

Beach dynamics and oscillations of shoreline position in recent years at Miramar beach, Goa, India - A study from GPR survey

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Concise and Informative Title: Beach Dynamics at Miramar beach, Goa from GPR survey

Abstract

Human influences are crucial to understand the coastal sediment supply and associated shoreline responses prior to undertaking coastal hazard management studies. An observation of the widening of some selected Indian beaches, especially over the last six decades is of significance. In this perspective, the Miramar beach, Goa, India was studied using three Ground-Penetrating Radar (GPR) shallow subsurface profiles (4 m depth). Based on a series of depositional siliciclastic packages, six progradational packages were recognized which were interrupted by sharp erosional boundaries. These erosional boundaries represent transgressive phases of the shoreline migration. It is observed that the shoreline migration is coupled with the deposition and erosion of sediments and this is supported by the historical admiralty charts. The optically simulated luminescence dating of the sediments collected at the 1st progradation period reveals the age to correspond to the years 1952-57 which also corroborates the information provided by the local populace. In the past six decades, the shoreline growth was rapid due to the heavy sediment influx from the Mandovi River because of increased mining activities (since 1950s) in upstream areas. Since 1950s, the shoreline has rapidly prograded, building a beach from ~40m to ~280 m wide (average rate of 4m/year) in response to enhanced sediment supply from the Mandovi River created by mining activities upstream. Superimposed on this overall regressive trend are a series of depositional and erosional cycles. Perhaps, if a similar trend continues then there could be a possibility of a further widening of the beach in the future. A close monitoring network is needed to understand the causes of the cycles in shoreline position and to predict its future behaviour. The present investigation on the nature of coastal response to anthropogenic activities in a river basin as well as the role of short-time cycles on shoreline behavior in the last six decades could be an ideal reference study and motivate to search for similar areas along other coastal locations.

Index words: *Subsurface mapping, shoreline migration, fluvial sedimentation, GPR, OSL dating, mining activities*

Introduction

Beaches are dynamic and exhibit varied degrees of morphological changes. Subsurface features and nature of buried sand layers provide information about beach dynamics through time and also on the shoreline positions in the past. The characteristics of the beach deposits and their distinctive relationship with the transgression or regression of the coastline, facilitate to infer the shoreline migration (Helle 2004). Besides other techniques, GPR (Ground-Penetrating Radar) have been widely used in the coastal areas to identify and understand the buried structures, sand layers and facies in the beach, spit, barrier island deposits and, to interpret the sedimentology, stratigraphy and evolution of these features (Da Silva and Scherer 2000; Daly et al. 2002; Buynevich et al. 2004; Neal 2004, Hein et al. 2012; Shukla et al. 2013; Hede et al. 2013). These tools and techniques have also been used to investigate the sedimentological signatures of individual events. For example, Loveson et al. (2005) studied the nature of buried sand layers deposited by the tsunami event of 26th December 2004 along the southern coast of India.

We present the results of a GPR, topographic, chronologic and sedimentologic study conducted at the Miramar beach, Goa on the west coast of India, for high resolution subsurface mapping (up to 4 m depth) from the dune to the low tide level. The objectives were to assess the beach dynamics during the recent past and to evaluate the spatial and temporal style of sedimentation patterns. This study on the Miramar beach, a popular recreational spot, helps to understand the dynamic changes of the shoreline migration and to support the coastal development strategies. In other words, a proper elucidation of the depositional aspects and shoreline retreats in recent years (past six decades) would help in designing suitable coastal hazard mitigation and coastal zone management plans for the future sustainable development of this region.

2. Regional setting

The Miramar beach (15°27'50" to 15°30'00" N latitude) is a popular tourist destination in Panjim, the capital city of Goa. The study area is in the northern part of the Miramar Bay with the Mandovi River meeting the Arabian Sea in the north (Fig. 1). The Miramar beach, which on the southern side is known as Caranzalem beach, is located between two promontories – Aguada headland (north) and Cabo Raj (south). The Miramar and Caranzalem beaches are situated on the left bank of the Mandovi River, while on the right bank, the beaches are either poorly developed or totally absent (Murty et al. 1976). The Mandovi River is about 77 km long and originates from the sub-Ghats region at an elevation of 888 m. The Mandovi estuary has a heavy traffic of commercial barges, mechanized fishing boats, moored casinos and tourist boats. The navigation channel is located close to the left bank and is flanked by two shoals – the Aguada Bar and Reis Magos Bar. Of these, the former is more prominently developed and projects seawards from Gaspar Dias (Fig. 1). The northern edge of the bar has a steep gradient (60°) sloping towards the navigational channel and the south side has a gentle slope.

The tides in the area are semi-diurnal with a range of about 2 m, and the currents are dominated by the flood and ebb tides. The flood and ebb velocities in the northern area of the Aguada Bar are ~108-160 cm/sec at the surface and 98-128 cm/sec near the bottom. The waves and swells vary with the seasons. Low swells from W to NW dominate in fair season and high W-SW wind waves occur during the SW monsoon (Reddy 1970). The wave heights (up to 3.8 m) at Miramar are higher compared to those at Caranzalem (up to 1.9 m). On their entry into the bay, the waves first break over the bar, reform and break again on the Miramar beach.

In contrast, the southern side of the Caranzalem beach receives only the refracted and diffracted portions of the wave fronts converging at the Cabo Raj headland (Fig. 1). The net result of the varying energy inputs is the erosion scraps at the foreshore at Miramar and formation of a flat and wider foreshore (Murty et al. 1976). The net longshore sediment transport rate (along NW-SE) was estimated for the Miramar beach (Jayakumar et al. 2002; Seelam et al. 2013) using the Walton's equation (Walton and Bruno 1989).

$$Q = \frac{1290 \rho g H_b W v C_f}{0.78 (3\pi/2) \left(\frac{v}{v_0}\right)_{LH} LH}$$

where Q is the annual alongshore sediment transport at ($m^3/year$), ρ the density of water ($1024 \text{ kg}/m^3$), g the acceleration due to gravity ($9.81 \text{ m}/s^2$), C_f the (friction coefficient = 0.01), H_b the breaker height (m), W the surf zone width (m), $(v/v_0)_{LH}$ the theoretical dimensionless longshore current velocity. During post-monsoon period, the net longshore sediment transport ranges between $0.016 \times 10^6 m^3/yr$ and $0.62 \times 10^6 m^3/yr$ (Jayakumar et al. 2002; Seelam et al. 2013); and during pre-monsoon period, it varies between $\sim 0.02 \times 10^6 m^3/yr$ and $0.04 \times 10^6 m^3/yr$ (Jayakumar et al. 2001). The sediments brought by the Mondovi River are initially deposited between the two headlands (Aguada headland in the north and Cabo Raj in the south) i.e., along the Miramar beach and later moved along north by longshore currents.

