Characterizing Gully Morphology using Structure from Motion-Multi-View Stereo (SfM-MVS) technique in Garhbeta Badlands, West Bengal, India

Atrayee Biswas[1], Sunando Bandyopadhyay[1] and Abhijit Chakraborty[2]
[1]Department of Geography, University of Calcutta, Kolkata, India
[2]Department of Geology, Jogamaya Devi College, Kolkata, India

Abstract— **One of the principal causes of geo-environmental degradation in the humid tropics is gully erosion, reducing the productivity of land and increasing sediment discharge in rivers. Although there is extensive literature on gully erosion, less attention has been given to the study of gully morphology than to the factors responsible for gully initiation. The present work aims to analyze the effectiveness of modelling a single gully channel in Garhbeta badlands of West Bengal, India, with high-resolution topographic data derived from Structure from Motion-Multi View Stereo (SfM-MVS) using Canon EOS 60D camera and simultaneously extract cross-sectional properties of gullies. This close-range photogrammetric technique uses an image-matching process, whereby multiple overlapping offset images of the same surface is taken from different positions to generate a 3D object system. Markers were distributed along the gully length and the coordinates of these ground control points (GCPs) were established using Total Station and GPS. The 3D dense, point cloud obtained from SfM-MVS was used to create a high-quality DEM data and cross-sectional profiles were extracted at regular intervals along the gully length to measure morphometric parameters of the gully. Such close-range photogrammetry provides a very cost-efficient means of acquiring high-resolution topographic data, essential in the analysis of gully morphology and its response to the underlying lithological properties as this is crucial to the understanding of the gully development processes.**

I. Introduction

The recognition of spatial patterns and their temporal changes forms a key element of any research in geosciences, the essential requirement of which is a high-resolution topographic data to quantify landform variability. In recent years substantial advancement has been made in the acquisition of 3D terrain models, with the focus having shifted from traditional photogrammetric and topographic survey methods (using Total Stations and dGPS) which are laborious and often challenging in remote and inaccessible areas to superior quality, high-resolution data using airborne (LiDAR) and terrestrial laser scanners (TLS). However, these too pose their own challenges due to the high capital investment cost and specialized expertise of users for data acquisition and processing. In contrast, the Structure from Motion-Multi-View Stereo (SfM-MVS) technique, which amalgamates the advances made in computer vision and photogrammetry, provides a cost-effective means of acquiring high-quality, dense, 3D point cloud of landforms using digital cameras and smartphones. This close-range photogrammetric technique creates 3D structure using multiple overlapping offset images similar to stereoscopic photogrammetry. The principal advantage of SfM-MVS is that it can calculate the scene geometry, camera positions and orientation automatically without the prior knowledge of the 3D positions of ground targets. Numerous studies provide a detailed workflow of the SfM-MVS technique, including examples showing its applicability in the study of glacier landforms, riverbank erosion, alluvial fan deposition, coastal cliff erosion [1,8,12,13,16]. This close-range digital photogrammetric technique has been used extensively in badland terrain modelling to study gully erosion rates, headwall retreat, soil loss estimation, quantifying landscape changes due to episodic rainfall events and long-term surface changes of badlands [5,9,15,16,17,18]. The accuracy of the SfM-MVS derived 3D model has been compared to those of airborne (LiDAR) and terrestrial laser scanners (TLS), revealing that ground based SfM-MVS is more capable in quantifying gully characteristics [2,10].

In the present work the SfM-MVS technique has been applied to generate a high-resolution topographic data from overlapping offset images recorded from multiple viewpoints along the length of a single gully channel. The processing was done in three chunks which were later combined to produce a high-resolution DEM of the gully channel. The main aim of this study is to assess the effectiveness of the SfM-MVS derived DEM data in the study of gully morphology in humid tropics where soil erosion is a significant cause of geo-environmental degradation. For this purpose, multiple cross-sections were extracted from the DEM data at regular intervals from the gully head to gully mouth and morphometric parameters describing the shape of the gullies were measured. The characterization of gully morphology is crucial not only for the estimation of erosion rates but also for understanding the underlying factors and mechanism of gully erosion and development.

