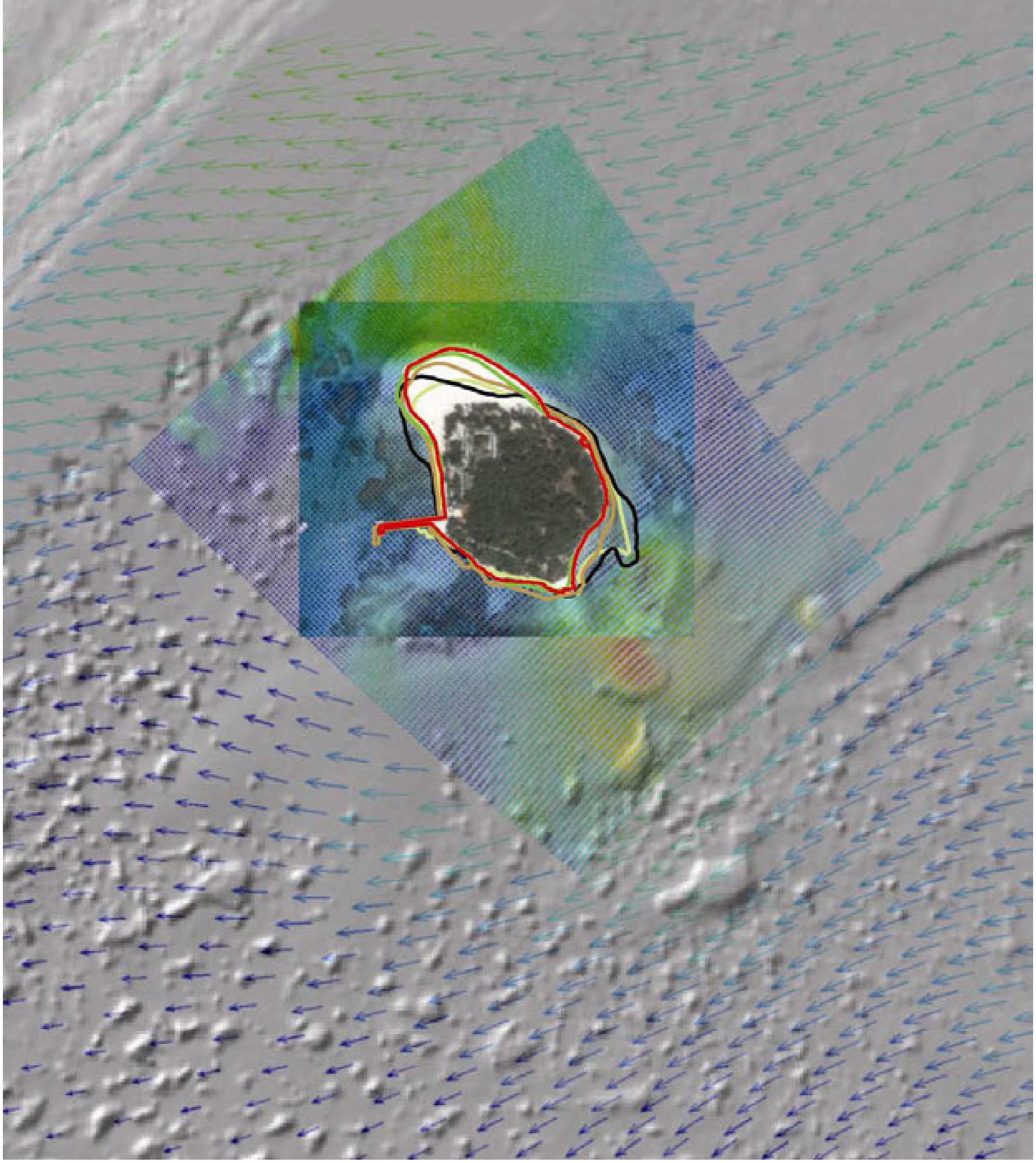
Mañagaha Island Shoreline Stability Assesssment

Coastal Resources Management Office
Commonwealth of the Northern Mariana Islands
2007



Mañagaha Island
Shoreline Stability Assessment

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Fletcher, C.H., Barbee, M., Dyer, M., Genz, A., Vitousek, S., 2007. Mañagaha Island Shoreline Stability Assessment, Report to the Coastal Resources Management Office, Commonwealth of the Northern Mariana Islands, Saipan, 90 p.

This report was prepared under award NA04NOS4190051 from the Office of Ocean and Coastal Resources Management, National Oceanic and Atmospheric Administration. The statements, findings, conclusions, and recommendations are those of the authors and do not necessarily reflect the views of OCRM or NOAA.

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Cover image – QuickBird, Inc., 2004

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EXECUTIVE SUMMARY

The purpose of the Mañagaha Island Shoreline Stability Assessment is to evaluate coastal erosion hazards and potential management responses on the island of Mañagaha, Saipan. Mañagaha Island is a registered National Historic site, a Marine Conservation Area managed by the Department of Lands and Natural Resources Division of Fish and Wildlife, and important tourist destination with visitor facilities managed under a 10 year lease by Tasi Tours & Transportation, Inc. Recent studies by the US Army Corps of Engineers and the Commonwealth of the Northern Mariana Islands Coastal Resource Management Office have documented erosion of the shoreline along the southeast, east, and northeast side of Mañagaha Island.

Using historical aerial photographs and recent satellite imagery to document past shoreline positions, a hydrodynamic model of easterly trade winds and tides, as well as field observations including surveyed topographic profiles, the following patterns of shoreline change are documented in this report:

1. Mañagaha shoreline behavior can be classified in four regions.
    a. Region 1 is located on the north end of the island and is characterized by shoreline accretion at rates ranging approximately 1 to 5 m/yr since 1996.
    b. Region 2 includes the northeast and east shorelines and is experiencing coastal erosion ranging approximately 0.5 to 4 m/yr since 1996.
    c. Region 3 includes the south and southwest shorelines and is experiencing variable behavior including eroding in some years and accreting in others since 1996. Rates of shoreline change typically occur less than 1 m/yr. The pier blocks sediment transport to the north and there is historical progradation of the beach in Region 3 due to sediment build-up on the south side of the pier.
    d. Region 4 includes the beach immediately north of the pier which is eroding at less than 1 m/yr since 1996. Accretion in Region 1 may be blocking sand movement into Region 4 leading to erosion. Sand impoundment south of the pier is also a likely factor contributing to erosion in Region 4.
2. Debris removed from Region 2 in 1996 led to significant changes in shoreline behavior in all four regions: accelerating erosion in Regions 2 and 4 and accelerating accretion in Region 1.

3. All shorelines on the island share sand to some degree.
4. Trade winds from the east combine with tides to generate currents which split into two directions at approximately the location of the removed debris: one leg travels south along the eastern shoreline in Region 2 and one leg travels west along the northern shoreline into Region 1. These form two littoral cells that exchange sand.

Various methods available to mitigate shoreline erosion each have advantages and disadvantages. A selected option should be based on what stakeholders feel are the most important issues surrounding management of the area. Sand is the most precious asset on an eroding coast, and erosion management options need to be considered from the perspective of how sand is managed.

1. In the next two years we recommend careful monitoring of erosion patterns and rates designed to answer the critically important question: “Is the rate of erosion decreasing, increasing, or staying the same?” If after two years the answer is that erosion is not decreasing, then we recommend bringing in an experienced coastal engineering firm with the mission of proposing a structural management solution and implementing the recommendation. We recommend that within 5 years the problem should have been addressed and an acceptable management approach adopted and implemented.
2. If a consideration of economic, conservation, and recreational factors leads to the conclusion that an engineering solution is desirable immediately, then a groin/breakwater system designed to correct the recent history of erosion along the eastern shore is recommended. Our model results suggest that a temporary groin at the approximate location of removed debris in 1996 might be successful in stabilizing the shoreline. It is recommended that large sand bags, filled with offsite sand, or quarried rock if it is more easily available, be set in place and monitored to achieve optimum configuration. It would also be advisable to back fill the enclosed area of the groin with back-passed sand from Region 1 where the beach has experienced accretion in the past decade.
3. Alternatively, to avoid a structural approach, a sand back-passing system without a groin is recommended employing a pump in Region 1 that delivers sand to Region 2

INTRODUCTION

Study purpose

The purpose of the Mañagaha Island Shoreline Stability Assessment is to evaluate coastal erosion hazards and potential management responses on the island of Mañagaha, Saipan. The assessment describes the pattern, rates, and extent of historical shoreline change in the context of geologic and oceanographic factors affecting shoreline stability. The assessment also reviews potential management responses to shoreline change but does not provide specific cost information.

General Methods

The methods used in the assessment include collection and review of previous work and other relevant materials including anecdotal as well as historical information (e.g. reports, maps, remote imagery, beach profiles). Through field-collected data, the assessment develops a description of existing conditions. Remote imagery document historical trends and patterns of shoreline change. These are analyzed to yield information on the magnitude of annual average shoreline change. This assessment includes maps of present erosion rates and shoreline conditions, a projection of the 10 year shoreline hazard zone at 95% confidence, and an evaluation of potential erosion management measures for Managaha.

Mañagaha Island

Mañagaha (aka *Ghalaghal*) Island is a registered National Historic site, a Marine Conservation Area managed by the Department of Lands and Natural Resources Division of Fish and Wildlife (Schroer, 2005), and important tourist destination with visitor facilities managed under a 10 year lease by Tasi Tours & Transportation, INC. Recent studies by the US Army Corps of Engineers (US Army Corps of Engineers Honolulu Division, 2001) and the Commonwealth of the Northern Mariana Islands (CNMI) Coastal Resource Management Office (CRMO; Agulto and Yuknavage, 2006) have documented erosion of the shoreline along the southeast, east, and northeast side of Mañagaha Island. Erosion is a natural part of any shoreline experiencing a sediment deficiency and or dynamic processes capable of transporting sand. However, the historical rate of erosion at Mañagaha appears to have accelerated, and some previously stable areas have begun to erode following the 1996 removal of WWII debris (ship wrecks and a pier) posing a safety hazard in the area. This history implies that wave and current modification provided by the debris were significant to island stability.

Sand eroded from the east shore appears to contribute to accretion along the north and northwest shore, although no attempt has been made to quantify the sediment budget of eroded vs. accreted sand volumes. Simple consideration of coastal processes suggests that wave and current dynamics associated with normal easterly trade winds is consistent with sand transported from the eroding eastern shore, via the northeast shoreline, to the accreting northwestern shore. An impervious pier blocking sand transport on the south shore indicates a southerly route is not viable, and therefore the northeast shoreline is the dominant corridor of sand movement to the northwest.

Erosion has been a chronic problem since 1996. Continued erosion leads to the collapse of trees, threatens a bird nesting habitat, is unsightly and unsafe for visitors, and uncovers buried debris in the shoreline. Coastal erosion on Mañagaha Island represents an important consideration in future management efforts.

ENVIRONMENTAL CONDITIONS

Geography and Location

Mañagaha Island (WGS 1984 UTM Zone 55 361752N 1685412E) is found in the Northern Mariana Islands (Fig. 1) approximately 2.7 km off the west coast of Saipan in the Tanapag Lagoon. It is a low carbonate feature comprised of sand, carbonate rock, and fill from past dredge and construction activities on and near the island (US Army Corps of Engineers Honolulu Division, 2001). The 4 ha island has a major axis running SE-NW approximately 350 m in length and a minor axis of approximately 245 m. Because of ongoing erosion and accretion the shoreline varies in composition and stability around the island, including segments consisting of: fine to medium-grained carbonate sand, undercut vegetation, beachrock, engineered structures, and anthropogenic debris.

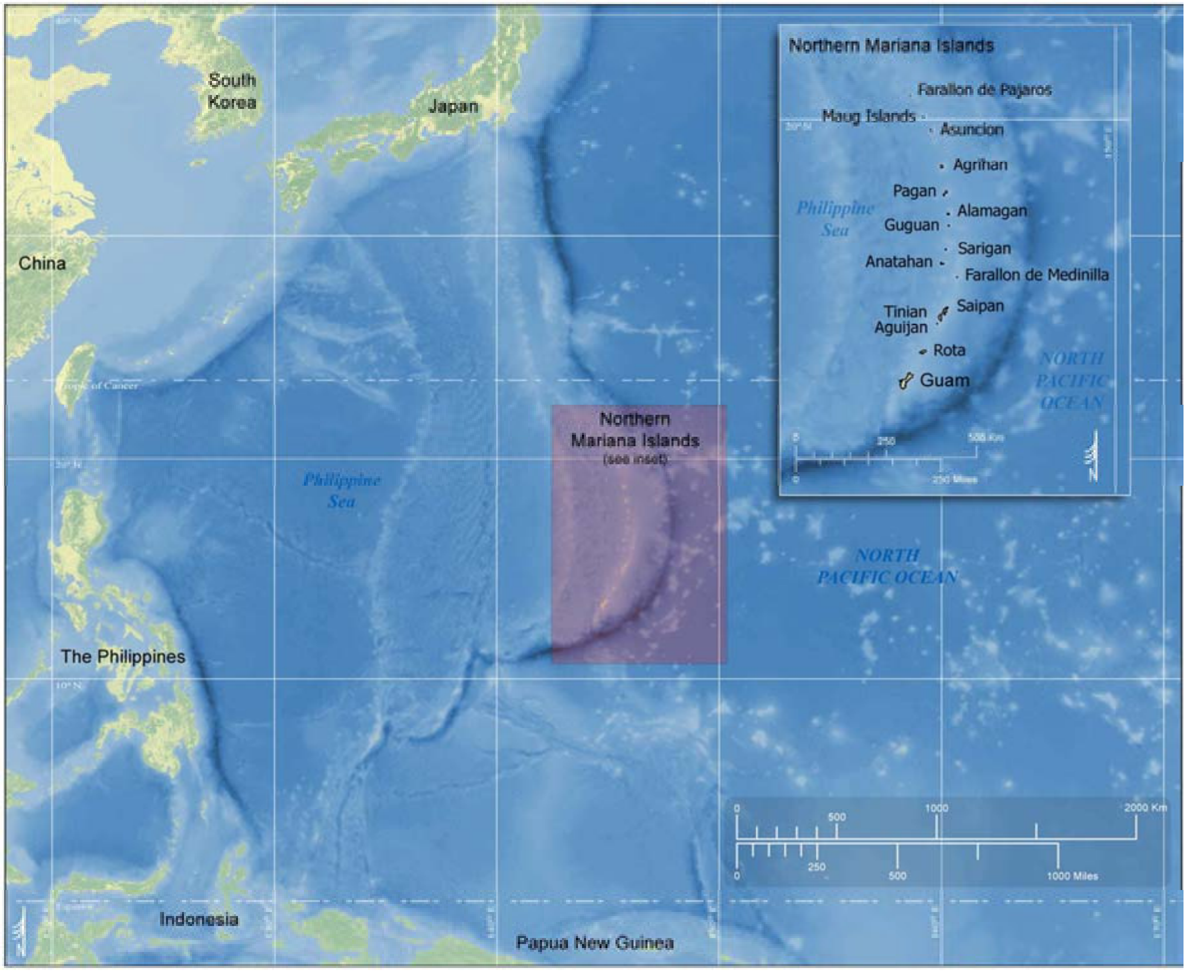

Figure 1. Commonwealth of the Northern Mariana Islands (CNMI)

Mañagaha is a *cay*, a sandy islet resting atop a fringing reef (Fig. 2) that has a steeply dipping front slope, a crest, and a broad and shallow reef flat making up Tanapag Lagoon. The reef crest is located about 600 m to the west and northwest of Mañagaha and significantly attenuates incident wave energy from the west, north, and south. The reef flat consists of patch reefs, barren limestone surface, sand and gravel, and rubble zones. It is cut by channels that are important in tidal flow. There is a dredged channel approximately 160 m wide located 1000 m to the south where depths average -12 m (Fig. 3). Waters surrounding Mañagaha range in depth from approximately -1 m to -8 m while directly adjacent to the island they are less than -3 m deep. Located just seaward of the reef crest is the reef slope where the seafloor quickly drops off to depths exceeding -20 m and wave energy is pronounced.

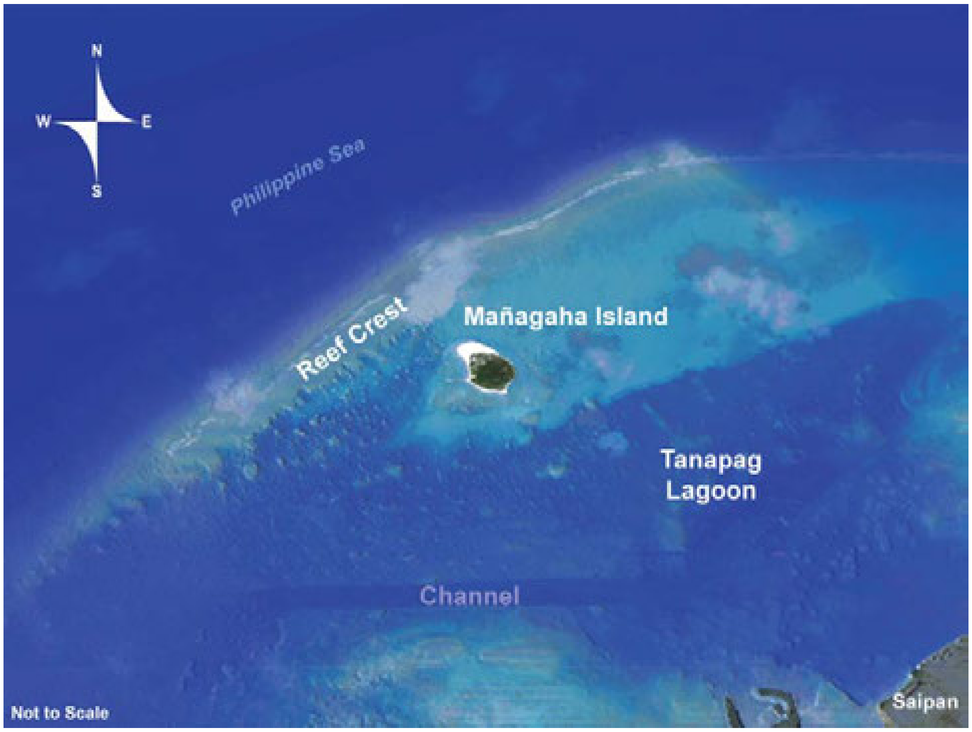

Figure 2. Mañagaha Island is a sandy cay on the Saipan fringing reef (QuickBird, Inc., 2004, 2006).

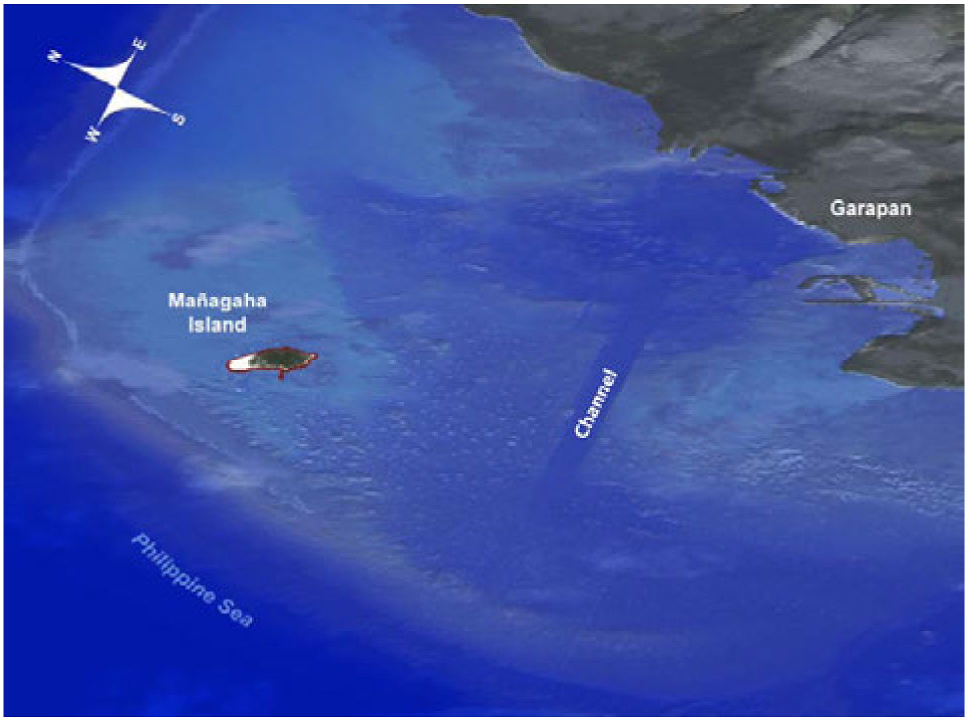

Figure 3. Digital elevation model, northwest Saipan perspective (Visual Nature Studio - USGS/USACOE/NOAA/QuickBird Inc. data).

Winds, Waves, and Tides

Mañagaha is situated in the low, northern latitudes of the western Pacific (~15^{o} N lat.) and experiences consistent trade winds about 70% of the year (Fig. 4). When trade winds are absent, dominant weather conditions are either variable or stormy. Prevailing winds are E to ENE on average but can vary from the SE to N. Trade winds are strongest and most consistent in the dry season—January through May. Annually on Saipan, trade winds blow approximately 13 - 18 km/hr 40% of the year, 20 - 30 km/hr 26% of the year, and 4% of the year wind speeds are greater than 30 km/hr (US Army Corps of Engineers Honolulu Division, 2004). Average annual trade wind velocity is about 17 km/hr, predominantly from the east. During the wet season, July through December, variable winds and storm/typhoon winds are more likely. In recent history an average of 3 tropical cyclones pass annually within 300 nautical miles of Saipan (Minton and Palmer, 2006). This number varies with the ENSO. During an El Nino phase the CNMI are more likely to experience cyclones than the years following an El Nino due to the positioning of warm Pacific waters and their proximity to the CNMI.

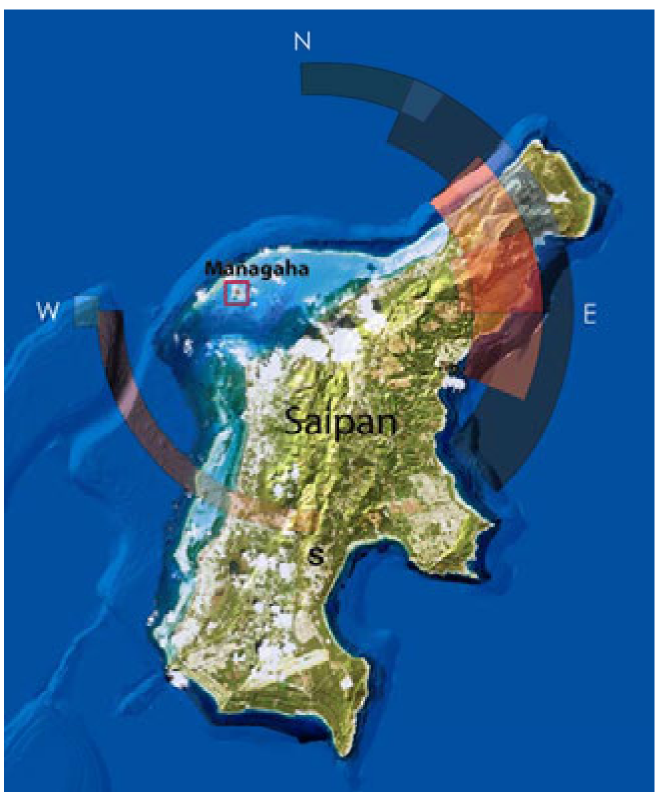

Figure 4. Wind (orange) and wave (blue) directions in Saipan and Mañagaha (red box). (USGS and NOAA DEM, QuickBird Inc. image, 2004)

Mañagaha, in the shelter of Saipan and protected by Tanapag Lagoon, is not directly exposed to open ocean wind energy from the NE (45^o) to the SSW (160^o). However, the fetch between Saipan and Mañagaha is sufficient to develop choppy seas on the surface of Tanapag Lagoon during trade wind conditions and Saipan does not block winds in the azimuth NE to N. Diurnal heating may in fact accelerate winds from the NE to N as thermals develop above the main island. It is waves generated by these winds, combined with tidal currents, which are the likely source of energy eroding the eastern shore. Swell from other directions are partially blocked or attenuated by the shallow fringing reef crest located west and north of Mañagaha. Lifeguards on Mañagaha report that large swell from the west and north can produce high run-up that penetrates the vegetation line on the NW side of the island at high tide.

Wave energy directly impacting the shoreline of Mañagaha consists of four principal types: 1) Local choppy seas created by trade winds across Tanapag Lagoon that generate westward moving alongshore currents; 2) Energy from north, west, or southwest waves crossing the shallow reef crest from deeper water; 3) Infrequent wind energy from the north generating alongshore currents running to the south; 4) Waves associated with tropical cyclones that may impinge on the island from any direction.

Energy associated with 1) is the dominant annual condition. Tidal differences on average throughout the year in Saipan are within 0.4 m with a recorded mean high water of 0.56 m and a mean low water of 0.17 m. The role of tide-generated currents in transporting sand is poorly documented. However, modeling and field experience indicate that tides combined with easterly winds are consistent with the observed pattern of recent shoreline change.

THE MAÑAGAHA PROBLEM

Description of the Problem

Dramatic and accelerated shoreline change at Mañagaha has been documented since 1996 (Fig. 5) when debris was removed (Fig. 6) on and near the immediate shoreline. Since then, the contiguous southeast, east, and northeast shorelines of Mañagaha have experienced persistent erosion and shoreline retreat.

Figure 5. Shoreline changes at Mañagaha accelerated following debris removal in 1996. (QuickBird, 2006)

Figure 6. Debris (circled) in the area of modern erosion was removed in 1996. (1987 aerial photo)

Narrative Aerial Photo History

1945 - Present: At the time of aerial photography (Fig. 7) in 1945, a sandy spit extended to the south from the eastern shoreline of Mañagaha. In the following 50 years, this spit sporadically

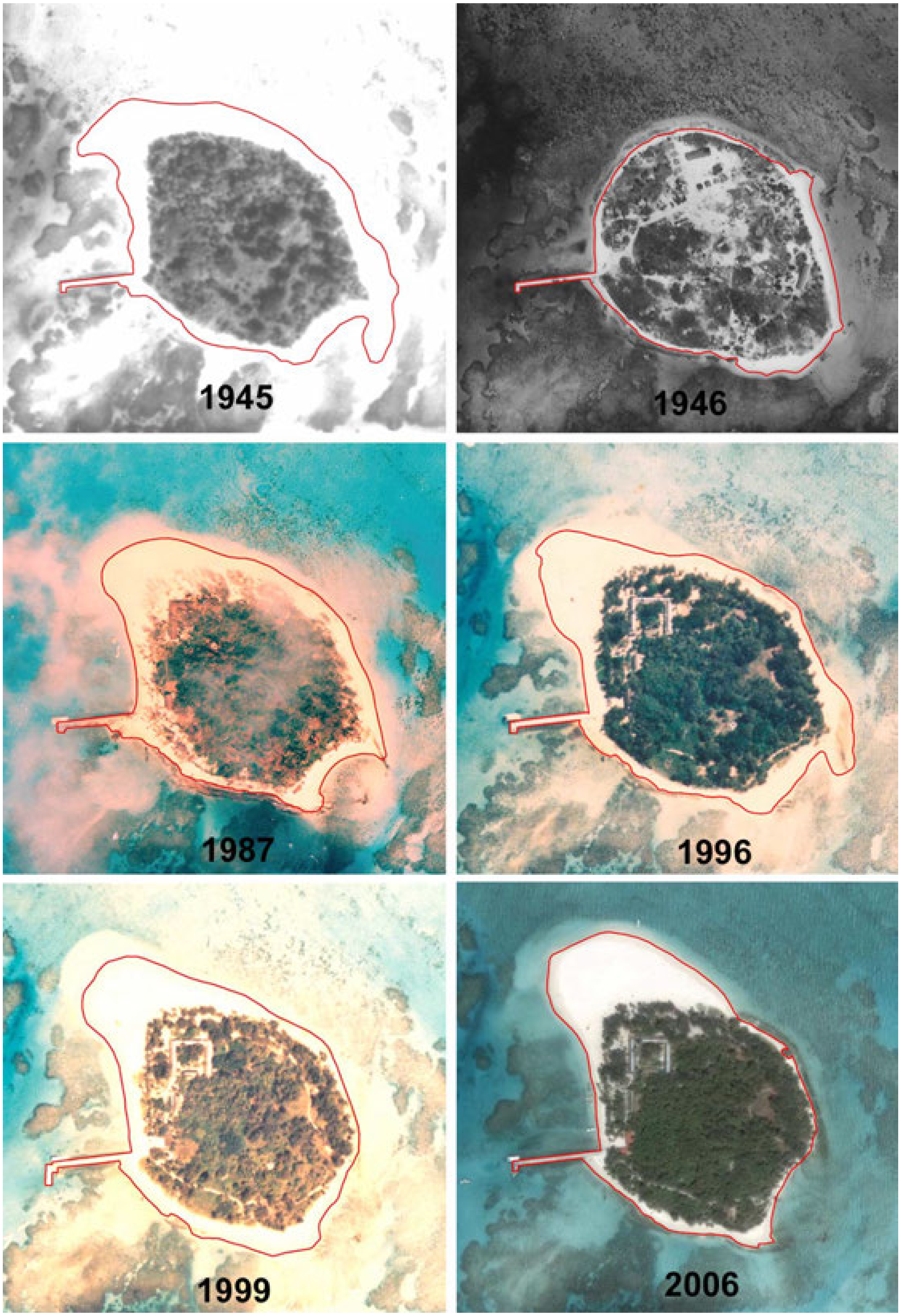

Figure 7. Historical changes to Mañagaha Island. Red vector marks the low water shoreline.

retreated at rates ranging from 1 to >7 m/yr. Sand leaving the region fueled dramatic shoreline accretion on the northwest side of the island, reaching rates exceeding 5 m/yr.

The southern shoreline is dynamic and exhibits variable behavior. Presently, it has achieved a quasi-stable configuration with long-term rates of accretion generally less than 1 m/yr on the eastern end and erosion of approximately 1 m/yr on the west end. Overall, the southern shoreline has been generally eroding since 1996.

The western shoreline immediately north of the pier is deficient of sand due to the impervious construction of the pier which acts as a groin. Down-drift offset reveals flanking and sediment deprivation north of the pier destabilizing the western shore such that since 1996 it has been eroding at rates generally between 1 and 4 m/yr.

1946 Extensive anthropogenic reconstruction of Mañagaha: The 1946 image shows Mañagaha in its most deviated state. The island in 1946 has radically changed shape from 1945 showing an almost complete absence of beach in the northwest, and spits that were present in the east in the previous year are no longer distinguishable. The vegetation line on the eastern shore has been filled such that it extends into what was once the shallow water of the reef flat. Changes of this magnitude in less than a year are a sign of human manipulation. Dirt roads and structures not present the previous year are seen across the island surface. Also visible is debris in the water directly offshore and on the beach of the eastern and southern shores that was not visible in 1945.

1987 The beach returns to a natural state: In comparison to 1946, the shoreline has evolved to near its original shape, although on the eastern shore the beach is not as extensive as it appeared in the 1945 image. There is, once again, a large beach in the northwest that is consistently accreting, but this area is not as wide or as long as it was in 1945. There is also noticeable accretion south and east of the pier where sand has accumulated up-drift of the structure. Whether or not the processes responsible for returning this beach to it original shape were natural or anthropogenic is unknown, possibly some combination.

1996 Continued northwest accretion trending towards 1945 configuration: Noticeable differences from 1987 are apparent on the eastern shore. The shoreline has evolved seaward compared to 1987 indicating net accretion and a spit or tombolo has formed in the lee of debris located offshore. The sand spit that is visible in 1945 has reappeared though in reduced extent. The trend from 1987 to 1996 on the eastern shore is one of seaward shoreline evolution forming a spit similar to the one shown in 1945. The shoreline has also progressed seaward to the north of the pier and along the northwest shore.

1999 Erosion of eastern shore, accretion of northwest shore: Areas of erosion are prominent on the eastern shoreline. The sand spit that had formed in 1996 is now largely gone. Accretion southeast of the pier has occurred as a consequence of blocked longshore sediment transport by the structure. Most visible debris just offshore has now been removed.