The geological formations in the area are pre-Cambrian sandstones and intensively laterized ferruginous quartzites. Wagle (1982) has reported that most of the coastal lineaments (faults and fractures) trend predominately in an NW-SE direction and that there is no evidence of any neo-tectonic activity around the study area.

Observations by the local populace revealed that six decades ago, the Miramar beach was about 40 to 50 m wide, and this increased gradually to the present width of 280 m. In spite of this interesting fact, there has been no large scale detailed surveys conducted at the Miramar beach. In this context, this present investigation was carried out with a goal of understanding the interplay between the coastal processes and beach response in the recent years which could probably aid to explain the gradual but rapid growth of the Miramar beach.

3. Materials and methods

A series of GPR profiles were collected along four transects (M1, M2, M3 and M4) perpendicular to the coastline and up to the low tide line (Fig. 2; shown only discussed profiles M1, M2 and M3). An SIR-20 model GPR (Geophysical Survey Systems Inc., GSSI) system with 200 MHz antenna was used and sub-surface profiles of 2 m, 4 m and 8 m depth penetration were generated. The M1 profile survey line (212 m long) was fixed at the Mandovi River side and traversed from upper Miramar beach to the low tide line. The M3 profile (215 m long) was fixed nearly 250 m to the south of the M1 profile. In between M1 and M3, the M2 profiling was carried out (255 m long) from the backshore to the low tide line. Further, nearly 70 m south from the M3, the M4 profile was selected. Since the M3 and M4 survey lines are located near each other and their profiles are quite similar; hence, the line M4 is not presented here. Due to their clarity, coverage and depth to the saturation level (groundwater level), only the 4 m depth profile with respect to all the three survey lines are discussed.

The GPR data were normalized with the surface and antenna corrections while elevation normalization was done with beach profile data, generated by topographic surveys. The time domain GPR data were digitally processed and enhanced with various image processing techniques like IIR and IFR filtering, Hilbert transformation etc., and viewed through line scan, oscilloscope and wiggle modes. Using these techniques, the data quality was improved and interpretations were accordingly made (Neal 2004; GSSI 2003).

Beach topography profiling was carried out using an automatic level (Nikon model) and Quarryman Pro (Laser equipment) along the chosen GPR transects with the reference chart datum. The data were then converted with reference to mean sea-level (MSL) at Mormugao Port which was 1.30 m above the chart datum. A handheld GPS (Trimble) was used to record the coordinates along the survey lines. From the collected GPR profiles and depending upon the observed structure of sedimentation patterns, locations were selected for digging of test pits / trenches (1m x 1m x 1m) for ground truth (Fig. 2). The sedimentological, mineralogical and bedding characteristics of the various sand layers were recorded from these pits and samples were collected from the respective layers for laboratory-based analyses. These analyses were carried out following standard procedures (Folk 1968). For geo-chronological studies (Optically Stimulated Luminescence, OSL), two sediment samples at depths 73-80 cm and 91-99 cm were collected along M3 profile, about 30 m from the starting point of the GPR profile. The sediment samples were collected from the test pits by using metal pipes during late evening and with due care to avoid exposure to light. These tubes were sub-sampled in the laboratory and pure quartz fraction in the size range of 90-150 μm was extracted using a sequential pre-treatment of the sample with 1N HCl (to remove carbonate), 30% H_2O_2 (to remove organic matter), sieving to get the desired grain size fraction and magnetic separation (to remove feldspar and heavy, magnetic fractions). This fraction was then etched with 40% HF for 80 min, followed by 12N HCl treatment (to convert fluorides to chlorides) and sieved again to remove the fine fraction (<90 μm). The grains were then placed on stainless steel disc and their purity was tested using their infrared stimulated luminescence. The glow curve was typical of quartz. A single aliquot regeneration protocol with a pre-heat of 240°C for 10s was used for the estimation of equivalent dose 'De' for each of the aliquots (Murray and Wintle 2003). The dose selection criterion was based on the recycling ratio being 1+0.1 and the dose recovery to <10%.

4. Results and Interpretation

4.1 Beach profiles

Beach profiles were generated and plotted with reference to the MSL. The M1 profile area is surrounded by landforms mainly formed by fluvial processes while the regions along profiles M2 and M3 have mixed influences of fluvial and marine processes. The topography along M1 profile is undulatory in nature with a prominent swale feature at 110 m. The M2 profile indicates more or less a flat terrain with less rolling features. While compared to other profiles, the M3 profile illustrates an elevated terrain with a raised berm. Overall, the study area has a narrow foreshore (nearly 50 to 60 m wide) and a wider backshore area (nearly 150 to 200 m). The foreshore area has a steep intertidal zone with an elevated berm (about 1.0 to 1.2 m above MSL). The backshore gently slopes to a flat beach with scarce vegetations (*Ipomoea*, *calatropies*

cactus, *casurina* plantation) on the berm. Coconut plantation occurs in the dune areas. In a few places, the dunes are intact while coconut farm occurs in the areas where the dunes have been levelled.

4.2 GPR survey

The profile near the Mandovi River (M1) clearly revealed stratified sands (Fig. 3a). The sand cover, about 50 cm, that occurs at the top has two distinctive breaks and subsequently overlaps at 25 and 90 m (Horizontal distance mentioned in this paper is always with reference to the starting point of the GPR profile i.e., "0" in the scale of the figure from the backshore). Up to a distance of 25 m from the starting point, a water saturated zone is observed below 1.5 m depth. Further towards the shoreline, the dry sand layers / less moisture-laden sand layers occur up to the high tide zone. Due to sea water influence (saturated zone), the signals in the time domain GPR profile are significantly poor and wiggle diagram shows a lower conductivity zone with poor amplitude. The M2 profile (Fig. 3b) indicated progressive sediment deposition under sub-tidal condition. The sand ridge-like features noticed in the GPR profiles represents the stagnant intermediate periods of deposition. Due to an increase in sedimentation, the shore regressed and migrated progressively towards the west (seaward). The location along the M3 profile is topographically higher than the other two profiles. Unlike the M2 profile, the M3 indicates buried dry sand layers (strong reflectance) in the middle part of the profile, followed by a weak reflectance of saturation zone at 135m (Fig. 3c). Due to a significant variability in reflection strength, the sub-surface features observed in all the three profiles are comparable (Fig. 3).

Based on the nature and patterns of the sand layers, a series of depositional siliciclastic packages was recognized in the three GPR transects. These packages occur concealed under the sand overburden in the backshore area and are interpreted as depositional packages that are interrupted by sharp, high (erosional) boundaries. These erosional boundaries could mark rapid changes in the sea level elevation (i.e., rapid uplift) and associated destabilization until equilibrium was reached. However, such changes would have to be tectonically influenced. But there are no available evidences of any significant tectonic events that could have caused an uplift of nearly 1 to 2 m in this region; therefore the assumption of the tectonic influence is dismissed. We attribute these siliciclastic packages and erosional boundaries to a heavy load of sediment discharge from the Mandovi River and subsequent readjustment and differential local sinking. This cyclic sedimentation has at times caused the repetition style of regressions and transgressions of the shoreline.

