatra and Somalia along the westward path of the tsunami. The country stretches 823 km north to south and 130 km east to west (Figure 1). The numerous coral reef islands, 1,190 in total, form an archipelago of 26 natural atolls. Open seas or deep channels with a depth of more than 200 meters separate the atolls. The largest atoll, Huvadhoo, is 65 km wide and 82 km long, while Thoddoo, the smallest, is about 1.8 km in diameter. Depths within the atoll lagoons usually vary between 30 to 50 meters but in some places, such as Huvadhoo, depths may reach up to 90 meters. Over 99 percent of the Maldives' area is ocean. Only 0.331 percent of its 13,423 km^2 is land, corresponding to 298 km^2. Out of the incredibly large number of islands only 200 islands are inhabited. The total population of the Maldives in 2004 was 270,101. At first site the archipelago with elevations of less than 2 m above sea level appears extremely vulnerable. Reports indicate more than 82 people confirmed dead, with an additional 26 missing and presumed dead, and over 12,000 people homeless. Some 4,000 houses were damaged. In the tourism sector, the country's largest foreign income earner, out of the 87 resorts, 19 were severely damaged and had to be closed down, while 14 others have suffered major partial damages. Agricultural crops were swept away and most parts of the agricultural land are covered with salty mud leaving it unusable.

2 Post Tsunami Field Survey

A tsunami survey plan was initiated within a week of the earthquake; the authors formed part of International Tsunami Survey Teams (ITST) on the south coast of Sri Lanka (Liu et al., 2005). Two separate survey teams were dispatched from Sri Lanka to the Maldives on January 13 and 16, 2005. Both survey teams were supported by the local disaster management center and various local researchers. On January 14 and 15, 2005 the latter two authors surveyed a total of 7 islands on 3 different atolls: Dhiffushi, Huraa, Hulhule and Malé (North Malé Atoll), Embudhu Finothu (South Malé Atoll), Gan and Fonadhoo (Laamu Atoll). On January 18 and 19, 2005 the first two authors surveyed a total of 6 heavily damaged islands on 5 different atolls: Vilufushi and Madifushi (Thaa-atoll) and Kolhufushi (Meemu-atoll), Kandholhudhoo (Raa-atoll), Eydhafushi (Baa-atoll) and Hinnavaru (Lhaviyani-atoll). The islands were visited by seaplane and speed boats. The locations of the islands within the chain of atolls are shown in Figure 1.

Figure 1

The goals of the ITST were to document *inundation*, the horizontal extent of water penetration; *run-up*, the maximum vertical elevation above mean sea level of the land flooded; and to collect information on the human impact of the tsunami. A variety of standard tsunami field survey techniques (*e.g., Tsuji et al.,* 1995; *Okal et al*., 2002) were used. However these had to be adapted to the special topography of the Maldives. Most islands were completely flooded by the tsunami due to their low lying land. Therefore neither inundation lines nor classic run-up were observed. The team measured local *flow depths*, the water level above ground surface, based on the location of debris in trees and watermarks on buildings. The maximum tsunami amplitude was determined relative to the sea level at tsunami impact. Each watermark was located by means of global positioning systems (GPS) and photographed. Numerous eyewitness interviews were recorded on video to estimate the number of waves, their height and period as well as the tsunami arrival time. The acquired database is shown in Table 1. A total of 78 locations were surveyed some with multiple data points. Maximum flow depths are typically on the order of 1 to 4 m. Thus, the absolute values are roughly half to those reported in Somalia at twice the distance from the epicenter along the same ray path of the tsunami (Fritz and Borrero, 2006). However in Somalia mostly run-up was measured on relatively steep beaches in sharp contrast to the flat Maldives over washed by the tsunami.

Table 1

3 Field Observations

Male (North Male Atoll)

The capital of the Madives, Male, was one of the few islands in the country that was not completely overwashed by the tsunami (Figure 2). Consistent with other reports, the first of three waves arrived as a positive around 9:15 AM local time. Witnesses describe a gradual rise in the ocean level from all directions. The island has been markedly reclaimed with concrete seawalls and tetrahedrons placed on

the outer reef. The north side of the island was damaged less than the south. This could be due in part to protection afforded by the runway at the Male International Airport on Huhule Island west of Male which was overwashed in the tsunami. Most of the visible damage on Male was from seawalls and roads that were undermined by the advancing or retreating waves. Buildings suffered surprisingly little, obvious structural damage. In several places, we witnessed watermarks on plate glass windows that were not broken, suggesting a slow and gradual wave rather than a rapid and turbid wave seen in the other affected areas.

Figure 2

Vilufushi Island (Thaa Atoll)

The Thaa Atoll is located 200 km south of the capital Malé. The British Admiralty conducted the most comprehensive bathymetric survey of the Islands. An extract of the digital nautical charts is shown in Figure 2. The atoll is of roughly circular shape with an average diameter of 45 km. The deepest point inside the atoll with a depth of 88 m is located in the center. Thaa atoll is separated from its northern neighbors Dhaalu and Meemu by roughly 17 and 28 km wide channels with a depth around 500 m. The 30 km wide channel separating Thaa from Laamu is 1800 m deep. The total population on the atoll was 8513 in 2004. The tsunami killed 19 people on the atoll and damaged 563 buildings. The team surveyed the two hardest hit Islands Vilufushi and Madifushi.

Figure 3

The Island of Vilufushi is located on the north-east corner of the Thaa Atoll facing Kolhufushi on Meemu Atoll across the narrowest part of the channel between Thaa and Meemu. The Island is shown from the air in Figure 4a). Vilufushi is barely 1 km long and up to 300 m wide. The island is bounded on the east by a coral reef located roughly 1 km offshore. The land is flat with an elevation of 1m. Vilufushi is one of the largest communities on Thaa-atoll with a population of 1886. Unfortunately, Vilufushi was the hardest hit individual island in the Maldives. As of this writing, the death toll remains at 18. In addition to the human loss 192 houses were damaged. Characteristic houses are

properly designed and built out of coral stones or concrete stones sometimes with steel reinforced concrete columns (as shown in Figure 4b). This is in sharp contrast to the wooden huts found along Sri Lanka's coasts (Liu et al., 2005).

Figure 4

Vilufushi was completely washed over by the tsunami. Abundant watermarks were found on the outside and inside of remaining houses as well as in the form of seaweed, clothing and fishing nets on trees and concrete columns. Examples of tsunami flow depth measurements are shown in Figure 5.

Figure 5

The highest flow-depth of just over 3 meters was measured on Vilufushi, which corresponds to a maximum tsunami height relative to the sea level at tsunami attack of over 4 meters. A summary of all the measured flow depth points on Vilufushi is shown in Figure 6.

