

Characterizing the estuarine riverbed using remote acoustic technique

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Abstract-We have acquired single transect of multi-beam bathymetry and backscatter data from Mandovi estuary of Goa for three days during the pre-monsoon session. The measurements were made during the high-tide. In this work, non-linear statistical technique e.g., 'Hurst exponents' were estimated using bathymetry and backscatter data. We have chosen seven study blocks from estuary to river side of the bed. The selected bed features are: outer ripple and interesting feature from the shoal area, two ripple bed blocks from inner part of the river channel, bed area closed to the pool, and two river bed blocks identified at middle part of the river, and near the Jetty. Our present analyses relate estimated 'Hurst exponents' parameters with the bed load and other physical characteristics.

I. INTRODUCTION

The riverbed is dynamic and prone to temporal and spatial variations as a result of the various processes that affect it [1]. Traditionally riverbed characterizations were carried out using in-situ sampling, which is time consuming and therefore, remote acoustic techniques can be employed. In this study, riverbed characterization has been carried out using geostatistics and non-linear techniques. These methods have been applied to bathymetry and backscatter data collected using multi-beam echo sounder (EM 1002, M/s Kongsberg) operating at a frequency of 95 kHz, installed onboard the Coastal Research Vessel (CRV) Sagar Sukti.

'Hurst exponents' (H) can be used to determine roughness of the topography and characterize it [2]. It provides realistic description of the structures in geology and geophysics than the Euclidean geometry. In this study, 'Hurst exponent' parameters were estimated using semivariogram method [3]. The aim of this study is to investigate the statistical properties of the Mandovi estuary bed topography. This river is a major part of the estuarine system in Goa on the west coast of India (Figure 1), and has been studied as a tide-dominated coastal plain estuary. During the pre-monsoon period three surveys were conducted for six kilometer length towards the sea-side of the estuary. We have collected multi-beam data for three days viz. Match 21, May 4 and May 16 of 2007. Present study involves analysis of processed bathymetric and backscatter dataset from the seven spatially segmented blocks covering seaward ripple bed, shoaling areas, pool systems, and inner ripples etc. In order to estimate 'Hurst exponent' semivariogram function is used. 'Hurst exponent' parameters [4] of the backscatter and bathymetry data have been computed to characterize the estuarine bed features and relate it to the physical processes of the sedimentation.

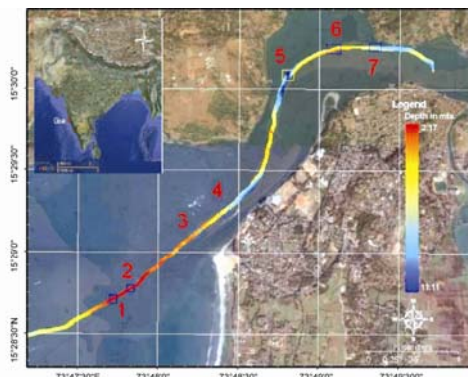


Fig. 1: Mandovi Estuary and location of the seven study blocks

We have estimated ‘Hurst exponent’ of riverbed (depth varying from 2-11m) geomorphic features derived from the seven selected blocks using suitable grid spacing. Again, in order to understand the riverbed processes and related sediment movement in spatial and temporal terms during peak tide condition estimated ‘Hurst exponent’ parameters were compared with sediment bed load. This paper comprises of the sections such as: Materials and Methods (section II) consist details about the study area settings, multi-beam data acquisition details, and estimation of ‘Hurst exponents’ of the bathymetry and backscatter data. Section III of ‘result and discussions’ provide data analyses, and section IV offers conclusions.