2004 Eastern erosion, erosion in southeast, northwest accretion: Noticeable erosion is present along the eastern shoreline. All apparent beach sand is absent and the water line corresponds to overhanging vegetation and fallen trees indicating a loss of almost all beach sand. The spit that appeared to be accreting in 1994 is now completely gone. The shoreline of the entire island, with the exception of the northwest coast, has receded. The northwest coast has extended seaward (accretion).

2006 Island-wide shoreline continues previous pattern: The shoreline around the Island continues the same pattern as in previous years: erosion on the east coast, accretion on the northwest coast, variability/erosion on the south coast, and erosion of the west coast.

Methods

The University of Hawaii Coastal Geology Group *http://www.soest.hawaii.edu/coasts/index.html* has established an innovative and flexible system of measuring shoreline change that is the subject of several peer-reviewed publications in international scientific journals (i.e., Fletcher et *al*, 2003; Miller and Fletcher, 2003; Rooney and Fletcher, 2005; Genz et *al*., 2006). A primary goal of these efforts is to accurately characterize shoreline change, minimize statistical uncertainty, and maximize understanding and shoreline forecasting.

A series of vertical aerial photographs and satellite images 1945-2006 document the dynamic nature of the island. In order to track changes in island configuration, the low water mark (lwm) has been vectored on a series of vertical aerial photographs around Mañagaha from the following years: 1945 (1:10,000), 1946 (1:10,000), 1987 (1:10,000), 1996 (1:10,000), 1999 (1:10,000), 2004 (1:50,000), and 2006 (1:50,000) (Fig. 8). Images from 2004 and 2006 are digital satellite images (pixel = 0.6 m). The remaining images are high-resolution scans from aerial photography.

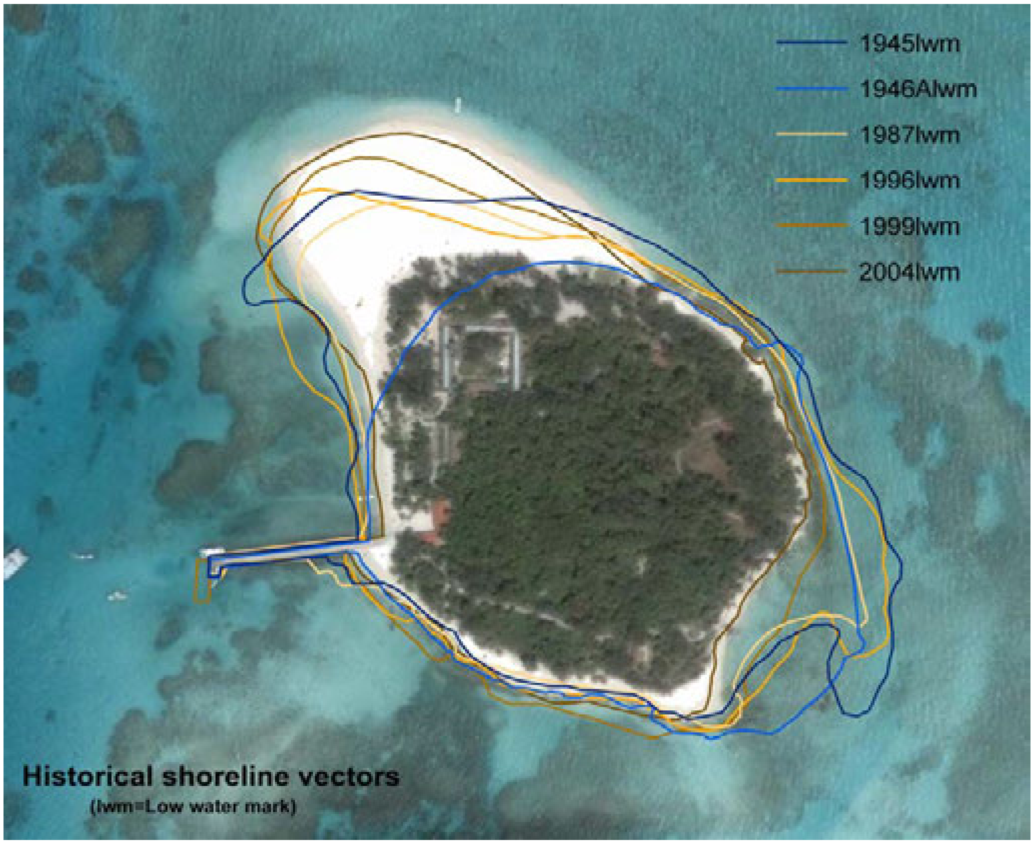

Figure 8. 2006 satellite image of Mañagaha and historical shoreline positions (lwm = low water mark).

We identify the low water mark as a vector, a proxy for the shoreline. This is usually delimited by a topographic feature marking the base of the foreshore known as the "toe" or "base of the step" (Fletcher et *al*., 2003). We recognize the low water mark in vertical imagery based on changes in color and gray-scale associated with water deepening and wave behavior at the base of the beach foreshore. The low water mark is identified by manipulating the color, contrast, and illumination of digital images, and interpreting wave behavior, environmental context, and tone of an image to bring this feature into recognition. We use the commercial software PCI, Inc. for this procedure, although any commercial remote sensing software is useful. Field verification is an important component of proper vectoring.

The low water mark is a true geomorphic feature on a beach profile that typically shifts landward during erosion phases and seaward during accretion. Hence, it reflects the relevant physical process of sediment gain and loss. Monitoring data of the low water mark at Mañagaha indicates that it shifts less than 0.5 m horizontally during the diurnal tides, thus it is a stable feature marking shoreline position. Other workers tend to use a wet-dry line, debris line, vegetation line, or other proxy for the shoreline in imagery analysis (i.e., Hapke et *al*., 2006), but this feature is tied more to wave, water level, and wind state than to true beach position. For instance, changes in wave state immediately preceding an acquired image can significantly shift the position of the debris line or wet-dry line in a way that does not reflect chronic, long term shoreline erosion or accretion. Also, the vegetation line often grows independent of beach processes. Because it is a geomorphic feature, the low water mark can be monitored with surveys, combining imagery and survey datasets to improve understanding of shoreline change.

In the present study, changes in shoreline position 1987-2006 were tracked at a series of 34 transects (Fig. 9). A transect is a vector that is perpendicular to the beach and intersects the shoreline of each year. Shorelines from 1945 and 1946 are not included due to the extensive reconstruction of the island in this time frame. This interrupted the natural progression of the beach and is not indicative of the long term beach processes we seek to understand. Analysis revealed that improved statistical significance was achieved with removal of these shorelines.

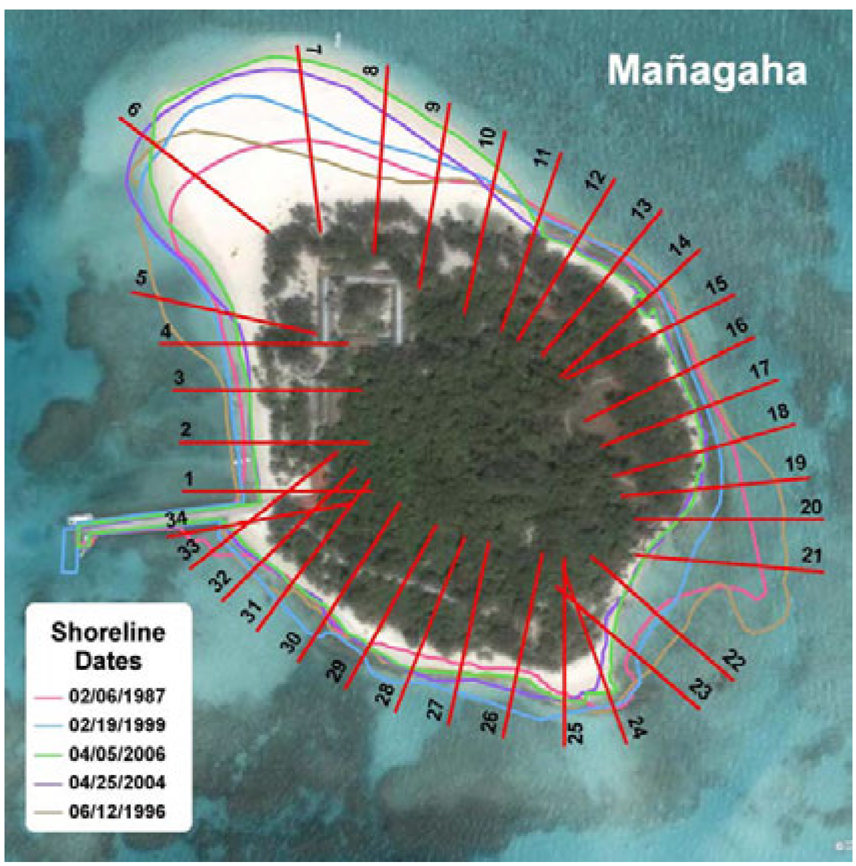

Figure 9. Transects (red) used in shoreline change analysis.

We apply a range of statistical methods to improve understanding of shoreline behavior. Using two sets of shorelines, 1987-2006 and 1996-2006, we employ linear and nonlinear models of shoreline history to forecast rates of change and future hazards as well as improve our understanding of changes in shoreline stability since 1996 debris removal. The linear model depicts long-term rates over the full time series assuming no change in rates, and the nonlinear model depicts changes in rate that may have occurred over the same period. We also employ a linear model to the series 1996 to 2006 to describe the last decade of change.

Throughout this document derived rates are reported in meters per year (m/yr). Positive rates indicate a landward trend of the shoreline or erosion. Negative rates indicate seaward movement of the shoreline or accretion. Each rate is followed by an uncertainty calculated at the 95% confidence interval (CI95). The confidence interval is symmetrical about the rate and is reported as a positive number. It is described following the rate with a '±' to indicate that the derived shoreline change rate is bounded by the upper and lower limits of the confidence interval.

Linear Shoreline Change Analysis: 1987-2006

The Digital Shoreline Analysis System (DSAS) was created by the US Geological Survey as a standard toolbox for calculating single-transect shoreline change statistics. Several statistical methods are employed by the software to generate a table of rates organized by method and by transect number. Of the methods incorporated in DSAS, weighted least squares regression (WLS) is the only method to incorporate uncertainty or accuracy of individual shoreline positions in calculating a rate of change. The rate uncertainty (WSE) or standard error of the estimate is the degree to which shoreline positions diverge from a best-fit linear regression along a single transect (S-T). The results of S-TWLS and the rate uncertainty (S-TWSE) are shown as columns 2 and 3 in Table 1 depicting linear shoreline change rates 1987-2006.

Columns 4 to 9 of Table 1 are the results of linear polynomial modeling (PX). PX modeling improves on the standard approach of calculating rates along one transect at a time. PX is a class of methods that simultaneously models all shoreline positions from all transects within a beach system or littoral cell. PX assumes that transects along a beach are dependent on each other. This is a reasonable assumption, as the entire beach system is affected by coastal processes, such as sediment transport. A polynomial is used to model the shoreline change rate from all transects.

PX is comprised of three polynomial schemes to calculate shoreline change rates: 1) LX – Legendre polynomials; 2) RX – Trigonometric functions, and; 3) EX – Empirical orthogonal functions of the shoreline data. One advantage of the PX method is that rate uncertainties are minimized because the number of shoreline data increases when modeling all transects simultaneously. In other words, we are most confident of PX rates relative to S-T rates (Fig. 10), and among these the most significant rates are provided by EX (Fig. 11).

Table 1 Shoreline Change Rates 1987-2006

The single-transect method, S-T(WLS), uses weighted least squares at each transect and does not incorporate shoreline data from neighboring transects. The 95% confidence interval (column 3: S-T CI95) indicates that most rates using this method are not statistically significant (CI95 > 1). Polynomial methods (LX, RX, and EX) and their rate uncertainties (CI95) utilize all shoreline data (columns 4 – 9). This increases statistical significance. Ex was found to have the least uncertainty.

	Single Transect Method (m/yr)		Polynomial Modeling (m/yr)					
Transect #	S-T(WLS)	S-T CI95	LX	LX CI95	RX	RX CI95	EX	EX CI95
1	0.58	0.82	0.74	1.19	0.56	0.49	0.52	0.09
2	0.33	1.11	-0.06	0.89	0.65	0.51	0.30	0.14
3	0.41	1.28	0.47	0.78	0.71	0.56	0.37	0.16
4	0.66	2.77	0.92	0.73	0.68	0.63	0.79	0.30
5	0.74	3.86	0.81	0.89	0.48	0.73	0.92	0.44
6	-1.64	1.41	-1.97	0.98	-1.40	0.98	-1.47	0.55
7	-2.49	3.23	-2.50	0.81	-2.79	0.84	-2.38	0.39
8	-1.95	2.86	-1.62	0.65	-2.01	0.70	-1.81	0.31
9	-1.31	1.57	-0.88	0.60	-1.00	0.64	-1.17	0.19
10	-0.32	1.16	-0.36	0.58	-0.19	0.62	-0.21	0.04
11	0.52	0.73	-0.01	0.55	0.34	0.61	0.50	0.08
12	0.48	0.82	0.22	0.53	0.56	0.59	0.43	0.09
13	0.53	1.05	0.37	0.52	0.55	0.58	0.48	0.11
14	0.80	1.66	0.52	0.52	0.46	0.57	0.71	0.18
15	0.61	0.59	0.72	0.52	0.46	0.57	0.56	0.09
16	0.60	0.80	0.94	0.51	0.61	0.56	0.58	0.09
17	0.66	0.90	1.22	0.50	0.93	0.55	0.65	0.11
18	0.96	1.37	1.52	0.50	1.38	0.55	0.96	0.16
19	1.64	3.35	1.86	0.53	1.96	0.57	1.75	0.31
20	2.48	4.12	2.09	0.56	2.36	0.61	2.60	0.42
21	3.78	4.94	2.26	0.60	2.63	0.66	3.88	0.64
22	1.29	3.05	1.85	0.62	1.94	0.68	1.23	0.34
23	0.96	2.63	1.46	0.61	1.39	0.66	0.94	0.29
24	0.77	1.53	0.60	0.61	0.37	0.62	0.75	0.12
25	-0.14	0.91	-0.04	0.61	-0.22	0.61	-0.20	0.18
26	-0.42	1.86	-0.47	0.59	-0.50	0.60	-0.66	0.30
27	-0.39	1.19	-0.59	0.59	-0.51	0.59	-0.53	0.23
28	-0.46	1.05	-0.48	0.62	-0.35	0.58	-0.53	0.26
29	-0.10	0.63	-0.20	0.66	-0.13	0.57	-0.17	0.11
30	-0.03	1.41	0.07	0.65	0.09	0.55	-0.21	0.20
31	0.06	1.29	0.21	0.67	0.26	0.54	-0.04	0.20
32	0.16	1.05	0.26	0.78	0.38	0.51	0.12	0.16
33	0.77	0.40	0.48	0.77	0.48	0.50	0.64	0.20
34	1.17	0.83	1.29	1.16	0.56	0.49	1.06	0.40

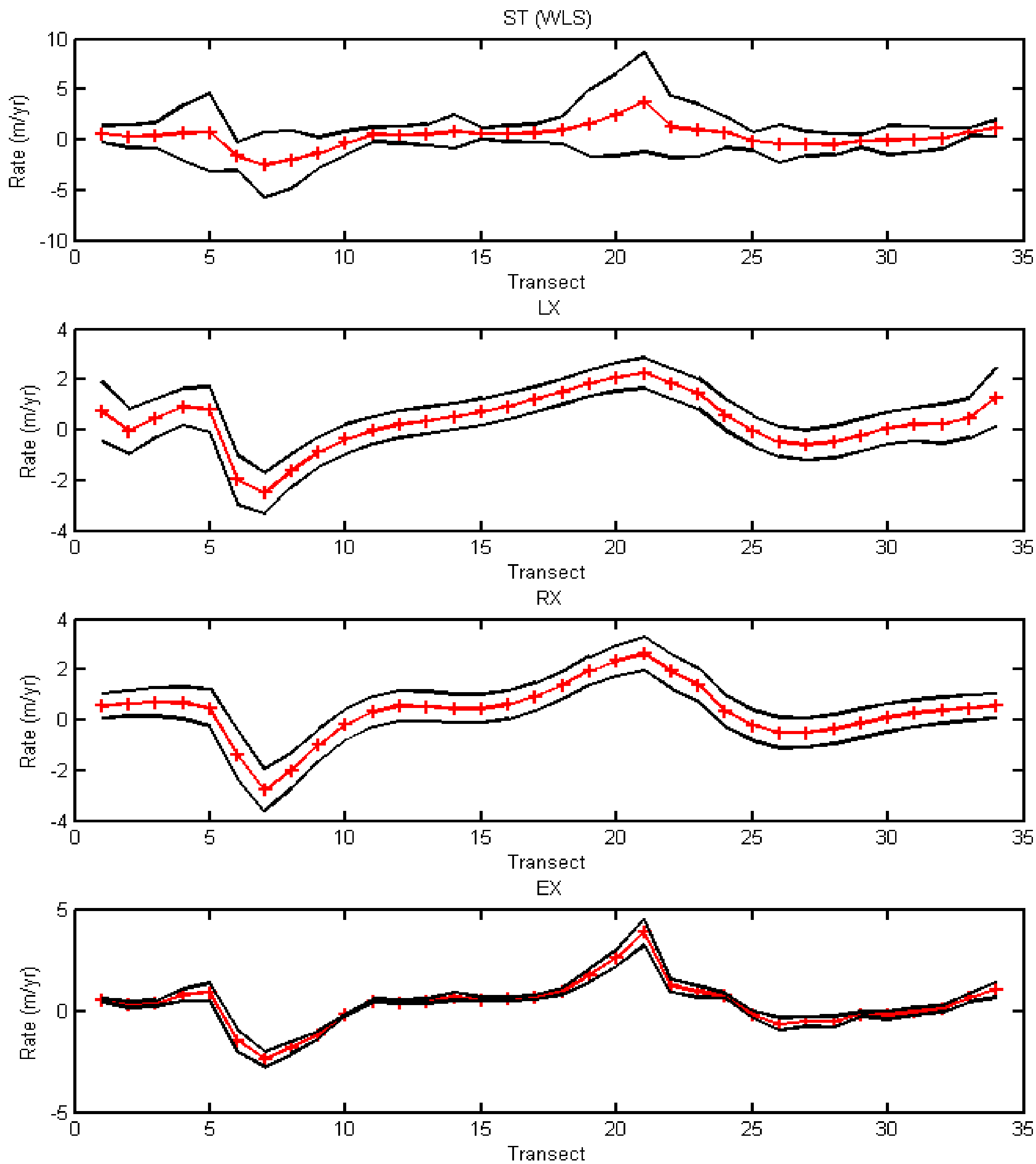

Figure 10. Shoreline change 1987-2006 and 95% confidence band.

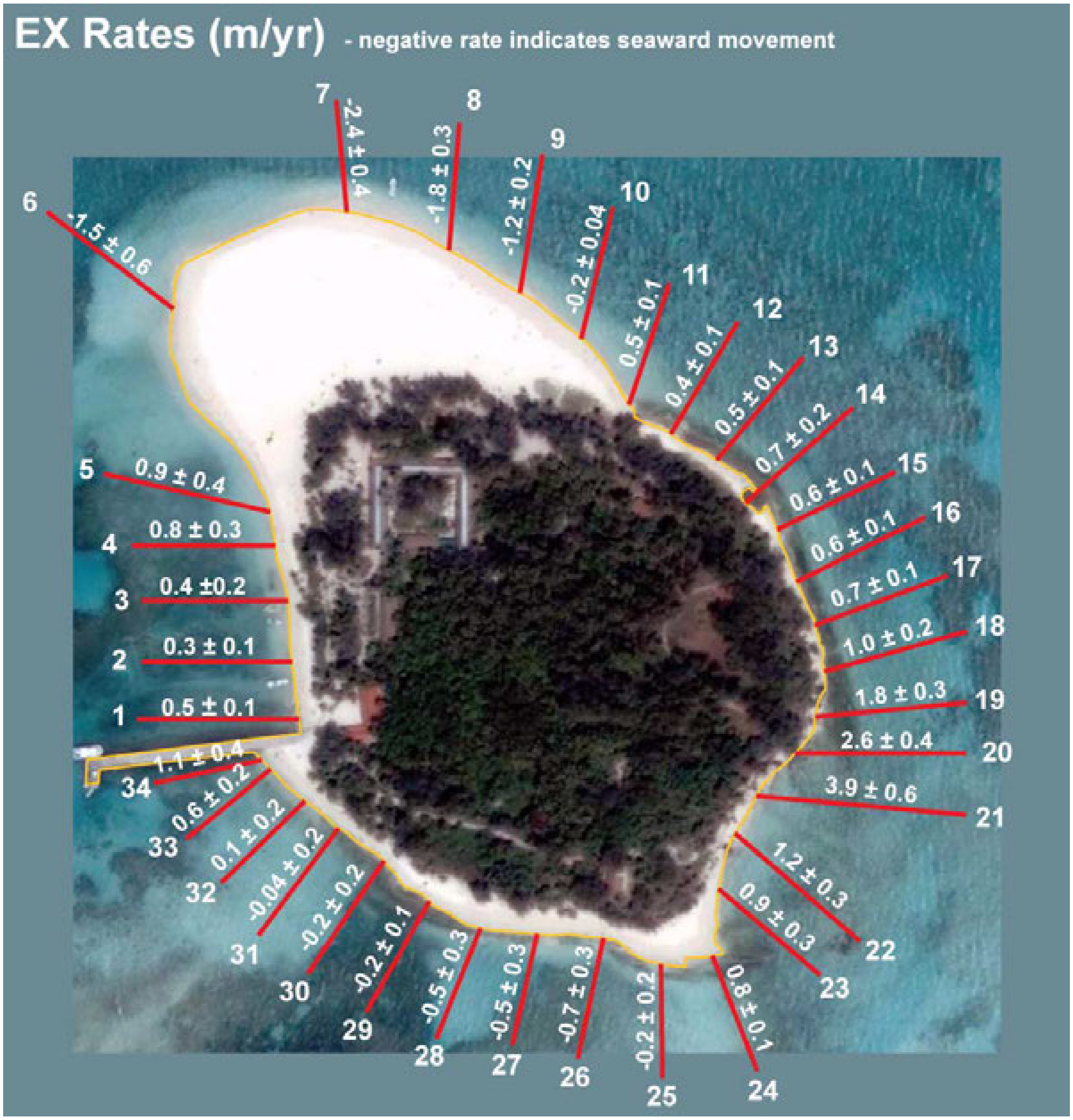

Figure 11. EX rates of historical shoreline change at Mañagaha Island 1987-2006 (-/accretion, +/erosion).

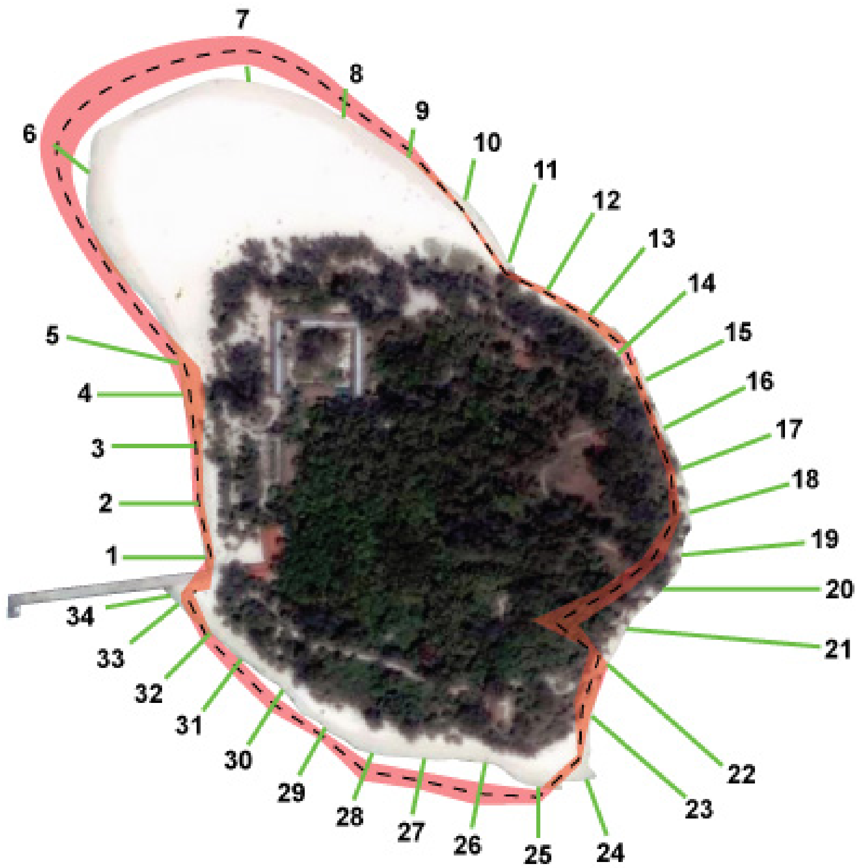

Figure 12. EX 10-year shoreline position (dashed line) with 95% confidence (red band) on 2006 Quickbird. As a result of the location and orientation of transect 21, the predicted shoreline position appears as a sharp indentation. This is due in part to the location of the transect (perpendicular to the trend of historical shorelines) and in part to re-orientation of the shoreline following debris removal in 1996. The true future shoreline will most likely be in the shape of a smooth, gradually curving arc at the same location.

Based on EX rates, it is possible to forecast the future shoreline hazard. Figure 12 illustrates the 10 year hazard zone and 95% confidence band based on the assumption of linear change over 1987-2006. However, if the rate of change has accelerated since 1996, this projection underestimates the hazard. This projection implies several consequences: 1) The NW shoreline will experience continued accretion due to sediment delivery largely from the east; 2) The eastern shoreline will experience continued sediment deficiency and chronic shoreline recession due to sediment loss to the NW and S with the greatest recession located in the area of transects

20-22; 3) The south shore will experience shoreline stability and moderate accretion due to sediment delivery from the east; 4) North of the pier the shoreline will undergo recession probably due to sediment impoundment by the pier.

If the individual transect plots of shoreline history for the 1987-2006 period are examined (Appendix A) it is clear that since the 1996 removal of debris, shoreline stability has decreased and the rate of both accretion in the NW and erosion in the east have increased. This indicates the need for analysis of the 1996-2006 epoch to improve understanding of present conditions.

Shoreline Change Analysis: 1996-2006

We employ two methods for analyzing shoreline change 1996-2006: 1) Linear and nonlinear modeling (1996-2006) since debris removal, and 2) Nonlinear modeling of 1987-2006 to detect changes in the rate of shoreline change.

1996-2006: 1996-2006 is a short period with only 4 shorelines. Because this history is under-sampled we apply a range of methods to determine the model that minimizes uncertainty. These include single transect (S-T), A-binning, PX, and PX with acceleration (PXT). A-binning uses an information test (Akaike Information Criterion) to identify adjacent profiles with similar history and employs WLS using all the data from the group to determine a rate of change. This method was tested and published by Genz et *al*. (2006). PXT is a class of methods that simultaneously models all shoreline positions in space and time. Similar to PX, rates are modeled with a polynomial. Unlike PX, rates can vary with time (acceleration or deceleration in the rate of change). The EXT method is a type of PXT that uses empirical orthogonal functions (EX) of the beach data and is allowed to vary with time (T).

The EX model minimizes the uncertainty of the methods tested on the 1996-2006 shoreline data. Appendix B provides a graph and table with the results of these methods as well as individual transect plots of shoreline history modeled using EX. Figure 13 shows rate of shoreline change modeled with EX and Fig. 14 displays the 10 year hazard.

1987-2006: To detect shoreline changes 1996-2006 we model 1987-2006 using PXT methods, and A-binning. Results are shown in Appendix C. The method that minimizes uncertainty is EX, shown previously in Figures 10, 11, and 12. Appendix C also shows transect plots modeled with EXT to illustrate accelerations and decelerations in rate that have occurred since 1987.

Appendix D displays a 10 year shoreline hazard map based on extrapolation of EXT (1987-2006) and EX 1996-2006 rates to the year 2016. It should be emphasized that a 10 year projection on the basis of only 10 years of data is not statistically valid. However, if present rates of erosion continue, or accelerate, the projection may be valid and for this reason it is especially important to continue to monitor the shoreline to test the validity of the projection.

Results: Although EX minimizes uncertainty compared to EXT, it is nonetheless useful to inspect EXT results for changes in shoreline stability revealed by that model. A change in slope and sign on transects modeled using EXT (Appendix D) indicate that all segments of the island lost shoreline stability ca. 1996. This is a rather unexpected result in that it suggests sand is shared around the entire circumference of the island.

In 1996, transects 1-5 changed from moderate accretion to significant erosion. If this is related to removal of debris along the eastern coast it signals that the west beach is not isolated by the pier and that sand must move onto the west beach from the north, counterclockwise around the island. Erosion at transects 1-5 since 1996 suggests that sand is no longer making that trip and is stopped in the northwest where there has been dramatic accretion. Hence erosion on the west beach is a result of accretion on the northwest beach. Transect 6 shows moderate accretion and can be interpreted as a transition area.

Transects 7-10 reveal that 1996 marked the end of relative stability along the northwestern shoreline. Dramatic accretion at rates of 2 to 5 m/yr has marked the past 10 years. This is likely due to sand released from eastern segments of the island moving to the northwest and causing build-out of the beach. Sand trapping here has led to erosion of the beach to the west.

At transects 11-24, the rate of shoreline change since removal of debris in 1996 has accelerated a former trend of moderate erosion (compare Figs. 11 and 13). This entire section of the island is destabilized and is rapidly eroding at rates as high as 7.5+/-0.6 m/yr (transect 21). The worst erosion is located directly adjacent to the site of debris removal and it is difficult to avoid the conclusion that erosion is linked to the 1996 removal.

Transects 25-34 show a variable history, including a zone of transition from the adjacent eastern shoreline. Transects 23-25 indicate that erosion has moderated in the past 2 years. Whether this is short term or a new phase of shoreline stabilization will only be known in hindsight. This area is marked today by an accreting sandy spit reminiscent of earlier features on the island at this location. Continued monitoring is valuable in this regard. Transects 26-32 all show erosion since 1996 as well as no significant sign of decrease since that time. Field observations however indicate the shoreline has stabilized in the past year and former erosion has abated, at least temporarily. Overall transects 25-32 show continued erosion at rates that are less than the neighboring shoreline to the east. Transects 33 and 34 record moderate accretion, this is due to sand accumulation on the down drift side of the pier and is a localized effect.

