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Estimation of sediment volume through Geophysical and GIS analyses - A case study of the red sand deposit along Visakhapatnam Coast

K. Nageswara Rao, Ch.Udaya Bhaskara Rao[1] and T.Venkateswara Rao

Department of Geo-Engineering, Andhra University, Visakhapatnam - 530 003
[1]Department of Geography, Mizoram University, Aizawal - 796 001
E.mail: nrkakani@yahoo.com

ABSTRACT

Estimation of the volume of the coastal red sediment deposit near Bhimunipatnam north of Visakhapatnam, which is reported to contain heavy minerals of potential economic importance, was attempted in this study. The contours that represent the surface configuration of the area were extracted from the topographic map and the bedrock contours were interpolated from the depth to bedrock estimated from the geo-electrical resistivity survey at 100 points in the 10.55 km^2 area of study. Both these maps were used to generate digital elevation models in GIS software to obtain the thickness as well as the volume of the sediment in the area. The study revealed that the volume of the red sediment deposit is ~145 million cubic meters.

INTRODUCTION

Abundant beach- and dune-placer deposits of considerable economic potential occur at a number of locations along the east coast of India. The coastal section, north of the port city of Visakhapatnam, is one such stretch that is particularly rich in placer mineral-sand deposits. Reddy & Prasad (1997), Reddy et al., (2001) and Dhana Raju (2005) noted the presence of heavy minerals like ilmenite, garnet, sillimanite, rutile, monazite, zircon, etc., in the coastal zones along Bhavanapadu, Kalingapatnam, Baruva and Bhimunipatnam at different locations, up to ~120 km north of Visakhapatnam. Notably, higher concentrations of these heavy minerals are found in the finer fractions with dune sands accounting for >50% in quantity (Reddy & Prasad 1997). Taking the presently exploited Australian mineral-sand deposits as a basis, the presence of ~5 wt. % of ilmenite and ~0.5 wt. % of rutile in easily-separable range of grain-size makes the sands economically workable, and rutile, being the costliest of the heavy minerals in the mineral-sand deposits, some ilmenite is converted into synthetic rutile (with ~92%TiO_2) and other value-added products like Ti-slag and Ti-sponge (Dhana Raju, *pers. commn.,* through e-mail on May 18, 2007). Similar to these heavy mineral-rich dune sands along the present shoreline, extensive palaeo-dune sands occur behind the present coastline up to several kilometers inland at several locations along the east coast of India. These 'red sands' are extensive along the Tamil Nadu coast between Rameswaram and Kanyakumari, and also along the Andhra Pradesh coast in the Visakhapatnam region (Gardener 1995). Majority of red sediments are of eolian origin, with their red colour due to chemical weathering that results in the formation of authigenic clay minerals and oxides of iron, dominated by haematite (Gardener 1995), besides hydroxides of iron (limonite). Thus, the red sediments that are basically deposited as wind-blown sands derived from the coastal dunes and beaches are likely to contain heavy minerals of economic potential. In fact, earlier studies indicated that these palaeo-dune sand deposits along the Visakhapatnam-Bhimunipatnam coastal sector contain 10-15% heavy minerals with appreciable amounts of sillimanite, garnet, magnetite, ilmenite, zircon, monazite (Rao 1978) and rutile (Rao & Raman 1986). The clay fractions from these sediments are also found to contain 3200-8140 ppm of titanium (Rao & Raman, 1986). Therefore, it is desirable to estimate the volume of such economic mineral-bearing red sediments to add to the hitherto known reserves of heavy minerals in sand deposits. An attempt is made in this paper to demonstrate a geophysical field method, coupled with Geographic Information System (GIS) technique, to estimate the volume of red sediments, taking one of the relict sand patches along the Visakhapatnam-Bhimunipatnam coastal sector as a case-study.

STUDY AREA

About 20 km north of Visakhapatnam near Bhimunipatnam, a predominantly red-looking sand deposit occurs extending over a 10.55 km^2 area up to 2.5 km inland from the beach road that runs along the backshore zone (Fig. 1a). Although the deposit is considered to be the product of several geomorphological processes involving multiple cycles of deposition (Nageswara Rao et al., 2006), a major part of it is considered as wind deposited dune sand except in its basal part (Vishnuvardhan Rao & Durgaprasada Rao 1968; Prudhvi Raju et al., 1985; Rao et al., 1993b; Nageswara Rao et al., 2006). Khondalites (garnet-sillimanite gneisses) are the predominant rock formations in the region in association with leptinites (garnet-biotite gneisses) and charnockites. Quartzite veins in khondalites and leptinites, besides sandstones and laterites are also found in patches in the area. Bedding, foliation and banding lineation, augen structures and joints are characteristic features of the rocks in the area with the strike of foliation and bedding are mostly oriented in NE-SW and NW-SE directions, and the dip angles of khondalites ranging between 70º and 85º (Rao, Rao & Yoshida 1993a).