In the M1 profile, six sets of packages characterized by different sets of slope and depositional patterns were noticed (Fig. 4a) which indicated the various progradational periods. The first progradational package is observed from 20 m to 35 m distance from the starting point (Fig. 2). Within this package, several minor depositional layers are observed that point to the progressive movement of the coastline with seaward deposition. The slope of these layers was steep ($>35^\circ$) at the time of their formation. The second progradational package, mapped from 35 m to 60 m distance maintains a similar slope as that of the earlier one. The third and fourth progradational packages are observed starting at 60 and 96 m, respectively, with different slopes of the sand layers.

At 115 m, the M1 profile revealed a sudden change in the surface topography and a swale occurs. Consequently, disturbances in the sand layers were noticed at 1.0 to 2.0 m depth (Fig. 3a and 4a) and the surface level was lowered by at least 0.6 m due to a scarcity in the sediment supply. The 5th and 6th progradational packages are at 118 and 127 m, respectively. The horizontal distance between these package

boundaries (5 and 6) is only a few meters (9 m) as compared to others (Table 2) (Fig.4a) and again, severe disturbances of the sand layers were observed in the sub-surface towards the coast. The profile also recorded slumping and disturbances in the sand layers after the 5th package i.e., in the berm area. The overall inference signifies that up to the 3rd package (up to 96 m) there was a regular cycle of deposition followed by erosion during short supply of sediments (indicated by sharp boundaries). The shoreline growth was progressive and gradual. But after the 3rd package, the sediment supply was reduced when compared to earlier progradational periods and accordingly the shore elevation was lowered. There were also more disturbances in the various sand layers and the paleo-topography changed rapidly to form a rolling terrain. The entire episode is reflected in the GPR profile and is also significantly magnified by the present day beach topography.

The M2 profile is about 255 m long (clear reflection up to only 240 m) and indicates a continuous pattern of sediment deposition (Fig. 3b). Unlike at the profiles M1 and M3, the sand was deposited at M2 under the influence of differential submergence conditions. This phenomenon has been observed from a significant change in low amplitudes and reflectors. After 175 m, the signals / amplitudes were observed to be poor and the records were not clear due to saltwater intrusion and poor conductivity (Fig.3b). Six progradational packages were recognized in the profile M2 (Fig. 4b), each with sharp erosional boundaries. During the 1st progradational period, the slope of the sand layers was steep (40-50°) and gradually became moderately gentle (5-20°) due to progressive sedimentation. Between packages 1 and 2 (nearly 40 m long), two minor erosional boundaries occur. The second progradation package is observed from 48 m to 80 m distance and has a steep slope (~ 40°). Likewise, erosional boundaries of packages 3, 4, 5 and 6 are marked in the profile at 80, 110, 142 and 167 m, respectively (Fig. 4b). During the initial period of each progradational package, the near-shore bed slope seemed to have been steep and gradually became moderately gentle due to subsequent deposition. A paleo-lagoon like feature / high moisture zone (Fig. 3b) bearing low reflectance character is observed throughout the profile (middle part) which suggests progressive sedimentation in a shallow submerged environment.

The M3 profile is about 215 m long (clear signals are observed up to 175 m) and about 250 m away from the M1 profile. The thickness of the top sandy cover varies from 0.8 to 2.0 m (Fig. 3c). In this profile also, six progradational packages are observed which are remarkably asymmetrical and narrow when compared to the nearby M2 profile. There are three prominent buried beach ridges (at 60, 75 and 103 m) that indicate irregular erosional boundaries after the 2nd package. The depositional pattern is also different in comparison with the other two profiles. The nature of these features illustrates the dominant influence of coastal process. The progradational packages are also not wider which could be due to a limited supply of sediments as the profiled area is well away from the mouth of the river and has an elevated terrain. From the 4th package, the intertidal / near-shore beds had a moderate slope as compared to the steep slopes observed in packages 1 and 2. The morphology of the backshore signifies the typical action of coastal processes by way of forming alternative ridge and swale topography.

4.3 Sedimentology and Mineralogy

The sediments of the Miramar beach are sandy with variable proportions of shells and heavy minerals. The grain size statistical parameters of the samples from the two test pits indicate that the sediments from the

top layers are uni-modal and poorly sorted whereas down-depth, the sediments are bimodal or polymodal. This observed bi- or poly-modality indicates more than one source for these sediments. Overall, the sediments are fine to very fine sands and their sorting varies from moderately well-sorted to well-sorted. Sediments from the top layers (0-73 cm) are finely skewed while below 73 cm these are coarsely skewed (Fig. 3). This variation from fine to coarse skewed sands suggests the influence of winnowing action which removes the finer sediments.

Observations of the pit samples reveal that around the progradational package contacts, the sediments are relatively coarser, angular to sub-angular along with flat and polished lateritic granules which indicate that the sediments were not transported long distances. Thus, the formation of the depositional packages is attributed to the cyclicity in sedimentation and erosion influenced by the fluvio-marine processes. Detailed studies are warranted to establish the sedimentological aspects and cyclicity in decadal monsoon behaviours in forming these depositional packages.

The percentage of heavy minerals varies from 4% to 81%. The maximum (81%) heavy mineral concentration is in the bottom-most layer (99-107 cm) followed by layer 73-80 cm (74%) while the lowest (4%) occurs between 91-99 cm. The heavy minerals are represented by magnetite at (27% at 99-107 cm, 29% at 73-80 cm and 10% at 32-38 cm) whereas ilmenite in the same layers show concentrations of 29%, 39% and 16%, respectively. The heavy mineral suite is probably derived from the erosion of the hinterland rock formations and from the overburden dumps of the iron ore mines.

4.4 OSL dating

We used the average dose for the age estimation. Interestingly, the samples showed extremely good sensitivity and the dose distribution was typical of a well bleached sample. The radioactivity of the samples was determined using a thick source alpha counting (U and Th) and a gamma ray spectrometry for the K estimation. The average water content was assumed to be 5%. If this were to be higher the age would increase proportionally due to the dilution of the average dose rate. Table 1 provides the experimental data. The OSL ages for the 73-80 cm and 91-99 cm depth sample were 54 and 59 years, respectively. These ages correspond to the calendar years 1957 and 1952, respectively and suggest recent deposition of the sands.

5. Discussions

5.1 Shoreline migration

Based on the six recognisable depositional siliciclastic packages occurring in the backshore area, we identified clear indications of shoreline migrations in the three GPR profiles (Fig. 4). The locations of each progradational package with respect to all the three profiles are shown in Table 2. The erosional boundaries represent periods of shoreline transgression within a gradually regressing shoreline. During each progradational period, the progressive sedimentation and resultant layers within the package were observed to be significant.