II. MATERIALS AND METHODS

A. Study area setting

The Mandovi River is around 80 km long and originates from a cluster of 30 springs at Bhimgad in the Western Ghats of the Karnataka state of India. It is a tidal-stream estuary, influenced by seawater inflow up to a distance of 40 km with freshwater runoff mainly during the south-west monsoon. Salinity parameter of the river varies sharply during the monsoon and other seasons and so does the physicochemical quality of the river. The river Mandovi enters Goa from the north via the Sattari Taluka, and flows through Cumbarjua, Divadi and Chodné, eventually pouring into the Arabian Sea. Mandovi joins with another river Zuari at a common point at Cabo Aguada, forming the Marmugoa harbor. Seven study blocks (Figure 1) have been selected based on the observed features (Figure 2). They are referred as blocks: (1) outer ripples in the proximity of the Aguada shoaling area, (2) shoaling area having lowest water depth closed to Aguada sand bar, the blocks (3) and (4) consisting of ripple bed inside the navigational channel lying within the proximity of Reis Magos bar, (5) pool system near the navel jetty, (6) mid river channel, and (7) off Panaji jetty.

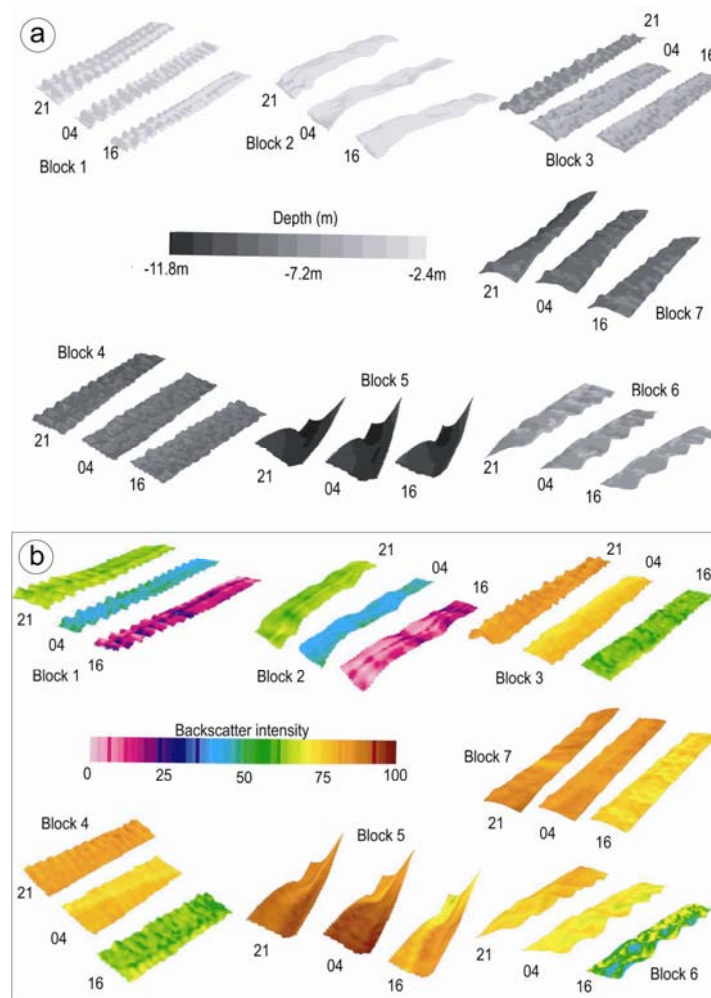


Fig. 2: Feature map of the seven study blocks; (a) bottom surface; (b) backscatter draped bottom surface (21, 04, 16 indicate March 21, May 04 and May 16 of 2007, when data was acquired)

Mandovi estuary is a funnel shaped estuary that exhibits a wide mouth (3.2 km distance between the Aguada and Cabo headland), narrowing a short distance upstream (within 4 km upstream it narrows down to ~1 km) and characterized by the presence of two shoaling bars viz. the Aguada and Reis Magos bar. Sea-waves from the deepwater enter the bay and approach the shores of the Mandovi mainly from the west and south west during monsoon. During fair-weather seasons, it enters the bay from the north-west. The bay is partially sheltered by Aguada headland to the waves coming from north-west. The wind speed and tide data were measured at Verem jetty (Figure 3) by use of Automatic Weather Station (AWS) [5].