II. STUDY AREA

The study area, also known as the Ganganir Danga, is located in Paschim Medinipur district of the Indian state of West Bengal (Fig. 1). Here, the Shilabati River has eroded its concave bank leaving a laterite capped escarpment incised by numerous gullies to form a typical badland topography. The area receives an average annual rainfall of 140 cm, with most of it occurring during the southwest monsoons. The soil profile shows all the horizons which are typical of a lateritic soil profile. There is a superficial cover of red clayey soil underlain by duricrust formed from the cementation of ferruginous concretions and quartz grains with colloidal iron oxide. At places, the retreating gullies have exposed the mottled clay horizon comprising a mixture of sand, silt and clay in various proportions along with iron oxide and hydroxide spots and concretions. Below this is the pallid zone, which is characterized by yellowish white clay, containing very little sand and iron oxide.

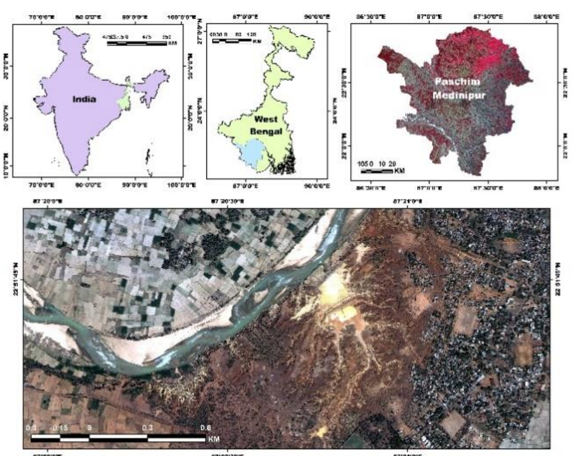

Figure 1. Location map of the study area

III. METHODOLOGY

For this photographic modelling a single gully channel was selected, and fieldwork was conducted during the winter months to reduce the obstruction posed by vegetation. However, where necessary, vegetation such as the short grasses along the gully walls and bottom were removed manually and the field site was prepared prior to collection of photographs. Markers were distributed at regular intervals along the gully walls and bottom and the coordinates of these Ground Control Points (GCPs) were established using Total Station and GPS. Photographs were then collected using the Canon EOS 60D camera (APS-C CMOS Sensor) with EF-S 18-55 mm STM lens and a constant focal length of 18 mm, from multiple viewpoints with a minimum of 50-60% overlap between consecutive images required to create the parallaxes for the 3D rendering. Considering the length of the gully, care was taken to conduct the survey under constant illumination conditions, while also avoiding the user's shadow when collecting the photographs.

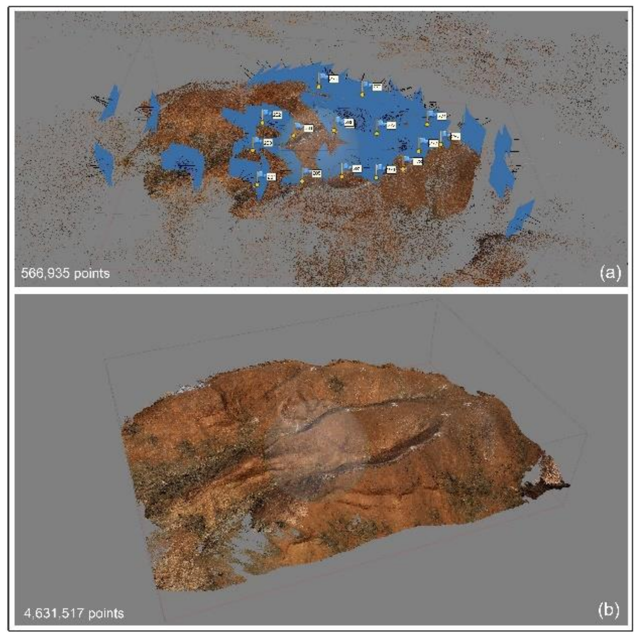

Figure 2. .Perspective views of the gully head region (a) Sparse point cloud with location of cameras and GCPs marked (b) Dense point cloud.