The M1 profile, near the Mandovi River, portrayed six progradational packages and their erosional boundaries at 20, 35, 60, 96, 118 and 127 m, respectively with reference to the starting point of the GPR profile (Table 2). This shoreline migration in terms of shoreline regressions are represented by periods of cyclic sedimentation and erosion. The distance between each package boundary was irregular and between

the 5th and 6th packages it only 9 m. At each erosional boundary the seaward slope of the inclined sand layers is nearly 45° or more. The details of the packages in profiles M2 and M3 are presented in Table 2. It is observed that the nature and pattern of the packages, erosional boundaries and slopes in the three profiles vary significantly.

As earlier stated, the OSL dates of the samples between 73 and 80 cm and 91 and 99 cm depth are 54±2 and 59±2 BP, respectively (Table 1) and these correspond to the years 1957 and 1952, respectively. Since the above sample collection site (Fig.2) was around the location of the 1st progradational period, it confirms that the progradation commenced around six decades before which corroborates the information provided by the populace. Thus the 1st stand in the GPR profile indicates the shoreline position of six decades back. Since then, the shoreline migrated with progressive sedimentation, documenting the transgressive and regressive cycles, and reached the present position.

Based on the OSL dating, a rough estimate indicates that the extent of shoreline migration was ~240 m (from 40 m to ~280 mand at average rate of 4 m/year) during last 60 years (1952 to 2012). This kind of rapid growth is possible but with dominant source of sediment supply from rivers to the coast (Menezes 2006; Chu et al. 2006; Milliman et al. 2008; Li et al. 2014). Since no convincing evidences on tectonic activity was documented in and around the study area, we attribute the shore transgression and regression cycles to the enhanced sedimentation of the Mandovi mostly contributed by anthropogenic activities related to iron ore mining in the catchment area. Dallas and Barnard (2011) reported that dredging and mining has caused shoreline changes in the San Francisco Bay coastal system in terms of long-term and short-term accretion and erosion. Though the anthropogenic influences like damming, hydraulic works etc are causing deficit sediment supply to coastal areas (Stefano et al. 2013), mining in the river catchment areas maximise the sediment input in the river system so as to cause the shoreline growth. Pulfrich and Branch (2013) studied sediment discharge from diamond mining to the Elizabeth Bay and documented a massive beach accretion (350-620m) during 1993-2012. The implications of mining activity in the Miramar catchment area and its relation to the shoreline migration are discussed below.

An earlier study in this area by Kidwai and Wagle (1975) indicated that minerals like kyanite, sillimanite and certain types of amphiboles were derived from weathering of the hinterland rocks. It is to be noted that the sediments to the Miramar beach are also contributed by excessive erosion along the Coco beach at the confluence of the Sinkerim River and Mandovi River (Fig. 1). Nigam et al., 2002 verified that an ex-ordinary increase in the suspended load was noticed in the Mandovi estuary during yester decades (i.e., 2.0 to 4.0 mg/l in 1972; 4.5 to 8.0 mg/l in 1982 and 6.70 to 114.50 mg/l in 1990). This increased suspended load could be attributed to mining activities (iron and manganese ores) in the catchment area of the Mandovi River and its tributaries (Nigam et al. 2002).

It is important to note that the iron ore mining in the hinterland of the river catchment area is being done by opencast method. In order to produce one ton of iron ore, nearly 2.5 to 3.0 tons of overburden has to be excavated and remains as mine waste dumps. It is reported that the mining activities in Goa were resumed in 1947 and intensified in 1950s. The export of iron ore has increased from 0.44 million tonnes in 1951 to 35.0 million tonnes in 2008 (<http://www.goadmg.gov.in>). Over the years, more than 1 billion metric tons of mining rejects are estimated to have been accumulated in the mining belt of Goa which enhanced the sediment input

to the Mandovi River. This mining rejects not only create an acute problem for the safe storage but also lead to environmental pollution and increased sediment load on the river system. The loose mining rejects get eroded during heavy monsoon and are transported downstream, thus increasing the suspended load in the Mandovi River and finally dumped near the river mouth at the Miramar beach (Nigam et al. 2002). This predominant source of sedimentation causes rapid accumulation in the Miramar shore due to which the shoreline progradation was significantly scaled-up from ~40m to a maximum of ~ 280 m width since 1950s.

As far as the aeolian sand transport within the Miramar beach is concerned, it was computed to be around 180 m³ (Reddy and Sastry 1988) and the removed sands were transported to the backshore and dune regions consequently. Also, the large tidal range and low water table at the shore support the transport of the sand from the berm and foreshore areas.

5.2 Beach dynamics

The interpretations of the GPR profiles revealed that the shoreline changes of the Miramar beach have been significant in the past six decades by extended from ~40m to ~280m seawards. In other words, the shoreline retreated by nearly 240 m, leaving six progradational packages. Similar to the nature of progradational packages observed in Miramar beach, Lindhorst et al. (2008) identified strong erosional boundaries with phases of progradational growth in the southern German North Sea coast. Roberts et al. (2013) observed similar inference along Mid-Atlantic coast. They interpreted that these strong erosional boundaries reflect severe storms. But, in the Miramar beach, no storms were recorded in the recent past. The observed progradational sedimentary packages were attributed to the Mandovi River sedimentation during severe monsoon periods followed by erosional phases caused by short of sediments during lean periods. Thus, the Mandovi River has an appreciable influence on the dynamics of the beach system by way of sediment influx and local readjustments.

It is observed that the nature of each progradational package at the Miramar beach varies at each profile. The M1 profile indicates a strong reflectance throughout which suggests less moisture and dry condition during sediment deposition and represents the dominance of fluvial processes. The M2 profile illustrates that the packages were deposited in a shallow lagoon as evinced by the poor amplitude and reflectance and undisturbed sediment layers. The M3 profile depicts undulatory and irregular packages which are typical of active coastal processes. The sediments deposited at the Miramar beach were subjected to a combination of these processes. All the profiles significantly indicate that in the last six decade the Miramar beach was highly dynamic. The predominant processes of deposition and erosion led to a rapid seaward migration of the shore. An analysis of the field data revealed that the beach processes and the fluvial sediment input appear to be the dominant causes for the sediment deposition (cf. Murty et al. 1976; Nigam et al. 2002).

The spatial locations of erosional boundaries of each progradational package in all the profiles are significant with reference to distance to each other and elevation. These characters portray the nature of sedimentation process and redistribution of sediments in the shore. Figure 5 illustrates the location of each erosional boundaries and their elevation attributes. These attributes reveal that the sediment input was excess along the M1 profile as it is located nearer to river source. The lesser shore width than M2 indicates the southerly redistribution of the sediments. The M2 profile shows that almost all the progradational

packages are equidistant and nearly flat that suggest deposition of the sediment in a less disturbed shallow lagoon condition. The M3 profile indicates a decreased sediment input as it away from the river source.