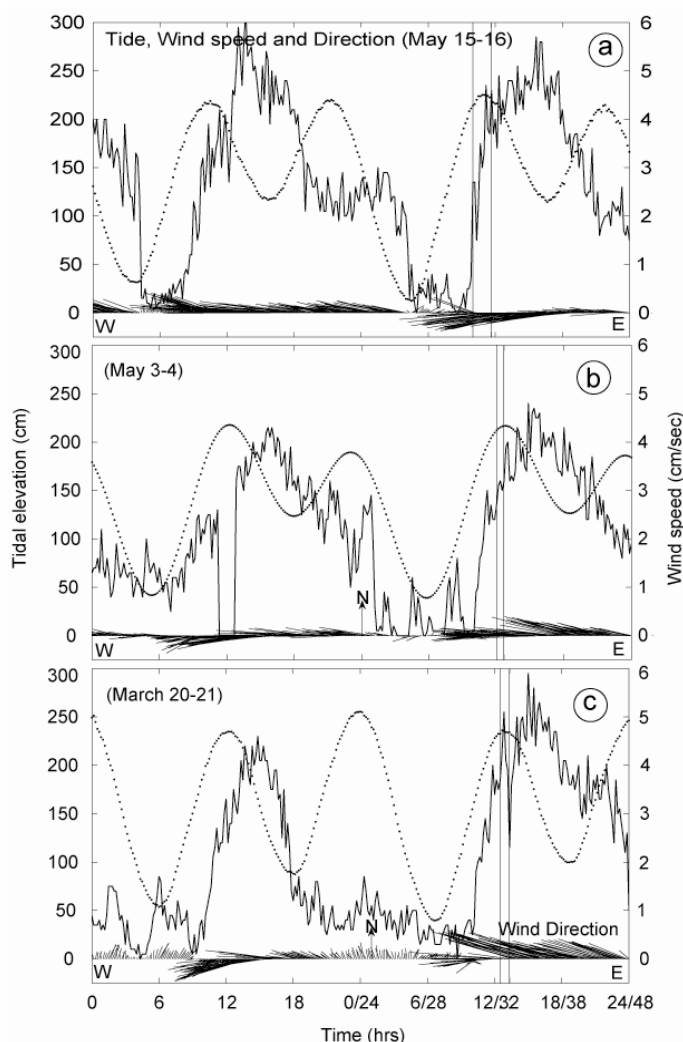


Fig. 3: Tidal elevation (cm); Wind speed (cm/sec); Wind direction during (a) May 15-16; (b) May 3-4; (c) March 20-21 of 2007.

Mandovi estuary is affected by mixed semidiurnal type tides with pronounced diurnal irregularity and large differences between the successive flood and ebb tides. The current velocity gradually increases from mouth to middle reaches of the estuary (7-11 km), but further ahead the velocity decreases during all the three seasons (monsoon, pre and post monsoon). During the pre-monsoon the average salinity in the estuary is high and saline water influences practically the entire length of the estuary, showing the marine dominance in the estuary. During the monsoon Mandovi sustains a large amount of fresh water influx. The estuary is well stratified during the monsoon and mixed during the pre-monsoon [6].

Fine sediment is generally transported as suspended load dispersed in the entire vertical column. When in suspension they tend to travel a considerable distance before they are accumulated (flocculation). Coarse sediment moves as thin layer along river/estuary bed. Contrary to suspended load, the average distance traveled between erosion and deposition is relatively short. The concentrations of the suspended particulate matter (SPM) are low towards the upstream, which increase generally seaward. These are the two of the windiest times, the former associated with the southwest monsoon and the latter characterized by a persistent sea breeze [7].