Figure 6

Several eyewitnesses were interviewed and recorded on video. Most inhabitants survived by fleeing in fishing boats towards the inner of the atoll, while others climbed to the roof of their houses and held on. The accounts generally mentioned one to four waves with a leading elevation in most cases. Some accounts mentioned an initial depression. The tide gauge records shown in Figure 7 all indicate an initial rise. The first wave arrived around 9:15 to 9:30 AM local time depending upon location within the island chain as indicated by the tide gauges shown in Figure 7. On the east coast of Vilufushi we recovered a broken clock, which stopped at 9:26 AM local time (= UTC + 5 hours). This is in agreement to the tide gauge records. Given the epicentral distances around 2600 km and taking into account the variable depth of the Indian Ocean Basin, travel times are expected to be 3.25 to 3.5 hours (Titov, 2005). With a seismic origin of 00:58:53 UTC, this predicts first arrivals around 9:15 to 9:30 local time, matching the initial rises on the tide gauge recordings as well as eyewitness accounts.

Figure 7

Kolhufushi Island (Meemu Atoll)

The island of Kolhufushi is located on Meemu Atoll some 30km northeast of Vilufushi across a 500 m deep channel. The islands located along the deep ocean channel separating Thaa Atoll from Meemu Atoll account for half the victims in the Maldives. The total population on Meemu was 4,845 in 2004. The tsunami caused presumably 34 victims on the atoll – 16 on Kolhufushi alone – and damaged 346 buildings. The team surveyed the hard hit Kolhufushi on the southwestern tip of the atoll. Kolhufushi was completely over washed by the tsunami. A summary of all the measured flow depth points is shown in Figure 8.

Figure 8

Kolhufushi is roughly 2.5 km long and 400 m wide. The transect recorded across the island indicates an even flow depth of 2 m above terrain across the entire island. The pre-tsunami satellite image shows a lagoon cutting into the island separating the northern third from the rest of the island. The two segments were connected by a narrow sand spit covered with vegetation along the eastern shoreline of the island. The sand spit had lost its vegetation and was partially breached prior to the tsunami. However the final breaching was induced by the overflow of the tsunami. The resulting cut separating the two island parts is shown in Figure 9 taken from the seaplane in final landing approach.

Kandholhudhoo Island (Raa Atoll)

The Raa atoll is located 180 km north-northwest of the capital Male. The atoll is of elongated shape spanning some 60 km north to south and 30 km across. Raa atoll is only separated from its southern neighbor Baa by a 3 km wide and 200 m deep channel. The total population on the atoll was 15,331 in 2004. The tsunami caused presumably 3 victims on the atoll and damaged 854 buildings. The team surveyed the hard hit Kandholhudhoo on the west side of the atoll – one of the few locations with an available amateur video recording showing the tsunami arrival. The island of Kandholhudhoo is located on the west side of the Raa atoll. The bathymetry inside the atoll is very shallow with less than

10 m depth between Kandholhudhoo Island and the center of the atoll protecting the island towards the east. The Island is shown from the air in Figure 10a. Kandholhudhoo is barely 500 m long and half as wide. Part of the island was reclaimed from the sea by the construction of an encircling seawall within the last 5 years, which partially collapsed due to tsunami induced erosion as shown in Figure 10b. The land is flat with an average elevation of 1.2 m relative to the sea level at the time the tsunami arrived.

Figure 10

Kandholhudhoo is one of the largest communities on Raa-atoll with a population of 3,664. The island is located 70 km west of Male. Fortunately the people of Kandholhudhoo were warned by a phone call from Male of the approaching tsunami 15 minutes prior to its arrival. The death toll was limited to 3 victims while 520 buildings were damaged. The damage on the west side surpassed the destruction on the eastside of the island. The west side is located on the outer rim of the Atoll whereas the eastside although oriented towards the tsunami ray path faces the shallow inner lagoon of the atoll. Nevertheless Kandholhudhoo was completely flooded by the tsunami. A summary of all the measured flow depth points is shown in Figure 11.

Figure 11

On the eastside of Kandholhudhoo Island an amateur camera man – alerted by the phone call warning from Male – recorded the arrival of the tsunami. The position of the camera man looking to the east towards the center of the atoll is shown in Figure 11. The amateur video shows the initial rise of the tsunami flooding the streets similar to a rapid rise of the tides beyond normal high tide. An extracted video image during the flooding is shown Figure 12a. At a later stage the white wall disappears completely under water. The survey team revisited the exact location on January 19, 2005 and documented watermarks, a partially collapsed white wall and massive scouring along the road corner (Figure 12b).

Figure 12

Hinnavaru Island (Lhaviyani Atoll)

The island of Hinnavaru is located on Lhaviyani Atoll some 150 km north of the capital Male. The total population on Lhaviyani was 8,158 in 2004. The tsunami caused no victims on the atoll and only 25 buildings were damaged. The team surveyed the minimally affected Hinnavaru on the northwestern rim of the atoll. Hinnavaru was completely over washed by the tsunami. A summary of all the measured flow depth points is shown in Figure 13. The highest point on Hinnavaru was elevated less than a meter above mean sea level at tsunami arrival. Most remarkably the flow depth did not exceed 1 m above terrain. Hinnavaru faired remarkably well during this devastating tsunami and perfectly represents the majority of the islands in the Maldives.

Figure 13

4 Conclusions

The rapid response of the survey team to the Maldives after the December 26th, 2004 catastrophic event led to the recovery of important data on the characteristics of the tsunami effects and inundation on coral atolls, which are astonishingly different from the effects along the coastlines of major landmasses. Further the complete submergence of the settlements during the main tsunami waves resulted in important documentation of structural behavior upon tsunami impact. The flow depths above sea level only reached up to 4 m on Vilufushi Island. The unique topography and bathymetry with offshore coral reefs and deep channels separating individual atolls significantly reduced the impact of the tsunami compared to Sri Lanka or even Somalia at twice the distance from the epicenter along the main westward tsunami trajectory. The human loss was orders of magnitude smaller than in Sri Lanka and a third of the death toll reported in Somalia. Most remarkably the victims and the bulk of the destruction were concentrated on a dozen islands, while the majority of the islands did not report any victims and only minimal damage. Although the terrain elevations of the entire island chain are lower than 2 m the December 26th, 2004 catastrophic tsunami had limited impact on the Maldives.

Acknowledgments

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Figure captions

Figure 1: Map of the Maldives with the locations of the islands surveyed and the maximum tsunami flow depths observed.

Figure 2: Male, capital of the Maldives. Flow depths shown at several locations around the island. The interior of the island (gray area) was not flooded during the tsunami.

Figure 3: Thaa and Meemu Atolls with surveyed islands on a digital nautical chart modified for use with GPS after updated British Admiralty maps and selected bathymetric profiles.

Figure 4: Vilufushi Island (Thaa Atoll): (a) SW-view with the harbor towards the inner of the atoll taken during landing approach from the seaplane; (b) classic blow out failure of a corral stone wall.

Figure 5: Flow depth measurements on Vilufushi: (a) watermark on an outside wall; (b) seaweed on a tree.

Figure 6: Vilufushi: measured tsunami flow depths and surveyed locations on a pre tsunami satellite image provided by the Maldives Disaster Management Center.

Figure 7: Tsunami arrival time: (a) analysis of tide gauge residuals; (b) broken clock recovered on Vilufushi Island stopped at 9:26 AM local time (UTC + 5hr).