Figure 4 shows that the width and slope of each package are different in all the profiles. While moderate slope of packages are observed in M1 and M2, steep slope of packages are noticed in M3. This observation revealed that the fluvial action in the past decades was differential in nature with reference to the slope and elevation of the shore and was coupled with dynamics of coastal and wind actions (Reddy and Sastry 1988).

The subsurface sedimentary structures as inferred from GPR profiles illustrate various kinds of depositional environment. The profile M1 indicates an undulating subsurface topography that was formed due to dominant fluvial processes whereas the nature of deposition in M2 profile portrays redistribution and reworking of the sediments. The M3 profile reveals the typical coastal processes that produced ridges and swales topography buried under sand. These observations advocates the dominant influences of fluvial, fluvio-marine and marine processes in M1, M2 and M3 profiles, respectively. Thus, an increasing in dominance of marine processes is seen further from the M1 profile area (River area) towards M3. The width of each progradational package provides an approximate perception on the amount of sediment deposited. As seen in all the profiles (Fig. 4), the width of each packages differ. Figure 6 portrays comparative information on the width attributes for all profiles, in turn, illustrates the deposition in given time. Double peak graph is observed for M1 profile which shows more deposition during 3rd and 6th progradational package period. In contrast, the deposition was low during 2nd, 3rd and 5th progradational period (M2 profile). Confirming the earlier observation, the M3 profile indicates a regular and undisturbed deposition during 1st to 5th progradational periods.

5.3 Sediment contribution from the Mandovi River

The sediments of the Miramar beach may have been derived from different sources: (1) erosion of headlands, (2) offshore, (3) hinterland or mixed.

1. Erosion of the headlands: The Cabo Raj and Aguada headlands are eroded due to convergence of wave energy and generate a large amount of coarse sediments and these are transported and deposited in the sheltered regions.
2. Offshore: Under the influence of the Holocene rise of sea level and increased sedimentation, shoaling has resulted in the formation of most of the estuaries. Because of shoreward transport of offshore sediments under the influence of a transgressing sea, substantial quantities of sediments may have been contributed to the Miramar beach.
3. Hinterland source: Due to intensive iron ore mining activity in the catchment area of Mondovi River, the mine rejects cause to increase the sediment load of the River and become a dominant sediment source to the rapid growth of the shore. Detailed discussion is presented under section 5.1. In support of contributions from mining activities, Nigam et al. (2005) studied the foraminiferal characteristics of 11 surface sediment samples collected from the Mandovi estuary during 2001. A comparison of these data with that of revealed a drastic fall in total foraminiferal number in the lower reaches of the river. The values

fell from 138/g dry sediment sample in 1994 to 41/g sediment sample in 2001. Furthermore, a decline in diversity was also noted from 22 (1994) to only 5 species (2001). The ever-increasing suspended load in the Mandovi estuary, probably due to mining activities in the catchment area, was suggested as the plausible reason for the decline of fauna. An enigmatic finding was the occurrence of substantial amount of reworked/older forams at the lower reaches of the estuary that could be indicators of Holocene high sea stand.

5.4 Causes of shoreline changes

It is apparent from the above discussion that in the recent years the shoreline has migrated coupled with the regressive - transgressive cycles of deposition and erosion in the Miramar beach. The analysis of the GPR profiles corroborates the fact that the rapid development of the beach in the last six decades has been a significant phenomenon. An enhanced fluvial sediment input resulted in an increase in the width of the shoreline (as noticed in M1 and M2) and subsequently the sediments were redistributed along the coastline (M3 and beyond). This process of sediment deposition in the recent years is one of the prime causes of the regression and transgression cycles of the Miramar shoreline. Since no previous geo-chronological information about the shoreline development is available hence, we consulted the available admiralty charts and maps of the last century. Based on the position of the shoreline (Fig. 2) the shore width along the profiles M1, M2 and M3 were measured (Table 3). It is noticed that the width of the shore varies from 60 m in 1758 to 100 m in 1881 and further decreased to 40 m in 1904 and again increased to 70 m in 1929 (Anon 1881; Anon 1904; Shirodkar 1991; Anon 1929). It appears that a pre-dominant erosion activity again reduced the shore width to a minimum (20-40 m) in 1950s, coupled with a sediment starved situation. This cyclic migratory movement of the shoreline through the historical times (Fig. 2) could be ascribed to the deposition and erosion of the sediments. But in the recent years, the shoreline growth was rapid due to the large influx of sediments from the Mandovi River. Perhaps the transport of significant mining waste along the Mandovi River could be one of the major reasons. All these activities of cyclic deposition and erosion phenomena has caused the shoreline to regress and transgress within 10s of meters width during 1758 to 1957 (200 years) which is insignificant when considering the time interval involved.

The OSL ages (54 ± 2 and 59 ± 2 BP, respectively for the sediment layers 73 and 80 cm and 91 and 99 cm) correspond to the shoreline position between the years 1957 and 1952. The shoreline growths in the recent years i.e., during 1952 to 2012 are phenomenal and noteworthy as revealed by the GPR profiles.

Interestingly, some of the disturbances in the sand layers were observed in all the three profiles which probably indicate local turbulence caused either by waves, tides and associated oceanographic processes during periods of transgression when sedimentation was low and erosion was high. Such impacts on the sand layers were noticed in all three profiles. The M1 profile shows a series of slumping due to heavy sedimentation after 3rd package. These observed confined disturbances in the sand layers indicate the local readjustment and resettlement around M1 profile area. But such disturbances are less clear in the M2 profile and however, such slumping nature is observed in 5th package. The M3 profile shows an earlier disturbance just after the 1st package was deposited. Based on the reflections, it appears that the sand layers were vertically overturned in the 6th package period.

Since there is no evidences of tectonic evidences around Miramar area, it is presumed that the sea level has not varied appreciably along the Goa coast. As such, continuous and cyclic variations in shoreline position during this time, which are clearly evident from historical maps and GPR profiles, cannot be attributed to variations in the elevation of the MSL. Rather, these are likely in response to river-mouth / shoreline dynamics. By contrast, the period of rapid shoreline regression and beach growth evident in the past 60 years is a new phenomenon. It is perhaps related to mining activities upstream in the Mandovi River basin. Even this period of rapid progradation was marked by apparently cyclical periods of transgression and regression, evidenced by progradational packages 1 through 6 observed in GPR profiles. Thus, it is expected that future changes along the Miramar beach would be dominated by cyclical erosive and progradational cycles, driven by shoreline dynamics, superimposed upon a gradual widening trend due to the high local sediment supply. Future close observation would assist in assessing such influences and predicting future changes at the Miramar beach.