B. Data acquisition

Six km of single line multi-beam data was acquired in the Mandovi estuary using multi-beam system (Figure 1). Bathymetric surveys were conducted during peak tide and the data were tide corrected. The draft of the CRV Sagar Sukti is 3.34m (including multi-beam system's arc shaped array transducer), which is installed at the fore part of the vessel. Because of this situation, the survey could be conducted only within the relatively deeper part of the river, and navigation above shoaling areas could only be carried out during the peak tide. The raw bathymetry data was cleaned and then gridded (grid cell size 0.25m) to create a 2D matrix structure using Neptune software. The generated grids were imported into ArcGIS. The map features were scaled to 2000 map scale. The map was then projected to Universal Transverse Mercator (UTM) in meter scale. To visualize the topography of the area, a raster Digital Terrain Model (DTM) was generated. The DTM was rendered into 2D space through perspective projection. This pre-processing helps in extracting datasets overlapping in three experiments. Seven study blocks are chosen for present study, are identified as blocks. Bed load parameters were calculated using 3-dimensional surface area (volume) for each of the blocks, which were normalized with respect to the block area (volume/m²) (Figure 4). Volume is calculated using linear interpolation to the area and volume of the blocks of the surface lying between the specified base value and the highest point from the TIN model.

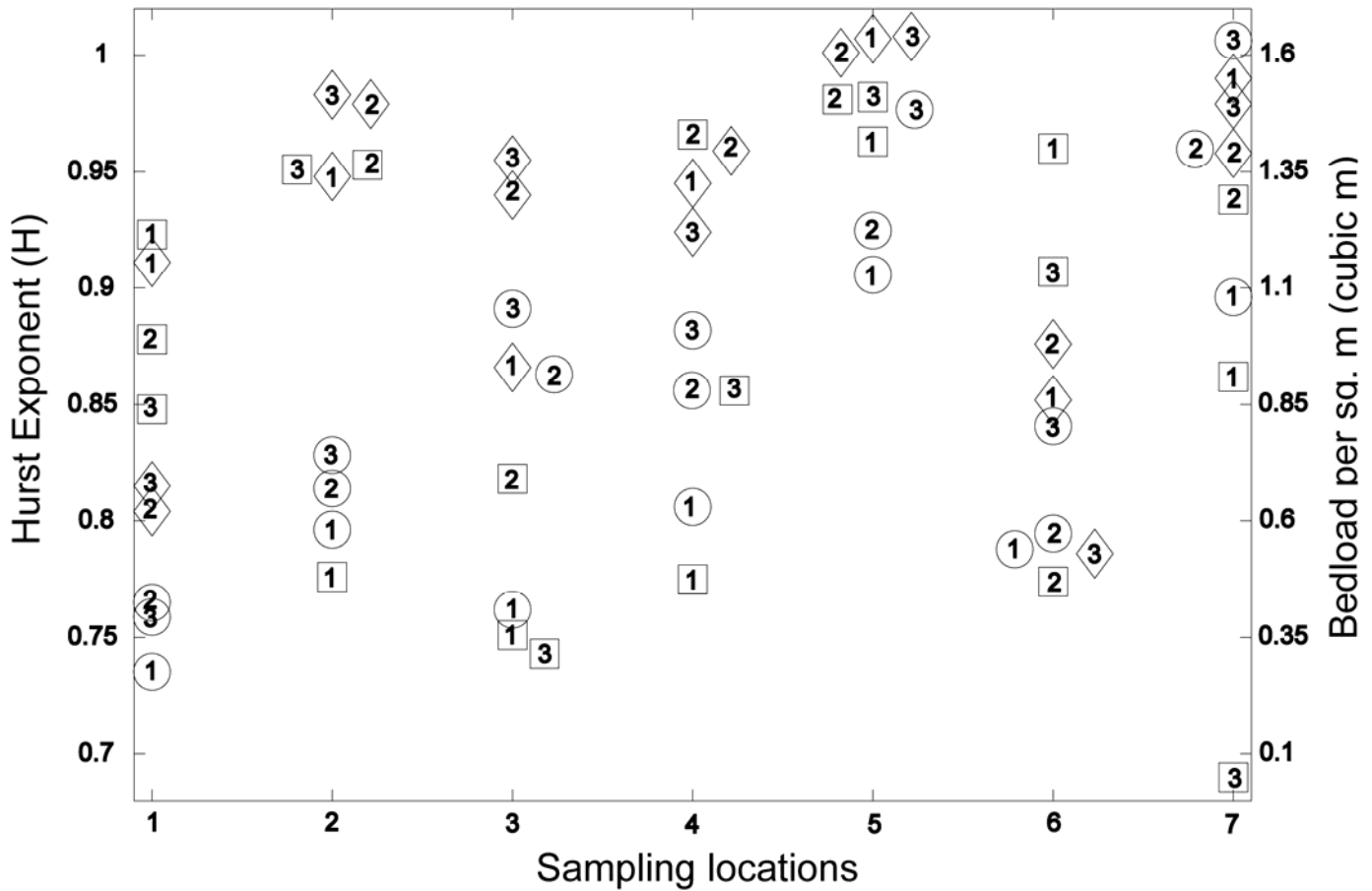


Fig. 4: Scatter Plot of Hurst Exponent (H) of Bathymetry (◇), Backscatter (□) and Bedload (○) for the seven study blocks. Nos. 1,2,3 inscribed indicate the dates of data acquisition – March 21, May 04 & May 16 of 2007 respectively.