Figure 8: Kolhufushi Island (Meemu Atoll): measured tsunami flow depths and surveyed locations. The sand spit connecting the northern end of the island is not breached on this pre tsunami satellite image provided by the Maldives Disaster Management Center.

Figure 9: Kolhufushi: aerial W-view of the lagoon and the sand spit, which was breached by the tsunami.

Figure 10: Kandholhudhoo Island (Raa Atoll): (a) E-view of the island from the air; (b) collapsed sea-wall with exposed armor on the northwest side of the island.

Figure 11: Kandholhudhoo: measured tsunami flow depths and surveyed locations on a pre tsunami satellite image provided by the Maldives Disaster Management Center.

Figure 12: Kandholhudhoo amateur video: (a) during flooding by the tsunami; (b) video location in the aftermath with partial wall collapse and massive scouring.

Figure 13: Hinnavaru Island (Lhaviyani): measured tsunami flow depths and surveyed locations on a pre tsunami satellite image provided by the Maldives Disaster Management Center.

Table 1: Dataset surveyed in the Maldives by the two ITST-teams in January, 2005.

#	Island	Atoll	Latitude	Longitude	Vertical Survey asl [m]		Dist. from shore	Date & Time Surveyed		watermark
			°N	°E	Terr. Elev.	Flow depth	[m]		(UTC)	
1	Vilufushi	Thaa	2.50356	73.30856	1.02	2.11	135	18-Jan-2005	06:08	inside house
2	Vilufushi	Thaa	2.50330	73.30868	1.02	3.29	139	18-Jan-2005	06:09	debris in tree
3	Vilufushi	Thaa	2.50333	73.30892	1.02	2.36	111	18-Jan-2005	06:14	outside house
4a	Vilufushi	Thaa	2.50322	73.30929	1.02	2.77	74	18-Jan-2005	06:18	seaweed outside
4b	Vilufushi	Thaa	2.50322	73.30929	1.02	2.35	74	18-Jan-2005	06:18	inside house
5	Vilufushi	Thaa	2.50315	73.30956	1.02	3.71	45	18-Jan-2005	06:22	seaweed on tree
6	Vilufushi	Thaa	2.50317	73.30952	1.02	3.07	49	18-Jan-2005	06:23	seaweed on tree
7	Vilufushi	Thaa	2.50329	73.30969	1.02	3.70	28	18-Jan-2005	06:26	fishernet on tree
8	Vilufushi	Thaa	2.50316	73.30986	1.02	3.75	11	18-Jan-2005	06:28	seaweed on pole
9	Vilufushi	Thaa	2.50317	73.30986	1.02	3.57	10	18-Jan-2005	06:28	seaweed on pole
10	Vilufushi	Thaa	2.50364	73.30961	1.02	3.43	14	18-Jan-2005	06:36	seaweed on tree
11	Vilufushi	Thaa	2.50375	73.30960	1.02	4.07	8	18-Jan-2005	06:38	debris in tree
12	Vilufushi	Thaa	2.50399	73.30940	1.02	3.74	13	18-Jan-2005	06:41	seaweed on tree
13	Vilufushi	Thaa	2.50444	73.30935	1.02	3.67	4	18-Jan-2005	06:48	seaweed on tree
14	Vilufushi	Thaa	2.50617	73.30790	1.02	3.27	21	18-Jan-2005	06:57	debris in tree
15	Vilufushi	Thaa	2.50546	73.30759	1.02	2.14	72	18-Jan-2005	07:07	inside house
16	Vilufushi	Thaa	2.50556	73.30728	1.02	3.03	102	18-Jan-2005	07:07	stairway
17	Vilufushi	Thaa	2.50423	73.30899	1.02	2.66	39	18-Jan-2005	07:16	outside house
18	Vilufushi	Thaa	2.50194	73.31004	1.02	3.44	5	18-Jan-2005	07:22	debris on column
19	Vilufushi	Thaa	2.50247	73.30857	1.02	3.59	163	18-Jan-2005	08:25	person on roof
19	Madifushi	Thaa	2.35708	73.35457	1.34	2.10	140	18-Jan-2005	09:28	inside house
20	Madifushi	Thaa	2.35750	73.35568	1.34	2.35	40	18-Jan-2005	09:40	debris in tree
21	Madifushi	Thaa	2.35777	73.35563	1.34	2.76	56	18-Jan-2005	09:46	inside house
22	Madifushi	Thaa	2.35802	73.35587	1.34	2.13	48	18-Jan-2005	10:04	on pole
23	Madifushi	Thaa	2.35632	73.35522	1.34	3.21	37	18-Jan-2005	10:23	inside house
24	Madifushi	Thaa	2.35555	73.35497	1.34	2.85	42	18-Jan-2005	10:28	inside house
25	Madifushi	Thaa	2.35608	73.35490	1.40	2.56	82	18-Jan-2005	10:38	outside house
26	Kolhufushi	Meemu	2.77183	73.42510	0.93	2.76	23	18-Jan-2005	12:27	debris in tree
27	Kolhufushi	Meemu	2.77225	73.42503	0.93	2.90	30	18-Jan-2005	12:33	damaged tree
28	Kolhufushi	Meemu	2.77297	73.42533	0.93	2.83	30	18-Jan-2005	12:39	debris in tree
29	Kolhufushi	Meemu	2.77343	73.42473	0.86	2.91	129	18-Jan-2005	12:47	debris in palm tree
30	Kolhufushi	Meemu	2.77385	73.42442	0.86	2.87	192	18-Jan-2005	12:49	inside house
31	Kolhufushi	Meemu	2.77402	73.42363	0.93	2.23	290	18-Jan-2005	12:54	outside house
32	Kandholhudhoo	Raa	5.62015	72.85435	1.18	2.87	147	19-Jan-2005	06:03	outside house
33	Kandholhudhoo	Raa	5.61995	72.85457	1.18	3.02	138	19-Jan-2005	06:06	outside house
34	Kandholhudhoo	Raa	5.61997	72.85465	1.18	2.95	125	19-Jan-2005	06:10	inside house
35	Kandholhudhoo	Raa	5.61850	72.85565	1.18	2.21	68	19-Jan-2005	06:20	outside house
36a	Kandholhudhoo	Raa	5.61832	72.85583	1.18	3.39	54	19-Jan-2005	06:33	outside house
36b	Kandholhudhoo	Raa	5.61832	72.85583	1.18	3.10	54	19-Jan-2005	06:33	outside house
37	Kandholhudhoo	Raa	5.61822	72.85568	1.18	2.72	71	19-Jan-2005	06:36	outside house
38	Kandholhudhoo	Raa	5.61803	72.85578	1.18	3.13	61	19-Jan-2005	06:38	outside house
39	Kandholhudhoo	Raa	5.61775	72.85580	1.18	2.42	64	19-Jan-2005	06:41	inside house
40a	Kandholhudhoo	Raa	5.61768	72.85587	1.18	2.66	60	19-Jan-2005	06:43	outside house