METHODS OF STUDY

The surface configuration of the study area is obtained by tracing the contours at 10-meter-interval from the Survey of India topographic map on 1:25000 scale. The subsurface bedrock configuration is prepared based on geo-electrical survey and the bedrock contours are interpolated at 10-meter-interval in GIS. Both the contour maps are used to create digital elevation models (DEMs) from which the thickness and volume of the sediment are derived through GIS analysis.

RESULTS

The study is based on a combination of geophysical and GIS analysis through which the two contour maps representing the surface topography of the red sand deposit and the bedrock configuration beneath the deposit were processed. The results of the study are detailed under the following headings.

Surface Configuration

The sediment volume in the area is a function of the surface configuration and the bedrock configuration. The surface configuration is obtained from the topographic map by tracing the contours at 10-meter-interval. The resultant map (Fig.1b) shows that the red sediment area has a maximum elevation of more than 90 m. It is clearly visible as the beach road that runs parallel to the shoreline is approximately at 5 m elevation from the mean sea level and forms the dividing line between the red sediment on the west and the beach ridges and dunes composed of light

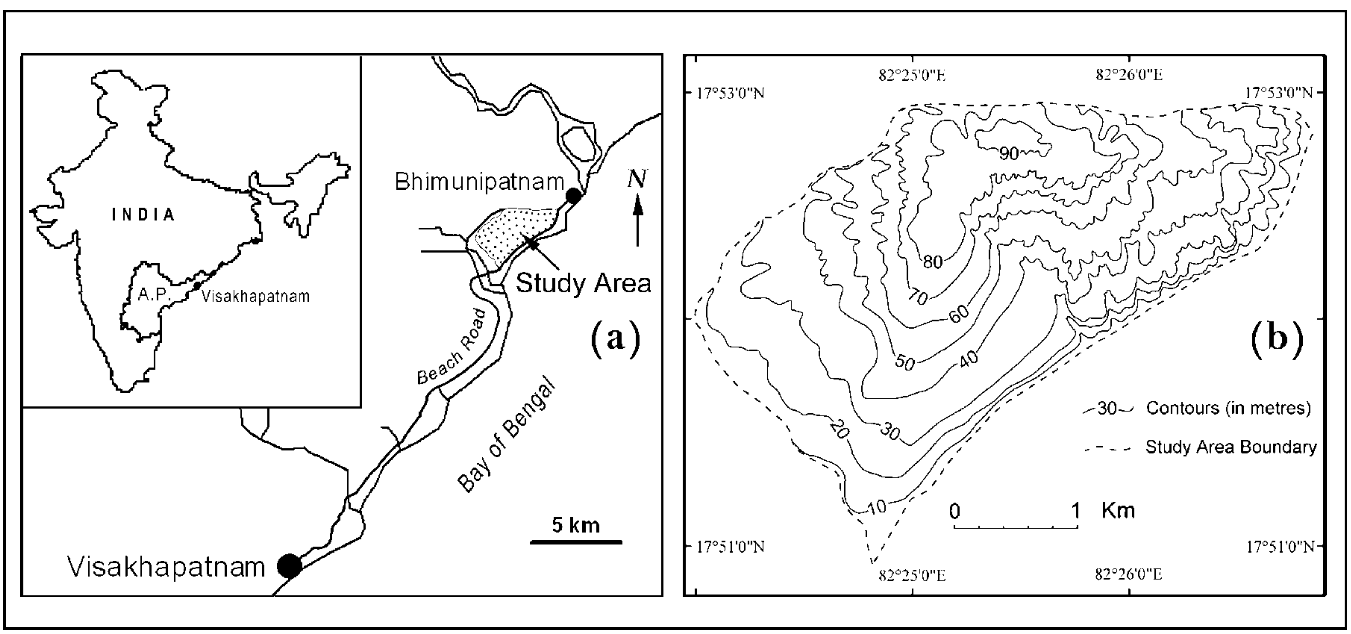

Figure 1 (a). Location of the red sand deposit near Bhimunipatnam along Visakhapatnam coast, and (b) surface configuration of the study area represented by contours at 10-m interval. The beach road (~5m above mean sea level) forms the eastern boundary of the area.

yellow sand of much later origin on the east (seaside). The whole area appears like a mound with its crest having an elevation of >90m above mean sea level at about 2.0 km inland across from the shoreline.