The EM1002 multi-beam echo-sounding system possesses 111 preformed beams i.e., recording 111 depth values in a single ping. In addition to the depth, the system also records quantitative backscatter data, which are utilized to generate backscatter imagery for studying the spatial distribution of the riverbed texture. In image processing technique, texture provides a measure of coarseness, smoothness or regularity. The depth values were recorded in meters (m) and backscatter strengths were recorded in decibels (dB) [8]. In order to accomplish the normalization of the backscatter data for further improvement a program named *PROBASI (PROcessing BACKscatter SIGNAL) II* has been developed [9].

C. "Hurst exponent" (H) estimation

The data from the seven blocks used in this study contain information about depth and backscatter intensity along with the position, which can suitably be used for semivariogram analysis. Present study has utilized BENOIT 1.3 - Fractal Analysis System software (SCION Corp., TruSoft, International Inc., 1999). For semivariogram analysis, traces were selected from each study block. From these, the 'Hurst exponents' (H) were estimated along with the standard deviation. The detrended backscatter and bathymetric data were utilized for estimation. Figure (5) show the example of representative fitted curves obtained using the Benoit software.

The 'Hurst exponent' (H) or the roughness parameters takes a value between the 0 and 1. When 'H'~0.5, we obtain usual Brownian motion. For self-affine time or space series, 'Hurst exponent' near the 'zero' or lower values indicate the rough data, whereas for higher 'H' values i.e., 'H' ~ 1 indicating smooth data. When 'Hurst exponent' value is equivalent to the 0.5, there is no correlation between the amplitude and time / space parameter changes of the series (signifying unpredictable processes).

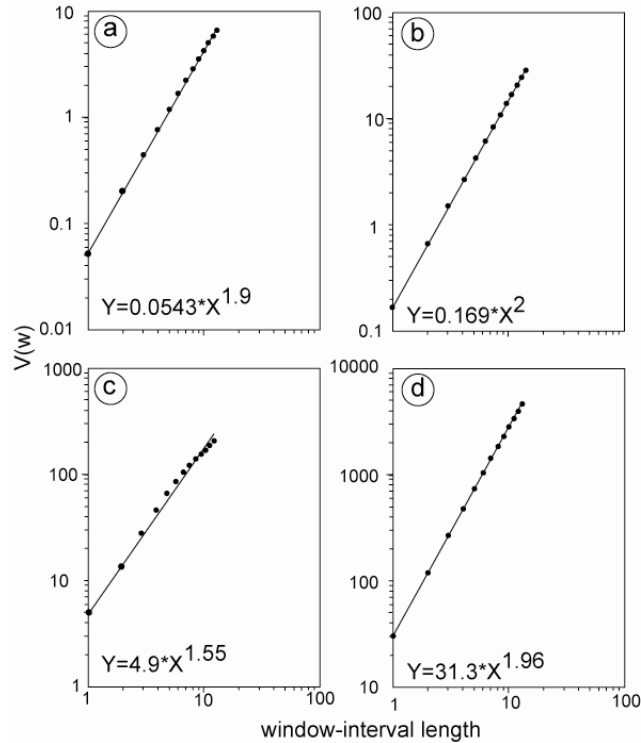


Fig. 5: Representative Variograms of Bathymetry (top) & Backscatter (bottom) data of Blocks 2 (left) & 5 (right) acquired on March 21 & May 04 of 2007 respectively