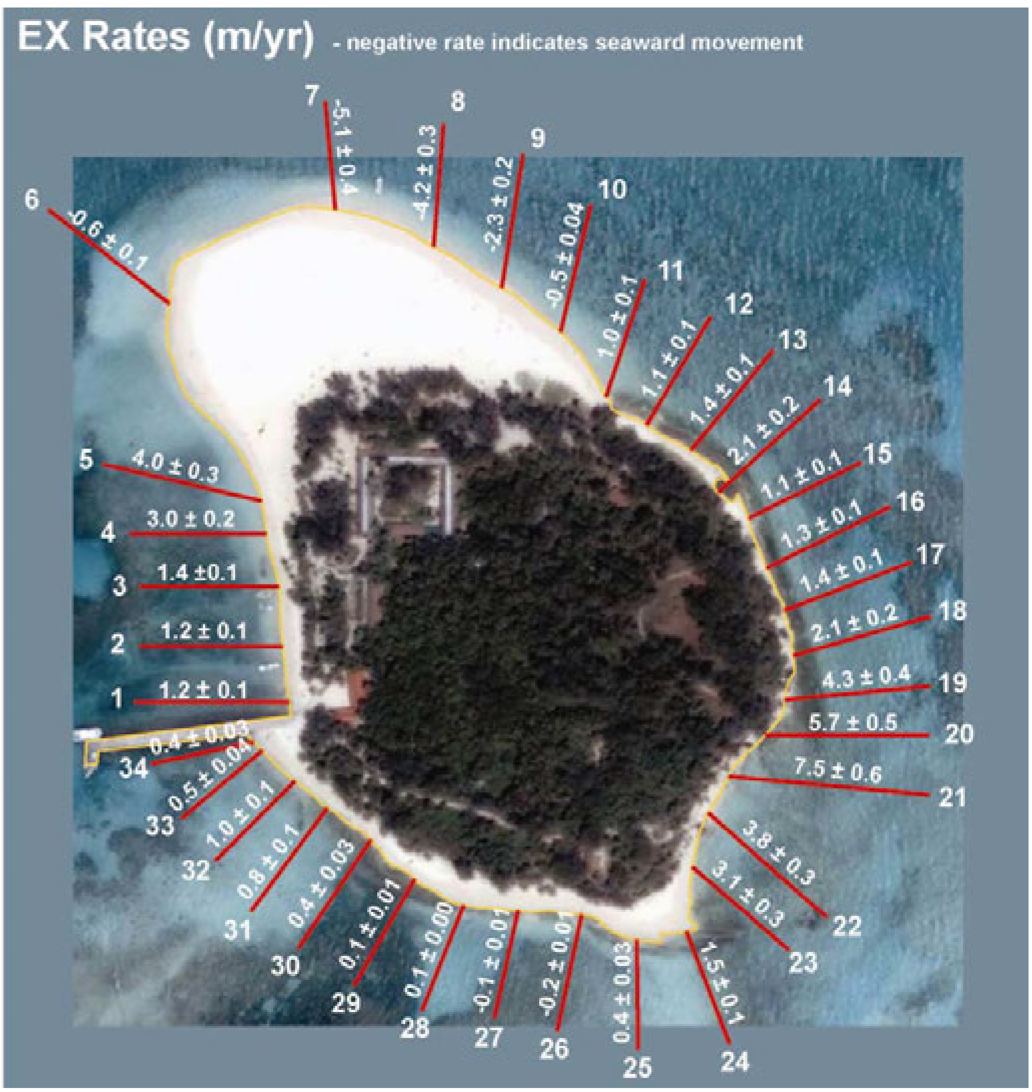

Figure 13. Shoreline change 1996-2006, using EX (-/accretion, +/erosion).

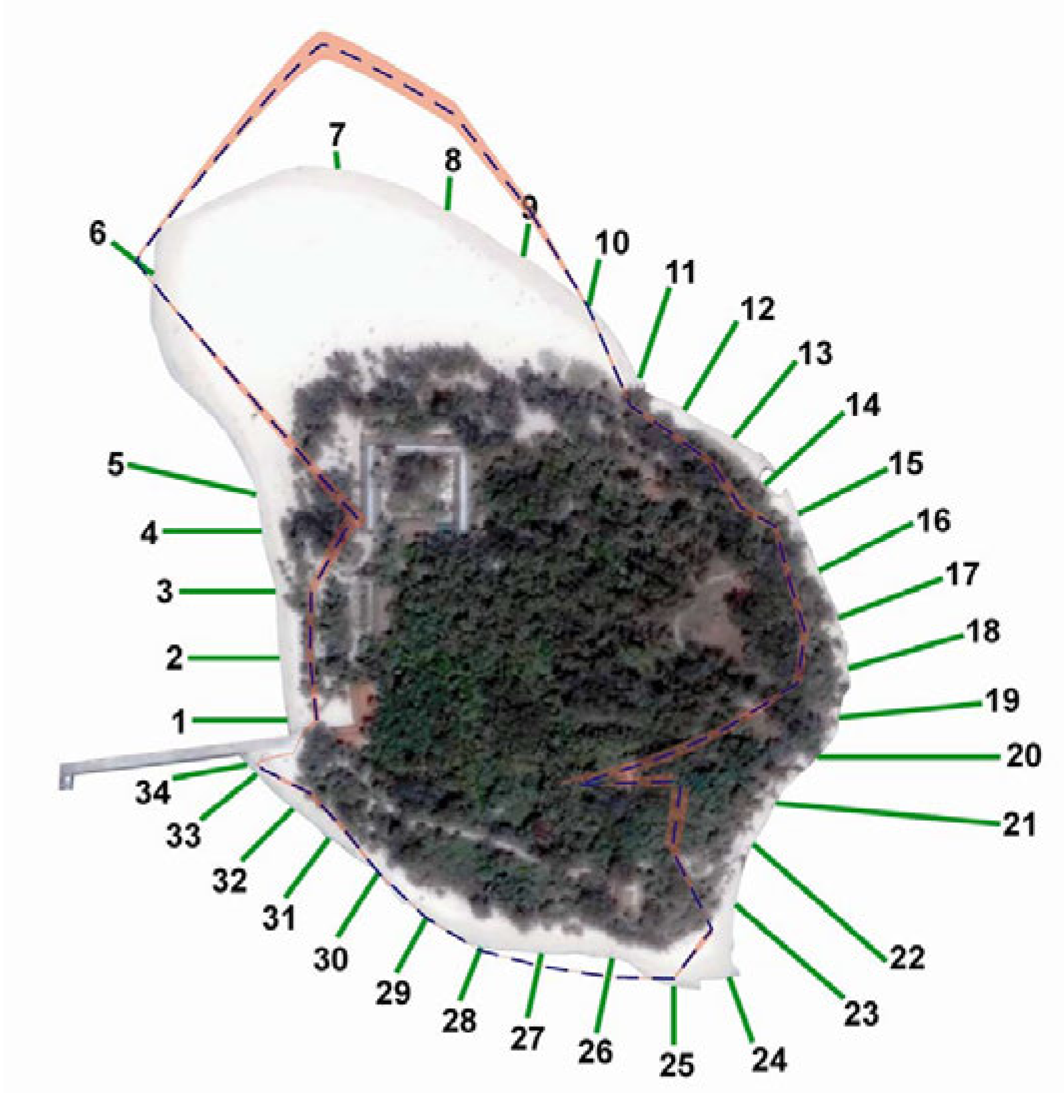

Figure 14. Map of 10 year hazard with 95% confidence (red band) based on EX model 1996-2006.

Hydrodynamic Model Results

To improve understanding of physical processes responsible for shoreline change at Mañagaha, a numerical model (Delft3D) of wave and current hydrodynamics is used to simulate tidal flow under normal trade wind conditions. Figure 15 depicts tidal residuals (average currents in m/s over several tidal cycles) based on a simple harmonic tide and wind forcing of 16 knots out of the east (typical trade conditions). Results indicate two hot spots for high current velocity; along the southeast coast and along the northeast coast of the island, and low velocities to the west. These are consistent with measured patterns of shoreline change.

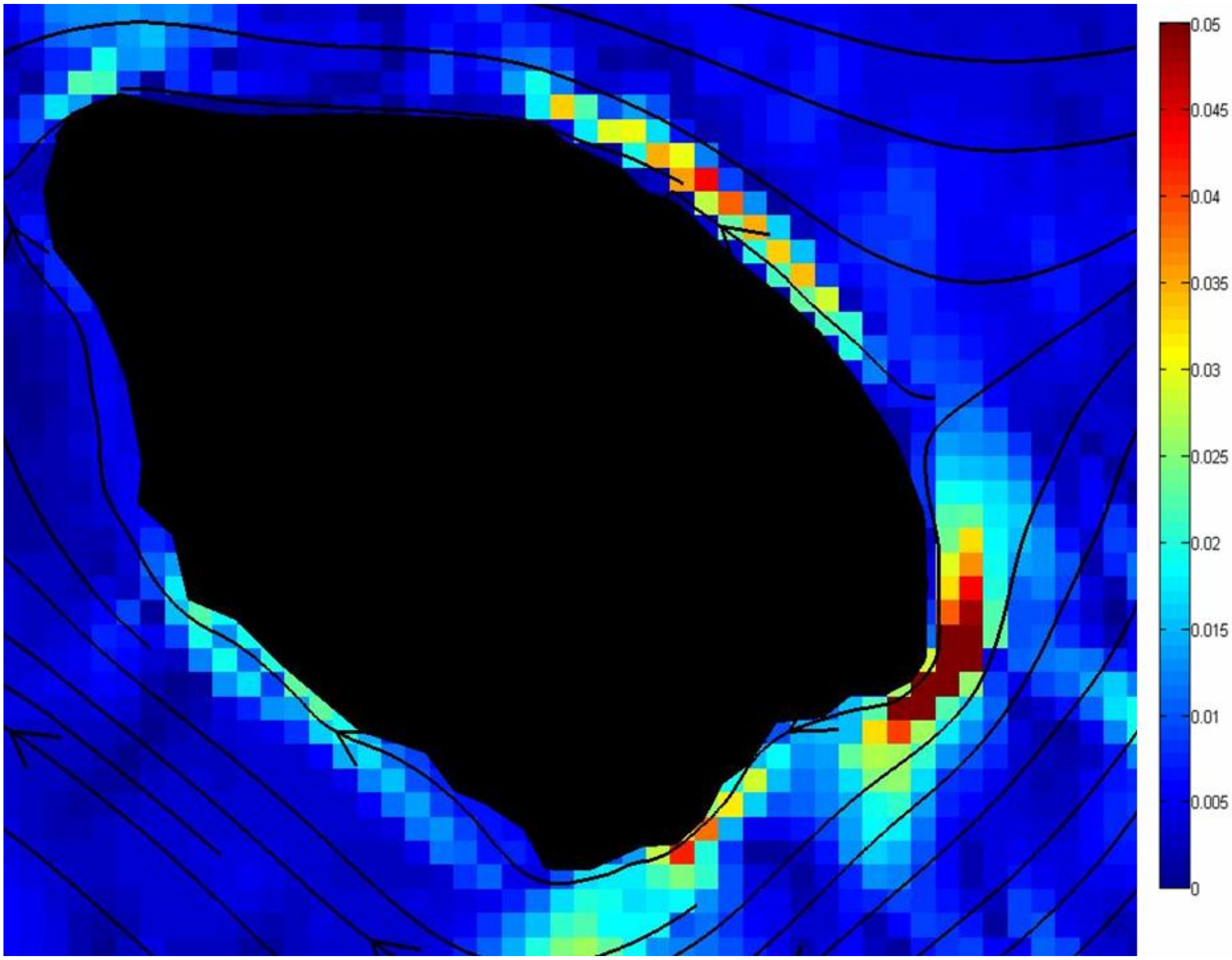

Figure 15. Average currents in m/s over several tidal cycles based on harmonic tides and wind forcing of 16 knots out of the east. Island outline represents the location of the 2006 vegetation line.

Modeling of current velocities reveals: 1) erosion at transects 1-5 on the west beach is not due to high current velocities, rather it is due to sediment starvation; 2) high rates of flow in the area of transects 11-23 indicate that erosion is related to scour and sediment transport away from this shoreline segment; 3) sediment is moving both clockwise and counterclockwise from the area of transects 18-22. Hence the area of greatest erosion (the eastern shore) is the likely source of sand to accreting segments at transects 6-10 and portions of the southern shore. 4) Currents generated by easterly trade winds split into two directions. One current travels to the west along the north shore and one current travels to the south along the eastern shore. This suggests that the area of greatest erosion is a null point marking the boundary between two littoral cells, one to the south along the east shore and one to the west along the north shore. This condition is the present equilibrium environment under normal trade wind flow. Model results agree with the historical shoreline analysis and improve confidence in the 10 year shoreline projection based on EX 1987-2006. Results also suggest the debris removed in 1996 was located at the boundary of the two littoral cells.

The removal of debris on the eastern shoreline in 1996 led to destabilization of the shoreline around the entire island. This produced significant erosion at transects 11-32 and 1-5, and dramatic accretion at transects 6-10. Sand released by erosion in the east fed accretion on the northwest shoreline which, in turn, blocked sediment movement onto the west beach. While beach accretion is a benefit to a recreation and conservation area, beach loss associated with erosion on the west and east coasts, and associated land loss, has negative impacts that might be corrected with stabilization of the shoreline to a pre-1996 configuration.

One approach to this is to test the use of a groin in the position and orientation of the lost debris. Figure 16 depicts the results of modeling two groin orientations, SE and S. The south orientation produces a larger wave shadow on the eastern shoreline which should lead to a reduction in erosion rate there. However, high current velocities at the location where the S groin attaches to the land indicate it may suffer flanking (erosion). Mitigation of this affect must be planned for. A SE orientation produces a reduced threat of flanking and better matches the position of the debris removed in 1996. Additionally, it is important to realize that reduction of erosion on the eastern shoreline will result in loss of sand in transport to the northwest. Accretion in the area of transects 6-10 will decrease and it is possible that the northwest coast may shift from accretion to erosion. Impacts to the west coast are uncertain.

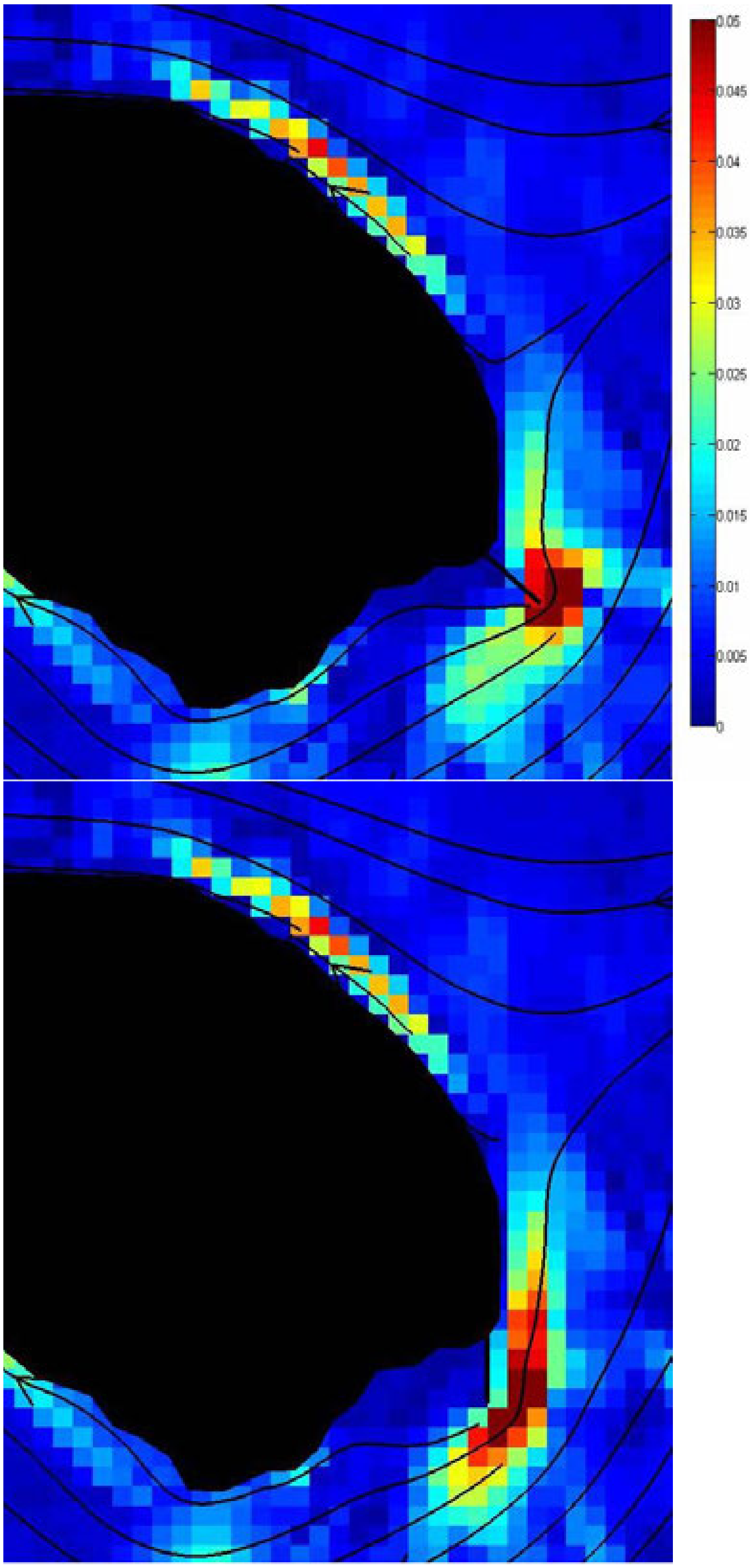

Figure 16. Two groin configurations: SE and S. The S option offers greater protection to the eastern shore.

Given the volatility of the island to changes in wave exposure, any attempts at stabilizing the shoreline with a groin should use sand bags or some other temporary method that can be easily reconfigured or removed in case of unanticipated negative impacts. If sand bags are used, an offsite source of sand needs to be used in filling the bags to avoid impacting the limited sand budget at Mañagaha. Construction of a groin should be accompanied by sand back passing from the area of transects 6-10 into the lee of the groin to rebuild the shoreline in the area of transects 20-23. Consideration should also be given to sand passing onto the west beach in the area of transects 1-5.

Existing Conditions

With improved understanding of shoreline behavior resulting from the above historical analysis, it is possible to describe existing conditions at Mañagaha. Island behavior is observed to fall into four regional segments numbered clockwise starting from the NW (Fig. 17):

- Region 1) accretion of a broad sand plain (NW, pink, transects 6-10);
- Region 2) generally eroding shoreline (NE to E, orange, transects 11-24);
- Region 3) quasi-stable shoreline (SW to S, yellow transects 25-34); and
- Region 4) eroding shoreline north of the pier (W, tan, transects 1-5).

Below, we offer a general description of conditions at Mañagaha Island using this scheme. The shoreline has moved into a condition of net accretion in Region 1 largely due to trade-wind driven, alongshore sediment transport whereby sand in Region 2 feeds Region 1 (Fig. 18). Chronic erosion characterizes Region 2 as it yields sand to both Region 1 and the eastern section of Region 3 under energy conditions associated with typical trade wind flow. Region 3 is characterized by quasi-stability to moderate accretion in the eastern section due to sediment input from Region 2 and erosion in the central section that has perhaps temporarily stabilized (ca. March, 2007). Region 4, starved of alongshore sand delivery by accretion in Region 1, is sediment deficient. Aerial photographs also reveal down drift offset due to sediment impoundment in Region 3 by the pier.

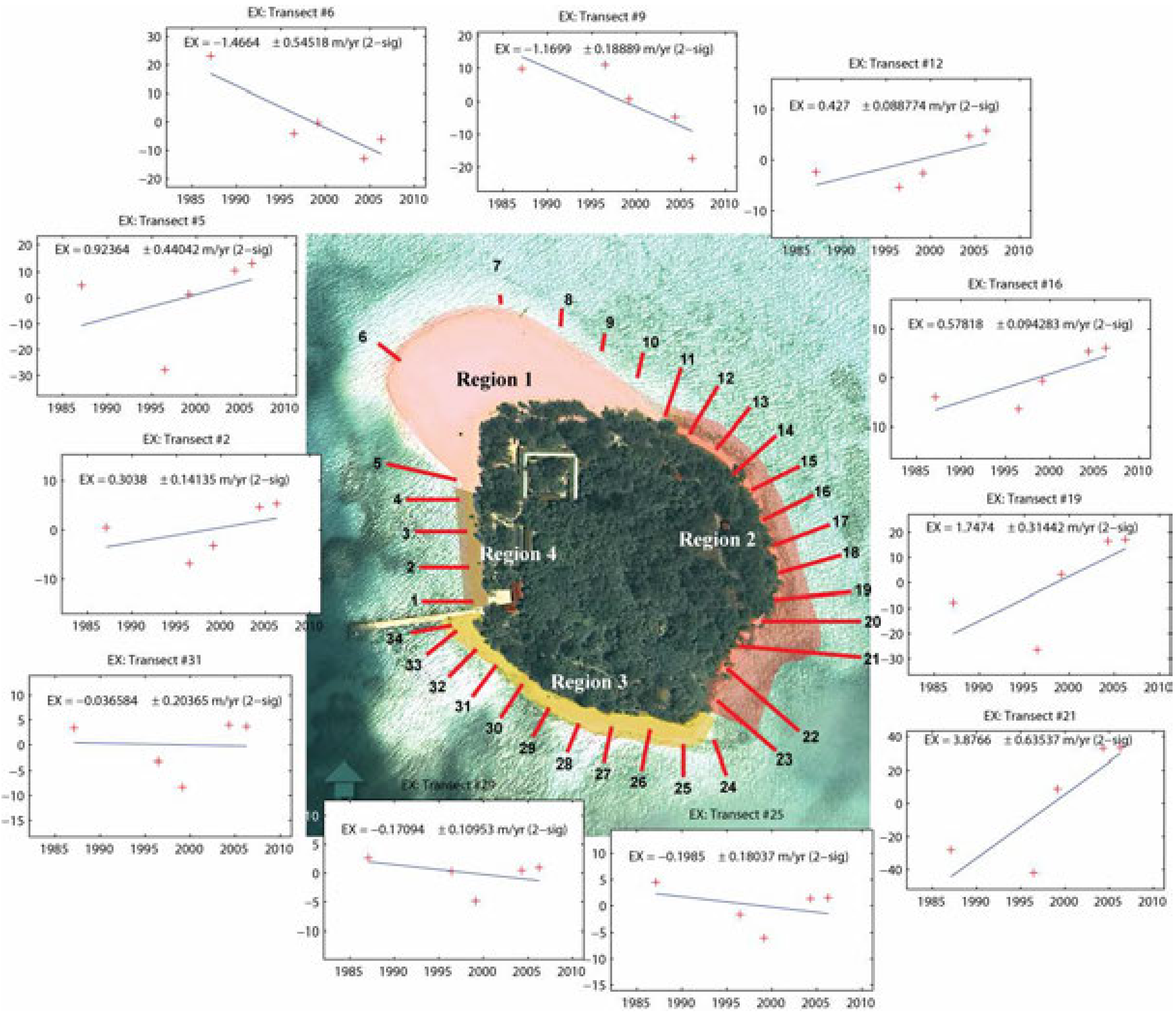

Figure 17. Using EX modeling for the period 1987-2006, four general regions characterize Mañagaha.

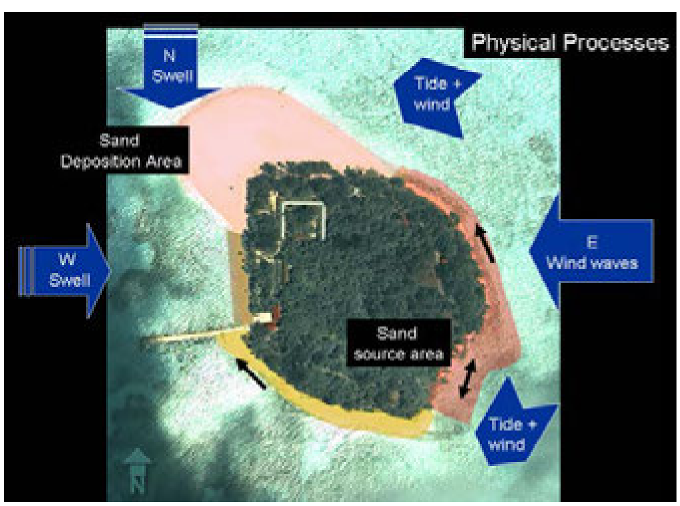

Figure 18. General physical processes and sediment transport directions (black arrows).

Chronic erosion raises several management concerns (Fig. 19). In Region 2 along the northeast shore is a Wedgetail shearwater bird nesting area with a growing number of mating pairs. Erosion in Region 2 will eventually decrease the land in this region and potentially threaten the bird habitat.

Erosion also undermines vegetation and exposes metallic and concrete debris. This and the fallen trees in Region 2 present a safety hazard for visitors. The concessionaire expressed concern that the debris is also unsightly and negatively impacts the visitor experience.

Figure 19. Special management concerns include visitor safety, visual impact, and a nesting area.

A map of existing conditions (Appendix E) indicates that no island infrastructure falls within the area imminently threatened by erosion. However, our forecast of the 10 year erosion threat (Appendix D and Figs. 14 and 12) give a range of potential futures ranging from dramatic island loss (Appendix D) to a less immediate threat in the next decade (Fig. 12). Which of these is most likely will only be revealed in time, posing a unique quandary for managers.

Region 1 is a broad accreting sandy plain that is generally extending in the north and northwest direction (Fig. 20).

Figure 20. View of Region 1 looking northwest along transect 6 (top) and north along transect 8 (bottom).

Region 2 faces north and east and is characterized by chronic erosion since the removal of debris located offshore of the sandy shoreline. Fallen trees, exposed beach rock, undercut vegetation, and recession of the upland are signs of ongoing chronic erosion (Fig. 21).

Figure 21. View of Region 2 looking east at the area of transects 12 and 13 (top) and looking north from transect 23 toward transects 22 and 21 (bottom). Note that a beach still exists despite land loss.

Region 3 has a southern exposure. The eastern portion (transects 25-28) has been quasi-stable to accreting and the western portion (transects 31-32) has been undergoing erosion. (Fig. 22).

Figure 22. Looking north toward the pier from transect 28 (top). View of flanking erosion on the south side of the pier (bottom).

Region 4 is to the immediate north of the solid pier (Fig. 23). The pier acts as a groin and blocks sand movement from Region 3 into Region 4. However, it is also likely that Region 4 is eroding as a result of sediment deficiency due to accretion in Region 1.

Figure 23. View looking north from the pier (foreground) across all of Region 4 (top). View of receding shoreline in the northern portion (transects 4 and 5) of Region 4 (bottom).

SUMMARY OF PREVIOUS WORK

US Army Corps, 2001: Mañagaha Island Erosion Study CNMI

Focus: Provide background information about Mañagaha Island to improve understanding of physical processes that are affecting this area with respect to the net loss of sand on the NE and E facing shoreline as documented 1997 - 2001.

Island formation: Coral outcrop and sand accretion due to wind, waves and currents. Evidence of fill that is likely the remains of dredging for seaplane runways and shipping channels.

Conditions: Three types of wind patterns. E-NE trades (45% 10.5 mph), slack winds or variable light winds, and typhoons. Tide fluctuation around 1.5 ft. Waves include trade wind waves, low-pressure system waves and storm waves.

Problem: Sand is being lost from the east and northeast shoreline at a greater rate than sand is deposited. The result is net chronic erosion.

Possible cause: The problem could be connected to the removal of hard points (WWII relics) that had previously provided points of protection and energy dissipation and redirection along the portion of the island dominated by trade wind and wave conditions. Over 100 ft of sand shoreline has been lost since 1997. Total recorded loss of up to 128.5 ft (32 ft/yr) can be seen in the most severe areas of erosion. Certain areas have also experienced small amounts of accretion.

US Army Corps, 2004: Saipan Lagoon Erosion Study

Focus: Present and past beach profiles (1996-1999), and modern shoreline observations, are used to assess shoreline conditions with respect to accretion and erosion.

Study area: Leeward lagoon (Lagunan Paragan and the respective shoreline that stretches from Puntan Muchot (northern headland) to Puntan Susupe (southern headland). Area is sheltered from trade winds and trade wind waves, with the exception of small waves created inside the lagoon. Beach environment ranges from low energy to extremely low energy with minimal to no wave run up. Analysis is derived from present observations: narrow beach, fine to medium grained calcareous sand and a vegetation line that runs almost directly to the high tide line.

Analysis: Memorial Park is low energy, sheltered from trades, and has eel grass beds. Aerial photos from 1948-1985 indicate a dynamic shoreline with substantial accretion. Post 1985 there has been erosion at Point Muchot and to the south, while east of the point accretion has occurred. Beach profiles show continuing accretion in the eastern section. South of the point at stations 0+00 and 5+00 there has been erosion of 30 ft and 6 ft respectively. 2004 beach profiles show erosion 300 ft east of transect 0+00 to 2+00 while accretion is recorded at 5+00. Results indicate this area is dynamic with varying amounts of accretion and erosion. Factors contributing to changes in shoreline could be small wind waves, storm swell from the west, the health of eel grass immediately offshore, and development of the near shore environment to the east that may retard or halt westward transport of sand.

Minton and Palmer, 2006: Historical Record of Tropical Storms of Saipan, CNMI

Summary: Storms have significant effect on islands with respect to flooding, erosion, and damage to structures, crops, and vegetation. Mechanisms include storm surge, severe rainfall, and wind. Saipan is in the immediate vicinity of the cyclone breeding ground of the western Pacific. Puntan Muchot is an example of a location susceptible to damage via tropical storms due to its low elevations and proximity to the coastline. Cyclone frequency is affected by decadal variation and ENSO. During ENSO, warmer waters migrate toward the central Pacific increasing the frequency and strength of storms that have the potential to target Saipan. Following ENSO the cyclone breeding ground moves into the Mariana Islands such that storm strength is relatively low when in the vicinity of Saipan and tends to increase as it moves away.

Statistics: Since 1970 an average of 3 cyclones per year passes within 300 nautical miles of Saipan. Decadal variation has caused cyclones in the 70's to be less frequent than in the 80's and 90's. July through December is the period in which cyclones are most common.

Since 1945: 186 cyclones passed within 120 nautical miles of Saipan

8 (4.3%) tropical depressions
40 (21.5%) tropical storms
138 (74.2%) typhoons
44 (31.9%) super typhoons
11 super typhoons passed within 120 nm
1990 very high storm frequency

Agulto and Yuknavage, 2006: Chronology of Events on Mañagaha

1984
Sept - Mañagaha Registered as National Historic site.

1995
May - CPA requests assistance with addressing Mañagaha wrecks as they pose a safety hazard
June - Samsung submits proposal to remove 9 wrecks with waiver of environmental liability.
- CRMO/CPA/EFC/Samsung meeting minutes, CRM Director, Manuel C. Sablan expresses disappointment that Samsung will not volunteer services given CRMO's cooperation with Samsung on the Baker/Charlie Dock project.

Nov - HPO informs CRMO that the removal plan may have to be modified as the wrecks are part of the historic properties of this National Historic site.
Dec - HPO permits the removal of 5 wrecks only
- CRMO/CPA/EFC/Samsung meeting minutes, decide 4 wrecks of the 9 need removal.
- CPA Carlos A. Shoda, requests that EFC offer assistance for a "smooth and easy issuance of all required permits".

1996
Jan - CPA Permit application received by CRMO and sent to Army Corps of Engineers.
- HPO tells ACOE that the proposed wreck removal is now in compliance with section 106
- EPA informs ACOE that they do not object to permit issuance
- CRMO requests 401 Water Quality Certificate

Feb - ACOE provisional permit granted
- DEQ waives 401 Water Quality Certificate
- CRMO waives the permit for CPA to proceed, based on CRM Agency waivers

April - Removal commences
May - Barge removal complete
June - Remaining metal shards and some erosion noticed by DEQ lab staff during sampling
Aug - Investigation of erosion requested by CRM Board
Sep - Super Typhoon Yates
Nov - Typhoon Dale
Dec - Typhoon Fern

1997
April - Typhoon Isa. More erosion reported
May - Typhoon Marie
June - Typhoon Nestor
Aug - Super Typhoon Winnie
Sep - Super Typhoon Oliwa
Oct - Super Typhoon Joan
Nov - Super Typhoon Keith
Dec - Typhoon Paka devastated Guam

1998
Jan - Erosion appears to have stabilized
Aug - Typhoon Rex

Sep - Typhoon Todd, Vicki, Yanni
Oct - Typhoon Zeb

1999

April - Rep Heinz S. Hofschneider requests assessment of Saipan Lagoon dredging impact.
- CRMO requests ACOE conduct emergency assessment study

1999

- DLNR, Bertha C. Deleon Guerrero, asks under what authority CRMO had the wrecks removed, inquires whether studies were conducted prior to removal.
- Survey shows pala pala cracking, 10 trees down, and picnic table nearly in water
- CRMO, Peter Barlas, says Saipan Channel dredging is the major culprit in the Variety.

May - Governor Pedro Tenorio calls for action to save Mañagaha
- Carolinian Affairs Office (CAO) express concerns over cultural loss
- CRMO, Peter Barlas, explains natural Typhoon impacts; Bennie Pangelinan says let nature take its course.
- ACOE agrees to take on a reconnaissance study

June - USGS warns against constructing seawall, revetment or any form of protection, as it will lead to further destruction elsewhere.

2000

Mar - CRMO, Peter Barlas, declares little erosion in the CNMI overall, but that on Mañagaha will be studied by ACOE. CRMO's position is against construction of structures.
- ACOE and CRMO state that Mañagaha should be allowed to stabilize naturally.