Bedrock Configuration

The major task in the estimation of sediment volume lies in obtaining the configuration of the bedrock over which the entire sediment column rests. For this purpose, geo-electrical survey with the Schlumberger array was conducted at about 100 locations in the area. This method involves estimation of the apparent resistivity of the various subsurface layers (Bhattacharya & Patra 1968). The electrical resistivity field curves are interpreted by comparing them with the standard curves proposed by Mooney & Wetzel (1956) and the bedrock depths at all the 100 surveyed points were obtained. A few typical sounding curves obtained in the area are shown in Fig.2 indicating the various subsurface layers such as sandy sediment of various hues, weathered rock, fractured rock and hard rock. The resistivity values of the upper sandy sediments ranged between 100 and 300 ohm-m, while that of the weathered rock ranged between 30 and 50 ohm-m and that of the fractured rock are around 50-

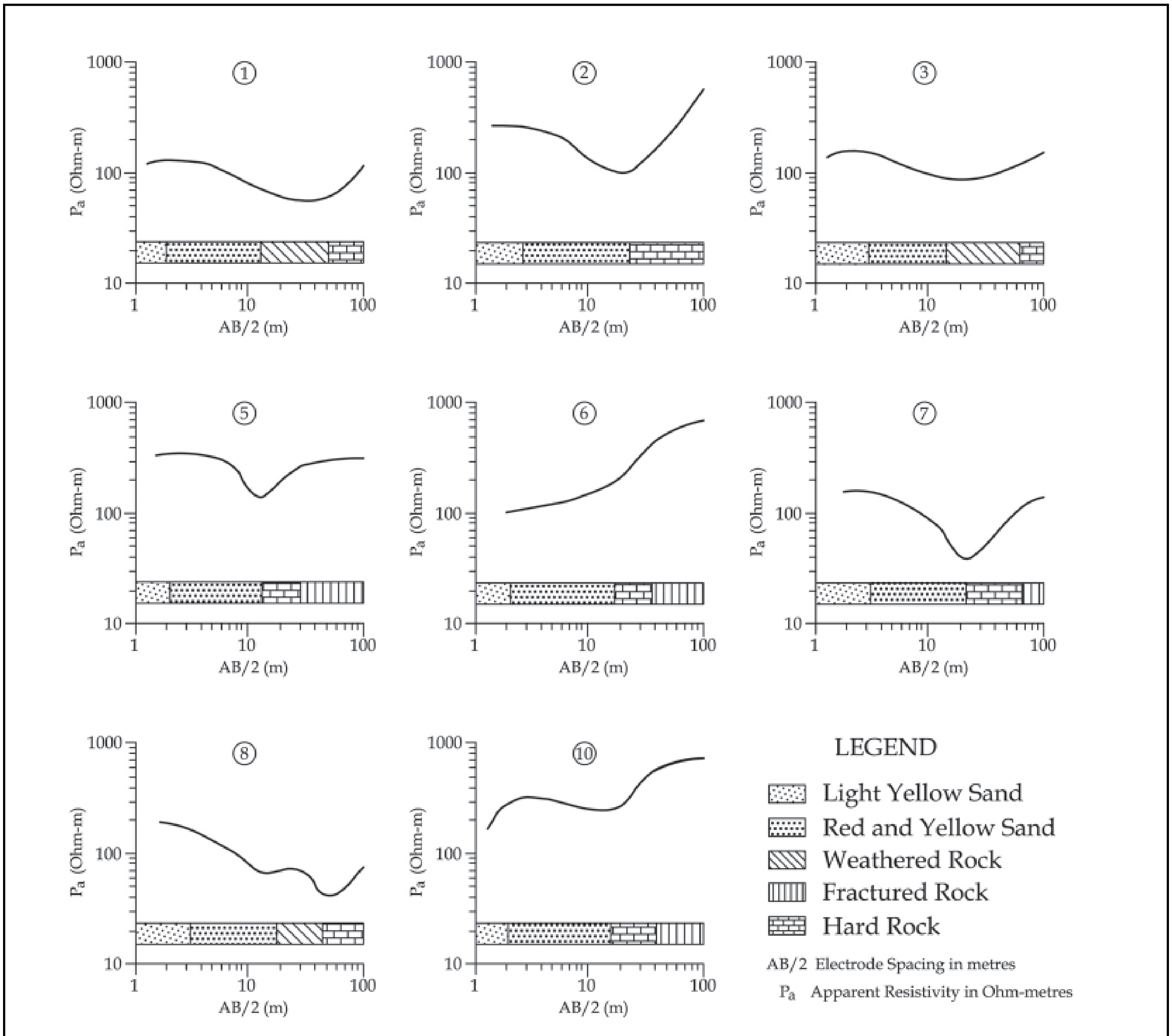

Figure 2. Sample resistivity curves showing the various subsurface layers in the study area. The locations of these eight curves are shown with encircled points and bold numbers in Figure 3a.