6. Conclusions

Observations from the three GPR profiles have allowed us to identify six progradational packages that occurred in the past six decades, at the Miramar beach, Goa. The variable nature of the depositional packages indicates that the beach dynamics were appreciably active in the recent years and continue to be so. Mining activities in the Mandovi River basin greatly enhanced fluvial sediment fluxes to the coast, driving a 60-year period of rapid shoreline progradation. More subtle coastal changes were driven by local readjustments of shoreline position and the transport of sand to the backshore and dune areas. The historical maps indicated that deposition and erosion cycles were regular phenomena along the Miramar coast but the rapid growth of the shore in the last six decades appears to be highly significant. During the past six decades, the beach widened and extended at least 150 m seawards with six progradational packages. If the same trend continues, then, one can anticipate a widening of the Miramar beach and subsequent incremental regression of the shoreline. Under such a situation, an integrated monitoring network is warranted to gather various parameters to facilitate an understanding of the processes and help devise an appropriate management plan for the Miramar beach.

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Table 1 Details of OSL dating of two samples from the Miramar beach, Goa.

| Sample | De (Gy) | U-238 | Th-232 | K% | Water content | Cosmic ray dose rate | DR Gy/ka | Age Years |
|-----------|-----------------|---------------|---------------|---------------|------------------|----------------------|----------|-----------|
| Miramar 7 | 0.049 ±0.005 | 0.96 ±0.04 | 3.43 ±0.10 | 0.31 ±0.01 | 5±1 [#] | 173.97 | 906±28 | 54±2 |
| Miramar 9 | 0.054 ±0.005 | 1.06 ±0.04 | 3.07 ±0.09 | 0.32 ±0.01 | 5±1 [#] | 168.15 | 907±28 | 59±2 |

Table 2 Distance and width of each progradational package in Miramar beach

| Progradational package | M1 Profile | | M2 Profile | | M3 Profile | |
|------------------------|-----------------------|-----------|-----------------------|-----------|-----------------------|-----------|
| | Starting Distance (m) | Width (m) | Starting Distance (m) | Width (m) | Starting Distance (m) | Width (m) |
| 1 | 20 | 15 | 9 | 39 | 8 | 37 |
| 2 | 35 | 25 | 48 | 32 | 45 | 15 |
| 3 | 60 | 36 | 80 | 30 | 60 | 15 |
| 4 | 96 | 22 | 110 | 30 | 75 | 28 |
| 5 | 118 | 9 | 140 | 24 | 103 | 17 |
| 6 | 127 | 35 | 164 | 12 | 120 | 22 |
| Saturated zone | 162 | 50 | 176 | 79 | 142 | 73 |
| Present coastline | 212 | 0 | 255 | 0 | 215 | 0 |

Table 3 Width of the shore during various years based on the Admiralty charts, OSL dating and present observation.

| Profile No. | Width of the shore (m) | | | | | |
|-------------|------------------------|-------------------|-------------------|-------------------|----------------------|-------------------|
| | 1758 ^a | 1881 ^b | 1904 ^c | 1929 ^d | 1952-57 ^e | 2012 ^f |
| M 1 | 60 | 100 | 40 | 70 | 20-40 | 212 |
| M2 | 60 | 100 | 40 | 70 | --- | 255 |
| M3 | 60 | 75 | 40 | 70 | --- | 215 |

a = Old Admiralty Chart; b = Anon (1981); c = Anon (1904); d = Anon (1929); e = OSL Dating; f = Present study

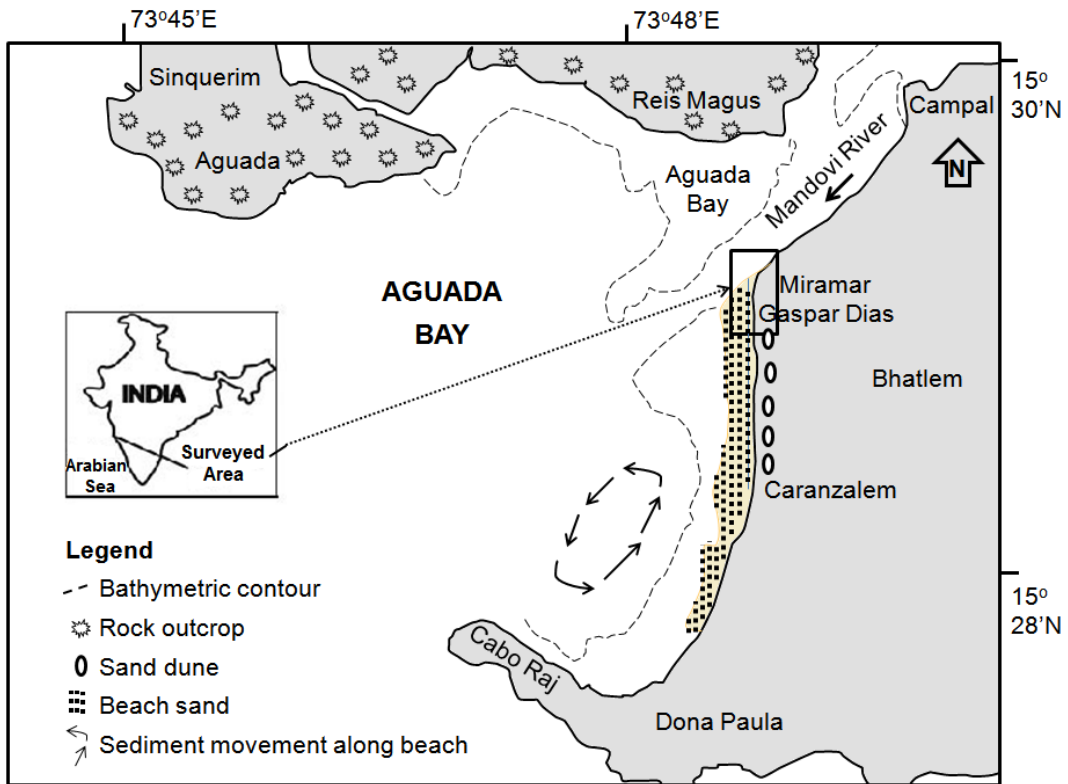
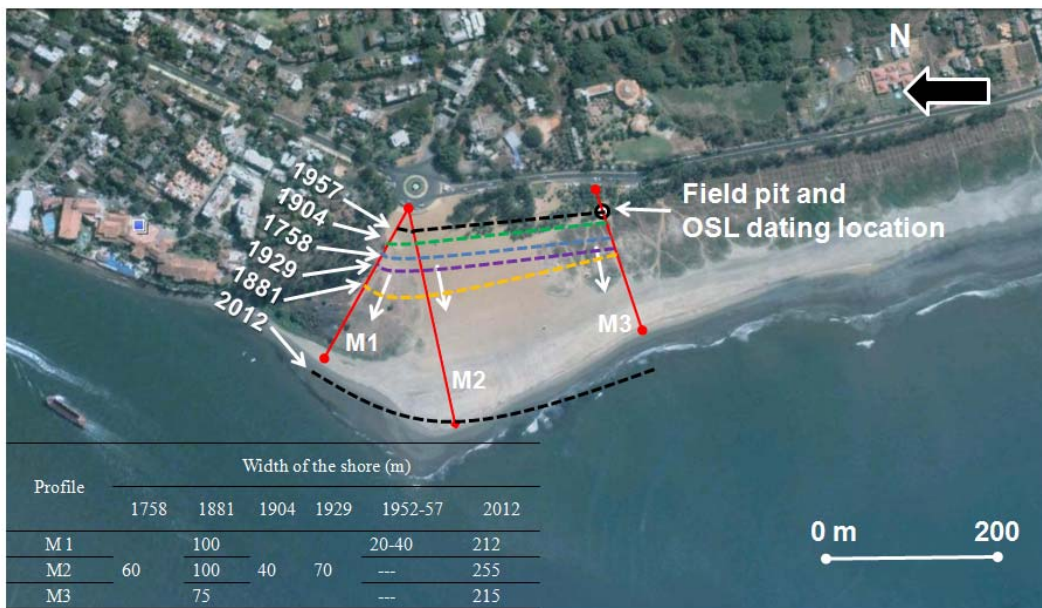