April - Division of Public Lands (DPL) requests cracking pala pala on NE shore have posts removed and relocated to another site and the rest be demolished and removed.
- CRMO informs DPL that they are working with ACOE to find appropriate solution to erosion, but that structures will not replace sand that is already lost.
- DPL informs Tasi Tour they are seeking approval of the demolition of pala pala.
- Variety reports CRMO will place poles and footings elsewhere to stave off erosion.
- DPL requests demolition of cracking pala pala, CRMO provides a conditional permit.

May - Typhoon Damrey
June - Camacho equipment selected for the demolition of the pala pala.
July - Typhoon Tembin
Aug - Typhoon Bilis
Sep - Typhoon Saomai

2001

- DFW discovers Shearwater bird nesting sites.

Aug - Typhoon Man-Yi
Sep - Mañagaha Erosion study complete. CRMO, Benny Pangelinan, states that ACOE is working on a Mañagaha Erosion model to be complete in 2003
Dec - Super Typhoon Faxai

2002

Jan - Mañagaha Erosion study distributed.

- CRMO, Benny Pangelinan, request National register to support federal funding request

May - CRMO provides corrected coordinates for Mañagaha Marine Protected Area using NAD83.

- Mañagaha is recovering. No action will be taken in constructing breakwater.

Jul - Typhoon Chata'an and Halong

Sep - Typhoon Higos

Dec - Typhoon Pongsona on December 8

2003

Jan - Tropical storm Yan Yan

Aug - DFW and PAWS remove feral cats from the island that are killing shearwater birds.

- DFW continues rat removal. Site 50 mating pairs of shearwater birds

Nov - Ironwood tree is near falling at profile site No. 4 on the NE side of the island.

Dec - DFW request assistance with protecting nesting sites from further erosion

2004

Jan - Joint inspection by CRMO, DFW, and MPLA results in an agreement to move pathway away from bird nesting area to increase their habitat.

Feb - Ironwood tree has fallen over at profile site No. 4.

June - Typhoon Ting Ting hits Saipan June 29th.

Aug - Typhoon Chaba

Sept - Typhoon Songda

Oct - Typhoon Nock-Ten

Dec - Tropical storm Noru

2005

Feb - 6.6 magnitude earthquake off Anatahan, no damage or tsunamis

Apr - Anatahan erupts emitting 50,000 ft ash plume

Sep - Typhoon Nabi

2006

Aug - Tropical storm Saomai

Additional Relevant Events

- Sept 1984 Mañagaha registered as a National historic site
- Dec 1995 HPO permits the removal of 5 wrecks. CRM Program Agencies/CPA/EFC/Samsung decide that four wrecks need removal
- April 1996 removal commences
- May1996 barge removal complete
- June 1996 remaining metal shards and some erosion is noticed by DEQ lab staff during sampling
- August 1996 investigation of erosion requested by CRM
- April 1997 more erosion reported

- Jan 1998 erosion appears to have stabilized
  April 1999: Rep Heinz Hofshneider requests assessment of Saipan lagoon dredging impact. CRMO, Peter Barlas says Saipan channel dredging is the major culprit. Pala Pala damage and downed trees are shown by a survey of the area.
- May 1999 Governor Pedro Tenorio call for action to save Mañagaha
- 1999 Dredging commences in the channel south of Mañagaha
- March 2000 ACOE and CRMO state that Mañagaha should be allowed to stabilize naturally.
- Jan 2001 Mañagaha erosion study distributed
- CRMO provides NAD83 coordinates of the Mañagaha Protected Marine area. Mañagaha is thought to be recovering. No action will be taken towards constructing a breakwater
- Jul, Dec, Jan, 2002, 2003 typhoon Chatan, super typhoon Pangosa (Dec 8) tropical storm Yan Yan.
- Nov 2003 beach at profile 4 is near gone

Management plan for the Mañagaha Marine Conservation area

Tourism: since 1980's average of 500 to 800 people each day visit the island.

Conservation area: 500 ha are designated for conservation around Mañagaha Island within the Tanapag Lagoon. Water depths range 1-6 m and bottom type consists of reef patch, reef flat, sand flat, and rubble zones. Underwater historical WWII relics found in conservation area.

Beach erosion: Since 2002 CNMI CRMO has monitored beach erosion on the island from 9 profile locations. Studies show that since 1995-2001 erosion rates have appeared to decline. The decline of erosion is thought to be evidence of beach stabilization.

Beach Profile Data

Profile data (Appendix F) has been recorded at 9 locations around Mañagaha since May, 2002. Data has been collected on average 4 times per year which would include 2 profiles taken during the dry season and 2 profiles taken during the wet season. There have also been additional profile data recorded in July and September of 2004 in order to capture the effects of Typhoon Ting Ting, Chaba, and Songda on the shoreline around Mañagaha. Data points include a starting point, the berm, and a beach slope. Other important features such as wet/dry line, debris line, and the beach toe are either absent or measured but not labeled.

Profile data vary from location to location, but with the exception of locations 4 and 5 (see map Appendix F) they do not reveal a clear erosion or accretion trend. In many cases the profiles show that the most recent berm is located furthest landward but the berm that is located furthest seaward is not the oldest profile. Hence, the profiles display seasonal and other forms of temporal variability. In these locations, profile data show a beach that has experienced variable erosion and accretion over the course of four years. However, profiles located on the NE side of Mañagaha indicate erosion has taken place consistently during the period of observation. From location to location, profiles during and after Typhoon Ting Ting, Chaba, and Songda, appear to be outliers. This indicates the beach in these locations is susceptible to immediate change in response to shifts in wind, wave and current dynamics, but then successfully recovers.

EROSION HAZARD MANAGEMENT

The following discussion presents management options that are applicable to eroding coasts, and is presented in the context of Mañagaha Island. It is important to recognize that eroding coasts experience a sediment deficiency. This is the case because sand is being exported at a greater rate than it is being imported. Often this results from "sand impoundment" such that sand is not available to an eroding coast, and/or a change to hydrodynamic conditions has produced a change in sediment dynamics such that there is net export.

Sand is the most precious asset on an eroding coast, and erosion management options need to be considered from the perspective of how sand is managed. Even the heavily eroding east coast of Mañagaha retains a beach, although it is unsafe due to tree-fall and metal debris. This beach is fed by sand released by erosion of the land (because the land is composed of sand). Fallen trees and debris decrease water energy that might export this sand, and so much of it is retained on site. Removing the fallen vegetation would likely result in increased sand loss – hence retaining fallen trees is an example of sand management. Any action that protects the eroding land without compensating for the source of sand freed by erosion will probably result in beach loss. Many engineering options neglect the fact that protecting sandy land results in "impounding" sand behind a wall or other structure. A groin, breakwater and other types of structures impound sand in one way or another. Sand management involves considering how any management action results in "denied sand" to any shoreline on the island.

Seawall

Seawalls are vertical structures built parallel to the shoreline out of concrete, rock, masonry, and other types of hard and generally impervious materials. The primary purpose of a seawall is to stop land loss. Seawalls are not designed nor are they intended to provide protection for a beach. Seawalls are a physical barrier between incoming wave energy and unconsolidated sand and sediment located landward of the wall. Mañagaha Island is largely composed of carbonate sand and any barrier to the availability of this sand to the coast constitutes impoundment, promoting a sediment deficiency.

Figure 24. Beach narrowing, sand impoundment, and beach loss occur when a wall is built on a chronically eroding beach.

Pros - A properly engineered seawall can be an effective, local barrier between wave energy and vulnerable land. The space required for the width and height of a seawall is relatively small. Short-term maintenance is also low.

Cons - While a seawall is useful as an immediate solution to a coastal land loss problem it is not an effective solution where the beach is an important feature. Seawalls tend to cause sand deficiencies and increase wave energy at the shoreline leading to seafloor scour. Walls built in areas of chronic erosion/shoreline recession will lead to beach narrowing and loss (Fig. 24). Seawalls should not be used if beach conservation is a goal. Mobile beach sand can respond to changing wave and current dynamics. This allows a beach to change shape to buffer wave energy. If sand is impounded behind a wall, the natural ability of a beach to respond to changing conditions is destroyed. This leads to an increase in wave energy at the armored shoreline. Reflective waves produced at a wall tend to carry away much of the sand seaward of a wall; this leads to undermining, expensive repairs, and eventual collapse. However a well-designed wall can be built to avoid these problems. Higher wave energy, reflected waves, and sand impoundment lead to changing substrate in the marine environment and the conversion from soft substrate to hard rocky substrate. Also, erosional flanking occurs at the end of walls. This causes an increase in the rate of erosion or conversion from stable shoreline to erosive conditions on the adjoining beach. To combat flanking, additional walls are often built, leading to seawall propagation and broadened impacts.

On Mañagaha, consideration should be given to building a wall along the eastern shoreline. Only if a beach is not important in this area, and if it is acknowledged that flanking needs to be managed and the likely loss of sand availability to other parts of the island will occur, then a wall is a viable option. If it is observed that erosion occurs at other beaches then additional sand management options might be considered to deal with those impacts separately. It should be acknowledged that armoring the east coast may lead to a chain of events elsewhere on the island requiring further action.

Revetment

A revetment is a seaward sloping structure (Fig. 25), often with a gradient between 1 on 2 to 1 on 3, that is made from wave resistant materials and, like a seawall, these materials are fixed or fitted together to form one solid structure. The purpose of a revetment is to dissipate incoming wave energy on the sloping, irregular surface of the structure. A proper revetment has high porosity and roughness to dampen wave energy. The irregularity of the revetment surface combined with appropriate sized voids results in wave energy being dissipated over a larger area when compared to the flat vertical surface of a seawall.

<u>Pros</u> - If properly designed the rock structure is durable, flexible and resistant to erosion brought on by consistent wave energy protection A revetment does a good job a dissipating a large variety of wave conditions. The structure can also respond to undermining by flexibly slumping, which otherwise might lead to seawall collapse.

Cons -A revetment functions in much the same way as a seawall in that it is designed to protect land but does not consider the beach as a goal of preservation. Revetments impound sand in the same way that a seawall does, hence it leads to a sediment deficiency, flanking, and beach narrowing and loss on retreating shorelines. Revetments require more footprint space than a seawall, leading to "placement beach loss" (the area under the footprint). In the long-term, a revetment will still have the same effect on sand located seaward and landward of the structure that a sea wall does, and as a result the pros and cons will be very similar to a sea wall.

Figure 25. Photographs of two different revetments. The shoreline is protected landward of the structure but the beach is lost.

Building a revetment at Mañagaha will require consideration of the large footprint of the structure. A strip of land or shallow seafloor, or both will need to be sacrificed to accommodate this. No particular benefit is obtained by using a revetment instead of a seawall, provided the seawall is well constructed and not vulnerable to collapse. All of the impacts resulting from building a seawall, such as sand impoundment and impacts to other island shorelines are also likely to occur in the case of a revetment because it does not manage sand.

Groin

A groin (Fig. 26) is a hard structure that is placed perpendicular to the shoreline in an effort to capture sand that would otherwise be transported along the shoreline by means of wave and tide generated currents. Groins tend to accumulate sand on one side (up current), but cause sand deficiencies on the other (down current). The Mañagaha Pier acts as a groin and the disparity in sediment movement can be seen in aerial photographs showing shoreline progradation to the south of the pier and shoreline recession on the north side.

Figure 26. Groins are effective at capturing sand on one side but cause a depletion of sand on the other.

Pros -A groin is effective in capturing sand and maintaining a volume of sand on the up-current (up drift) side. Long-term maintenance of a groin is low. Because of the asymmetry in sediment dispersal that is caused by a groin, they are most effective at the end of a sediment sharing system. So-called “terminal groins” may block and hold sand such that there is no down-drift environment to suffer negative impacts from the resulting deficiency. A groin intending to be used in the midst of a sand-sharing “littoral cell” is most effective if the interruption to natural sand transport is compensated by artificial means. This may include keeping the groin artificially “filled” with sand such that natural sand bypassing can occur around the groin, or augmenting the decreased sand flux downstream of the groin by artificial means. In either case, simply building a groin without compensating sand management will produce negative impacts elsewhere.

Cons – Groins prevent sand from reaching down-drift beaches. This leads to chronic erosion. Groins are capable of redefining nearshore dynamics producing sand accretion, erosion, and changes to nearshore circulation. Many groins are visible, although they may be constructed so that they are submerged throughout portions of the tidal cycle. The leeward side of groins creates an area deprived of sand. If a plan of sand nourishment on the down-current side is implemented this impact can be mitigated but it would constitute a continuing expense.

Building a groin on Mañagaha to mimic the effect of the debris removed in 1996 may have some merit as a management option. Our hydrodynamic modeling suggests that such a groin should be oriented nearly due south in order to create a large area of quiet water where erosion is greatest on the east shore. It is advisable to pump sand at the same time from the accreting beach in Region 1 to build out the shore in the lee of the groin. The groin could be constructed of flexible material to allow for redesign to optimize its configuration. A submerged groin is not recommended because water overtopping on a submerged structure often generates currents in the lee area that decrease shoreline stability.

Breakwater

A breakwater is a structure designed to modify wave energy to stop coastal erosion (Fig. 27). It may be submerged or visible. In tropical settings such as Mañagaha the structure may be built of common cement and possess porosity and rugosity such that marine organisms find it a suitable habitat, making an artificial reef. Breakwaters dissipate wave energy, creating a wave shadow zone where in optimal conditions the shoreline is stabilized. Some engineers state that submerged breakwaters allow overtopping wave energy that leads to erosive currents in the lee of the structure. High waves can overtop low breakwaters and raise the water level in the lee area generating flushing currents that erode sand. A breakwater may be considered a visual impact.

Figure 27. Breakwater (left) and artificial reefs (right) can be designed in a variety of sizes and shapes. But they are vulnerable to storm surge and may lead to unintended impacts.

Pros - A breakwater alters nearshore dynamics to change chronic erosion to shoreline stability or deposition. However, any sand deposited in the shadow zone represents a withdrawal from the regional sediment sharing system, and so adjacent areas are deprived of the same sand, potentially causing erosion on adjacent shores. In an optimal design, breakwater length, offshore distance, height, and orientation are all related to wave and tide conditions.

Cons – For a breakwater to work it must be correctly designed. A poor design can lead to numerous unintended negative impacts to circulation and shoreline stability. A detailed study of lagoonal and nearshore dynamics should be carried out in order to design and place an effective breakwater. In severe cases such as tsunami or storm surge, artificial reefs may be shifted and destroyed rendering them useless and hazardous. Debris removed from Mañagaha Island in 1996 was essentially functioning as a barrier to wave and current energy, similar to a submerged breakwater, such that the shoreline achieved a relative equilibrium that was disturbed in 1996.

Building a structure to mimic the role of the debris removed in 1996 spans the spectrum between a groin and a breakwater. That debris essentially functioned as a submerged breakwater but apparently had few of the negative effects. Likewise it was attached to the land in the manner of a groin. Why did it not have negative effects on adjoining lands? The answer may lie in our model results (Fig. 16). The null point noted earlier is due to a split in the currents approaching from the east where one leg moves west along the north shore and one leg moves south along the east shore. That split is approximately where the 1996 debris was located and it may constitute a *de facto* terminal position between two littoral cells. That is, the split in currents may be a place to build a "terminal structure" such that negative impacts to either littoral cell (a cell along the east coast and a cell along the north coast) are minimized.

Beach Nourishment

Beach nourishment (Fig. 28) counteracts erosion and attempts to create shoreline stability by maintaining a volume of beach sand in a problem area via mechanical placement of sand. Sand of appropriate characteristics, often sand that was previously on the beach but is now located offshore, or is being moved from one area to another ("back-passing" or "by-passing"), is placed on a beach to increase the volume of beach sand and thereby increase the stability of the shoreline. An analysis is needed to establish the volume and location of placed sand to achieve a desired result. One-time beach nourishment will usually only be temporarily successful. An effective program of nourishment must establish a regular schedule of nourishment and should have a source of funding identified to guarantee future continuation.

Figure 28. Beach nourishment projects under way showing methods of sand delivery.

Pros - Beach nourishment utilizes sand to mitigate shoreline erosion. An overall beach area is maintained and often inflated creating a more extensive beach environment that is designed to erode into a final shape. Using unconsolidated sand as a buffer between wave energy and the shoreline maintains the ability of a beach to respond to changes in wave energy and direction usually at little negative environmental impact.

Cons - For beach nourishment to be plausible there must be an available sand resource. Depending on conditions around Mañagaha, beach nourishment will be in the form of routine maintenance. Similar to a breakwater, a study of offshore sand availability and nearshore wave and current dynamics should be enacted for the specific purpose of nourishment.

Beach nourishment is likely to be successful in Region 2 and Region 4 provided an adequate source of sand is identified. Our survey of offshore sand deposits identified only one accumulation of sand that is close to the island. This area, immediately offshore of the swim area close to Region 4, is used for scuba and snorkel trips and would be damaged by dredging. A search for other submerged sand deposits should be conducted. Also available is beach sand in Region 1. This sand could be pumped both to Region 4 as well as Region 2 to restore sand deficiencies there. The frequency and volume of nourishment is unknown but could be estimated.

Natural State

Mañagaha shoreline has shown a past tendency to stabilize relative to hydrodynamic forces. It may still be in the process of stabilizing since the disruption of 1996. Another method for erosion management would be to allow the beach and shoreline to achieve, without intervention, its own state of equilibrium (Fig. 29). Allowing a shoreline to achieve a natural equilibrium requires that human infrastructure be designed for relocation, flexibility, and rapid response to erosion events as well as long-term chronic shoreline change. Unfortunately, it is not known when, or even if, the island shoreline will stabilize and erosion may decrease.

Figure 29. Lightweight, easily moveable infrastructure is an economical erosion management option.

Pros -The advantage of natural state management are price and feasibility. Anticipating that the Mañagaha shoreline will reach stability recognizes that future maintenance of the shoreline will be minimal. The primary cost will be redesigning activities and infrastructure to adapt to changing conditions. The primary risk is that the shoreline may not stabilize.

Cons - Allowing the shoreline to reach a stable state will likely involve further erosion. How much additional erosion will occur and how long it will take to achieve stability is impossible to quantify and there is no guarantee that past island behavior is any predictor of the future.

Little infrastructure is presently threatened by erosion at Mañagaha. However, fallen trees and other debris are unsightly and unsafe. Waiting for an equilibrium condition is not easy and the desire to take action is always strong. There is some indication that erosion is lessening. Waiting another two years, until summer 2009, seems an appropriate measure in this regard.

SUMMARY AND RECOMMENDATION

Methods available to mitigate shoreline erosion are effective. However, each has advantages and disadvantages. A selected option should be based on what stakeholders feel are the most important issues surrounding management of the area. Stakeholders at Mañagaha envision different futures for the island. Conservation scientists are concerned that wildlife and ecosystems are threatened by erosion. The visitor industry is concerned that tourists enjoy a safe and pleasant experience. Resource managers seek minimal negative impact, unanimity among stakeholders, conformity with rules and laws, and maximum predictability of outcomes. Given the uncertainty of future shoreline behavior, the varied goals and motivations of stakeholders are best addressed by management options emphasizing flexibility, corrective action, and minimizing the exclusion of a given party.

Below various options are evaluated:

1. **Armoring the east coast at Mañagaha.**

    a. Pros – a seawall or revetment on the east coast will preserve island upland. Trees, nesting habitat, pathways, and infrastructure will be protected and erosion will cease. Eroding shoreline can be cleared of unsightly debris and a walkway established around the island focused on vegetation and views of the lagoon.

    b. Cons – a beach will cease to exist in most of Region 2. Areas adjacent to armored coast are likely to erode, prompting consideration of more armoring. Sand released by erosion in Region 2 that feeds accretion in Region 1 will cease to be available where it is impounded by armoring. This may lead to erosion in Region 1 and Region 3. Wave reflection off armor units may scour the immediate shallow seafloor.

The degree to which armoring will impact behavior of other shorelines on the island is considered high. This option is seen as having a considerable degree of risk.

2. **Sand back passing from Region 1 to Region 2.**

    a. Pros – Moving sand from Region 1 to Region 2 will involve pumping a slurry of suspended sand through a line of flexible hose and discharging it on the eroding eastern shoreline. The hose can be submerged in shallow water adjacent to the shoreline and a pathway carefully mapped so that it will not impact the ecosystem (this was done in 2007 in Waikiki, Hawaii). Sufficient sand volume will need to be quantified such that back-passing corrects the sediment deficiency in Region 2.

    b. Cons – This approach requires investment in a contractor or equipment including a small dredge, discharge hose, operations platform, and earth moving equipment. Pumping will take several weeks and it may disrupt the visitor experience. If pumping occurs at night or off-peak times this can be mitigated. We recommend a large volume of sand is pumped initially and carefully monitored to determine a maintenance schedule. It may be found that necessary maintenance is relatively infrequent (seasonal to annual) and thus represents an acceptable expense and disruption. Or it may be found that pumped sand is not stable in Region 2 and frequent pumping (weeks to months) is necessary making this option less tenable.

It should be possible to calculate an initial volume of pumped sand based on a consideration of topography and past shoreline position. Much would be learned by a one-time operation placing sand in Region 2 but if the sand is not stable it is unclear if the effort and cost would be considered worthwhile.

3. **Experimental groin to replace 1996 debris accompanied by back passing from Region 1.**

    a. Pros – Our hydrodynamic modeling indicates that a groin attached to the shoreline in the area of the null zone and oriented due south along the east coast will effectively shadow wave and current energy with a high likelihood of stabilizing the shoreline and holding a volume of back-passed sand. However this orientation will experience erosional flanking along the shoreline where the groin meets the land. One solution to this is to construct a short seawall at that location, but this may start a pattern of seawall proliferation that is likely undesirable. According to model results, a southeast orientation reduces current velocities along the shoreline and may avoid this problem. We note that a SE orientation better matches the position of WWII debris that was removed in 1996. An experimental approach utilizing flexible construction units such as large sand filled bags or easily reoriented blocks would allow for tuning the structure to a minimal profile and foot print. It is important to recognize that the model we used assumed an emerged structure that does not allow overtopping.

b. Cons – The approach will require a major engineering effort at significant expense. Visual impact may be significant. If sand bags are used, an external source of sand needs to be identified so that the delicate sand budget at Mañagaha is not further disrupted. A barge and crane will be on site for several days to weeks to complete construction. Emerged sand bags will be unsightly and might be disrupted under storm or tsunami conditions. The expense and impact of back passing from Region 1 described in option 2 will accompany this method. Importantly, the groin will prevent sand from moving out of Region 2 into Region 1. The presently accreting beach in Region 1 may experience erosion because its source of sand will be disrupted. The extent of this erosion can not be predicted and may become a future problem. Erosional flanking of the groin on its north end where it meets the land is considered likely.

Impacts from this approach may be significant and so it is important to design a flexible approach that can be quickly corrected.

4. Elevated wooden pathway through Region 2 allowing visitor movement.

a. Pros – An elevated wooden pathway would be constructed from the east end of Region 3 that circumnavigates Region 2 and ends in Region 1. The pathway would be largely over water approximately 1-2 m deep some 10 to 20 m offshore of the coastline. The path would be footed in the seafloor. This approach does nothing to address the problem of erosion. It merely allows visitors to safely observe the eroding area and look into the bird habitat, while avoiding adversely impacting the bird's nesting sites. Visitors can observe the birds and processes in play there as well as recognize that island authorities have made a decision to leave the eroding coast in a natural state. Signage may point out this management approach to visitors as well as other natural aspects of the route. Visitors would not be allowed to exit the walkway and safety would be improved. The construction of an elevated walkway on pilings is not likely to impact sediment processes or shoreline stability. Localized scour may occur around pilings but this will be incidental to the larger scale processes acting on the shoreline. Path construction also offers a means of permanently keeping visitors off the expanding bird nesting area.

b. Cons – This approach largely focuses on addressing visitor attitude with regard to erosion. It does not mitigate the land loss caused by erosion. It is unknown if this will be an effective approach to improving visitor experience.

Recommendation

Based on our analysis we recommend that island stakeholders assess their ability to adapt to changing island conditions by avoiding erosion while monitoring beach conditions at least two more years. This is the most economic approach and least likely to lead to additional negative impacts. Further interruptions of the system by attempts to take corrective action may lead to unintended consequences. In the next two years we recommend careful monitoring of erosion patterns and rates designed to answer the critically important question:

1. Is the rate of erosion decreasing, increasing, or staying the same?

If after two years the answer is that erosion is not decreasing, then we recommend bringing in an experienced coastal engineering firm with the mission of proposing a structural management solution and implementing the recommendation. We recommend that within 5 years the problem should have been addressed and an acceptable management approach adopted and implemented.

However, if a consideration of economic, conservation, and recreational factors leads to the conclusion that an engineering solution is desirable immediately, then a groin system designed to correct the recent history of erosion along the eastern shore (Fig. 30) is recommended. Our model results suggest that a temporary groin oriented due south, at the approximate location of removed debris in 1996, might be successful in stabilizing the shoreline. It is recommended that large sand bags, filled with offsite sand, or quarried rock, if it is more easily available, be set in place and monitored to achieve optimum configuration. It would also be advisable to back fill the enclosed area of the groin with back-passed sand from the northwest shoreline where the beach has experienced accretion in the past decade.

Alternatively, to avoid a structural approach, a sand back-passing system without a groin is recommended employing a pump in Region 1 that delivers sand to Region 2. If shoreline stability increases (erosion decreases) in the near term, before Summer 2009, then we recommend utilizing an elevated walkway in conjunction with leaving the shore in its present condition as the preferred option to accommodate management concerns in light of the visitor experience.

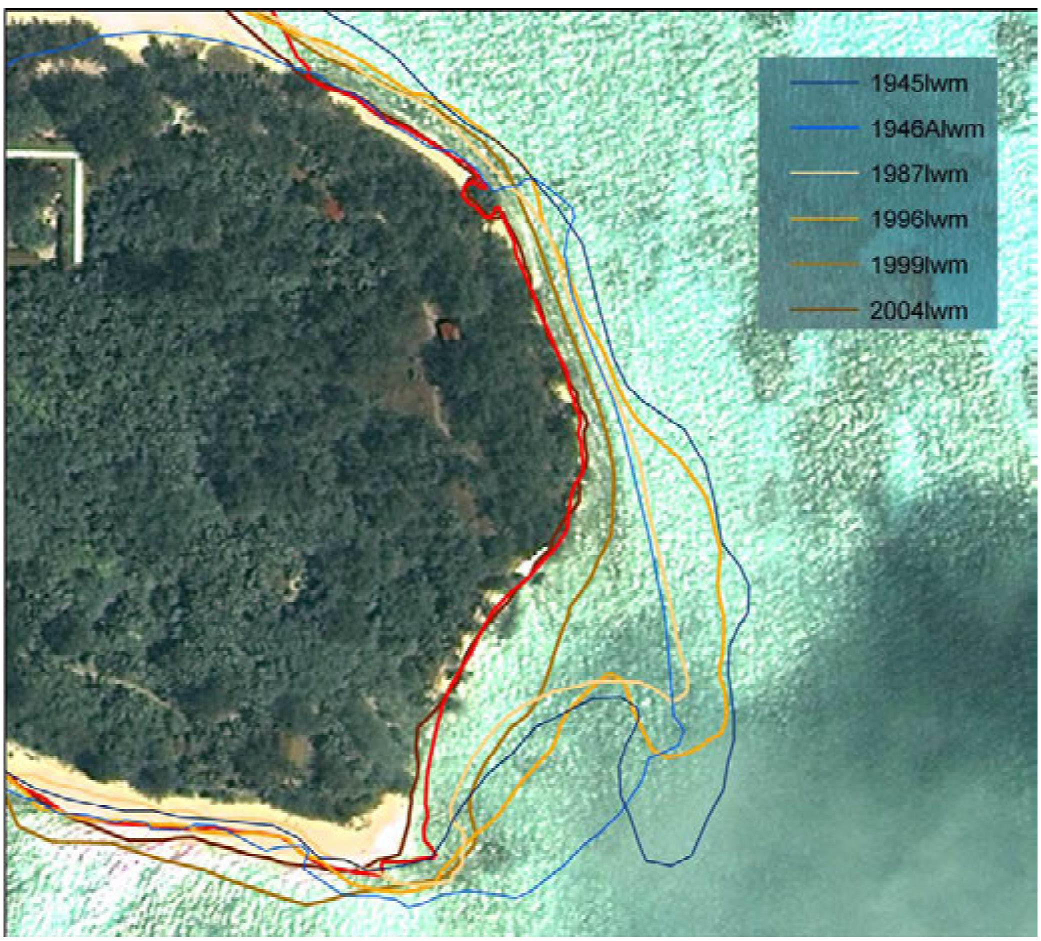

Figure 30. Changes on the eastern shore.