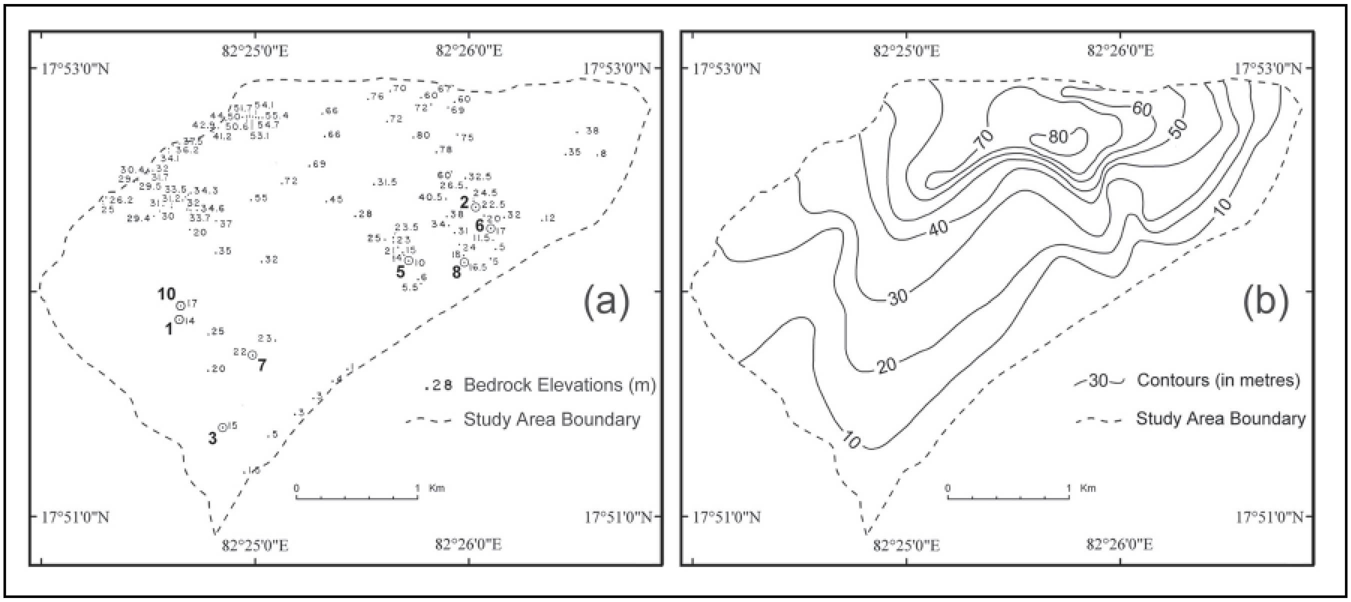

Figure 3. The study area showing (a) the bedrock elevations estimated at 100 locations based on geo-electrical resistivity surveys from which contours were interpolated representing (b) the bedrock configuration in the area. The encircled points with bold numbers in the left panel indicate the location of the sample resistivity curves shown in Figure 2.

80 ohm-m. The very high to infinity resistivity values reflected by steep upward slope (>45°) in the curves indicated hard rock. The higher resistivity values of 100 to 300 ohm-m in the upper sandy sediment were due to the absence of moisture content / water table in the layers, whereas the lower values of 30 to 50 ohm-m in the weathered rock wherever present immediately beneath the sediment (for example curves 3 and 8 in Fig. 2) were due to the presence of high moisture content / water table. For the purpose of estimating sediment thickness in the present study, however, the rock immediately beneath the sand deposit is considered as the bedrock, over which the sediment rests, irrespective of the condition of the rock.