III. RESULTS AND DISCUSSIONS

The semivariogram function of the bathymetry and backscatter traces from the blocks provides 'Hurst exponent' with power law fitting and related standard deviations. The backscatter data were normalized within the acquired highest value, and the bathymetry and backscatter traces were detrended. Figure (2) shows bathymetry and backscatter features of the study blocks. However, both the data were exaggerated suitably to visualize the features i.e., scaling is not uniform for all the features.

A. Ripple bed within the shoaling area (block 1)

The block is situated at the distance of 360m from the 5m depth contour of the shoal area (Figure 1). The histograms and statistical mean of the backscatter data of this block clearly indicates that the backscatter intensity decreases as the monsoon approaches. This may be due to the fine sediment deposition having less acoustic backscatter. The mean depths of this ripple bed block are measured to be 3.58m, 3.44m, and 3.48m for 21 March, 04 May and 16 May respectively. The mean depth data corroborates very well with the bed load. However, due to the increased amplitude of the wind speed (as recorded on 16 May) (Figure 3), suspended particulate matter (SPM) is higher [7] towards the seaward end which contributes towards the transport and settling of fine bed sediment. This in turn reduces the backscatter strength. Estimated 'Hurst exponent' (H) parameters of the backscatter and bathymetry traces indicate smooth ripple bed (Figure 4). It means the surface is generally smooth and slowly becomes rough (albeit negligibly) as the monsoon progresses. Overall, outer ripple bed remains smooth and shows signs of deposition of fine material having low backscatter.

B. Shoaling area having lowest water depth near Aguada sand bar (block 2)

This block is situated within the 10m distance from the previously mentioned ripple bed area. Feature wise the bed morphology is different (Figure 2) having higher bed wavelengths and occasional scour due to erosion [10]. Backscatter intensity values are gradually decreasing as the monsoon approaches. Bed load values also show increasing trend with sediment deposition (low acoustic backscatter) (Figure 4). The 'Hurst exponent' value of the backscatter data negligibly increases indicating smooth bed condition as the monsoon approaches. The mean depth (3.00 -2.90m) remains the same without any appreciable variations. The increasing bed load values do not corroborate well with almost constant 'Hurst exponent' value of the depth data. A critical look at Figure (2) indicates no change in the bed morphology even there is an increase in the bed load as the monsoon nears. However, for backscatter data SPM depositions indicate smooth bed texture.

C. Ripple bed blocks inside the navigational channel lying within the proximity of Reis Magos bar (blocks 3 and 4)

Inner channel ripple bed (block 3) is situated at a distance of 970m away from block 2. The mean water depths are measured to be 6.10m, 5.60, and 5.44m for 21 March, 04 May, and 16 May respectively. Corresponding bed load parameters also show a heavy deposition of material between 21 March and 04 May (Figure 4). Backscatter intensity data show initial higher intensity that subsequently decreases as monsoon progresses. Interestingly, the decrease in backscatter strength is comparatively less in comparison with the previous two shallow blocks. The tidal and wind amplitude levels are lower (Figure 3) on 04 May than the 16 May even though the bed loads are increasing (Figure 4). Based on the 'Hurst exponent' values estimated from the backscatter data of the riverbed, it is observed to be smooth on 04 May than the 21 March and again becomes rough on 16 May (though negligibly). This is further confirmed by the observed sediment deposition over ripple like feature of the riverbed and the subsequent smoothing (Figure 2). The surface smoothing could possibly be due to the depositional processes that could be inferred from the higher bed load / SPM. Though, the bed roughness reduces on 04 May and again increases on 16 May, it may be related to high amplitude level of the tidal and wind. For bathymetry data, initial 'H' parameter shows low value that increases by 04 May and remains steady until 16 May indicating that the river bed is smooth.