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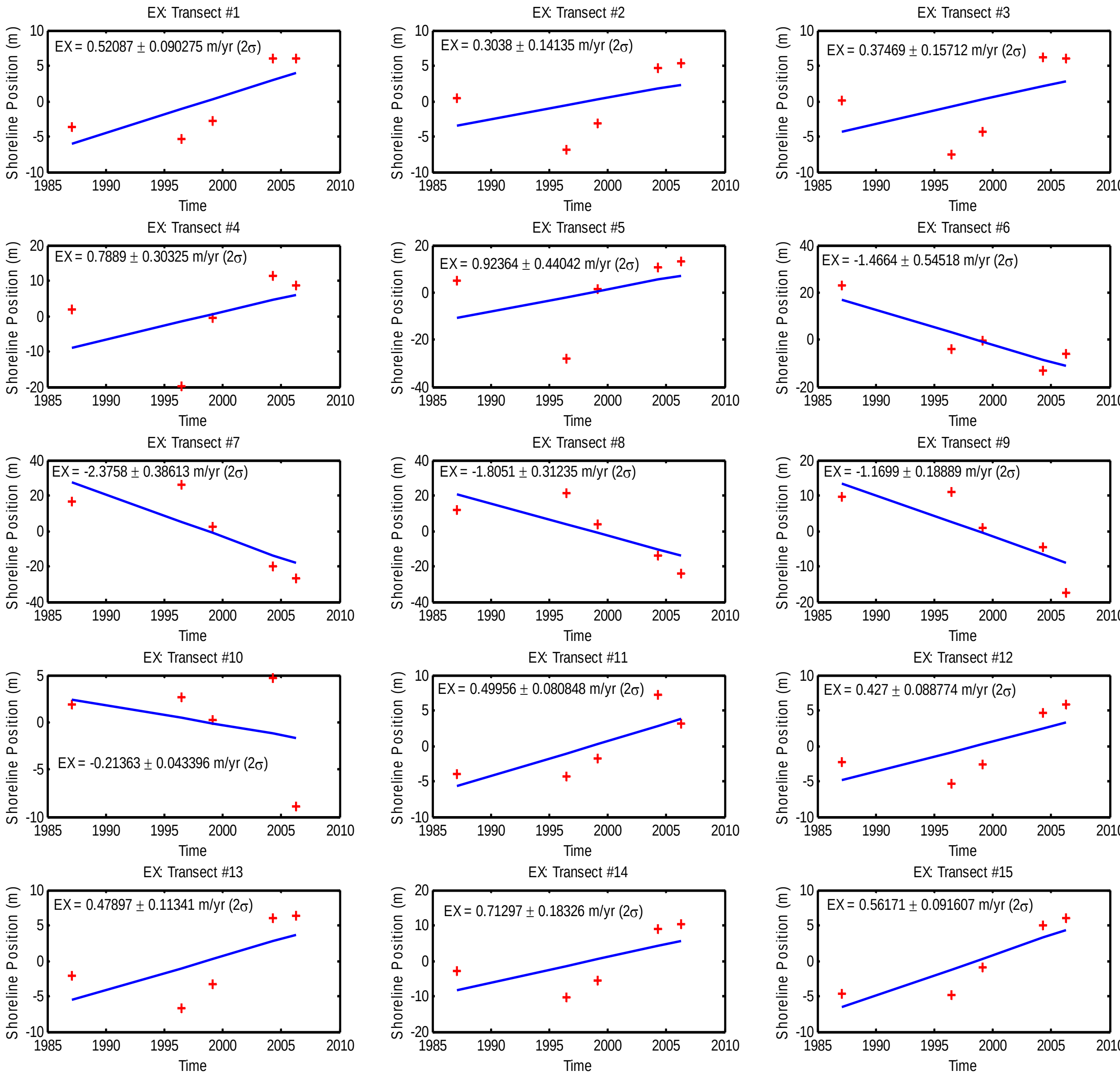
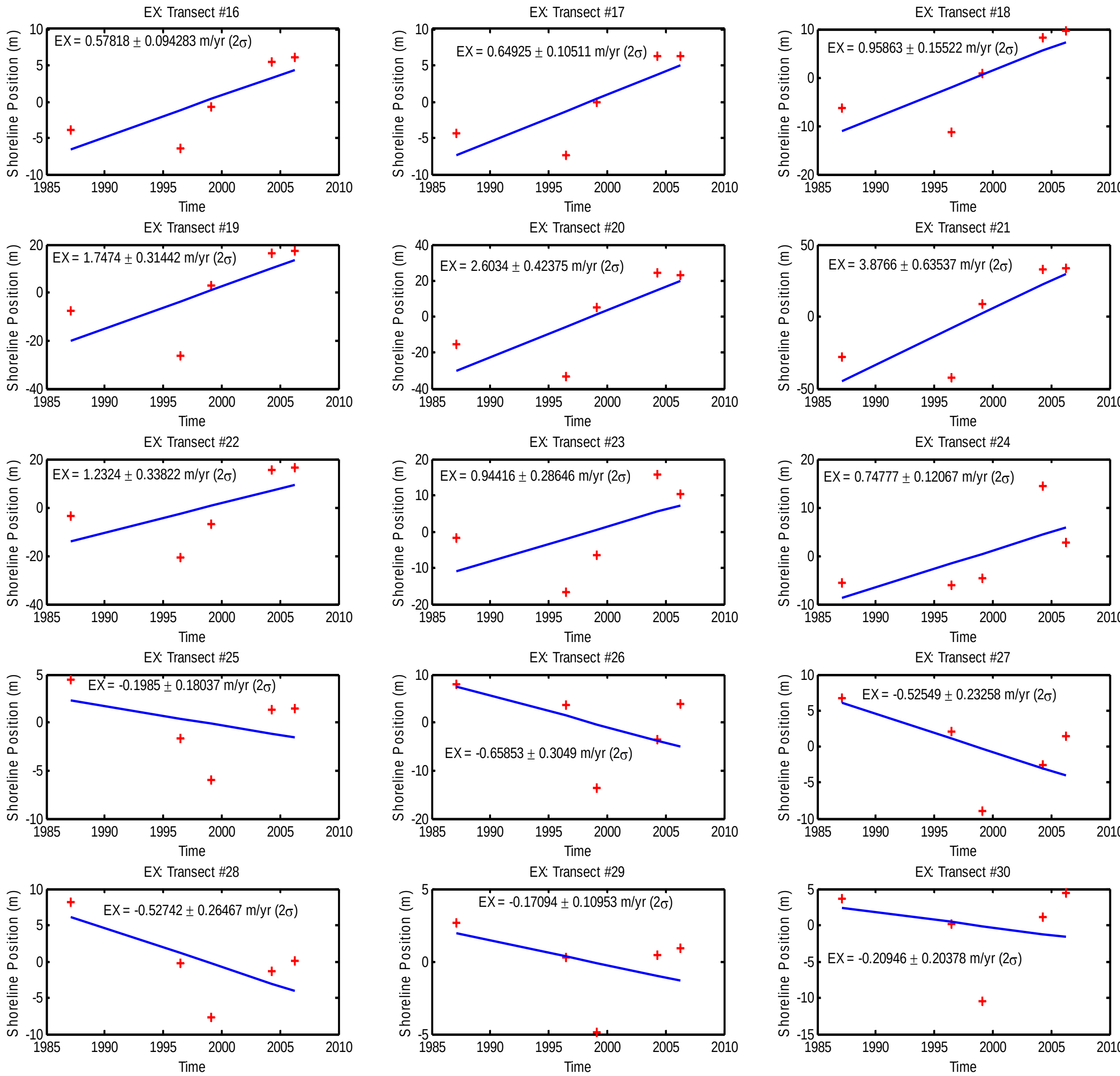
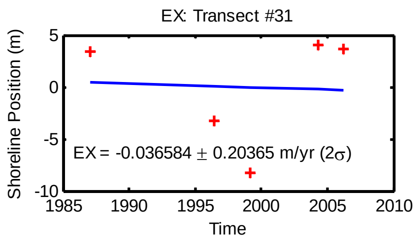
APPENDIX A

Shoreline History Plots using EX 1987-2006




EX: Transect #16
EX = 0.57818 ± 0.094283 m/yr (2σ)
EX: Transect #17
EX = 0.64925 ± 0.10511 m/yr (2σ)
EX: Transect #18
EX = 0.95863 ± 0.15522 m/yr (2σ)
EX: Transect #19
EX = 1.7474 ± 0.31442 m/yr (2σ)
EX: Transect #20
EX = 2.6034 ± 0.42375 m/yr (2σ)
EX: Transect #21
EX = 3.8766 ± 0.63537 m/yr (2σ)
EX: Transect #22
EX = 1.2324 ± 0.33822 m/yr (2σ)
EX: Transect #23
EX = 0.94416 ± 0.28646 m/yr (2σ)
EX: Transect #24
EX = 0.74777 ± 0.12067 m/yr (2σ)
EX: Transect #25
EX = -0.1985 ± 0.18037 m/yr (2σ)
EX: Transect #26
EX = -0.65853 ± 0.3049 m/yr (2σ)
EX: Transect #27
EX = -0.52549 ± 0.23258 m/yr (2σ)
EX: Transect #28
EX = -0.52742 ± 0.26467 m/yr (2σ)
EX: Transect #29
EX = -0.17094 ± 0.10953 m/yr (2σ)
EX: Transect #30
EX = -0.20946 ± 0.20378 m/yr (2σ)
Shoreline Position (m)
Time


EX: Transect #31
Shoreline Position (m)
Time
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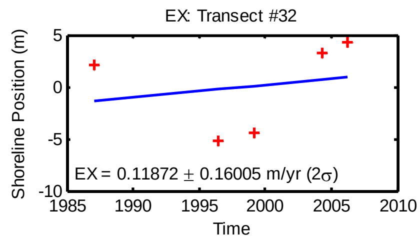
5
0
-5
-10
1985
1990
1995
2000
2005
2010


EX: Transect #32
Shoreline Position (m)
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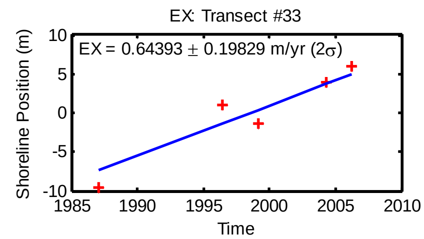
0
-5
-10
1985
1990
1995
2000
2005
2010


EX: Transect #33
Shoreline Position (m)
Time
EX = 0.64393 ± 0.19829 m/yr (2σ)
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5
0
-5
-10
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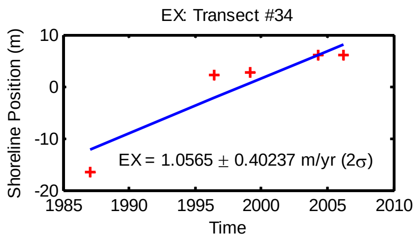
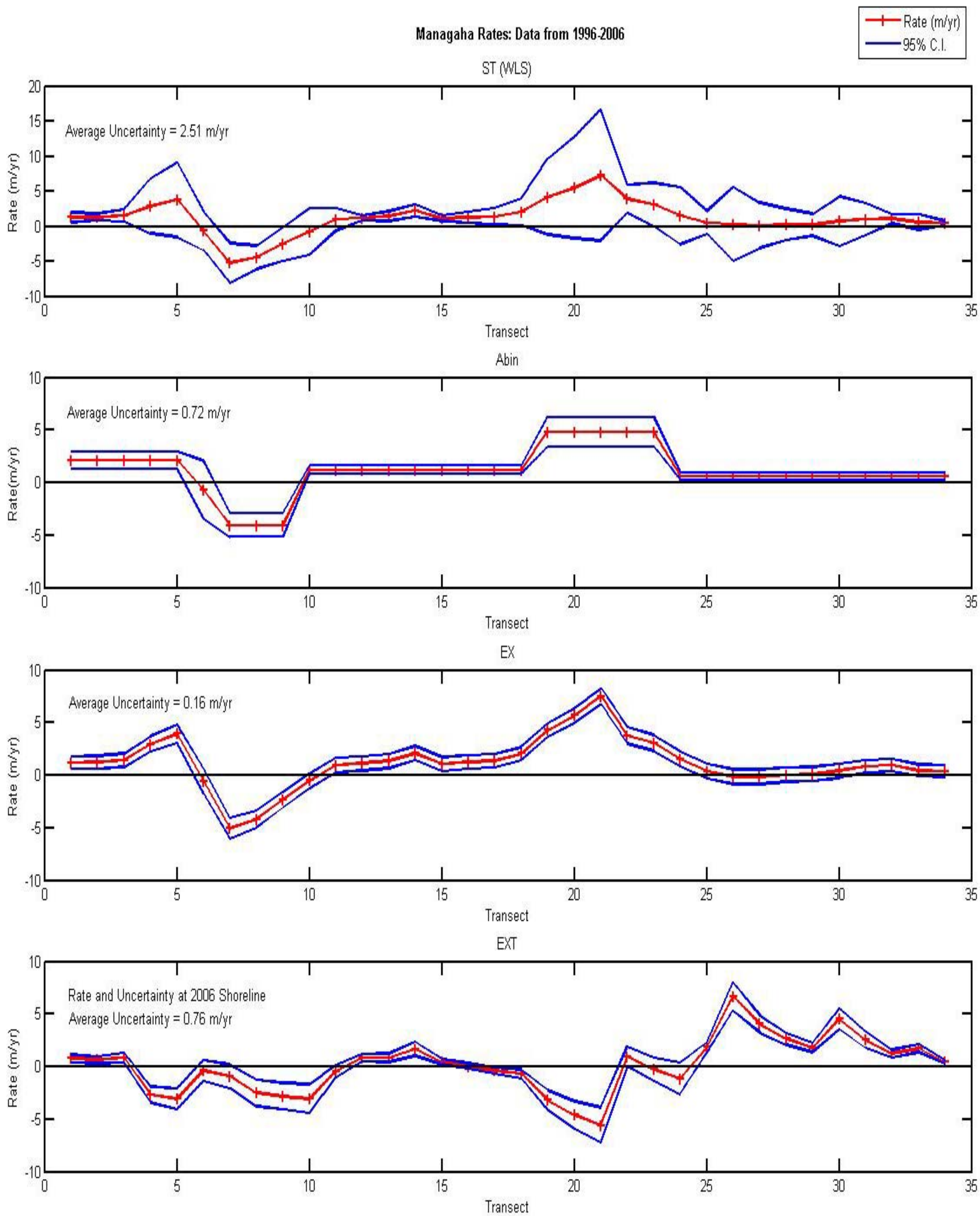
1990
1995
2000
2005
2010


EX: Transect #34
Shoreline Position (m)
Time
EX = 1.0565 ± 0.40237 m/yr (2σ)
10
0
-10
-20
1985
1990
1995
2000
2005
2010

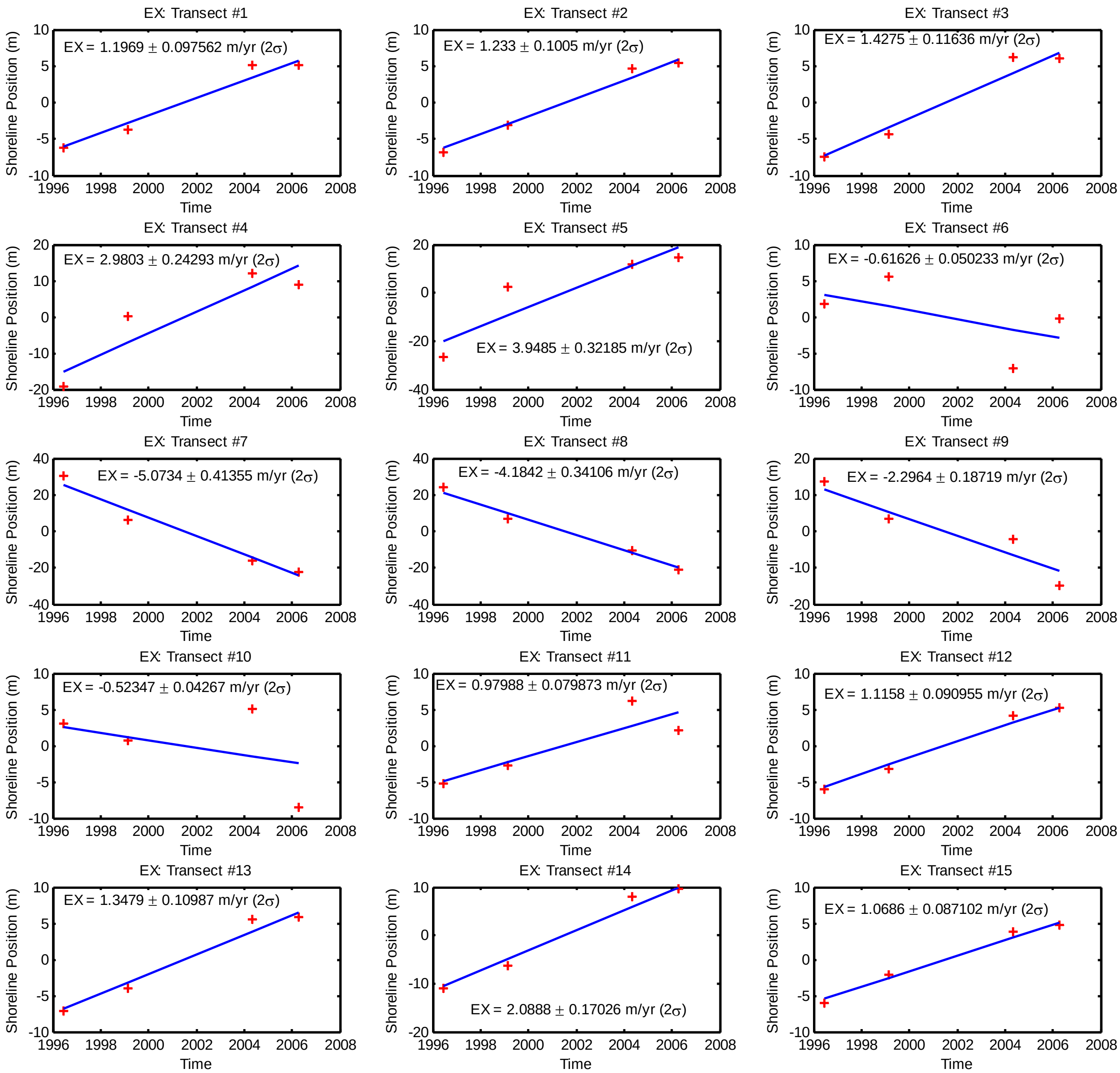
APPENDIX B

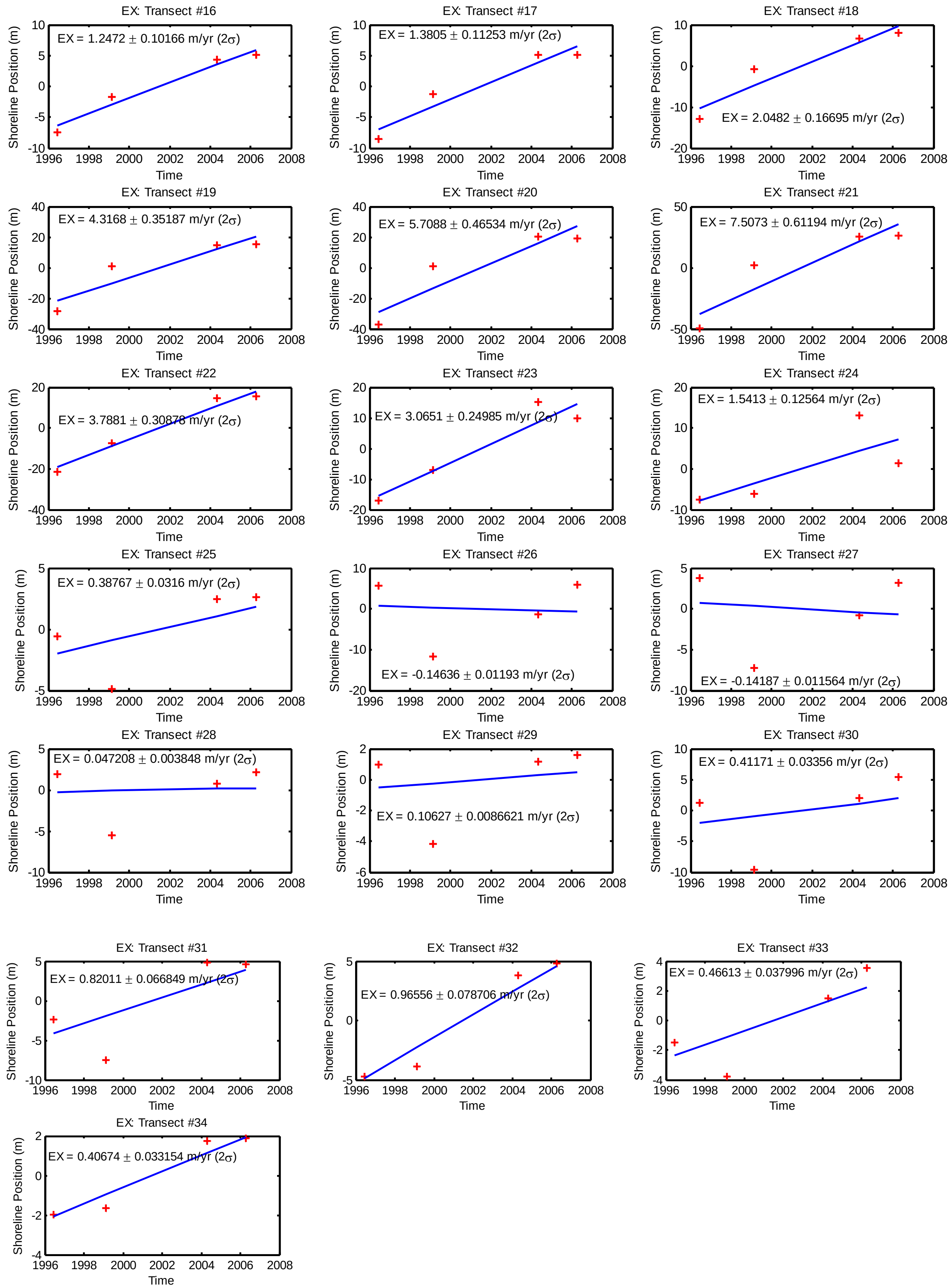
Methods tested 1996-2006. EX has the least uncertainty and is the preferred model.



Transect #	S-T(WLS)	S-T CI95	Abin	Abin CI95	EX	EX CI95	EXT	EXT CI95
1	1.27	0.72	2.15	0.81	1.20	0.10	0.77	0.40
2	1.30	0.50	2.15	0.81	1.23	0.10	0.65	0.34
3	1.52	0.88	2.15	0.81	1.43	0.12	0.87	0.47
4	2.86	3.91	2.15	0.81	2.98	0.24	-2.66	0.74
5	3.81	5.35	2.15	0.81	3.95	0.32	-3.06	0.99
6	-0.66	2.76	-0.66	2.76	-0.62	0.05	-0.37	0.99
7	-5.23	2.82	-4.06	1.12	-5.07	0.41	-0.93	1.14
8	-4.43	1.69	-4.06	1.12	-4.18	0.34	-2.50	1.25
9	-2.52	2.39	-4.06	1.12	-2.30	0.19	-2.81	1.28
10	-0.73	3.34	1.21	0.38	-0.52	0.04	-3.05	1.37
11	0.97	1.62	1.21	0.38	0.98	0.08	-0.42	0.57
12	1.20	0.36	1.21	0.38	1.12	0.09	0.86	0.34
13	1.43	0.69	1.21	0.38	1.35	0.11	0.84	0.42
14	2.24	0.88	1.21	0.38	2.09	0.17	1.67	0.67
15	1.12	0.39	1.21	0.38	1.07	0.09	0.45	0.26
16	1.27	0.79	1.21	0.38	1.25	0.10	0.04	0.26
17	1.38	1.19	1.21	0.38	1.38	0.11	-0.39	0.28
18	2.04	1.95	1.21	0.38	2.05	0.17	-0.70	0.42
19	4.18	5.40	4.80	1.41	4.32	0.35	-3.19	0.97
20	5.51	7.25	4.80	1.41	5.71	0.47	-4.57	1.29
21	7.27	9.33	4.80	1.41	7.51	0.61	-5.56	1.67
22	3.93	1.97	4.80	1.41	3.79	0.31	0.96	0.93
23	3.11	3.09	4.80	1.41	3.07	0.25	-0.27	1.09
24	1.51	4.06	0.62	0.36	1.54	0.13	-1.11	1.47
25	0.52	1.61	0.62	0.36	0.39	0.03	1.83	0.50
26	0.30	5.26	0.62	0.36	-0.15	0.01	6.67	1.34
27	0.13	3.28	0.62	0.36	-0.14	0.01	4.07	0.82
28	0.23	2.24	0.62	0.36	0.05	0.00	2.64	0.58
29	0.23	1.60	0.62	0.36	0.11	0.01	1.80	0.43
30	0.73	3.53	0.62	0.36	0.41	0.03	4.54	0.99
31	1.01	2.28	0.62	0.36	0.82	0.07	2.52	0.77
32	1.07	0.65	0.62	0.36	0.97	0.08	1.24	0.39
33	0.59	1.09	0.62	0.36	0.47	0.04	1.75	0.40
34	0.45	0.31	0.62	0.36	0.41	0.03	0.46	0.17

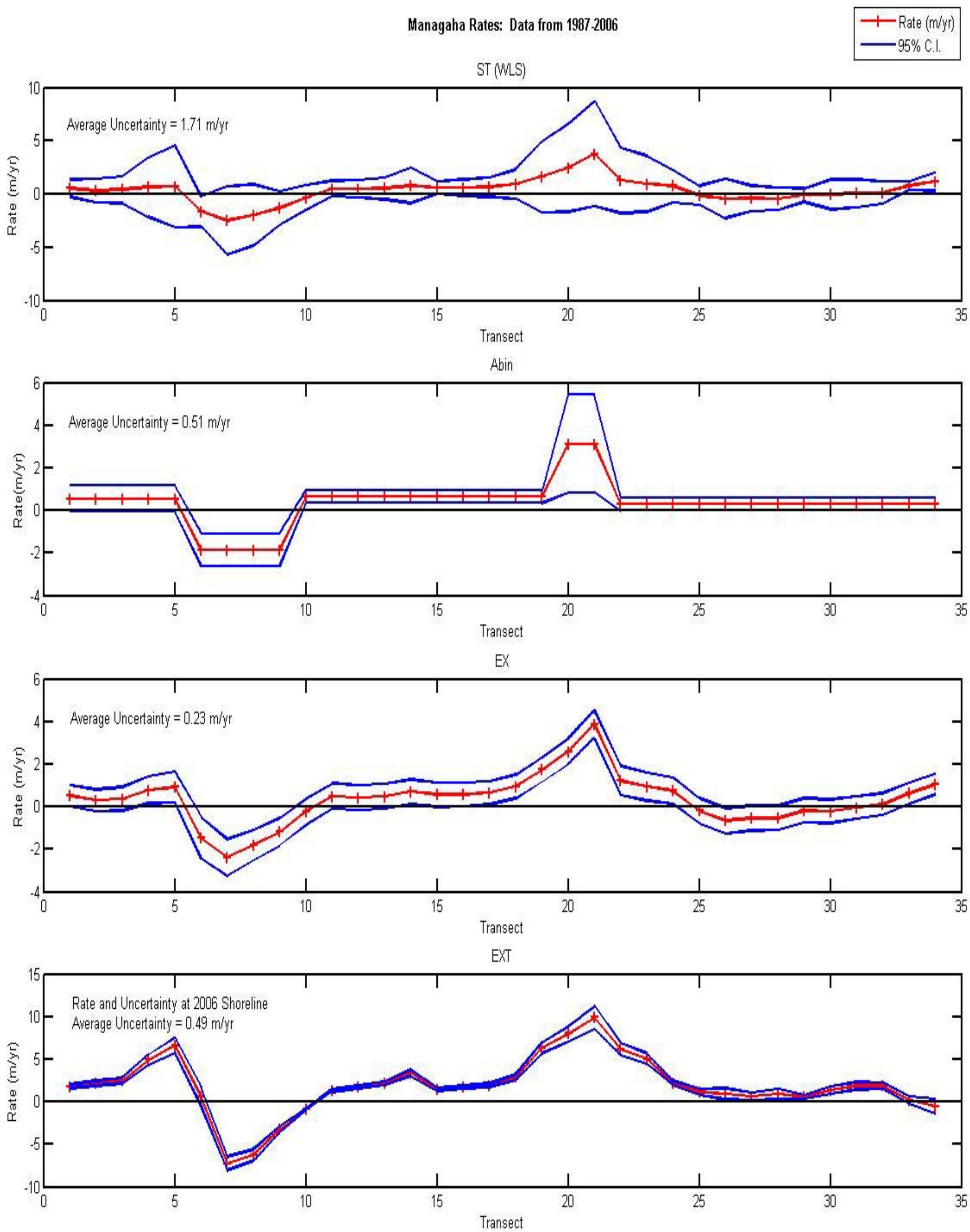
Shoreline History Plots using EX 1996-2006




EX: Transect #16
EX = 1.2472 ± 0.10166 m/yr (2σ)
EX: Transect #17
EX = 1.3805 ± 0.11253 m/yr (2σ)
EX: Transect #18
EX = 2.0482 ± 0.16695 m/yr (2σ)
EX: Transect #19
EX = 4.3168 ± 0.35187 m/yr (2σ)
EX: Transect #20
EX = 5.7088 ± 0.46534 m/yr (2σ)
EX: Transect #21
EX = 7.5073 ± 0.61194 m/yr (2σ)
EX: Transect #22
EX = 3.7881 ± 0.30878 m/yr (2σ)
EX: Transect #23
EX = 3.0651 ± 0.24985 m/yr (2σ)
EX: Transect #24
EX = 1.5413 ± 0.12564 m/yr (2σ)
EX: Transect #25
EX = 0.38767 ± 0.0316 m/yr (2σ)
EX: Transect #26
EX = -0.14636 ± 0.01193 m/yr (2σ)
EX: Transect #27
EX = -0.14187 ± 0.011564 m/yr (2σ)
EX: Transect #28
EX = 0.047208 ± 0.003848 m/yr (2σ)
EX: Transect #29
EX = 0.10627 ± 0.0086621 m/yr (2σ)
EX: Transect #30
EX = 0.41171 ± 0.03356 m/yr (2σ)
EX: Transect #31
EX = 0.82011 ± 0.066849 m/yr (2σ)
EX: Transect #32
EX = 0.96556 ± 0.078706 m/yr (2σ)
EX: Transect #33
EX = 0.46613 ± 0.037996 m/yr (2σ)
EX: Transect #34
EX = 0.40674 ± 0.033154 m/yr (2σ)
Shoreline Position (m)
Time
1996
1998
2000
2002
2004
2006
2008

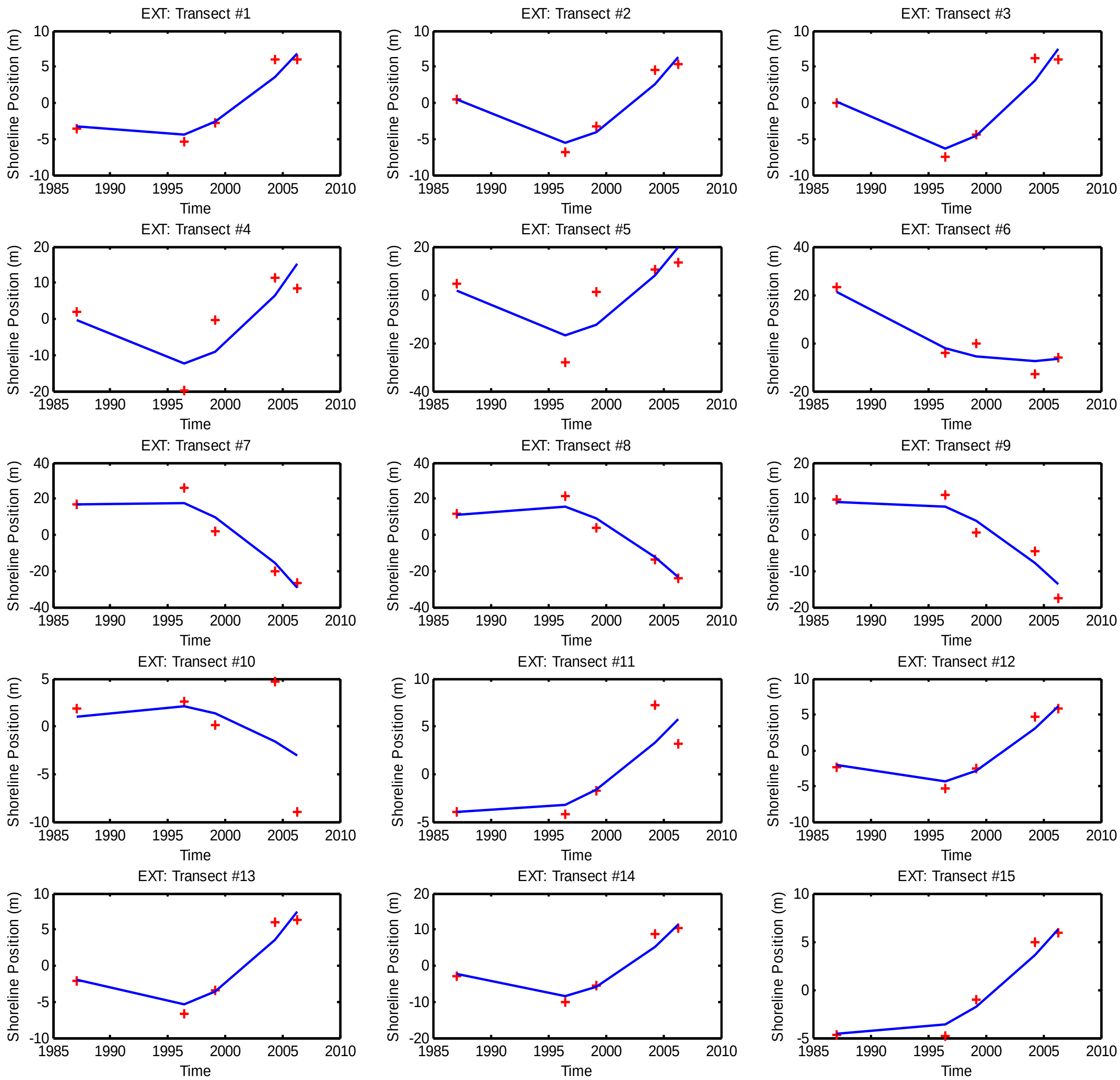
APPENDIX C

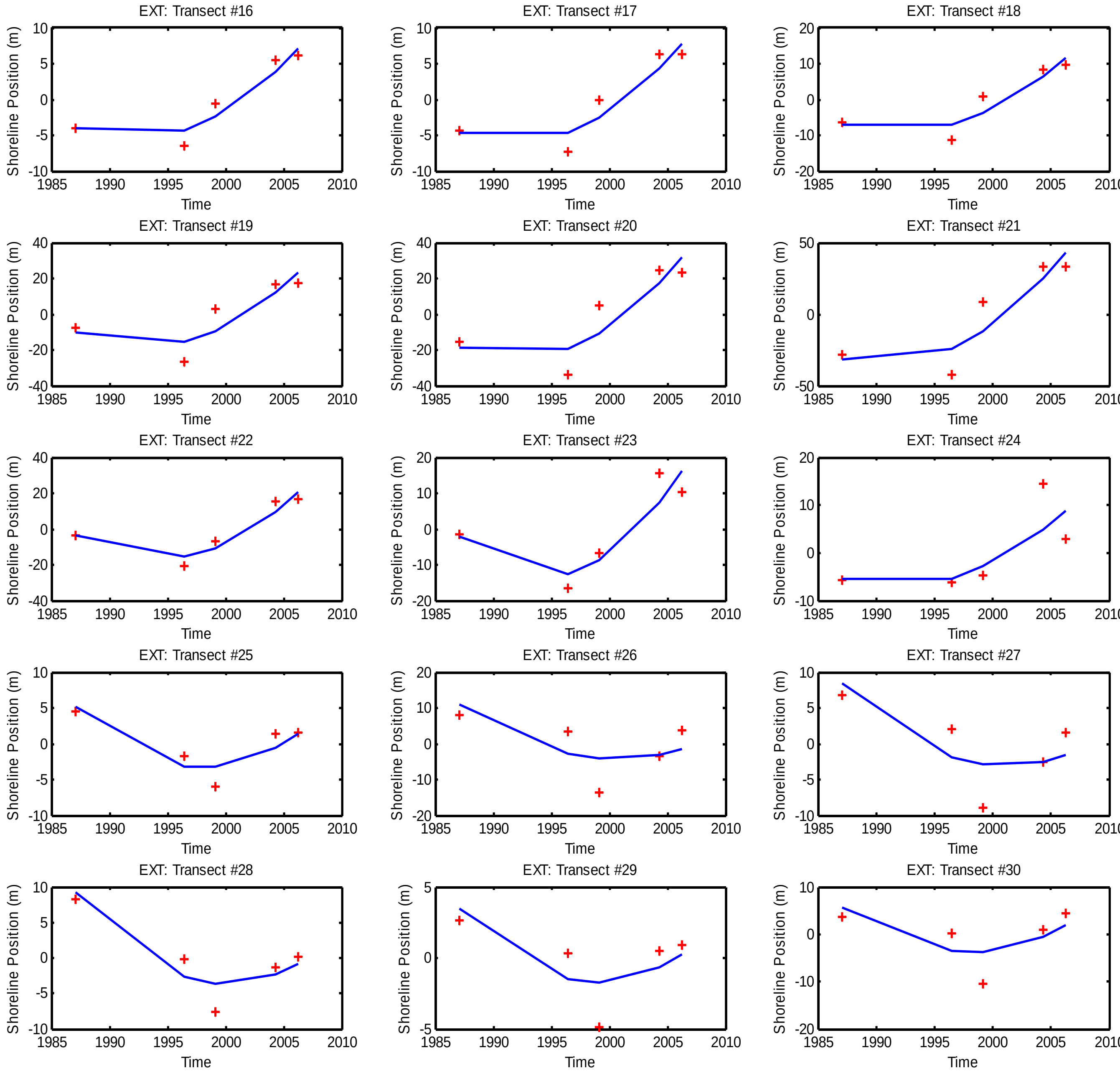
Methods tested 1987-2006. EX has the least uncertainty and is the preferred model.