The bedrock elevations with respect to the mean sea level at the 100 points (Fig. 3a) were obtained by deducting the bedrock depth values (estimated from the geo-electrical survey) from that of the surface elevations at the respective points read from the surface contour map. A contour map showing the bedrock configuration of the area was prepared with a 10-meter contour interval by interpolation based on the 100 bedrock elevation points (Fig. 3b). The maximum elevation of the bedrock beneath the sediment cover in the area is more than 80 m above the mean sea level, whereas the minimum elevation of one metre above the sea level is more or less aligned beneath the beach road, which means the bedrock is 4 m beneath the level of the beach road.

Estimation of Sediment Volume

Considering the fact that the red sediment deposit is resting over the bedrock, the sediment thickness at any point in the area is the elevation difference between the surface configuration of the sediment and the bedrock configuration. The contour maps representing the topographic surface of the area as well as the bedrock surface were used to create digital elevation models (DEMs) in the GIS environment in order to extract the sediment thickness and thereby the sediment volume. A grided surface with each cell representing ground segment of certain area is required to estimate the sediment volume. The first step in creating a grided surface from contour data is to generate a Trinagulated Irregular Network (TIN) surface from which a grid surface is created. Therefore, the TIN and GRID modules in ArcGIS software were employed for this purpose.

TIN Generation: A TIN is a digital terrain model in vector format on an irregular array of points which form a sheet of non-overlapping contiguous triangle facets (Maune et al., 2001). TIN models are useful for a number of applications including generation of grid surfaces for volume estimations as required in this study. Initially, the scanned images of both the surface contour map (Fig.1b) and bedrock contour map (Fig. 3b) are geo-referenced and contours are extracted through on-screen digitization. The 10-m contour interval of the two maps, however, is relatively coarse to generate a TIN representing the true shape of the study area as the contours are widely spaced. Therefore, in order to obtain a better control especially along the boundary of the study area, firstly the contours from the original maps were digitized even beyond the study area and then a TIN was generated. The TIN thus generated for the extended area was used to interpolate contours at 1 m interval. This fine-resolution contour layer was used to sub-set the study area through intersection procedure in ArcGIS, from which a TIN is again generated. This TIN represents the true shape and extent of the surface configuration (Fig. 4a) and the bedrock configuration (Fig.4b) of the study area.

However, being a network of triangular features with every triangle having the properties of slope, aspect and constantly changing elevation as a function of the terrain characteristics that it represents over the entire feature, a TIN cannot be directly used for statistical operations such as subtractions which are necessary when the differences between two surface features are to be extracted. To overcome this problem, the TIN is converted into a GRID format, in which each pixel represents a constant elevation.

GRID Generation: A GRID is a plain surface represented as rows and columns of raster cells, or picture elements (the short form of which are known as pixels) when they represent an image of a ground surface. Each cell (pixel) in such matrices has a value which is represented by a digital number in the computer. If the digital numbers are referring to elevations of an area as in this study, the GRID map therefore approximates the topography of that area. The GRID maps, being matrices of numbers, facilitate performance of statistical functions like subtractions to extract elevation differences between two surfaces. Therefore, the TINs of both the surface and the bedrock configurations of the area are converted into raster format, using 'TIN-to-Raster-conversion' function in 3-D Analyst module of ArcGIS, and the resultant GRID formats of the area are as shown in Fig. 5a and Fig. 5b, respectively. Obviously, finer the resolution of the rows and columns in a grid, closer such grid represents the actual topography of the surface that it refers to. Keeping this in view, the GRID resolution was set as 20 meters in this transformation from vector (TIN) to raster (GRID) format for both the surface and bedrock configurations.

The sediment thickness at any location in the area is the difference between the surface elevation and the bedrock elevation. The elevation value that a given raster cell represents in the bedrock configuration of the area, if subtracted from the value of the corresponding cell in the surface configuration, yields the thickness of the sediment at that location. Therefore, raster analysis of subtraction was performed using these two GRID formats of the area in the computer. The output is a GRID with each raster cell in it representing the thickness of the sediment at that geographical location.