40b	Kandholhudhoo	Raa	5.61768	72.85587	1.18	2.74	60	19-Jan-2005	06:43	outside house
41	Kandholhudhoo	Raa	5.61765	72.85588	1.18	2.82	57	19-Jan-2005	06:44	telephone booth
42	Kandholhudhoo	Raa	5.61757	72.85590	1.18	3.05	59	19-Jan-2005	06:45	outside house
43	Kandholhudhoo	Raa	5.61753	72.85620	1.18	3.10	28	19-Jan-2005	06:47	outside house
44	Kandholhudhoo	Raa	5.61762	72.85630	1.18	3.10	15	19-Jan-2005	06:48	outside house
45	Kandholhudhoo	Raa	5.61858	72.85493	1.80	2.30	143	19-Jan-2005	07:14	outside house
46	Eydhafushi	Baa	5.10142	73.07308	1.44	3.04	64	19-Jan-2005	08:43	outside house
47	Eydhafushi	Baa	5.10145	73.07278	1.44	2.11	171	19-Jan-2005	08:46	outside house
48	Eydhafushi	Baa	5.10177	73.07245	1.44	2.00	178	19-Jan-2005	08:50	outside house
49	Eydhafushi	Baa	5.10248	73.07215	1.44	2.00	229	19-Jan-2005	08:54	outside house
50	Eydhafushi	Baa	5.10265	73.07197	1.44	1.95	192	19-Jan-2005	08:55	outside house
51	Eydhafushi	Baa	5.10302	73.07147	1.44	1.61	175	19-Jan-2005	08:57	outside house
52	Hinnavaru	Lhaviyani	5.49463	73.41283	0.77	1.13	206	19-Jan-2005	10:44	outside house
53	Hinnavaru	Lhaviyani	5.49460	73.41245	0.70	1.30	248	19-Jan-2005	10:47	outside house
54	Hinnavaru	Lhaviyani	5.49373	73.41225	0.60	1.15	263	19-Jan-2005	10:53	outside house
55	Hinnavaru	Lhaviyani	5.49297	73.41190	0.70	1.30	309	19-Jan-2005	10:59	outside house
56	Hinnavaru	Lhaviyani	5.49288	73.41188	0.55	1.49	311	19-Jan-2005	11:01	outside house
57	Hinnavaru	Lhaviyani	5.49272	73.41178	0.55	1.26	322	19-Jan-2005	11:05	outside house
58	Hinnavaru	Lhaviyani	5.49218	73.41317	0.55	0.98	174	19-Jan-2005	11:08	outside house
59a	Hinnavaru	Lhaviyani	5.49195	73.41360	0.55	1.24	128	19-Jan-2005	11:10	outside house
59b	Hinnavaru	Lhaviyani	5.49195	73.41360	0.60	1.04	128	19-Jan-2005	11:10	outside house
60	Hulhule	N. Male	4.19453	73.52565	0.97	1.22	104	14-Jan-2005	04:30	on wall
61	Male	N. Male	4.17208	73.50235	0.95	1.15	82	14-Jan-2005	06:15	on wall
62	Male	N. Male	4.16942	73.50581	0.00	1.45	28	14-Jan-2005	06:15	damaged wall
63	Male	N. Male	4.16970	73.51338	1.15	2.05	20	14-Jan-2005	06:15	damaged fence
64	Male	N. Male	4.17372	73.51788	1.65	1.15	54	14-Jan-2005	06:15	wall overtopping
65	Male	N. Male	4.17866	73.51416	0.85	1.25	15	14-Jan-2005	06:15	on wall
66	Male	N. Male	4.18020	73.50963	1.05	1.35	0	14-Jan-2005	06:15	seawall damaged
67	Embudho Finothu	S. Male	4.18010	73.52455	0.33	2.33	0	14-Jan-2005	09:12	on dock
68	Embudho Finothu	S. Male	4.18010	73.52455	0.33	1.83	0	14-Jan-2005	09:12	in bungalow
69	Embudho Finothu	S. Male	4.18010	73.52455	1.23	2.93	0	14-Jan-2005	09:12	in bungalow
70	Fonadhoo	Laamu	1.83240	73.50333	1.62	3.12	130	14-Jan-2005	17:15	Inside house
71	Fonadhoo	Laamu	1.82420	73.49506	1.02	1.52	158	14-Jan-2005	17:15	outside house
72	Fonadhoo	Laamu	1.82463	73.49520	1.13	2.13	115	14-Jan-2005	18:15	outside walls
73	Fonadhoo	Laamu	1.93235	73.60000	1.88	3.28	0	14-Jan-2005	18:15	road flooding
74	Fonadhoo	Laamu	1.92293	73.54980	1.57	2.87	179	15-Jan-2005	02:50	on wall
75	Dhiffushi	N. Male	4.44435	73.71480	1.20	2.20	80	15-Jan-2005	08:20	on wall
76	Dhiffushi	N. Male	4.44392	73.71365	1.00	2.30	13	15-Jan-2005	08:20	on window
77	Huraa	N. Male	4.33356	73.60093	1.54	2.34	200	15-Jan-2005	09:45	debris in mangroves
78	Huraa	N. Male	4.24918	73.53676	1.84	3.34	0	15-Jan-2005	09:45	on wall