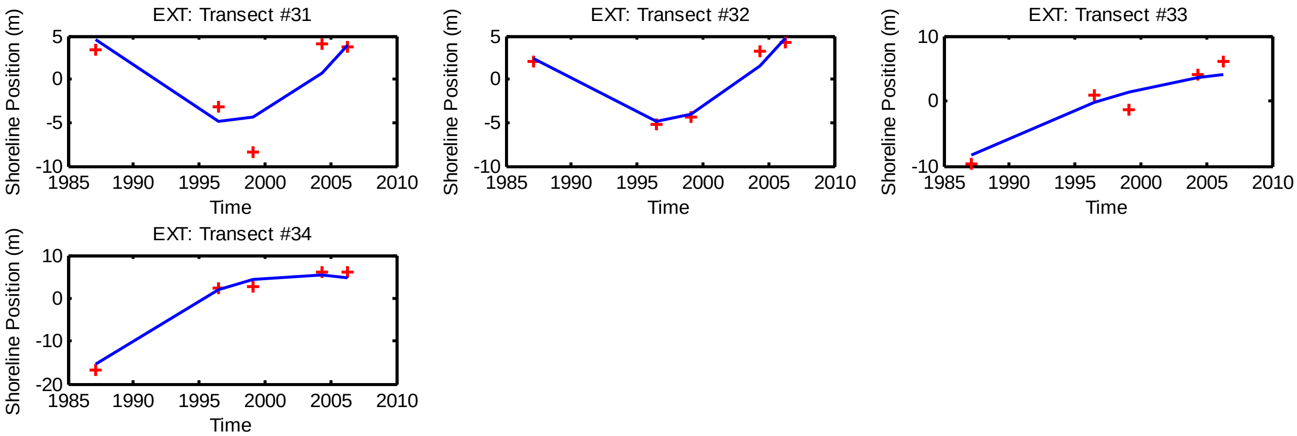


	Single Transect Method (m/yr)		Polynomial Modeling (m/yr)					
Transect #	**S-T(WLS)**	**S-T CI95**	**LX**	**LX CI95**	**RX**	**RX CI95**	**EX**	**EX CI95**
1	0.58	0.82	0.74	1.19	0.56	0.49	0.52	0.09
2	0.33	1.11	-0.06	0.89	0.65	0.51	0.30	0.14
3	0.41	1.28	0.47	0.78	0.71	0.56	0.37	0.16
4	0.66	2.77	0.92	0.73	0.68	0.63	0.79	0.30
5	0.74	3.86	0.81	0.89	0.48	0.73	0.92	0.44
6	-1.64	1.41	-1.97	0.98	-1.40	0.98	-1.47	0.55
7	-2.49	3.23	-2.50	0.81	-2.79	0.84	-2.38	0.39
8	-1.95	2.86	-1.62	0.65	-2.01	0.70	-1.81	0.31
9	-1.31	1.57	-0.88	0.60	-1.00	0.64	-1.17	0.19
10	-0.32	1.16	-0.36	0.58	-0.19	0.62	-0.21	0.04
11	0.52	0.73	-0.01	0.55	0.34	0.61	0.50	0.08
12	0.48	0.82	0.22	0.53	0.56	0.59	0.43	0.09
13	0.53	1.05	0.37	0.52	0.55	0.58	0.48	0.11
14	0.80	1.66	0.52	0.52	0.46	0.57	0.71	0.18
15	0.61	0.59	0.72	0.52	0.46	0.57	0.56	0.09
16	0.60	0.80	0.94	0.51	0.61	0.56	0.58	0.09
17	0.66	0.90	1.22	0.50	0.93	0.55	0.65	0.11
18	0.96	1.37	1.52	0.50	1.38	0.55	0.96	0.16
19	1.64	3.35	1.86	0.53	1.96	0.57	1.75	0.31
20	2.48	4.12	2.09	0.56	2.36	0.61	2.60	0.42
21	3.78	4.94	2.26	0.60	2.63	0.66	3.88	0.64
22	1.29	3.05	1.85	0.62	1.94	0.68	1.23	0.34
23	0.96	2.63	1.46	0.61	1.39	0.66	0.94	0.29
24	0.77	1.53	0.60	0.61	0.37	0.62	0.75	0.12
25	-0.14	0.91	-0.04	0.61	-0.22	0.61	-0.20	0.18
26	-0.42	1.86	-0.47	0.59	-0.50	0.60	-0.66	0.30
27	-0.39	1.19	-0.59	0.59	-0.51	0.59	-0.53	0.23
28	-0.46	1.05	-0.48	0.62	-0.35	0.58	-0.53	0.26
29	-0.10	0.63	-0.20	0.66	-0.13	0.57	-0.17	0.11
30	-0.03	1.41	0.07	0.65	0.09	0.55	-0.21	0.20
31	0.06	1.29	0.21	0.67	0.26	0.54	-0.04	0.20
32	0.16	1.05	0.26	0.78	0.38	0.51	0.12	0.16
33	0.77	0.40	0.48	0.77	0.48	0.50	0.64	0.20
34	1.17	0.83	1.29	1.16	0.56	0.49	1.06	0.40

Shoreline History Plots using EXT 1987-2006

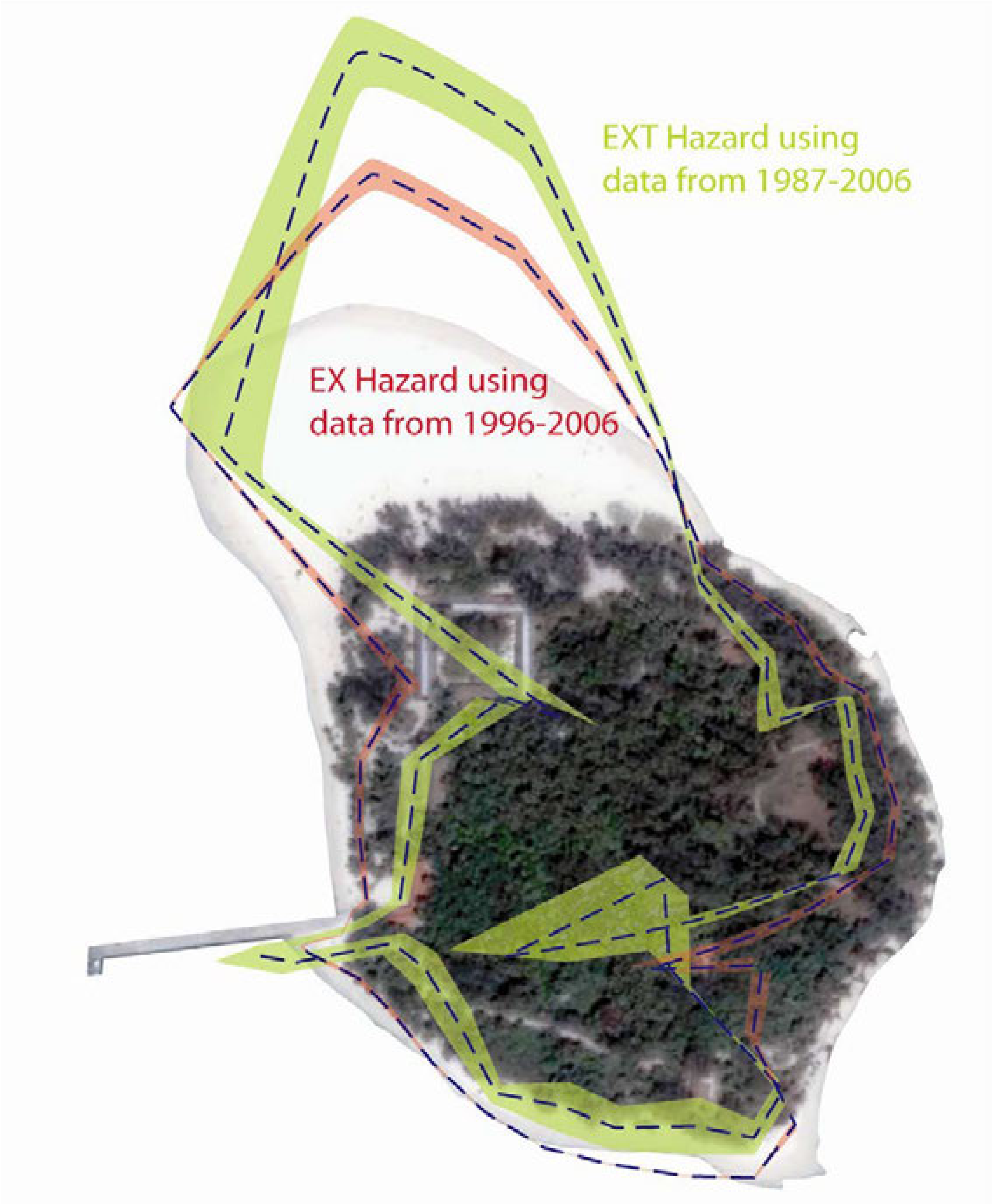



EXT: Transect #16
EXT: Transect #17
EXT: Transect #18
EXT: Transect #19
EXT: Transect #20
EXT: Transect #21
EXT: Transect #22
EXT: Transect #23
EXT: Transect #24
EXT: Transect #25
EXT: Transect #26
EXT: Transect #27
EXT: Transect #28
EXT: Transect #29
EXT: Transect #30
Shoreline Position (m)
Time
1985 1990 1995 2000 2005 2010


EXT: Transect #31
EXT: Transect #32
EXT: Transect #33
EXT: Transect #34
Shoreline Position (m)
Time
1985
1990
1995
2000
2005
2010

APPENDIX D

10 year shoreline hazard projection using EXT (1987-2006) and EX (1996-2006).

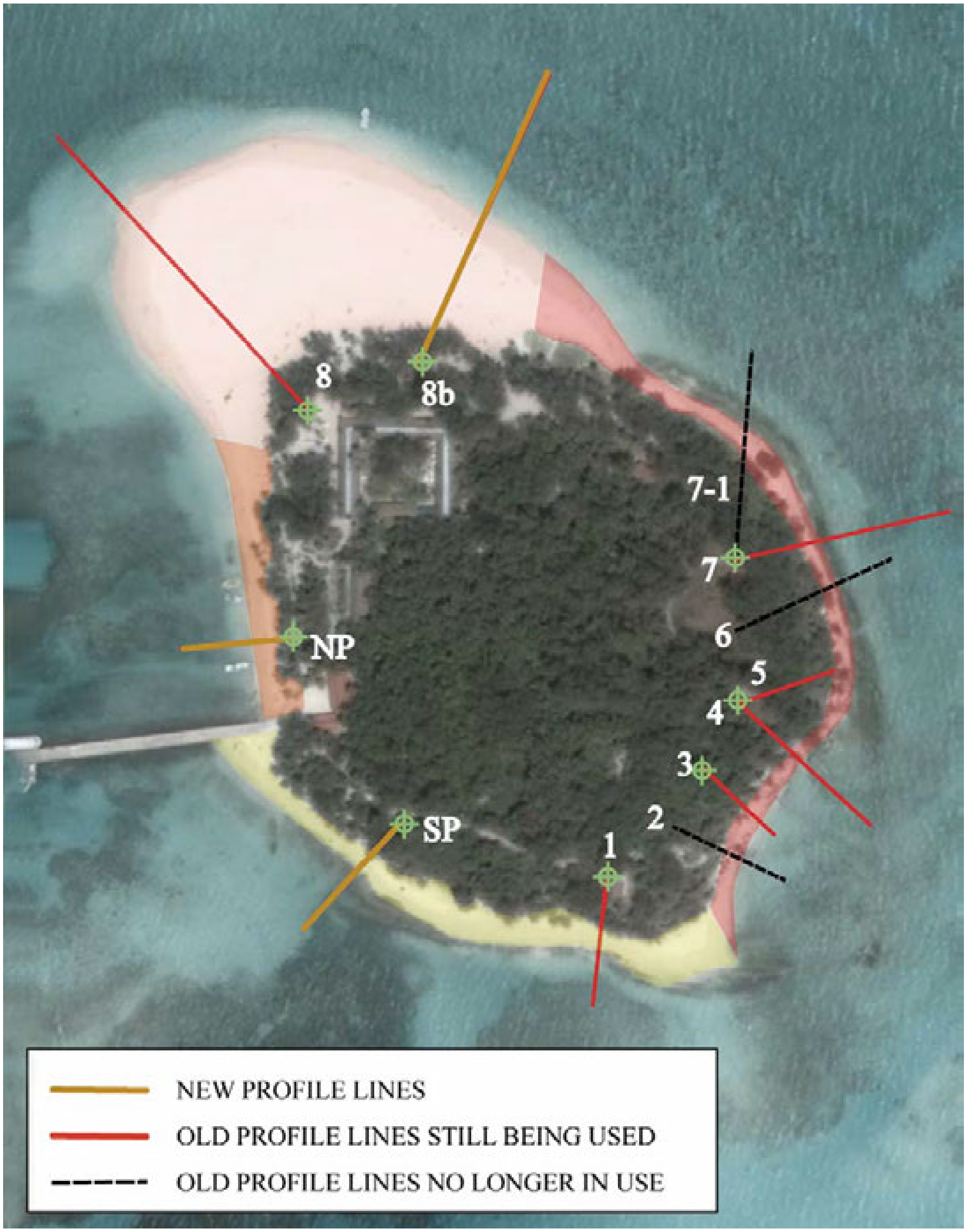


APPENDIX E

Map of Mañagaha Island

APPENDIX F

Beach profiles



PROFILE LOCATION DESCRIPTIONS

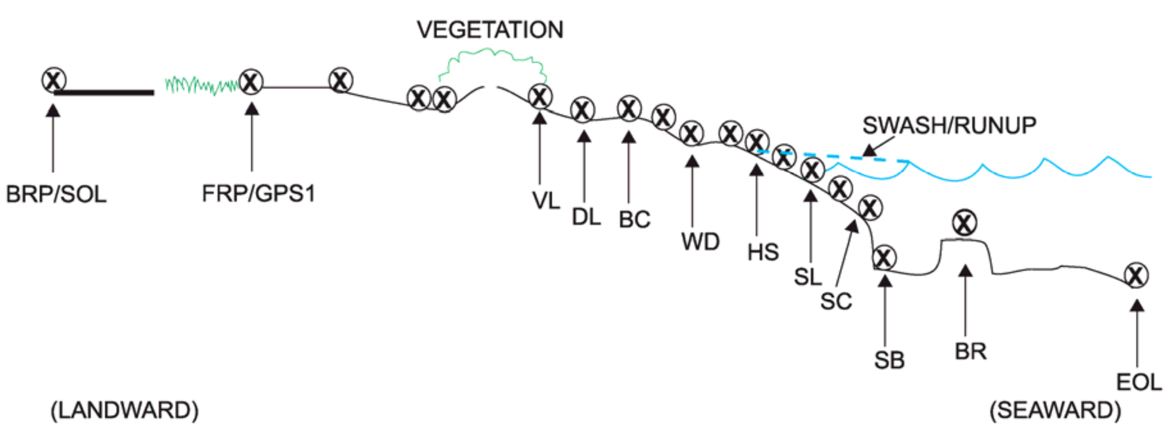
ID	LOCATION	LINE-UP	BRP	FRP
SITE 1	Red pavilion on the SE corner of Managaha. Azimuth = 196°	the north wall of the covered area	north base of the corner of most landward, north cement pillar	north base of the corner of second most landward, north cement pillar
SITE 3	low lying cement channel on ground located on the east side of the island in between the N and S points of the eastern shoreline. Cement channel is located approx. 4m landward of the coastal path. NOTE: grass may be covering this location. Azimuth = 138°	the inside face of the north side of the channel. Profile shoots directly through to palms at the top of the scarp. Trunks of palms are ~1m apart	back, inside north face of the cement channel	front, inside north face of the cement channel
SITE 4	concrete bunker on ENE side of Island. Bunker is directly off of the landward side of coastal path. Azimuth = 137°	the outside, N facing wall that defines the roof of the bunker	top, N, landward and outside corner of the bunker roof	N, seaward and outside corner at the bottom of bunker roof
SITE 5	concrete bunker on ENE side of Island. Bunker is directly off of the landward side of coastal path. Azimuth = 70°	uses only the 70 degree azimuth angle shot from the BRP of site 4	top, N, landward and outside corner of the bunker roof	line has only two points, the BRP and the TOP OF SCARP
SITE 7	second pavilion E from the main building. Pavilion borders the W boundary of the bird sanctuary. Azimuth = 85°	the 2 concrete pillars located on the NW end of the covered pavilion	seaward base of the most landward pillar located on the NW side of the pavilion	seaward base of the most seaward pillar located on the NW side of the pavilion
SITE 8b	located off the N side of the main structure on the NW side of the island. Azimuth = 24°	uses two trees off the NNW of the main building	seaward base of the most landward tree	Seaward base of the most seaward tree
SITE 8	two ironwood trees that line up of the NW corner of the main building. Azimuth = 324°	the base of two ironwood trees	seaward base of the most landward tree	Seaward base of the most seaward tree
SITE NP	cluster of palms of four palms on the west side of the island approx 45m N of the pier. There is a temporary covered area here with a yellow canopy. directly behind and north of the line. Azimuth = 274°	use the two south most palms that create a line directly off shore	seaward base of the most landward palm	Seaward base of the most seaward palm
SITE SP	pavilion just S of the pier. Line is located N of large concrete block on beach and S of metal debris just off shore Azimuth = 231°	the 2 concrete pillars located on the S end of the covered pavilion	seaward base of the most landward pillar located on the S side of the pavilion	seaward base of the most seaward pillar located on the S side of the pavilion

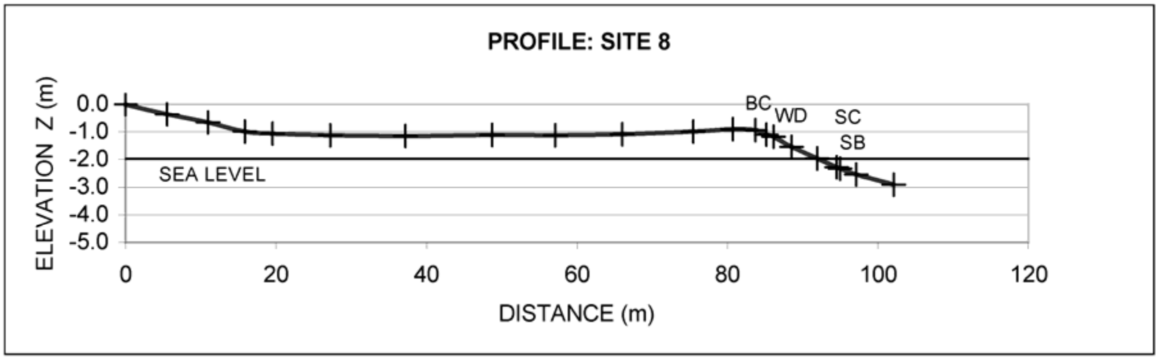
Profile Line Checklist
Beach Morphological Features

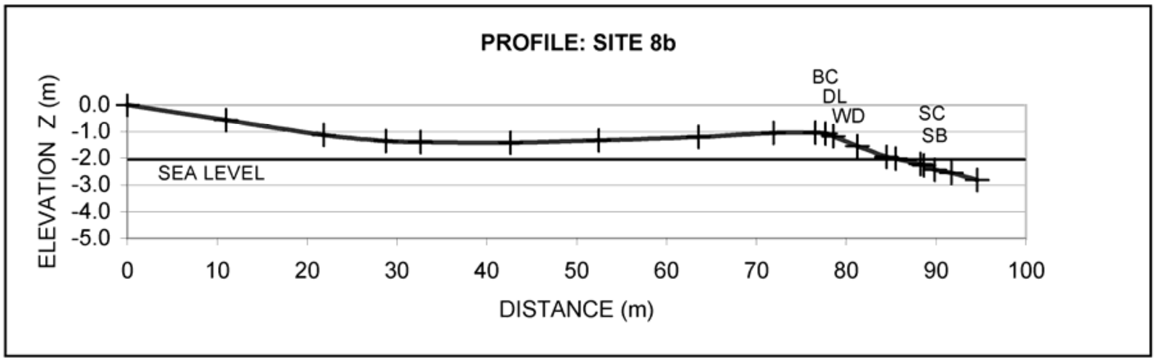
Feature	Description	Code
Onshore:		
Back Reference Point	Fixed survey reference point, mauka online	BRP
Front Reference Point	Fixed survey reference point, makai online	FRP
Side Reference Point	Fixed survey reference point, offline	SRP
Numbered Reference Point	Fixed survey reference point (number)	RP#
GPS Location	GPS surveyed point	GPS
Start Of Line		SOL
(Coastal Structures)	i.e. coastal paths (landward and seaward)	
(Dune Crest)	May be covered by vegetation. May be more than one	(DC)
Vegetation Line	Note type of vegetation (i.e. naupaka, grass, etc.)	VL
(Debris Line)	Notable last storm/high-wave deposition	(DL)
Berm Crest	Notable Break in Slope on Foreshore. May be more than one.	BC
Wet/Dry Line	Highest swash of last tidal cycle. Good to know at what period of tide cycle survey is being conducted in order to find Wet/Dry line.	WD
High Swash	Highest runup at survey time, associated with set waves	HS
Sea Level	Mean sea level	SL
Step Crest		SC
Step Base		SB
Toe of Beach	(if no step exists)	TB
Offshore:		
Sand		S
Ripples	Get crest, trough if possible	(RP)
Beachrock		(BR)
Rock		R
Coral Head		C
Rock/Sand		R/S
Sand/Rock		S/R
Bar	Offshore bar- crest, trough	BAR
End of Line		EOL

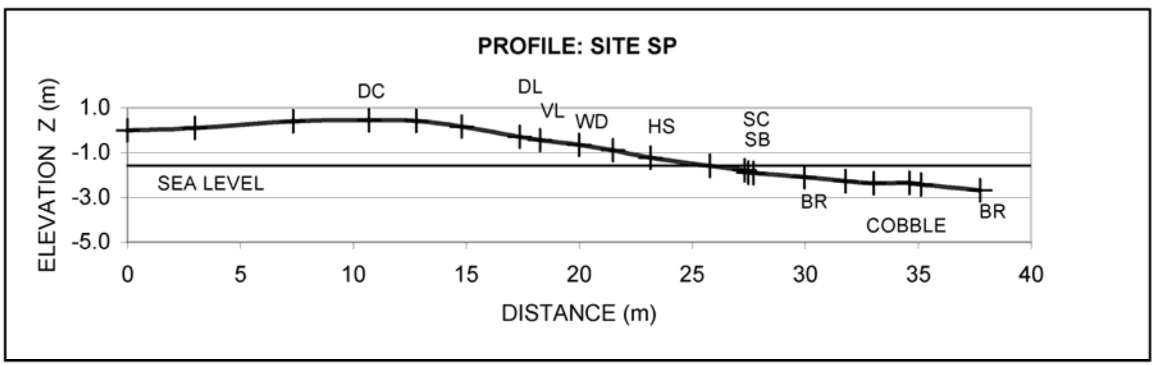
>Features in parentheses may not exist or be observed at a given survey
>Some may occur more than once at a given site.
>Beachrock may be found onshore within beachface.
vegetation clumps, walls, revetements, beachrock ridges, sand channels, sand fields, coral heads)

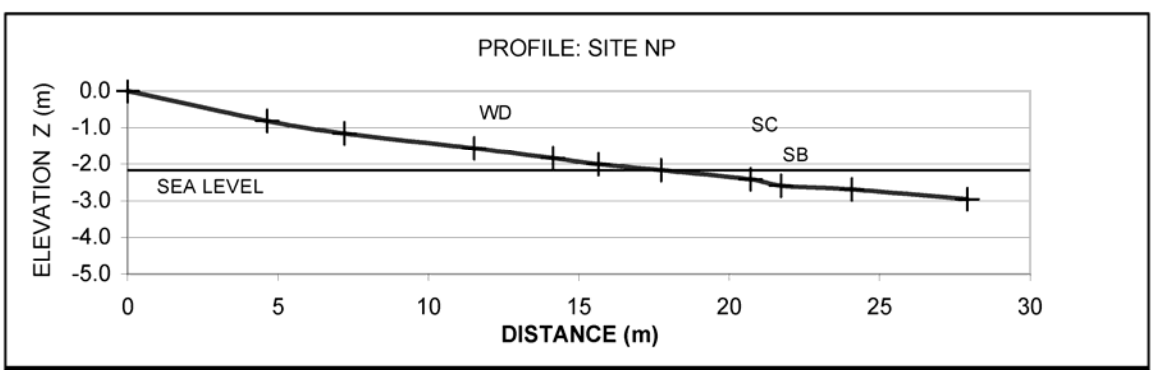
A Typical Beach Profile

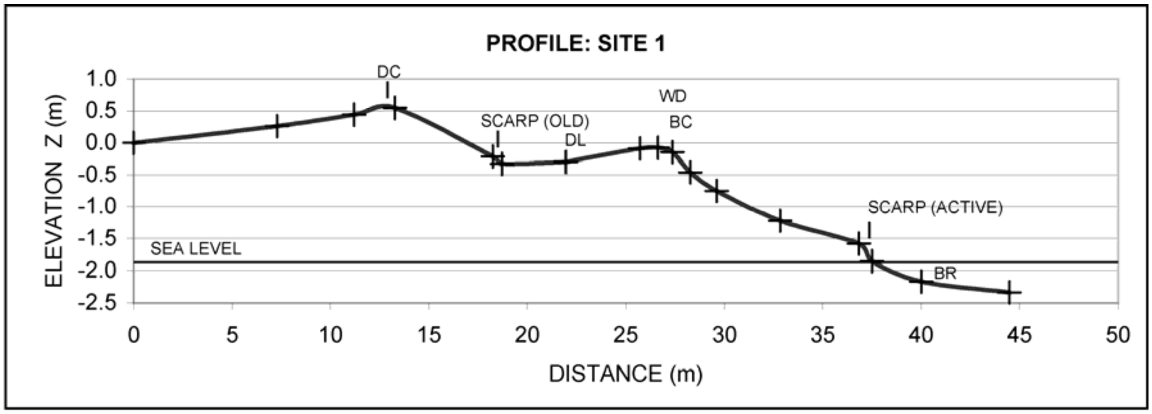


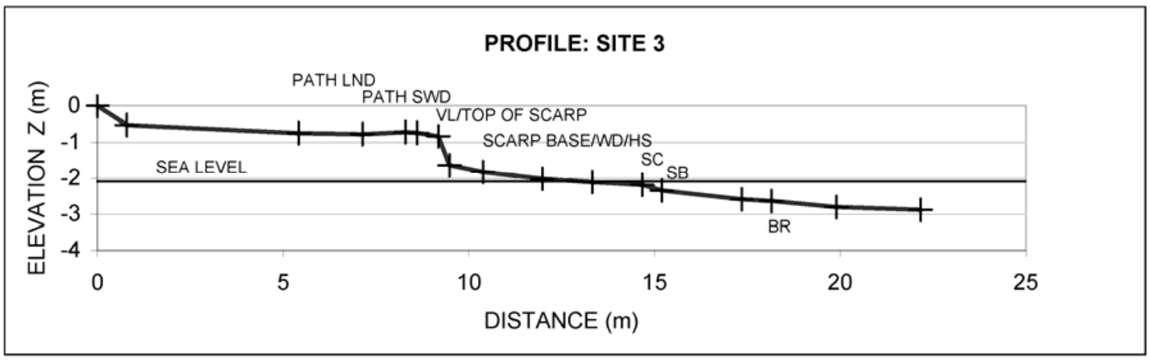

PROFILE: SITE 8
ELEVATION Z (m)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
BC
WD
SC
SB
SEA LEVEL
0
20
40
60
80
100
120
DISTANCE (m)

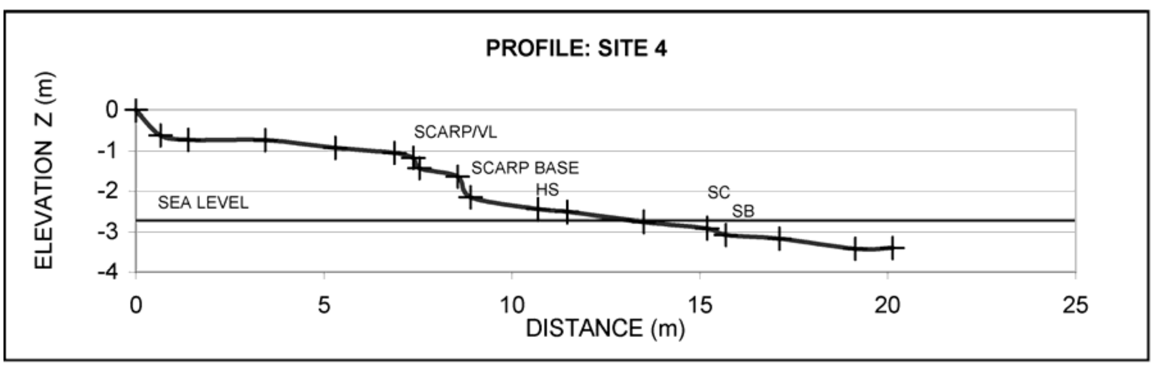

PROFILE: SITE 8b
ELEVATION Z (m)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
BC
DL
WD
SC
SB
SEA LEVEL
0
10
20
30
40
50
60
70
80
90
100
DISTANCE (m)