Figure 1



Source: Google image, 2003

Figure 2

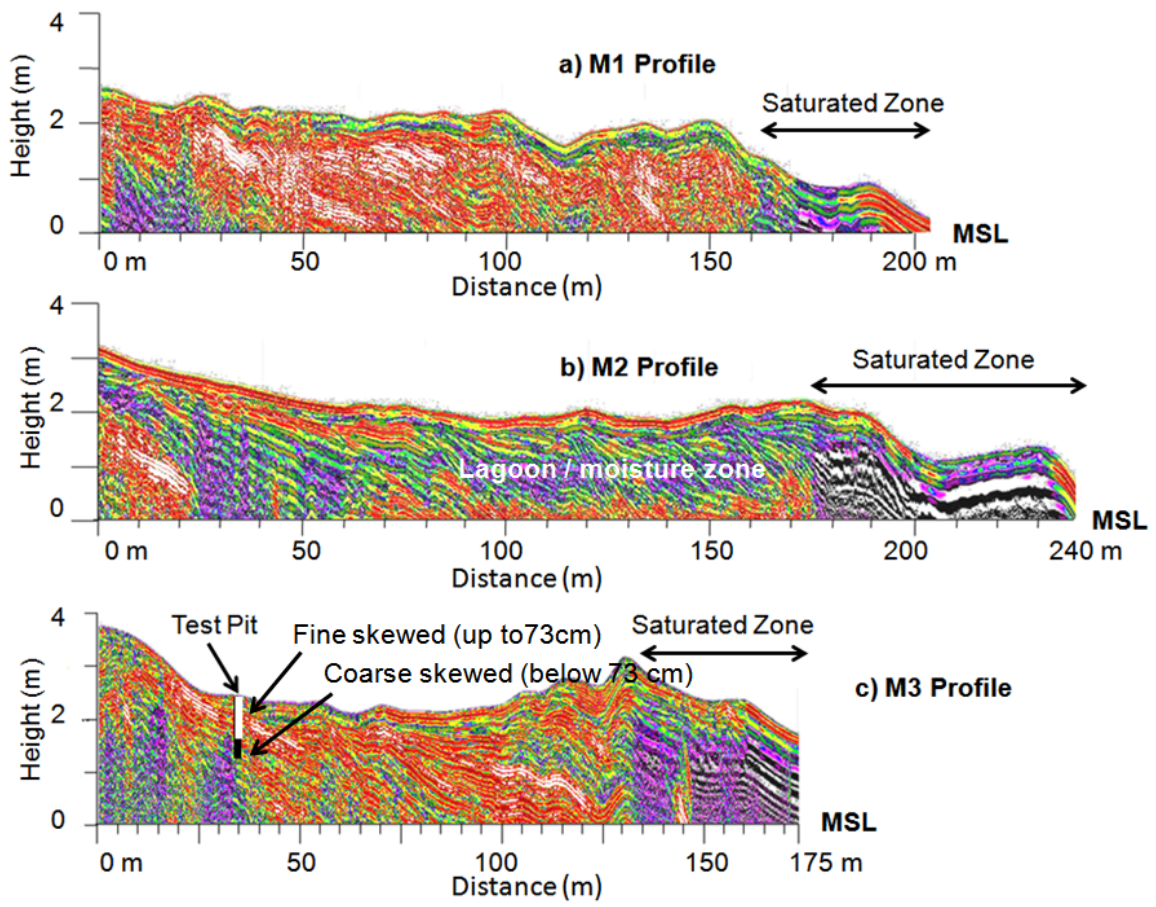


Figure 3

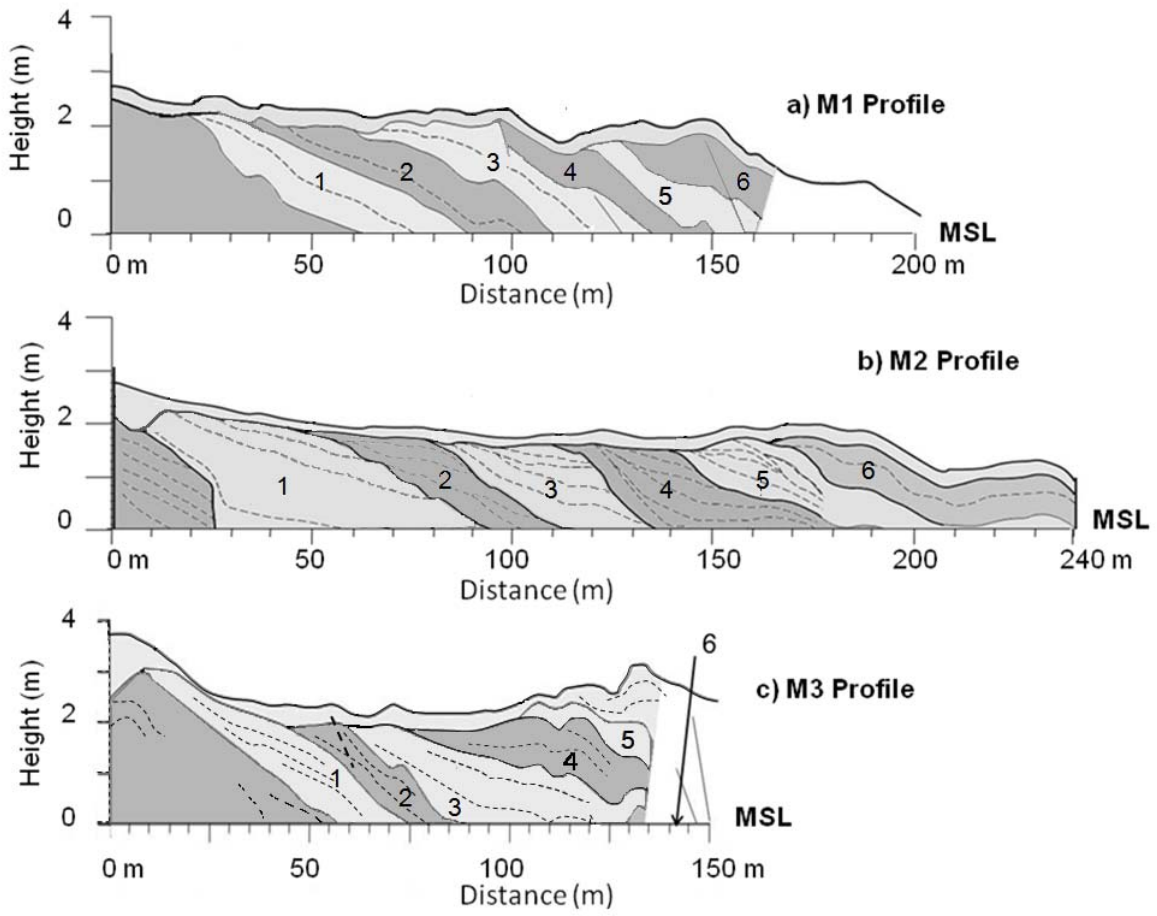