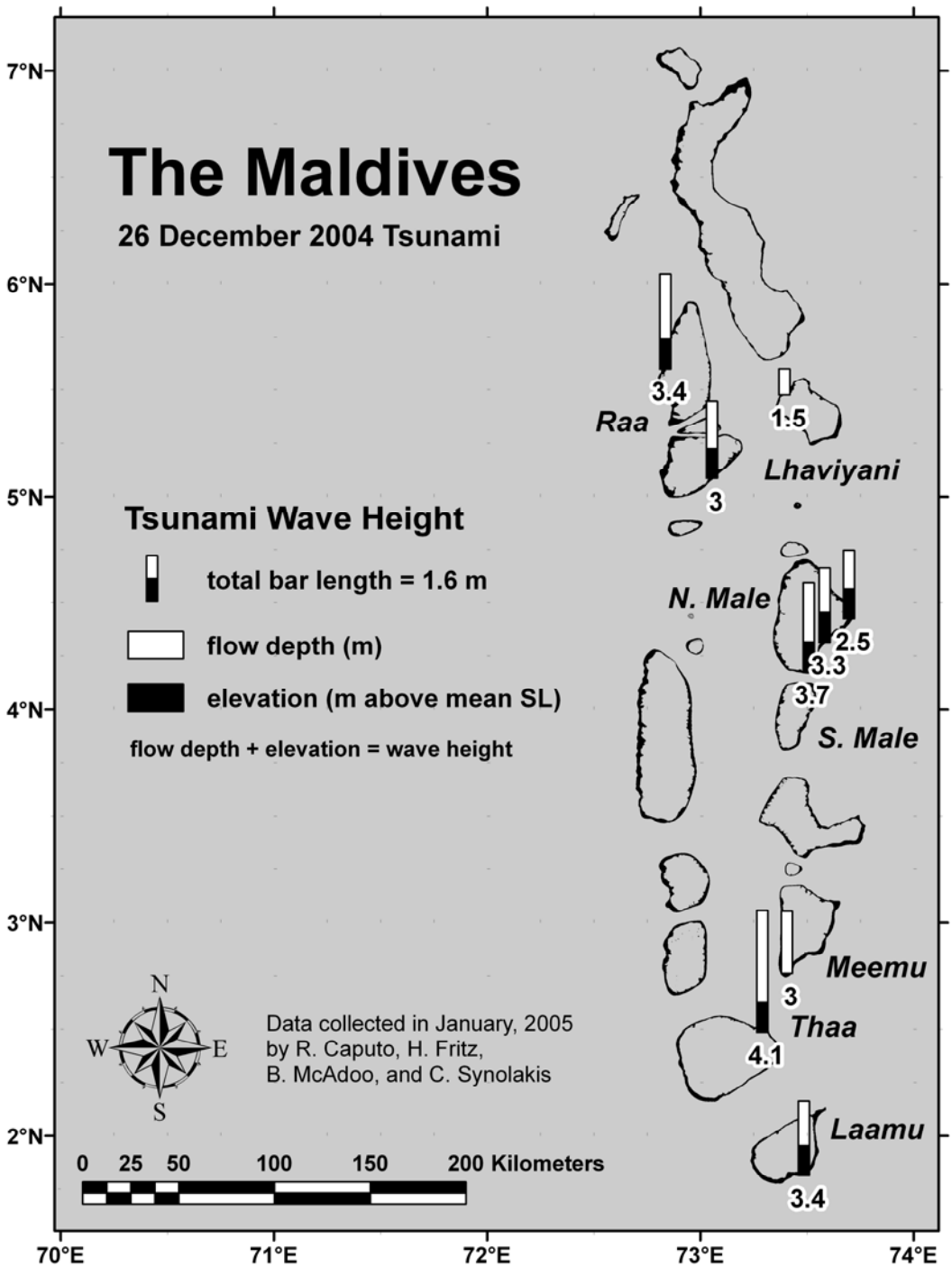
The Maldives
26 December 2004 Tsunami
Tsunami Wave Height
total bar length = 1.6 m
flow depth (m)
elevation (m above mean SL)
flow depth + elevation = wave height
Raa
Lhaviyani
N. Male
S. Male
Meemu
Thaa
Laamu
3.4
1.5
3
2.5
3.3
3.7
3
4.1
3.4
Data collected in January, 2005
by R. Caputo, H. Fritz,
B. McAdoo, and C. Synolakis
N
S
E
W
0 25 50 100 150 200 Kilometers
7°N
6°N
5°N
4°N
3°N
2°N
70°E
71°E
72°E
73°E
74°E

Figure 1

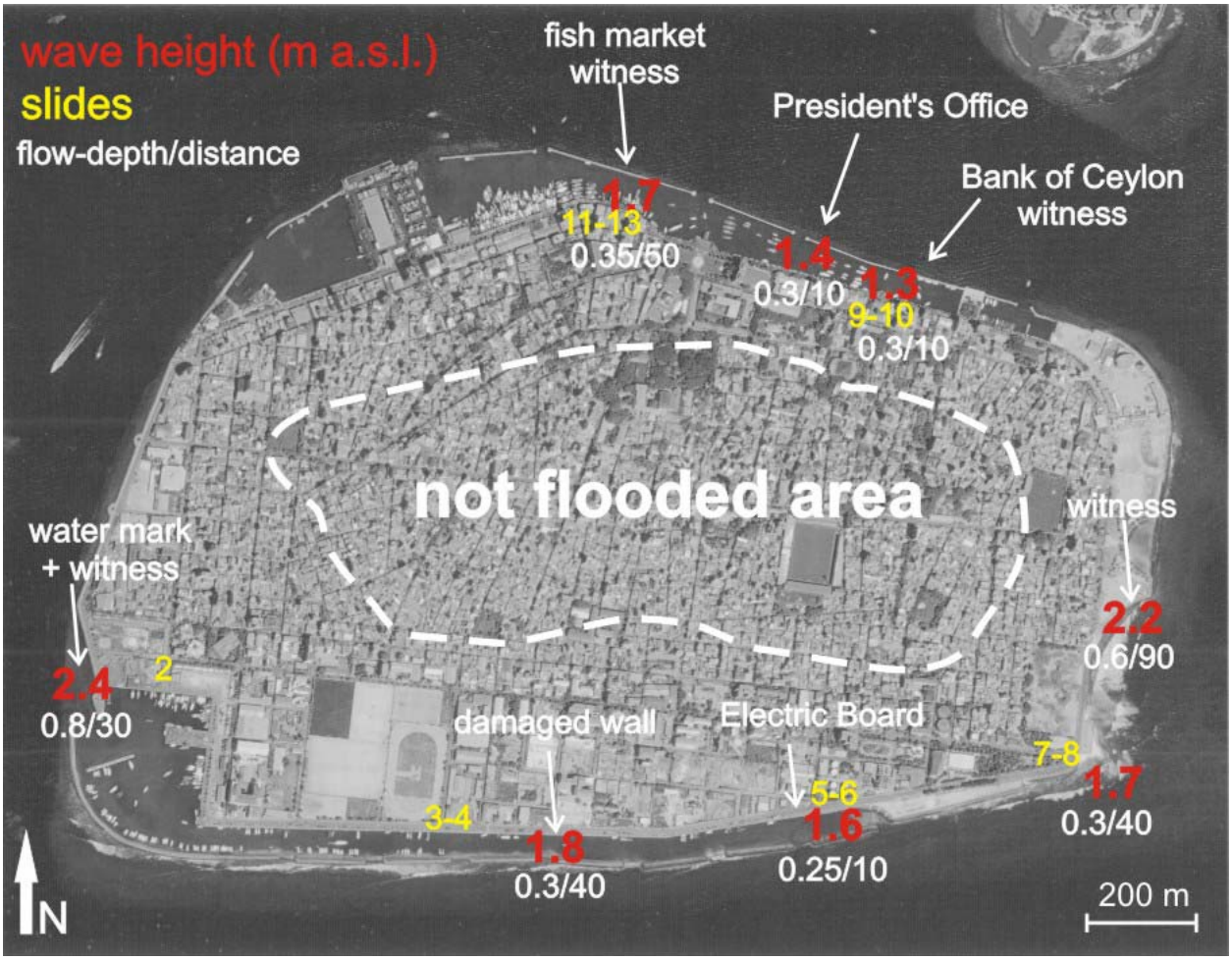
wave height (m a.s.l.)
slides
flow-depth/distance
fish market witness
President's Office
Bank of Ceylon witness
1.7
11-13
0.35/50
1.4
0.3/10
1.3
9-10
0.3/10
not flooded area
water mark + witness
witness
2.2
0.6/90
2.4
2
0.8/30
damaged wall
Electric Board
7-8
1.7
0.3/40
5-6
1.6
0.25/10
3-4
1.8
0.3/40
N
200 m