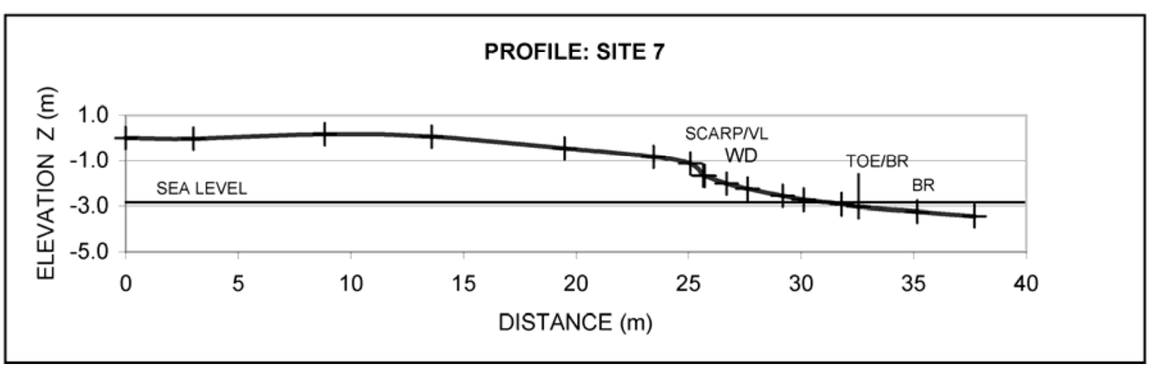

PROFILE: SITE SP
ELEVATION Z (m)
1.0
-1.0
-3.0
-5.0
DC
DL
VL
WD
HS
SC
SB
SEA LEVEL
BR
COBBLE
BR
0
5
10
15
20
25
30
35
40
DISTANCE (m)

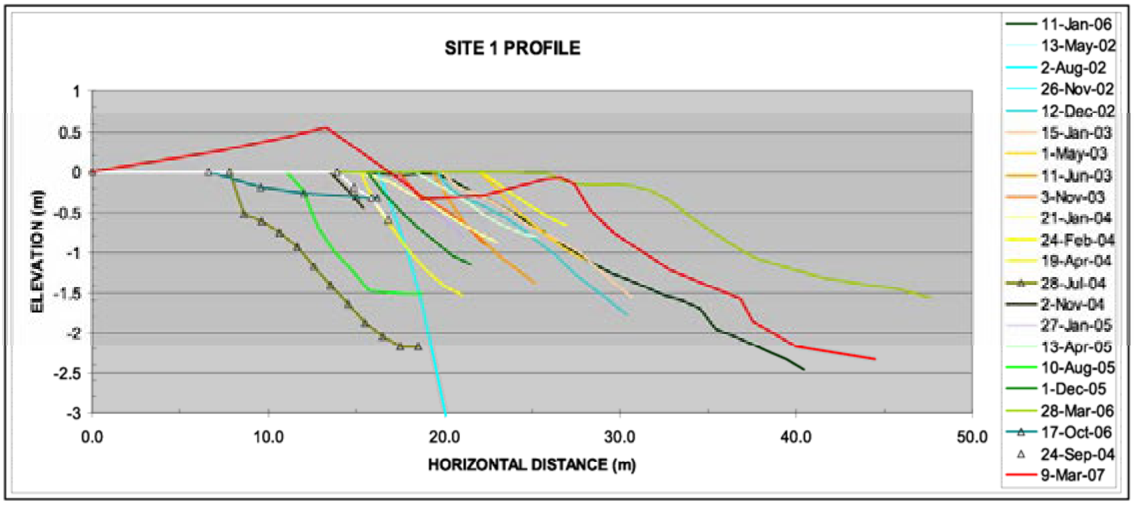

PROFILE: SITE NP
ELEVATION Z (m)
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
WD
SC
SB
SEA LEVEL
0
5
10
15
20
25
30
DISTANCE (m)

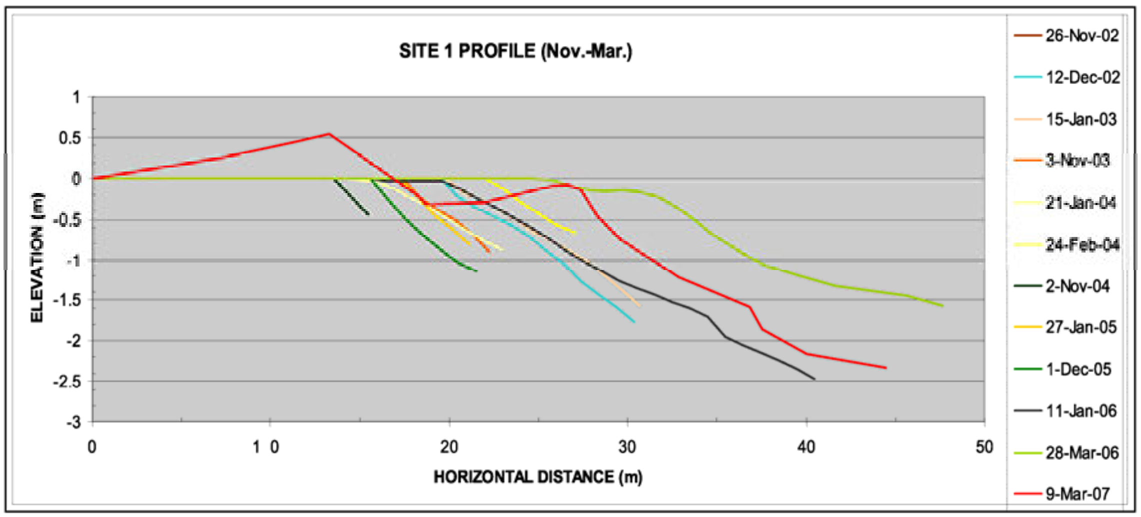

PROFILE: SITE 1
DC
WD
BC
SCARP (OLD)
DL
SCARP (ACTIVE)
SEA LEVEL
BR
ELEVATION Z (m)
DISTANCE (m)
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
0
5
10
15
20
25
30
35
40
45
50

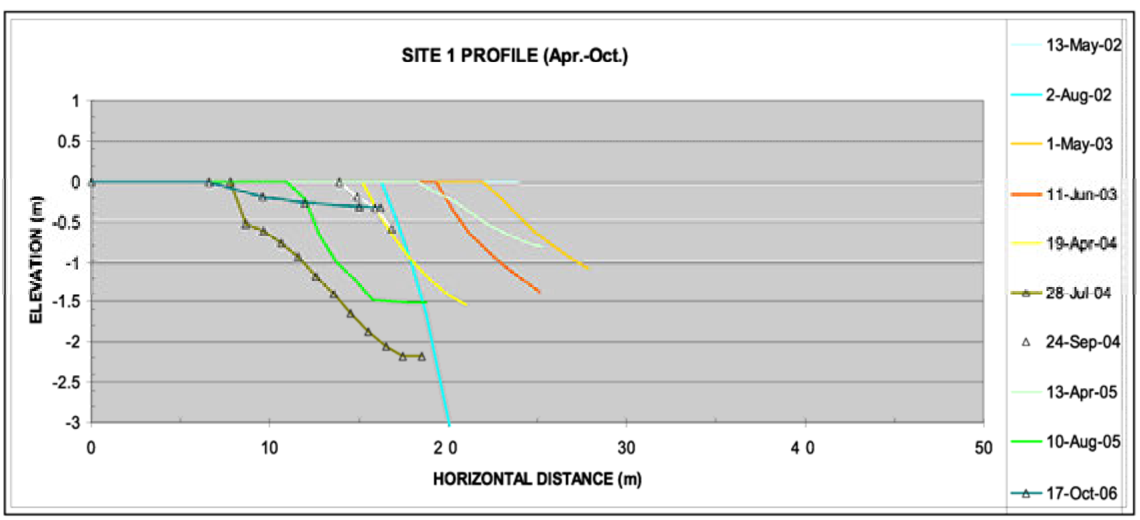

PROFILE: SITE 3
PATH LND
PATH SWD
VL/TOP OF SCARP
SCARP BASE/WD/HS
SC
SB
SEA LEVEL
BR
ELEVATION Z (m)
DISTANCE (m)
0
-1
-2
-3
-4
0
5
10
15
20
25

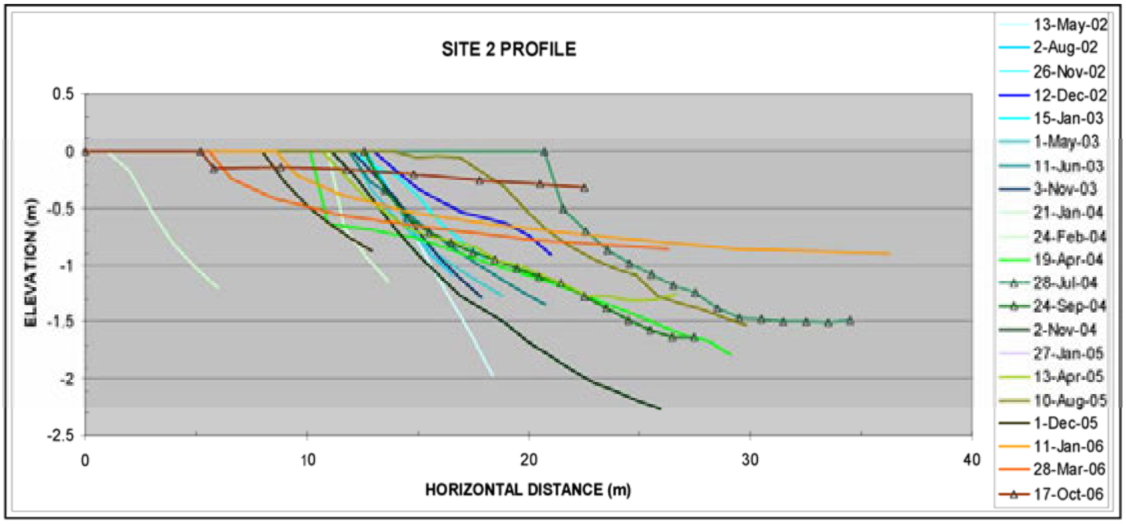

PROFILE: SITE 4
SCARP/VL
SCARP BASE
HS
SC
SB
SEA LEVEL
ELEVATION Z (m)
DISTANCE (m)
0
-1
-2
-3
-4
0
5
10
15
20
25

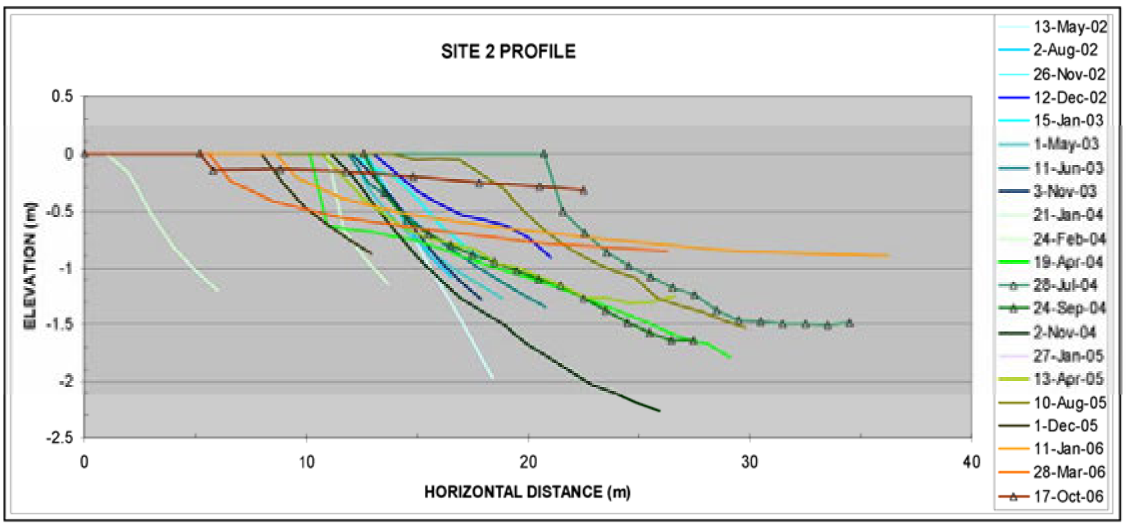

PROFILE: SITE 7
SCARP/VL
WD
TOE/BR
BR
SEA LEVEL
ELEVATION Z (m)
DISTANCE (m)
1.0
-1.0
-3.0
-5.0
0
5
10
15
20
25
30
35
40

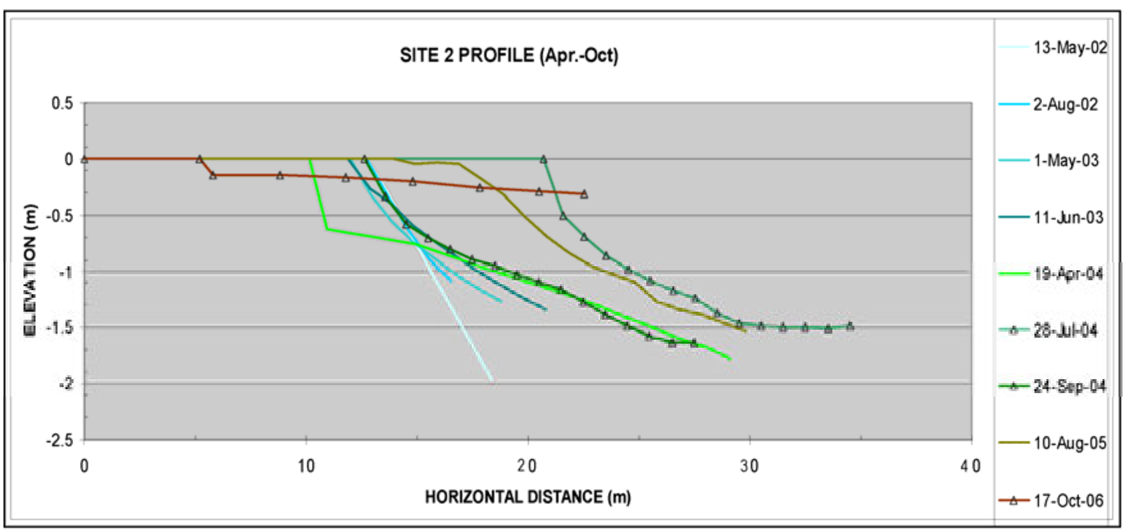

SITE 1 PROFILE
ELEVATION (m)
HORIZONTAL DISTANCE (m)
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
0.0
10.0
20.0
30.0
40.0
50.0
11-Jan-06
13-May-02
2-Aug-02
26-Nov-02
12-Dec-02
15-Jan-03
1-May-03
11-Jun-03
3-Nov-03
21-Jan-04
24-Feb-04
19-Apr-04
28-Jul-04
2-Nov-04
27-Jan-05
13-Apr-05
10-Aug-05
1-Dec-05
28-Mar-06
17-Oct-06
24-Sep-04
9-Mar-07

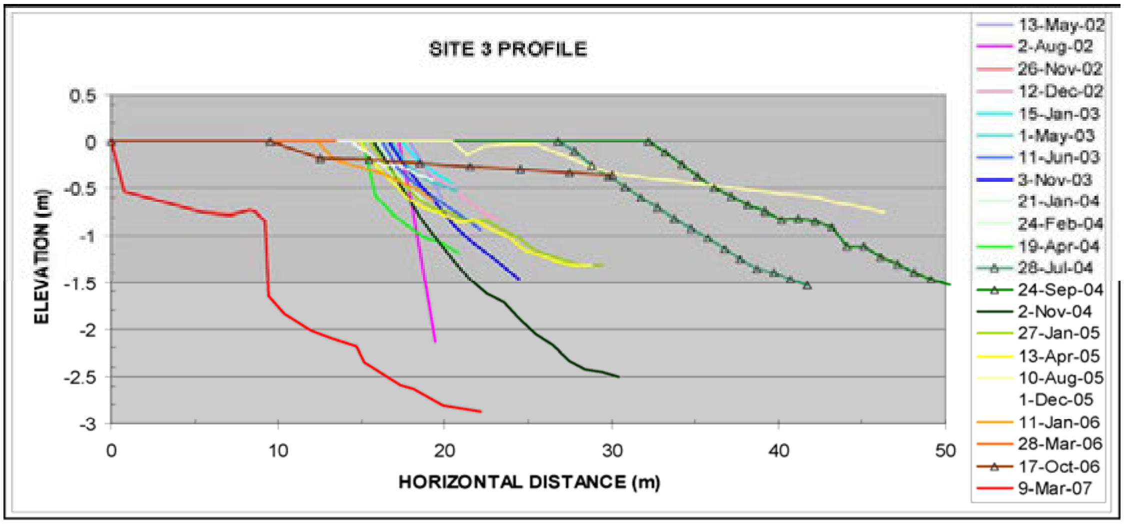

SITE 1 PROFILE (Nov.-Mar.)
ELEVATION (m)
HORIZONTAL DISTANCE (m)
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
0
1 0
20
30
40
50
26-Nov-02
12-Dec-02
15-Jan-03
3-Nov-03
21-Jan-04
24-Feb-04
2-Nov-04
27-Jan-05
1-Dec-05
11-Jan-06
28-Mar-06
9-Mar-07

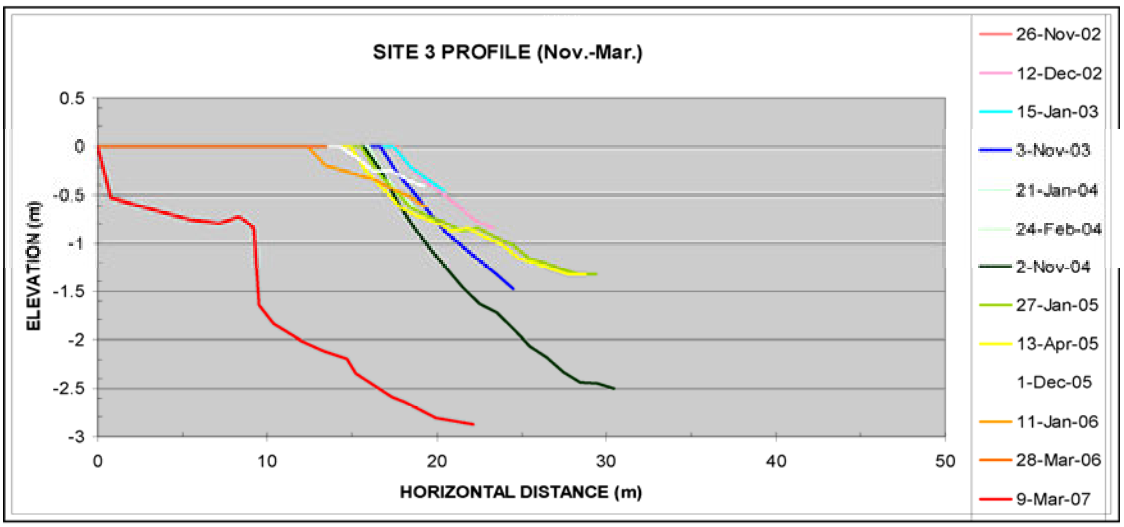

SITE 1 PROFILE (Apr.-Oct.)
ELEVATION (m)
HORIZONTAL DISTANCE (m)
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
0
10
2 0
30
4 0
50
13-May-02
2-Aug-02
1-May-03
11-Jun-03
19-Apr-04
28-Jul-04
24-Sep-04
13-Apr-05
10-Aug-05
17-Oct-06

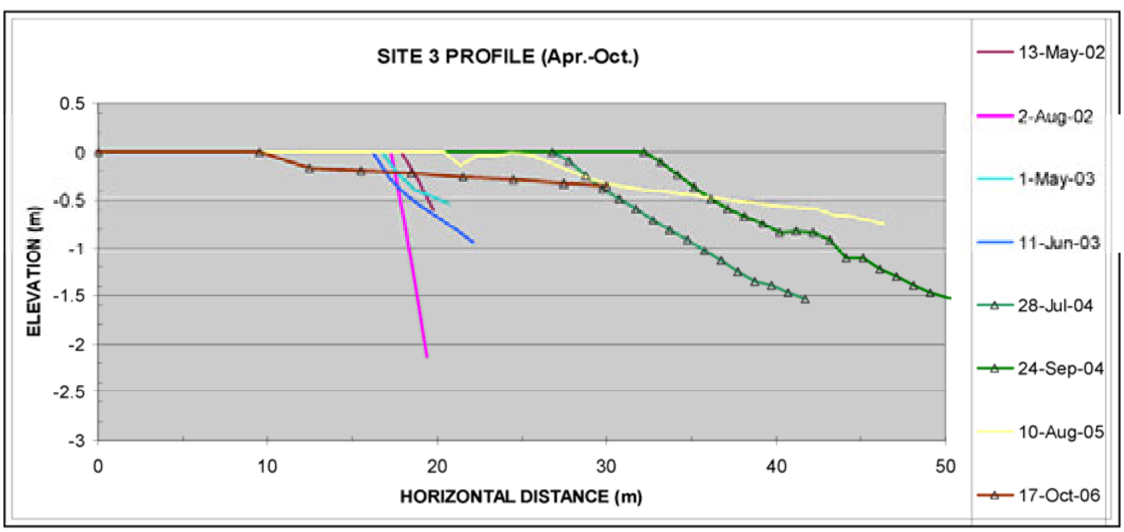

SITE 2 PROFILE
ELEVATION (m)
HORIZONTAL DISTANCE (m)
13-May-02
2-Aug-02
26-Nov-02
12-Dec-02
15-Jan-03
1-May-03
11-Jun-03
3-Nov-03
21-Jan-04
24-Feb-04
19-Apr-04
28-Jul-04
24-Sep-04
2-Nov-04
27-Jan-05
13-Apr-05
10-Aug-05
1-Dec-05
11-Jan-06
28-Mar-06
17-Oct-06


SITE 2 PROFILE
ELEVATION (m)
HORIZONTAL DISTANCE (m)
13-May-02
2-Aug-02
26-Nov-02
12-Dec-02
15-Jan-03
1-May-03
11-Jun-03
3-Nov-03
21-Jan-04
24-Feb-04
19-Apr-04
28-Jul-04
24-Sep-04
2-Nov-04
27-Jan-05
13-Apr-05
10-Aug-05
1-Dec-05
11-Jan-06
28-Mar-06
17-Oct-06


SITE 2 PROFILE (Apr.-Oct)
ELEVATION (m)
HORIZONTAL DISTANCE (m)
13-May-02
2-Aug-02
1-May-03
11-Jun-03
19-Apr-04
28-Jul-04
24-Sep-04
10-Aug-05
17-Oct-06


SITE 3 PROFILE
ELEVATION (m)
HORIZONTAL DISTANCE (m)
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
0
10
20
30
40
50
13-May-02
2-Aug-02
26-Nov-02
12-Dec-02
15-Jan-03
1-May-03
11-Jun-03
3-Nov-03
21-Jan-04
24-Feb-04
19-Apr-04
28-Jul-04
24-Sep-04
2-Nov-04
27-Jan-05
13-Apr-05
10-Aug-05
1-Dec-05
11-Jan-06
28-Mar-06
17-Oct-06
9-Mar-07


SITE 3 PROFILE (Nov.-Mar.)
ELEVATION (m)
HORIZONTAL DISTANCE (m)
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
0
10
20
30
40
50
26-Nov-02
12-Dec-02
15-Jan-03
3-Nov-03
21-Jan-04
24-Feb-04
2-Nov-04
27-Jan-05
13-Apr-05
1-Dec-05
11-Jan-06
28-Mar-06
9-Mar-07


SITE 3 PROFILE (Apr.-Oct.)
ELEVATION (m)
HORIZONTAL DISTANCE (m)
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
0
10
20
30
40
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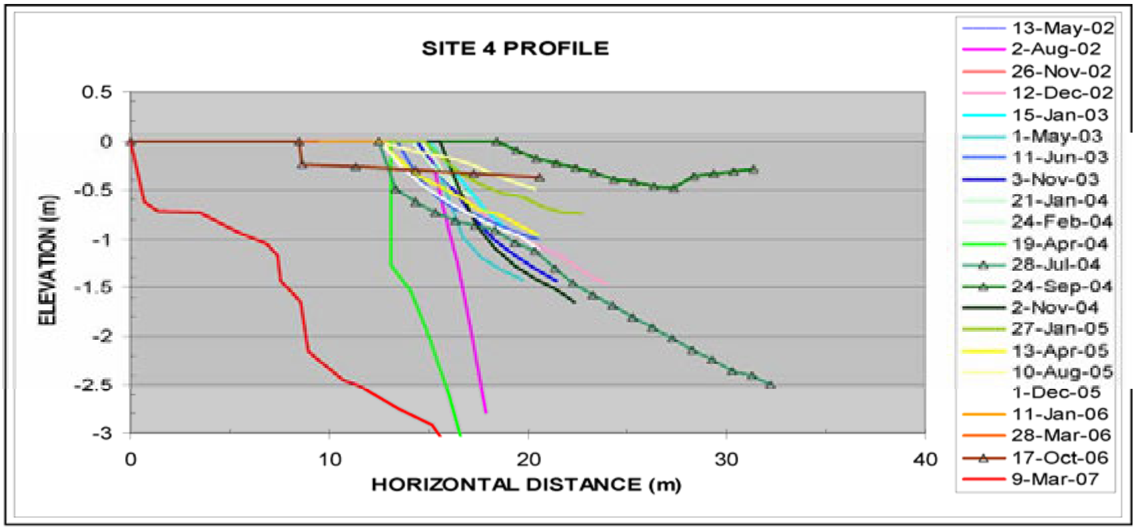
13-May-02
2-Aug-02
1-May-03
11-Jun-03
28-Jul-04
24-Sep-04
10-Aug-05
17-Oct-06


SITE 4 PROFILE
ELEVATION (m)
HORIZONTAL DISTANCE (m)
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
0
10
20
30
40
13-May-02
2-Aug-02
26-Nov-02
12-Dec-02
15-Jan-03
1-May-03
11-Jun-03
3-Nov-03
21-Jan-04
24-Feb-04
19-Apr-04
28-Jul-04
24-Sep-04
2-Nov-04
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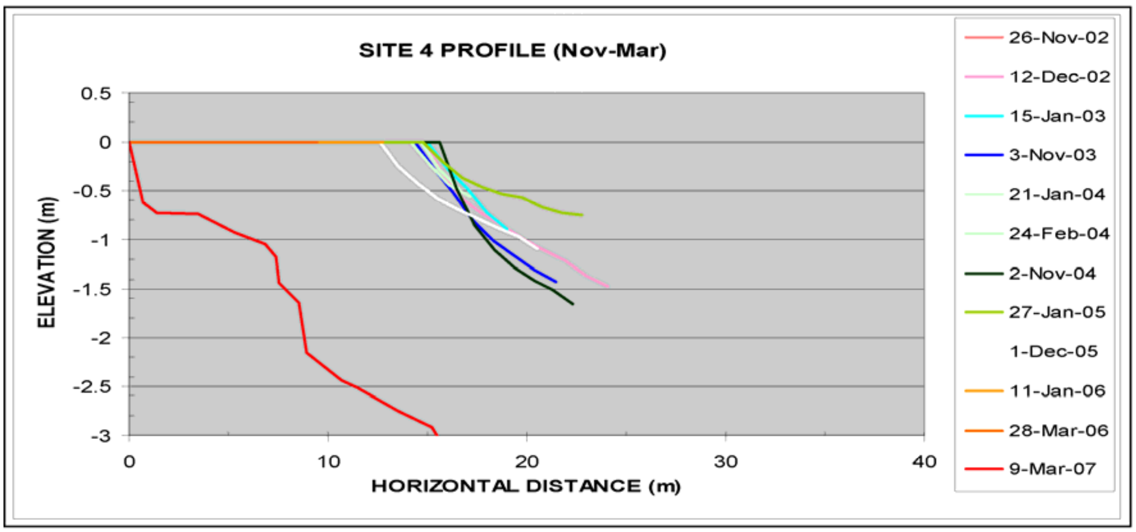
11-Jan-06
28-Mar-06
17-Oct-06
9-Mar-07


SITE 4 PROFILE (Nov-Mar)
ELEVATION (m)
HORIZONTAL DISTANCE (m)
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
0
10
20
30
40
26-Nov-02
12-Dec-02
15-Jan-03
3-Nov-03
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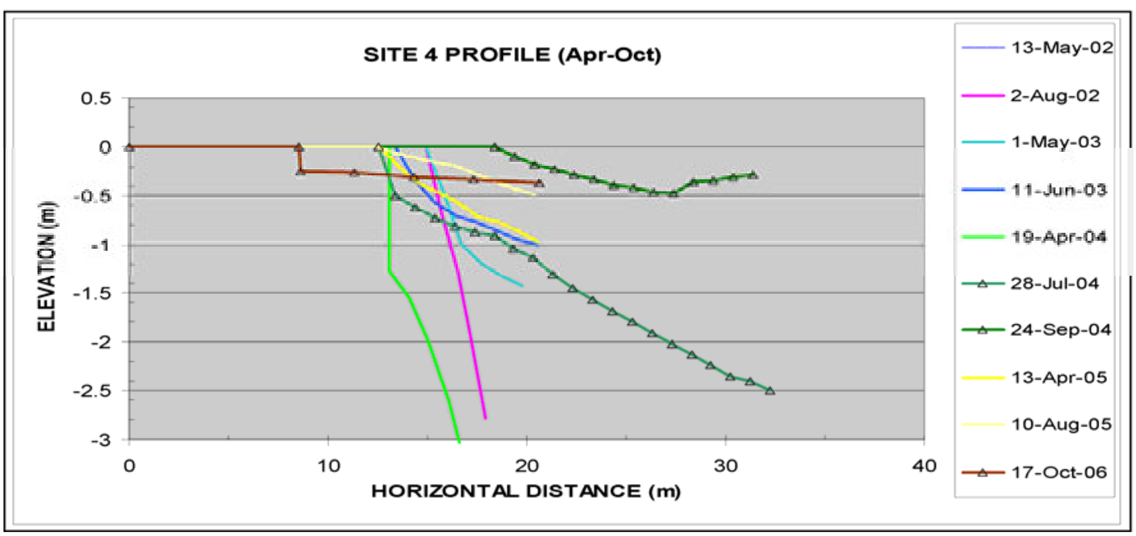
28-Mar-06
9-Mar-07


SITE 4 PROFILE (Apr-Oct)
ELEVATION (m)
HORIZONTAL DISTANCE (m)
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
0
10
20
30
40
13-May-02
2-Aug-02
1-May-03
11-Jun-03
19-Apr-04
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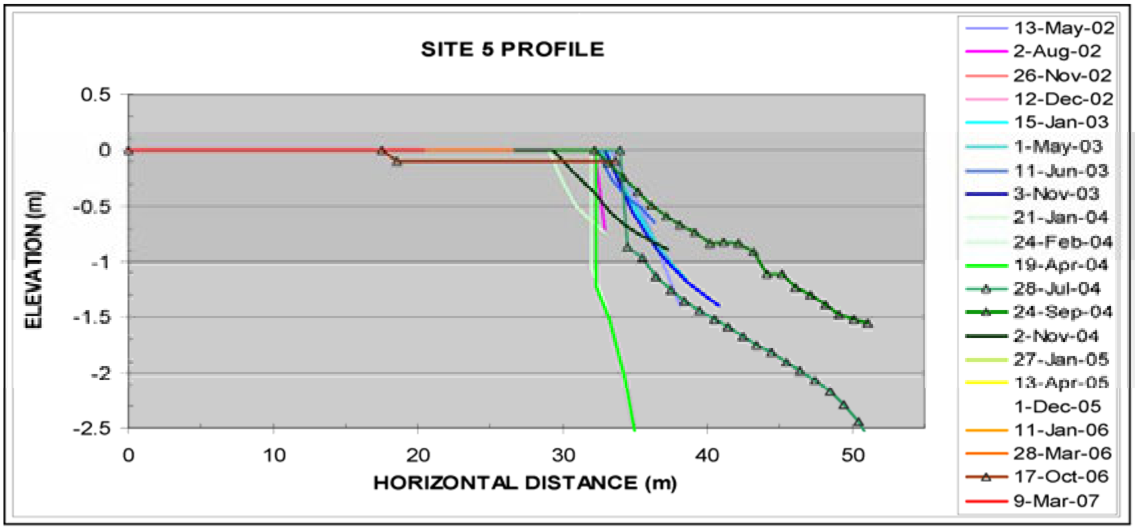
10-Aug-05
17-Oct-06