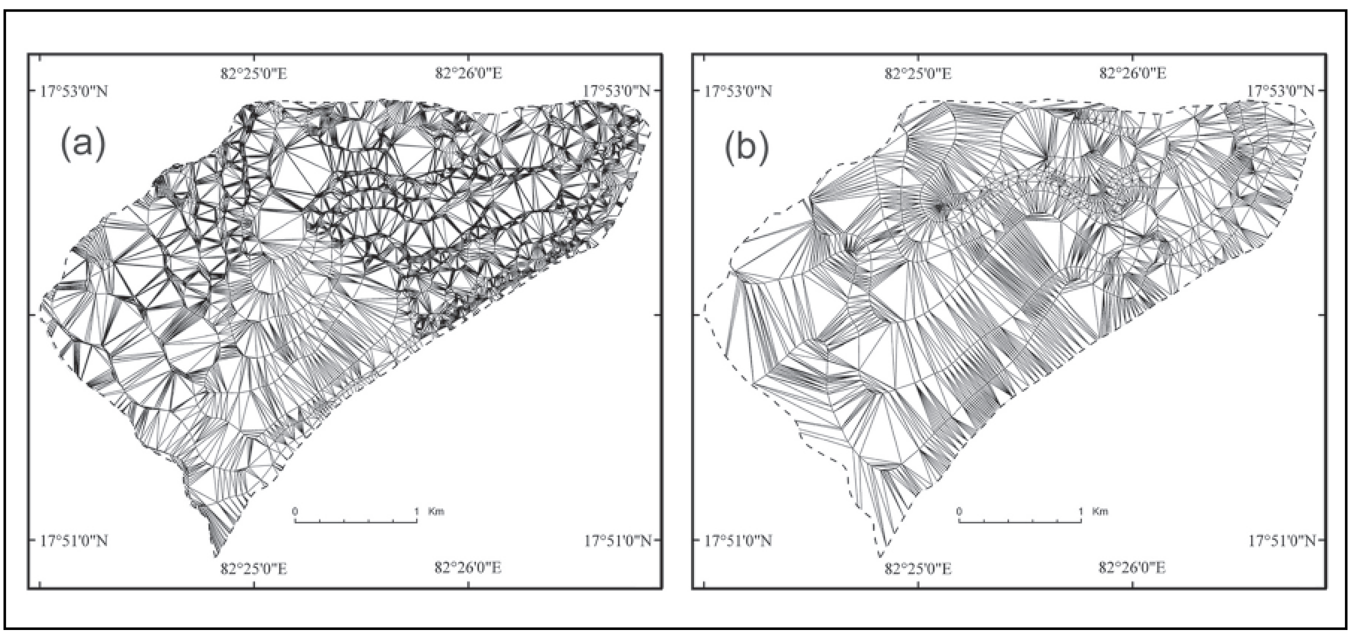

Figure 4. Triangulated Irregular Network (TIN) surfaces representing (a) surface configuration, and (b) bedrock configuration of the study area. These maps show the slope, aspect and elevations of the respective surfaces.