Block 4 inside river channel is situated 243m away from study block 3. The mean water depth shows 7.7m, 7.41 and 7.23 m for 21 March, 04 May and 16 May respectively. Though, the mean backscatter intensity is initially higher on 21 March, however, decreases slowly. Temporal change in bathymetry show decrease in depth over time, but bed load show significant increase in volume. This is indicative of sediment depositional processes. The roughness of the river bed is possibly due to the ripple like formations observed on the riverbed on 21 March, which becomes smoother as shown by a decrease in 'Hurst exponent' of backscatter data. There is no appreciable temporal variation in bed roughness as indicated by the "Hurst exponent" of the bathymetry data estimated for the three days i.e., the depositional process is not affecting the "Hurst exponent" parameter of the inner ripple block. However, backscatter data shows minimal reduction of bed roughness up to 04 May, and thereafter indicating a decrease.

D. Pool system near the Navel jetty (block 5)

As the thalweg or trace formed by the deepest portion of the channel, changes from side to side within the channel, the momentum of the flow affects the cross-sectional geometry of the river. In the bends, there is a concentration of flow due to centrifugal forces. This causes the depth to increase at the outside of the bend, and this area is known as a pool. Such pool system is observed near the Naval jetty opposite to Panaji city towards the northern side along the right bank of the river. Using multi-beam system, the depth of this pool system is measured to be 9.95m, 9.89m, and 9.60m on 21 March, 04 May and 16 May respectively. This block (5) is situated 1492 m away from previous ripple bed block (Figure 2). The bed load (Figure 4) is exceedingly higher on 21 March, and thereafter moderate increase is observed. The 'Hurst exponent' values show extreme values (~1.0) for the three measurement days indicating that the area is extremely smooth. Here, the 'Hurst exponent' using backscatter data are found to be equivalent to the parameters estimated of bathymetry data i.e., ~1.0.

E. Mid river channel (block 6), and off Panaji jetty (block 7)

This study block (6) is situated around 633m away from the previous block (5) i.e., pool system (Figure 1). The mean water depth of this block changes from 5.70m, 5.70, and 5.40m on 21 March, 04 May and 16 May respectively i.e., the depth changes only after 04 May. The bed load is moderate for the initial two measurement days and increases to higher value on 16 May. Backscatter intensity show a decrease from 21 March to 04 May, however, by 16 May considerable decrease is seen. As observed that the tide and wind amplitude levels are also significant on 16 May, therefore it is difficult to mention whether the decrease in backscatter intensity is due to the increase in the bed load or SPM. The 'Hurst exponent' parameters using bathymetry data provide almost constant value within the mid river study block during the pre-monsoon experiment days except for higher roughness on 16 May. The 'Hurst exponent' parameter of the backscatter data show increase in bed roughness on 04 May and again reduces by 16 May. These results affirm that the bed load and 'H' parameters of the bathymetry blocks are well correlated whereas for backscatter data the bed load do not correlate well with the 'H' parameter.

Block 7 closed to Panaji jetty is situated towards the southern end of the river towards the right bank of the river at 335m away from the mid river study area. The mean water depths are observed to be 8.0m, 7.63m, and 7.40m for 21 March, 04 May and 16 May respectively. Depth data shows considerable variations over time. There is considerable decrease in the depth of the riverbed and the bed load parameters also show considerable increase. However, 'Hurst exponent' parameters does not indicate changes in bed roughness using bathymetry data, which is extremely smooth throughout even though the bed load is increasing. Using backscatter data, the bed surface roughness is changing from smooth to rough by 16 May ('Hurst exponent').

IV. CONCLUSIONS

Increase in the bed load is not the same in all study blocks indicating that the deposition process is not uniform in all parts of the estuary region of the Mandovi during pre-monsoon. The estimated 'Hurst exponent' parameters indicate that the bed roughness does not follow a particular pattern throughout the river. Few blocks indicate bed smoothening while few have indicated increase in the bed roughness. Overall, the present study has further strengthened the idea that the Geostatistical analysis on bathymetry and backscatter data can provide valuable information such as nonlinear processes.

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