Figure 4

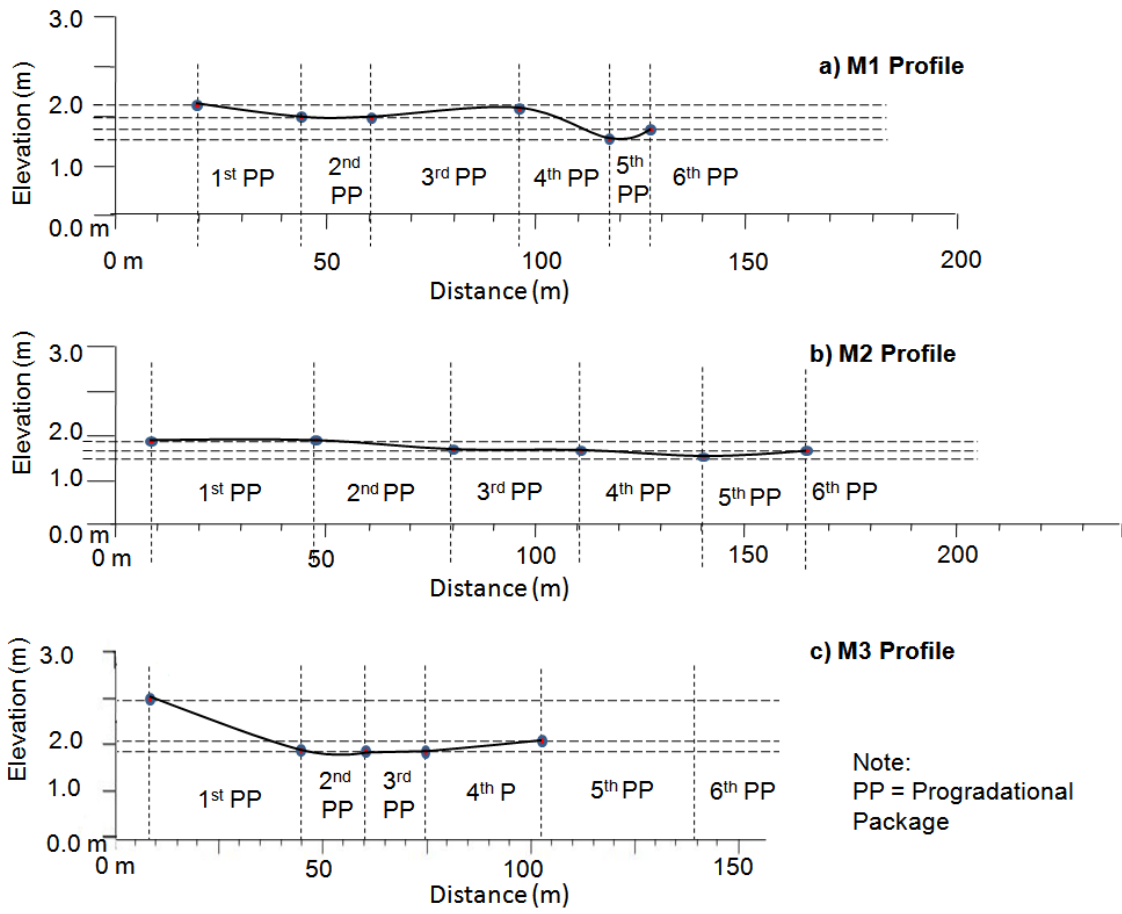


Figure 5

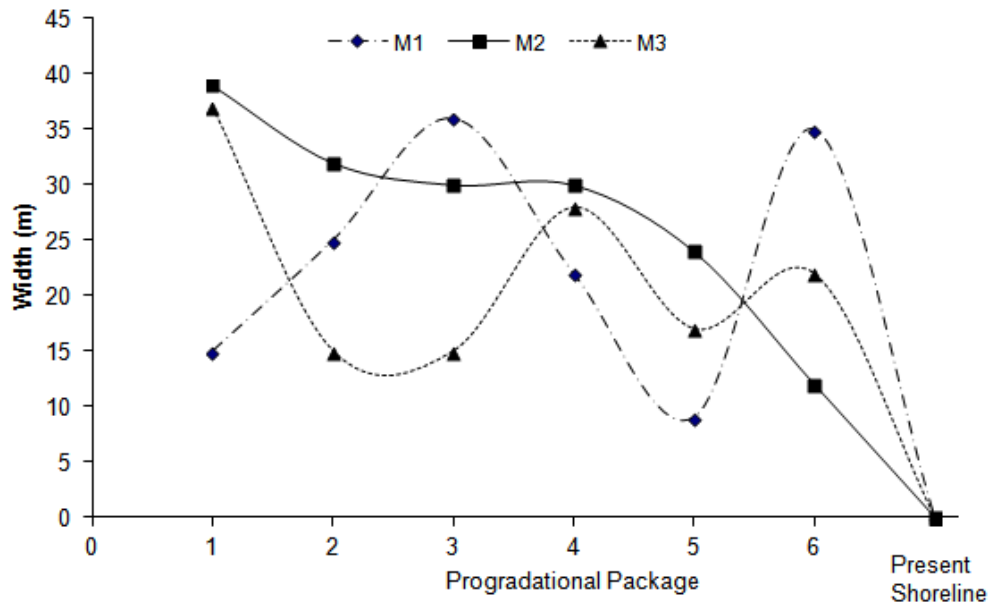


Figure 6