Figure 2

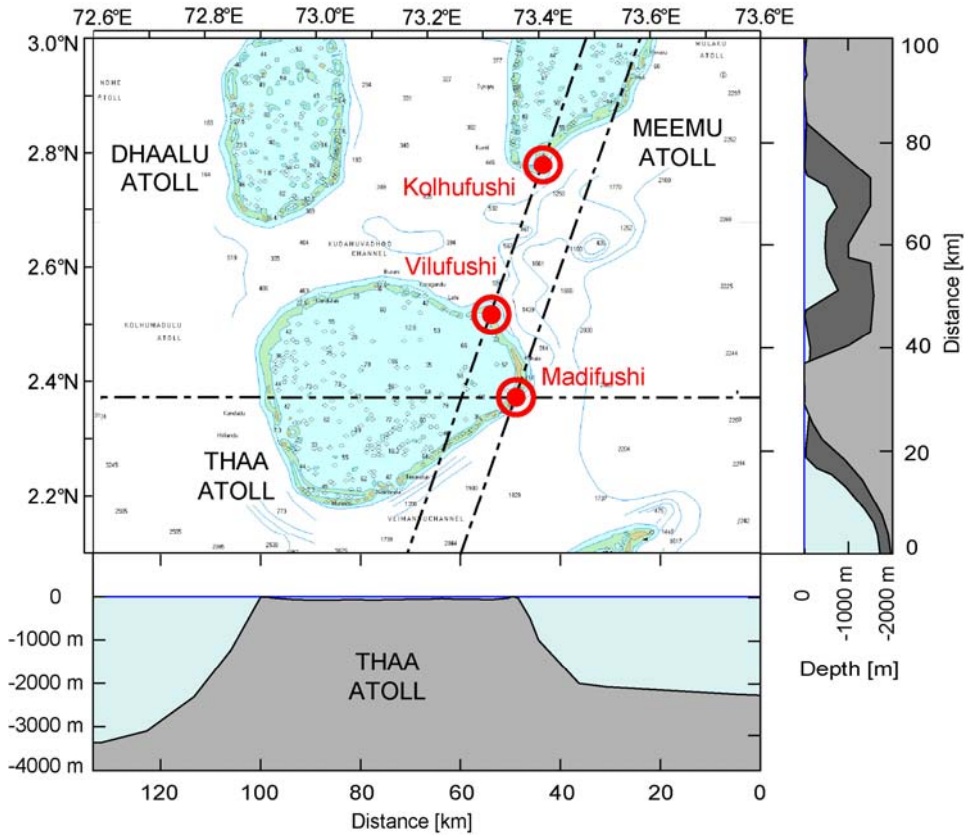
72.6°E
72.8°E
73.0°E
73.2°E
73.4°E
73.6°E
73.6°E
3.0°N
2.8°N
2.6°N
2.4°N
2.2°N
DHAALU ATOLL
MEEMU ATOLL
Kolhufushi
Vilufushi
Madifushi
THAA ATOLL
100
80
60
40
20
0
Distance [km]
0
-1000 m
-2000 m
-3000 m
-4000 m
THAA ATOLL
120
100
80
60
40
20
0
Distance [km]
0
-1000 m
-2000 m
Depth [m]

Figure 3

(a) 

(b) 

Figure 4

Figure 5

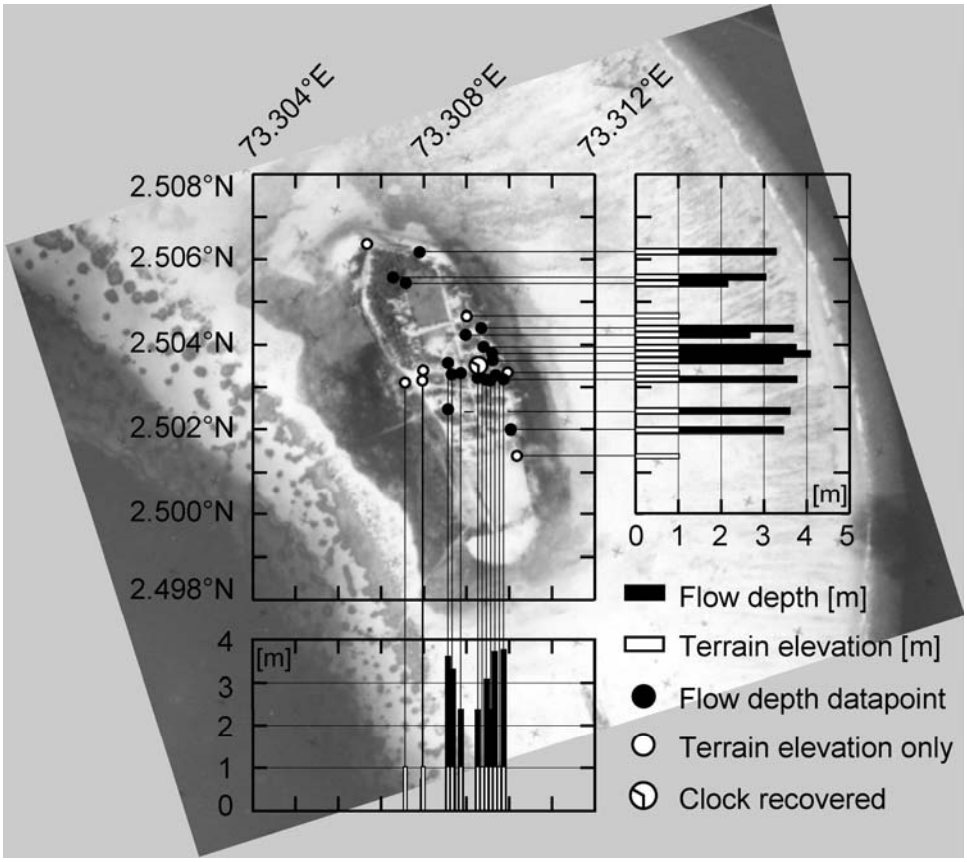
73.304°E
73.308°E
73.312°E
2.508°N
2.506°N
2.504°N
2.502°N
2.500°N
2.498°N
[m]
0 1 2 3 4 5
4
3
2
1
0
[m]
Flow depth [m]
Terrain elevation [m]
Flow depth datapoint
Terrain elevation only
Clock recovered