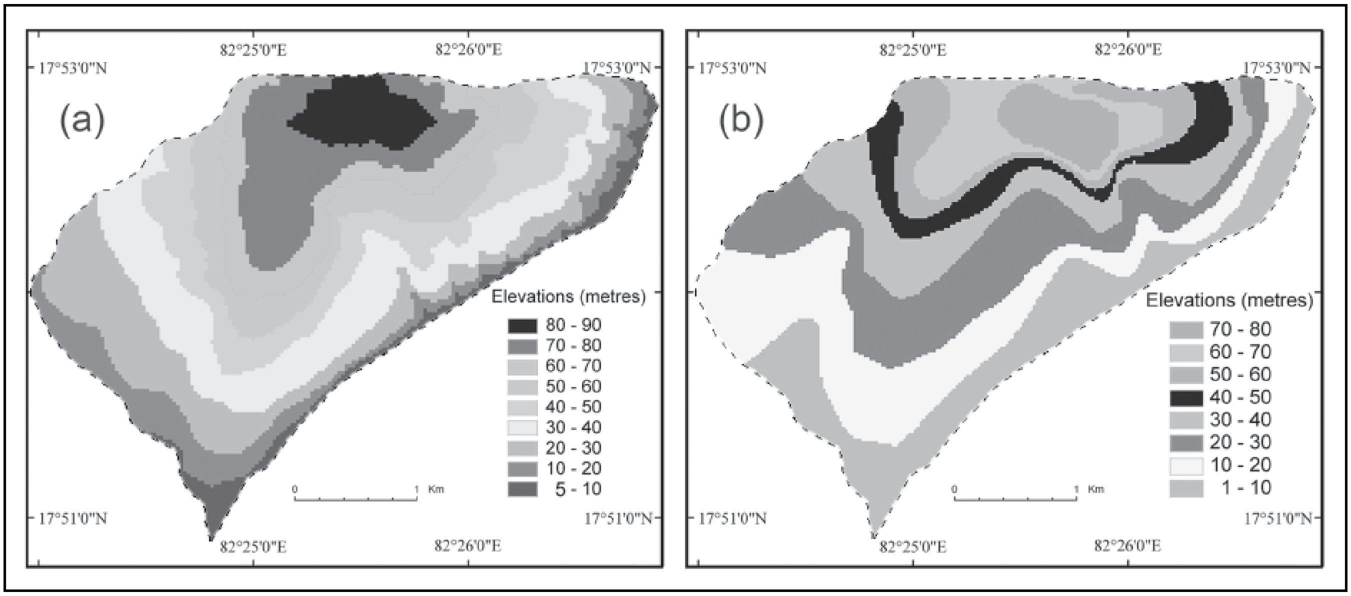

Figure 5. GRID maps of (a) surface configuration, and (b) bedrock configuration of the study area. The maps are composed of raster cells of 20m-by-20m area; hence the boundaries between various elevation ranges are not smooth.