SITE 5 PROFILE
ELEVATION (m)
HORIZONTAL DISTANCE (m)
13-May-02
2-Aug-02
26-Nov-02
12-Dec-02
15-Jan-03
1-May-03
11-Jun-03
3-Nov-03
21-Jan-04
24-Feb-04
19-Apr-04
28-Jul-04
24-Sep-04
2-Nov-04
27-Jan-05
13-Apr-05
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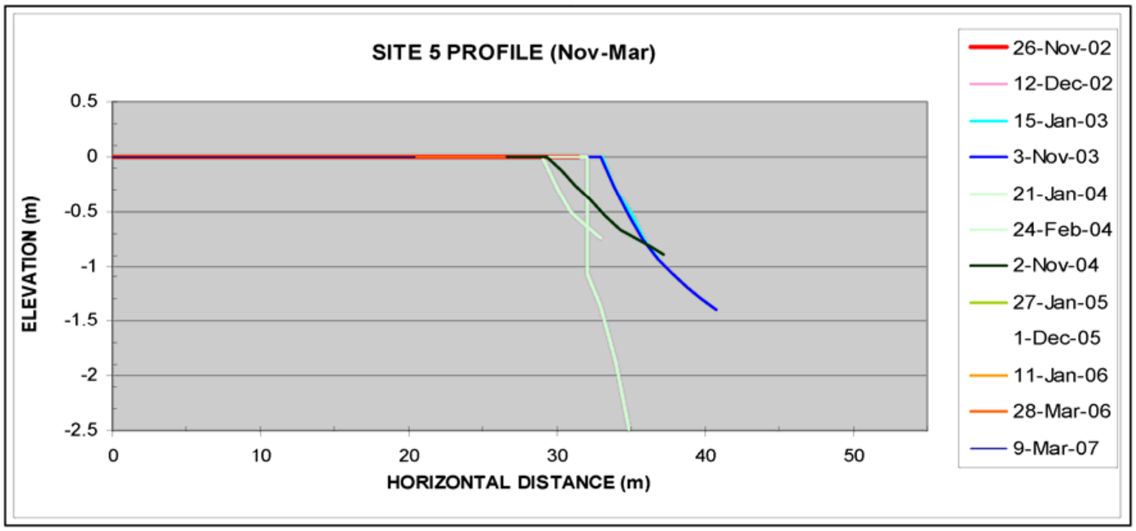
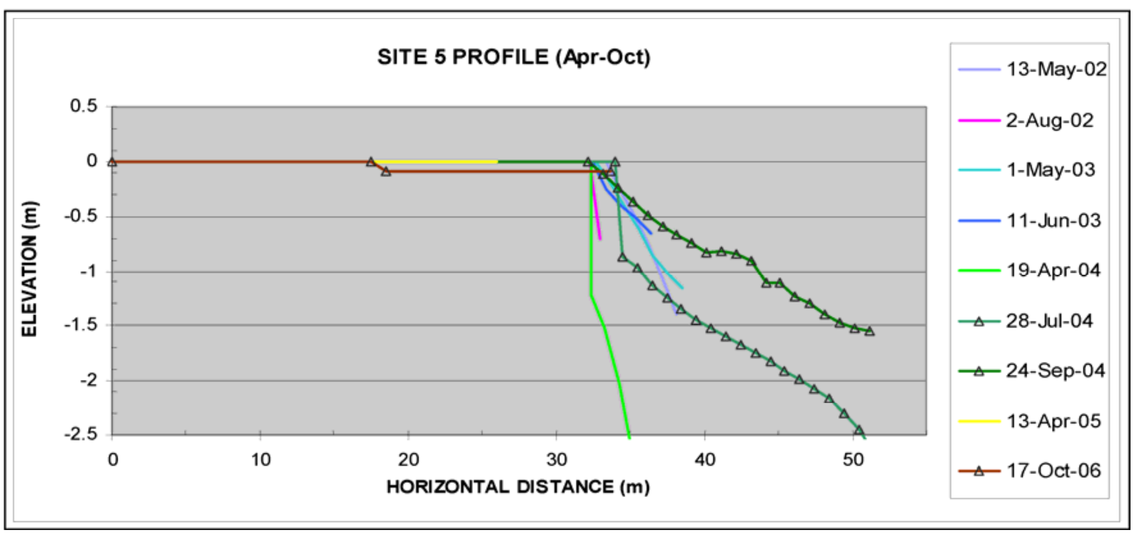
11-Jan-06
28-Mar-06
17-Oct-06
9-Mar-07


SITE 5 PROFILE (Nov-Mar)
ELEVATION (m)
HORIZONTAL DISTANCE (m)
26-Nov-02
12-Dec-02
15-Jan-03
3-Nov-03
21-Jan-04
24-Feb-04
2-Nov-04
27-Jan-05
1-Dec-05
11-Jan-06
28-Mar-06
9-Mar-07


SITE 5 PROFILE (Apr-Oct)
ELEVATION (m)
HORIZONTAL DISTANCE (m)
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2-Aug-02
1-May-03
11-Jun-03
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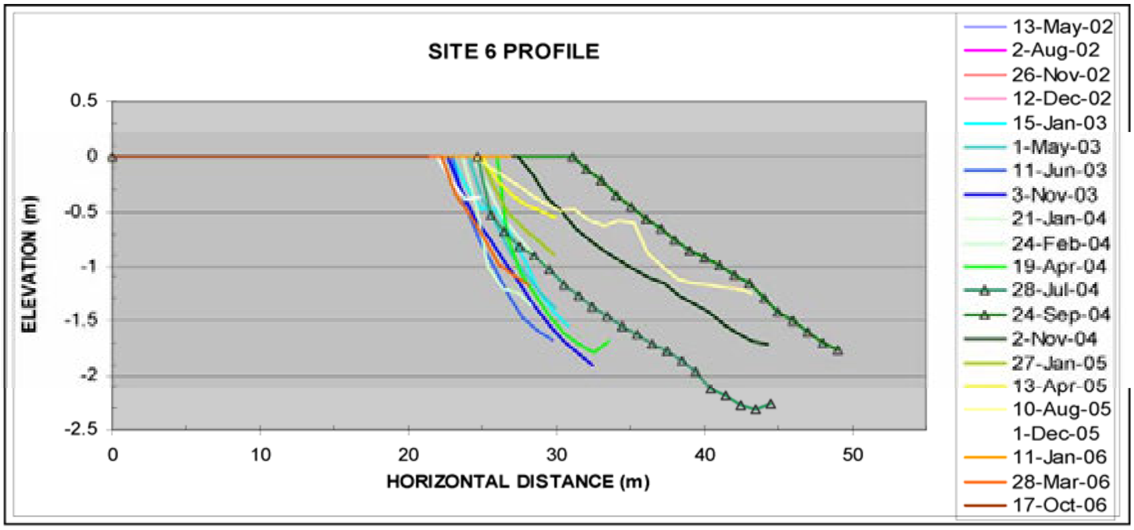
13-Apr-05
17-Oct-06


SITE 6 PROFILE
ELEVATION (m)
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
10
20
30
40
50
HORIZONTAL DISTANCE (m)
13-May-02
2-Aug-02
26-Nov-02
12-Dec-02
15-Jan-03
1-May-03
11-Jun-03
3-Nov-03
21-Jan-04
24-Feb-04
19-Apr-04
28-Jul-04
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27-Jan-05
13-Apr-05
10-Aug-05
1-Dec-05
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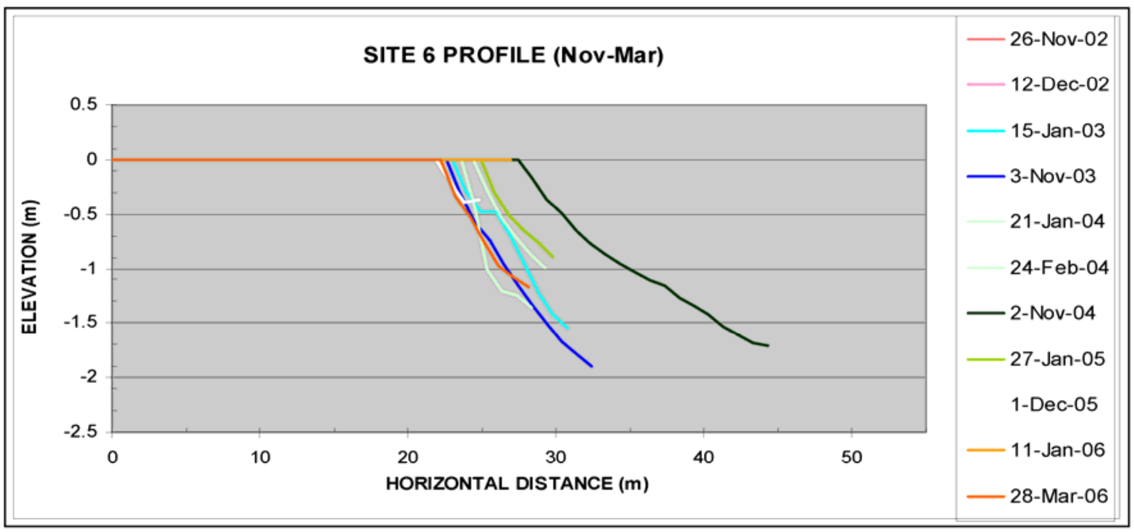
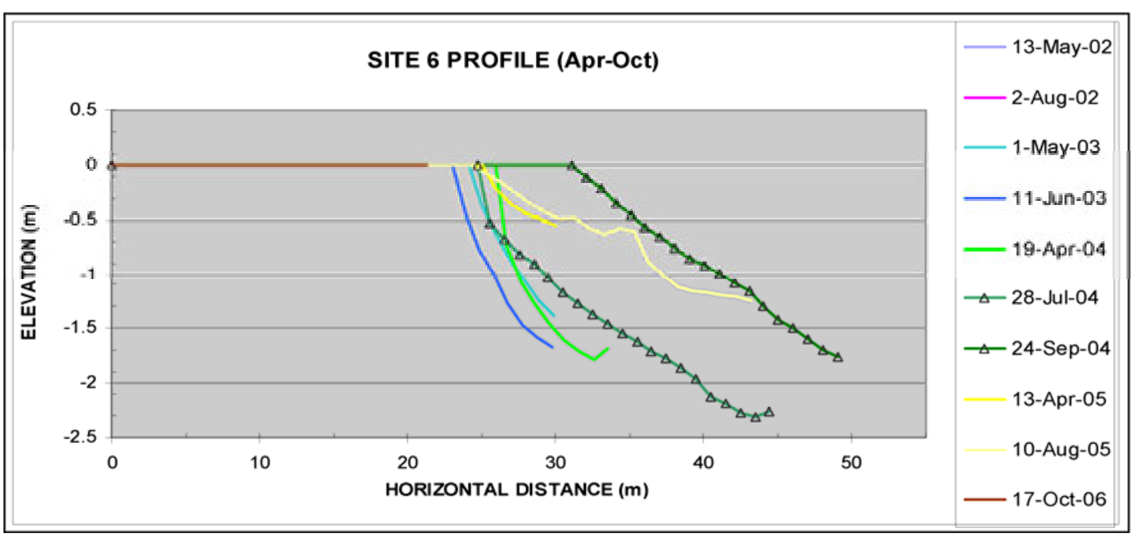
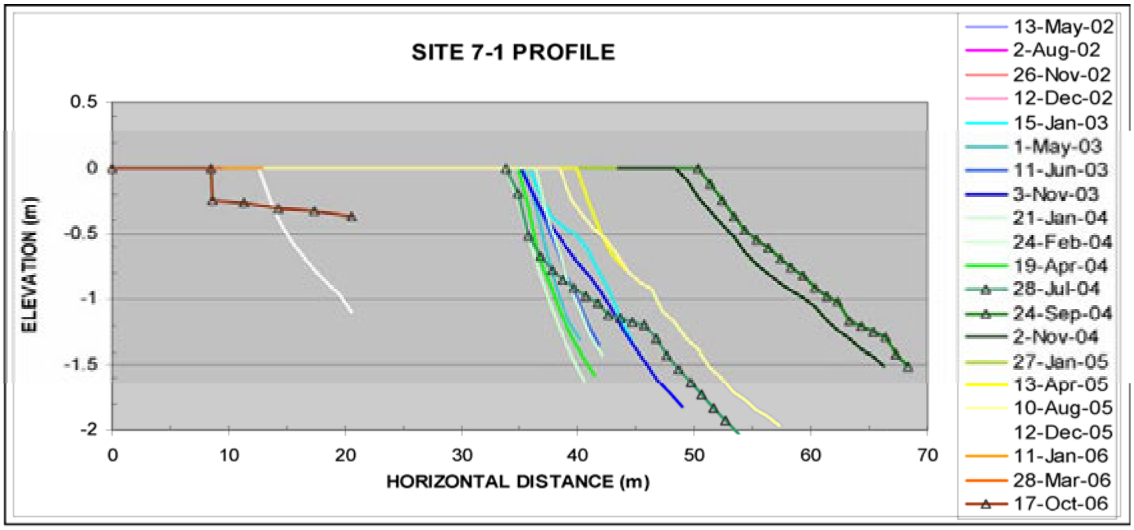
28-Mar-06
17-Oct-06


SITE 6 PROFILE (Nov-Mar)
ELEVATION (m)
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
10
20
30
40
50
HORIZONTAL DISTANCE (m)
26-Nov-02
12-Dec-02
15-Jan-03
3-Nov-03
21-Jan-04
24-Feb-04
2-Nov-04
27-Jan-05
1-Dec-05
11-Jan-06
28-Mar-06


SITE 6 PROFILE (Apr-Oct)
ELEVATION (m)
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
10
20
30
40
50
HORIZONTAL DISTANCE (m)
13-May-02
2-Aug-02
1-May-03
11-Jun-03
19-Apr-04
28-Jul-04
24-Sep-04
13-Apr-05
10-Aug-05
17-Oct-06



SITE 7-1 PROFILE
ELEVATION (m)
HORIZONTAL DISTANCE (m)
0.5
0
-0.5
-1
-1.5
-2
0
10
20
30
40
50
60
70
13-May-02
2-Aug-02
26-Nov-02
12-Dec-02
15-Jan-03
1-May-03
11-Jun-03
3-Nov-03
21-Jan-04
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19-Apr-04
28-Jul-04
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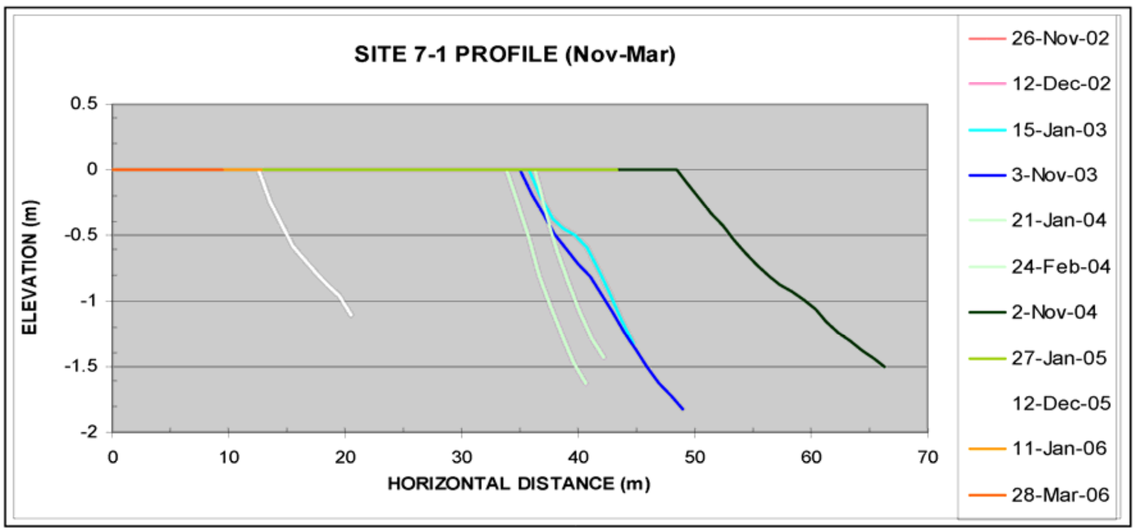
28-Mar-06
17-Oct-06



SITE 7-1 PROFILE (Nov-Mar)
ELEVATION (m)
HORIZONTAL DISTANCE (m)
0.5
0
-0.5
-1
-1.5
-2
0
10
20
30
40
50
60
70
26-Nov-02
12-Dec-02
15-Jan-03
3-Nov-03
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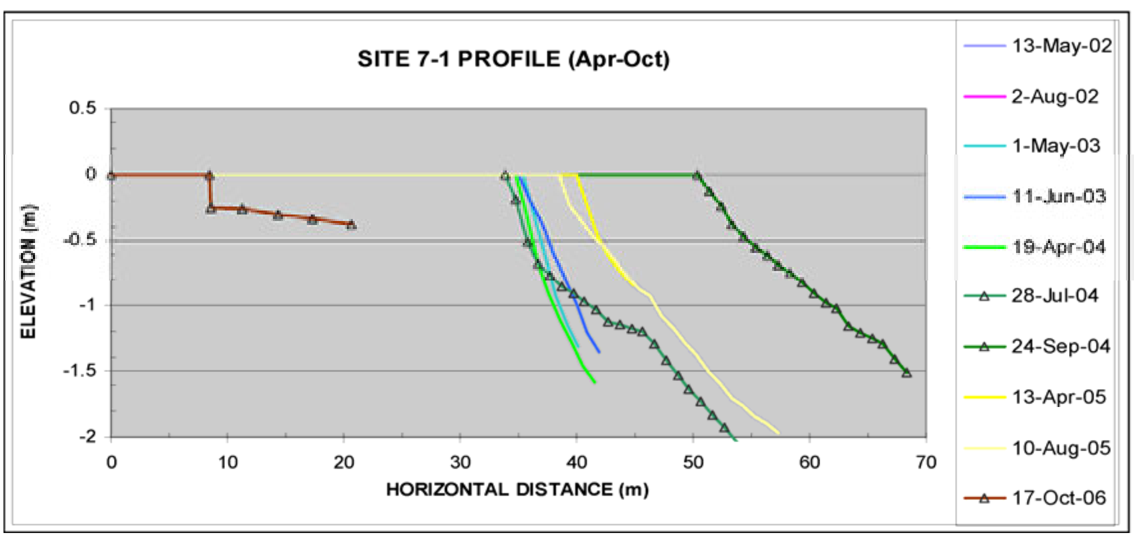
28-Mar-06



SITE 7-1 PROFILE (Apr-Oct)
ELEVATION (m)
HORIZONTAL DISTANCE (m)
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0
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-1
-1.5
-2
0
10
20
30
40
50
60
70
13-May-02
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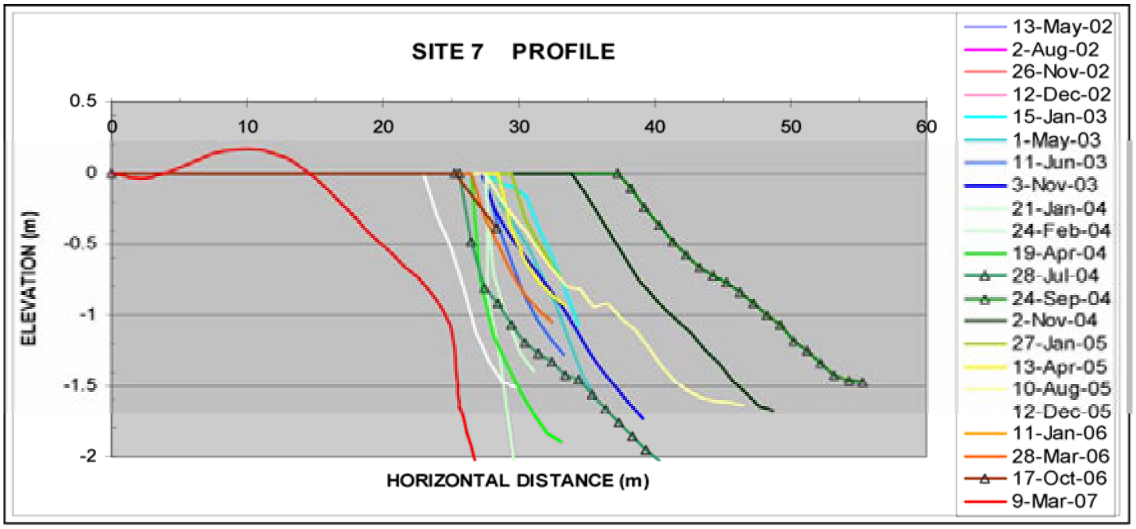
17-Oct-06



SITE 7 PROFILE
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0
-0.5
-1
-1.5
-2
0
10
20
30
40
50
60
ELEVATION (m)
HORIZONTAL DISTANCE (m)
13-May-02
2-Aug-02
26-Nov-02
12-Dec-02
15-Jan-03
1-May-03
11-Jun-03
3-Nov-03
21-Jan-04
24-Feb-04
19-Apr-04
28-Jul-04
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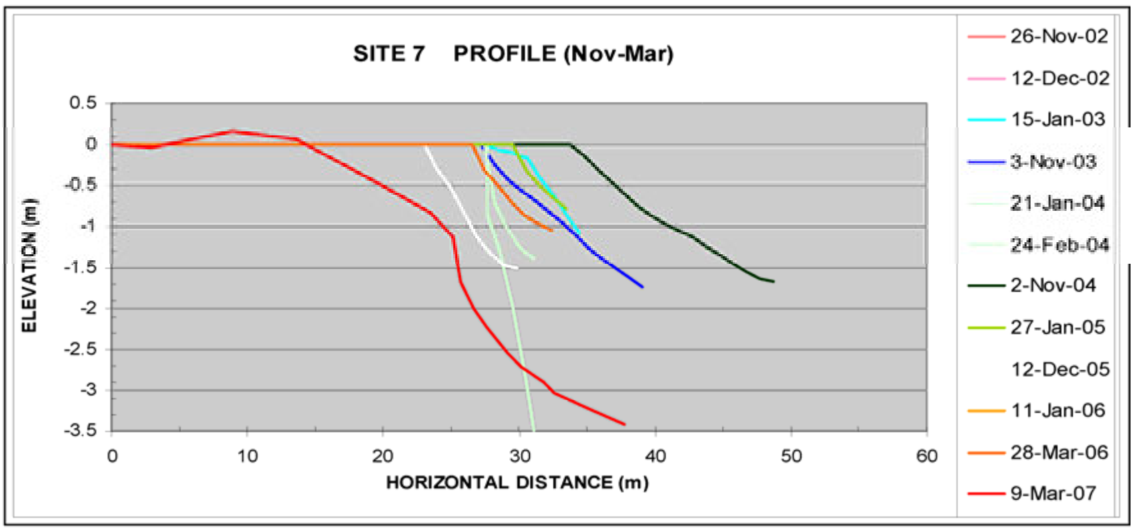
9-Mar-07



SITE 7 PROFILE (Nov-Mar)
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
0
10
20
30
40
50
60
ELEVATION (m)
HORIZONTAL DISTANCE (m)
26-Nov-02
12-Dec-02
15-Jan-03
3-Nov-03
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27-Jan-05
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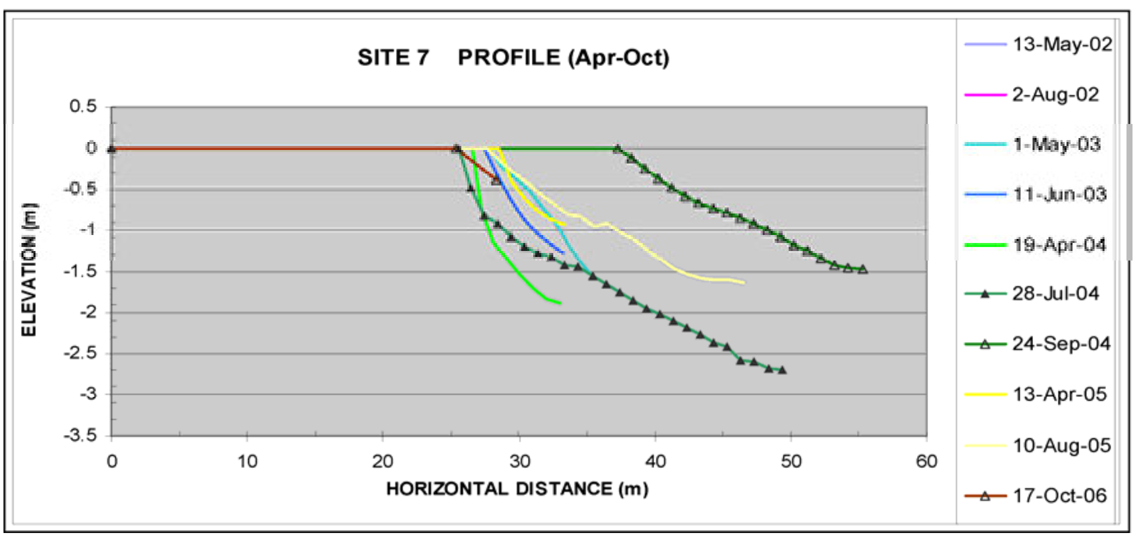
28-Mar-06
9-Mar-07



SITE 7 PROFILE (Apr-Oct)
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
0
10
20
30
40
50
60
ELEVATION (m)
HORIZONTAL DISTANCE (m)
13-May-02
2-Aug-02
1-May-03
11-Jun-03
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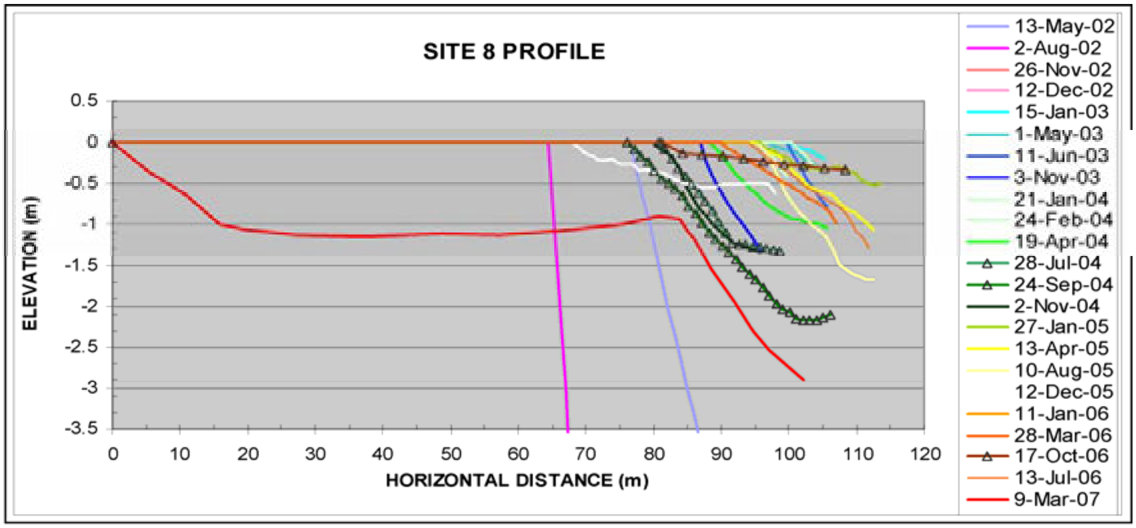
17-Oct-06


SITE 8 PROFILE
ELEVATION (m)
HORIZONTAL DISTANCE (m)
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-3
-3.5
0
10
20
30
40
50
60
70
80
90
100
110
120
13-May-02
2-Aug-02
26-Nov-02
12-Dec-02
15-Jan-03
1-May-03
11-Jun-03
3-Nov-03
21-Jan-04
24-Feb-04
19-Apr-04
28-Jul-04
24-Sep-04
2-Nov-04
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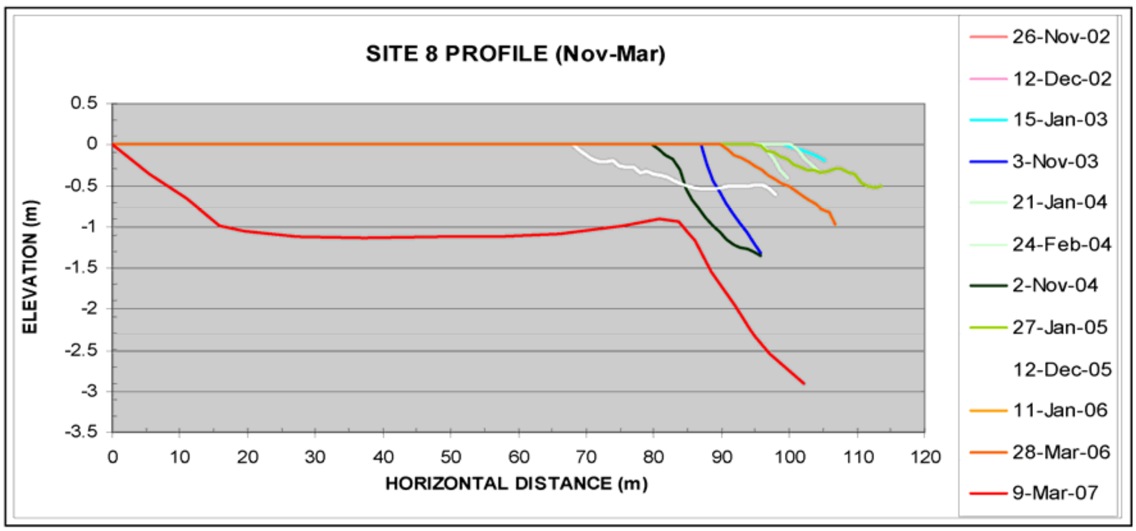
13-Jul-06
9-Mar-07


SITE 8 PROFILE (Nov-Mar)
ELEVATION (m)
HORIZONTAL DISTANCE (m)
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-1.5
-2
-2.5
-3
-3.5
0
10
20
30
40
50
60
70
80
90
100
110
120
26-Nov-02
12-Dec-02
15-Jan-03
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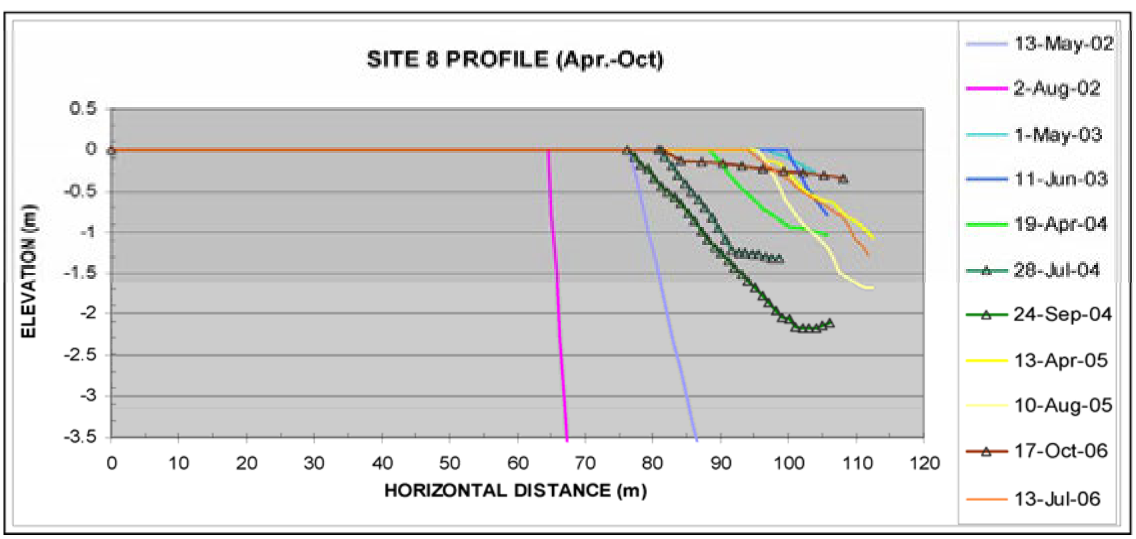
28-Mar-06
9-Mar-07


SITE 8 PROFILE (Apr.-Oct)
ELEVATION (m)
HORIZONTAL DISTANCE (m)
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0
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-1.5
-2
-2.5
-3
-3.5
0
10
20
30
40
50
60
70
80
90
100
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13-May-02
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1-May-03
11-Jun-03
19-Apr-04
28-Jul-04
24-Sep-04
13-Apr-05
10-Aug-05
17-Oct-06
13-Jul-06