Figure 6

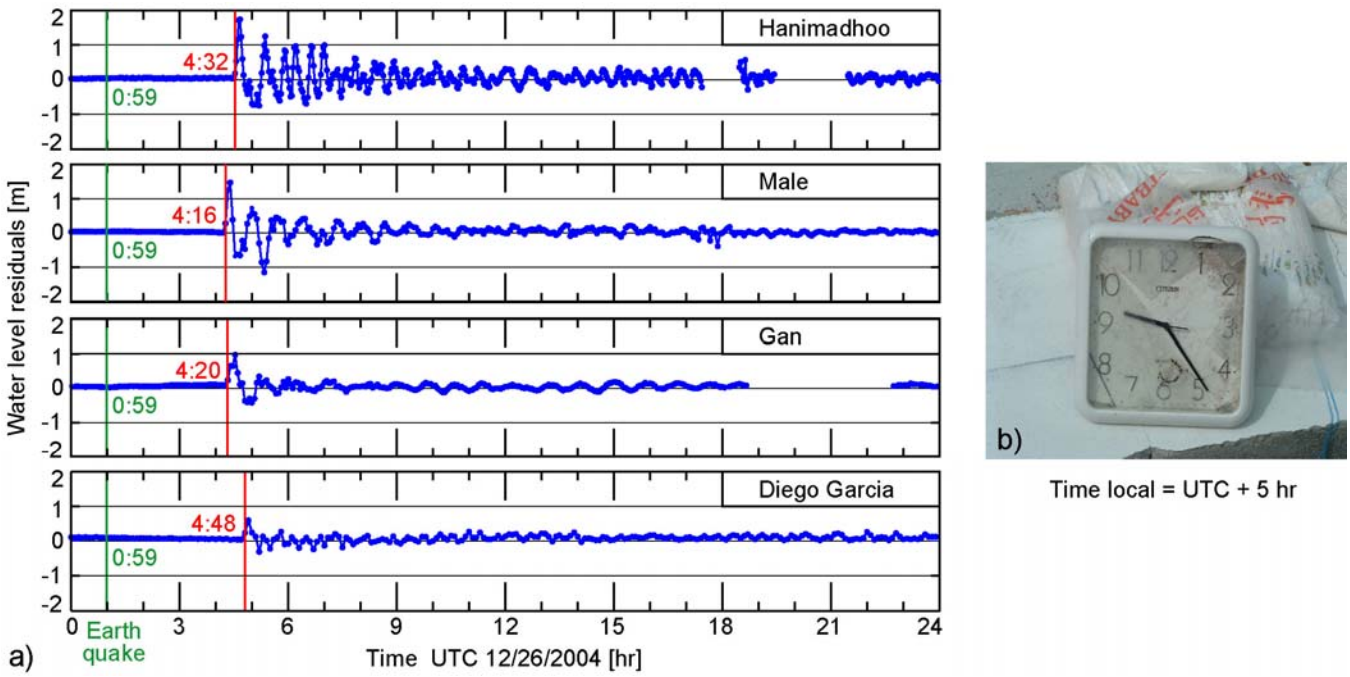
Hanimadhoo
Male
Gan
Diego Garcia
4:32
4:16
4:20
4:48
0:59
Water level residuals [m]
Earth quake
Time UTC 12/26/2004 [hr]
a)
b)
Time local = UTC + 5 hr

Figure 7

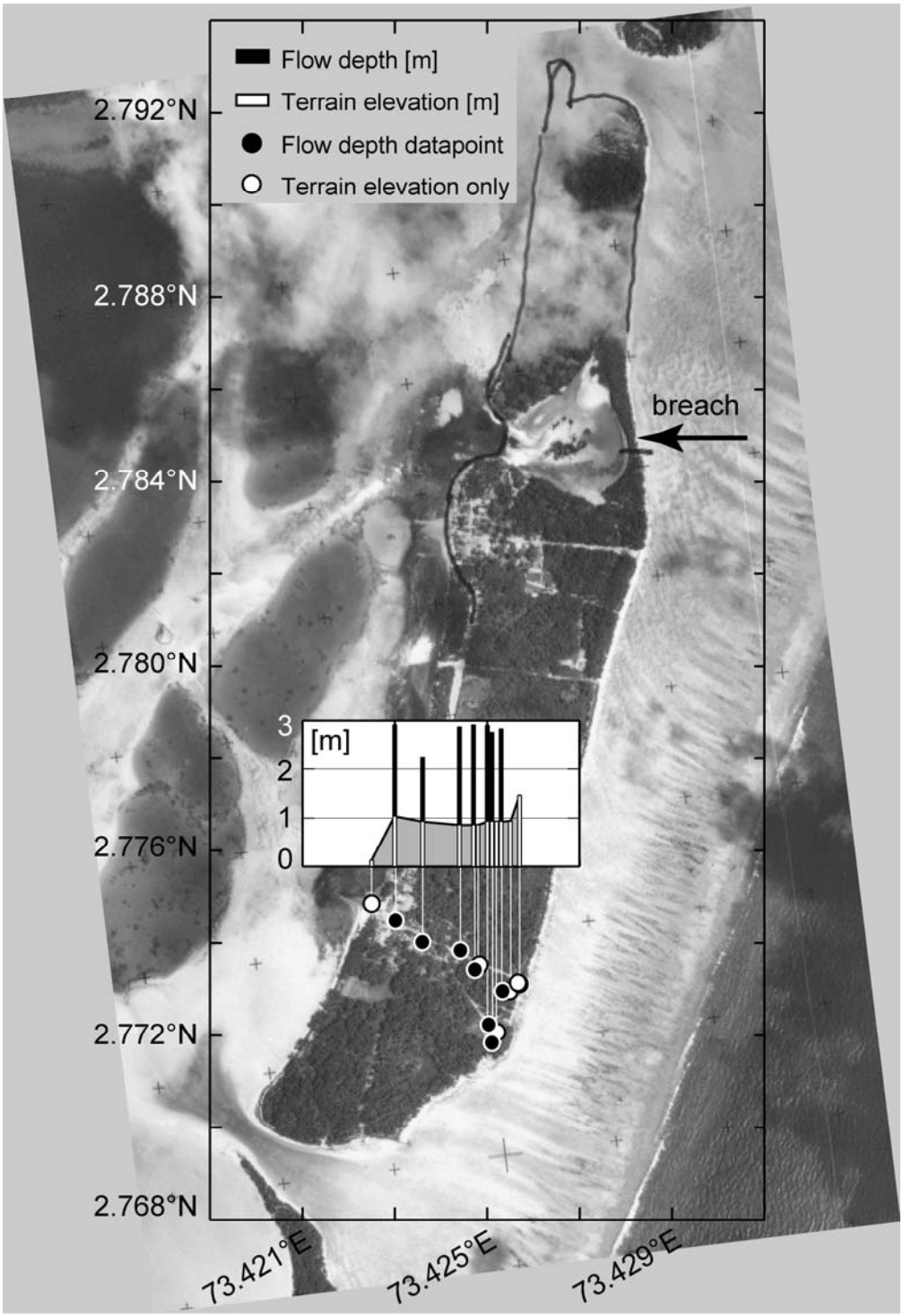
Flow depth [m]
Terrain elevation [m]
Flow depth datapoint
Terrain elevation only
breach
2.792°N
2.788°N
2.784°N
2.780°N
2.776°N
2.772°N
2.768°N
73.421°E
73.425°E
73.429°E
[m]
3
2
1
0

Figure 8

Figure 9

(a)

(b)