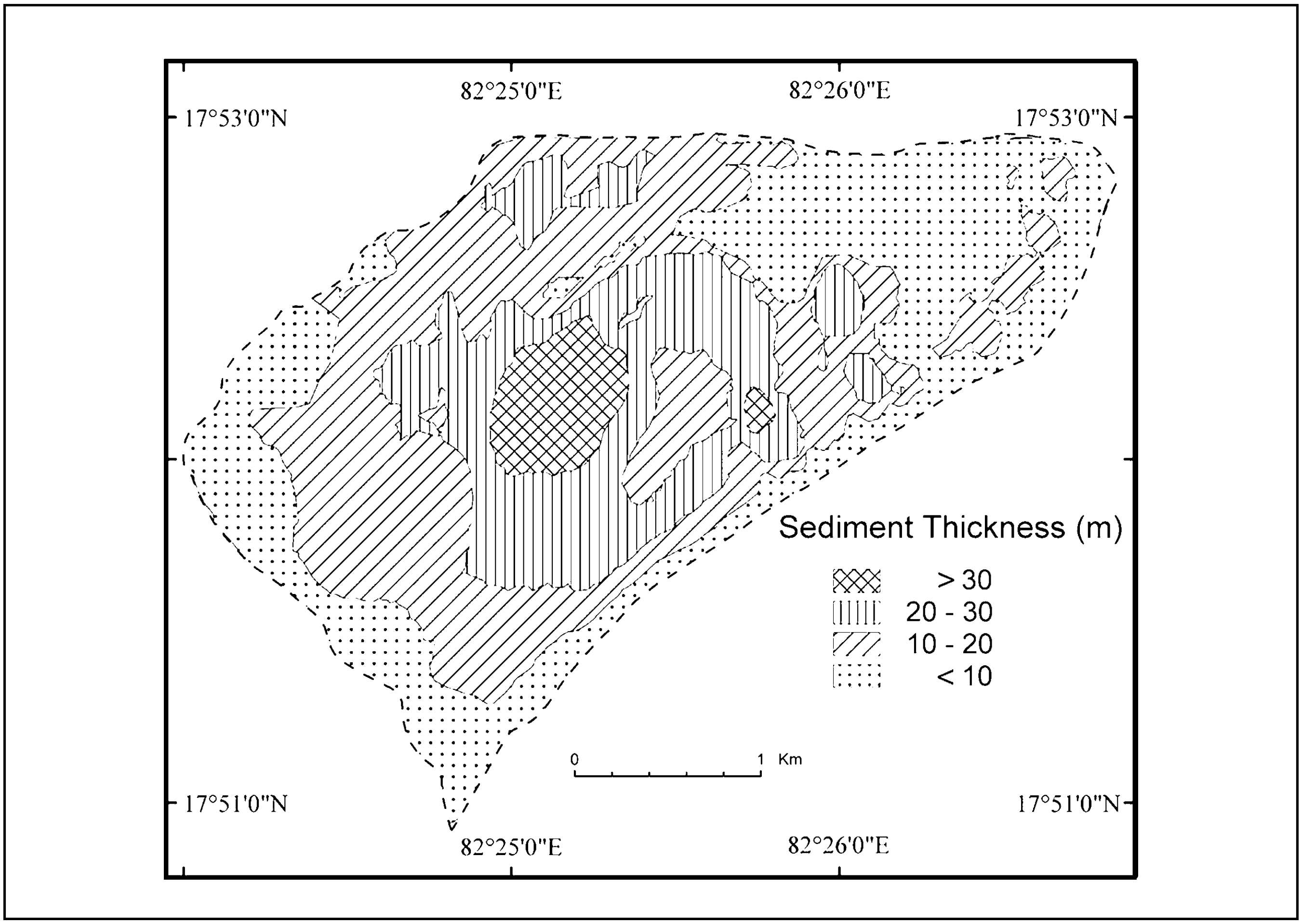

Figure 6. Isopach map showing the variations in the sediment thickness in the study area.

Sediment Volume: The raster GRID surface generated in the system through subtraction process described above was used to estimate the volume of the sediment in the area. The area covered by each 20m-by-20m grid cell is $400m^2$. Since each cell has a certain Z-value representing the thickness of the sediment at that location, the volume of the sediment at each cell is calculated by the system and all the cell-values are added up to arrive at the total volume of the sediment in the area. This computation is done through surface analysis techniques in 3-D Analyst module in ArcGIS. The process involves entering into the system the value of the reference plane over which the sediment thickness is to be computed. Therefore, the value of the reference plane was set considering the minimum value of the sediment thickness to estimate the sediment volume above the reference plane. Thus the total volume of the sediment in the area was found to be about 145.02×10^6 cubic meters.

Isopach Generation: Isopachs are the lines joining the points of equal thickness of the different units used generally to represent the subsurface layers. The thickness values of the sediment in the area extracted by subtracting the bedrock GRID (Fig. 5b) from the surface GRID (Fig. 5a). The resulting GRID containing 26,375 raster cells with each cell representing the thickness of the sediment at that location was classified in ArcGIS by grouping all the cells into four thickness classes. The isopach map thus obtained (Fig. 6) indicates that the sediment thickness is within 10-m range in the peripheral zones of the study area whereas the maximum thickness of more than 30 m is in the central parts of the area.

CONCLUSIONS

The geo-electrical resistivity surveys were useful in estimating the depth to bedrock beneath the coastal red sand deposits by interpolation. Application of computer-based Geographical Information System (GIS) for the creation of digital elevation models of the surface as well as bedrock configurations has helped in the estimation of the thickness and volume of the economic mineral bearing red sands in the area. The study revealed the potential of the synergistic application of the conventional geophysical and modern GIS techniques.

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Dr. K. Nageswara Rao is working as Professor in the Department of Geo-Engineering, Andhra University, Visakhapatnam. He has about three-decades of teaching and research experience in the evolution and dynamics of deltas, sea level changes, coastal zone management, and environmental issues involving geomorphological and land use / land cover analyses using remote sensing and GIS techniques. He has published more than 50 research papers and visited several countries like USA, Japan, Thailand, and Vietnam on research assignments.

Dr. Ch. Udaya Bhaskara Rao is working as Assistant Professor teaching Remote Sensing, GIS and Geomorphology in the Department of Geography, Mizoram University, Aizawal for the last two years. He has obtained his M.Sc. degree in Geography with geomorphology specialization in 1991, and Ph.D. degree in 1998 from Andhra University, Visakhapatnam for his thesis entitled "Quaternary evolution and environmental degradation of coastal sediments of Visakhapatnam, east coast of India". He has published research articles in several national and international journals.

Mr. T.Venkateswara Rao, graduated in Civil Engineering in 1997 and obtained M.Tech. degree in Remote Sensing from Andhra University, Visakhapatnam in 1999, has worked as a Project Manager in VIRGO for 8 years in the fields of Digital Mapping Solutions, Photogrammetric Analysis, Interpretation of Satellite Imagery and 3-D Analysis and modeling of the terrain for Civil Engineering applications. At present, he is working for his Ph.D. degree in the Department of Geo-Engineering, Andhra University on Watershed Management for Visakhapatnam Urban region.