Figure 10

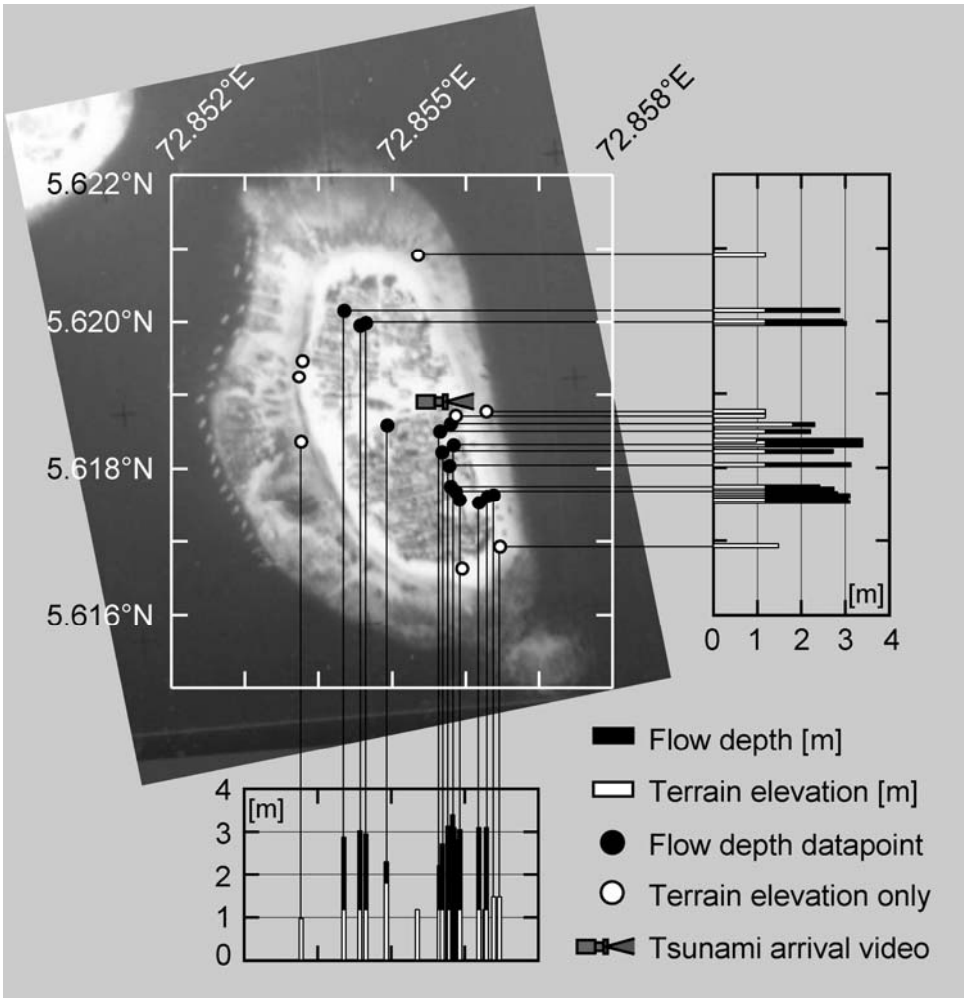
72.852°E
72.855°E
72.858°E
5.622°N
5.620°N
5.618°N
5.616°N
[m]
0 1 2 3 4
[m]
4
3
2
1
0
Flow depth [m]
Terrain elevation [m]
Flow depth datapoint
Terrain elevation only
Tsunami arrival video

Figure 11

a) 

b) 

Figure 12

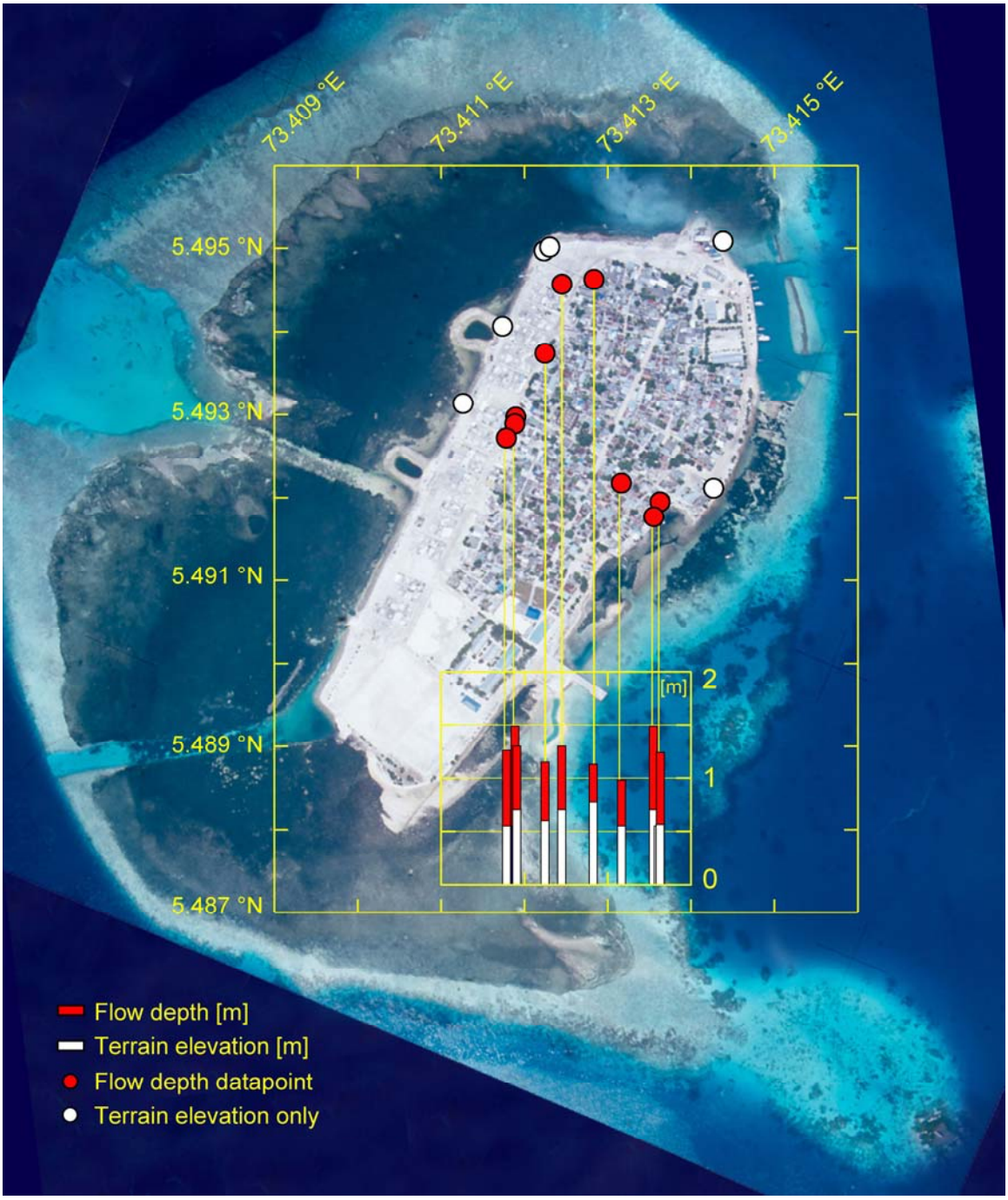
73.409 °E
73.411 °E
73.413 °E
73.415 °E
5.495 °N
5.493 °N
5.491 °N
5.489 °N
5.487 °N
[m]
2
1
0
Flow depth [m]
Terrain elevation [m]
Flow depth datapoint
Terrain elevation only

Figure 13