The initial step in image matching is the identification of common features in individual photographs, called 'keypoints' which are invariant to changes in scale and orientation and are required for wide baseline matching [1]. The Scale-Invariant Feature Transform (SIFT) object recognition system detects keypoints that are invariant to image scaling, changes in illumination conditions and camera positions and assigns a descriptor to each keypoint by computing the dominant direction of local intensity gradients using Gaussian weighting function [5,11,14,16]. Once the keypoints are identified, the geometrically inconsistent keypoint matches are eliminated using Random Sample Consensus (RANSAC), whereby all the keypoints are divided into two groups – outliers and inliers [1,4,16]. The RANSAC, through several iterations tends to generate a model which ignores all outliers and is composed singularly of inliers. A bundle adjustment then uses these geometrically correct feature correspondences to simultaneously reconstruct the 3D scene geometry (or structure) and the camera positions (motion) and generate a low-density 'sparse' point cloud. The 3D scene geometry is incrementally reconstructed using triangulation to estimate the 3D point positions, while the camera positions and orientation is reconstructed by means of a similarity transformation, using non-linear least squares method. The Multi-View Stereo (MVS) produces a dense point reconstruction of 3D scene geometry using the sparse point cloud produced by SfM as an input [1,6,7]. The clustering views for MVS (CMVS) decomposes the sparse point cloud into overlapping clusters to reconstruct each 3D point by at least one cluster thereby increasing the point density.

The 3D dense point cloud thus generated needs to be converted from a relative 'image space' coordinate system to a real world 'object space' coordinate system. This transformation was done by manually identifying the GCPs in the dense point cloud and incorporating the UTM-WGS 1984 coordinates into the model. All the artefacts were removed from the dense point cloud at this stage. The entire process was completed using Visual SfM, Cloud Compare and Agisoft Metashape softwares. The dense point cloud was then exported to a GIS platform to generate the final very high-resolution DEM.

Several cross-sectional profiles were extracted from the DEM along the gully length at regular intervals to measure the gully morphometric parameters, such as, gully top width (Wt), left width (Wl), right width (Wr), maximum depth (Dmax), depth of left side (Dl), depth of right side (Dr), area of left side (Sl), area of right side (Sr), total area of cross-section (S). [3].

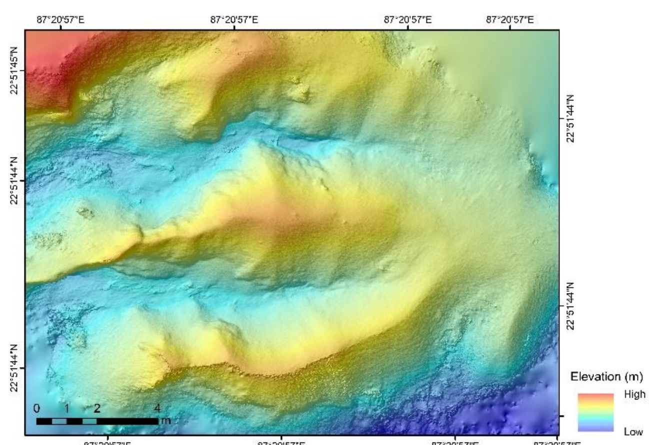

Figure 3. DEM derived from the dense point cloud for the gully head region.

IV. RESULTS & DISCUSSION

Figure 2a shows the locations of the cameras and the GCPs on the sparse dense cloud, where the black lines show the directions from which the photographs were taken, while the little blue flags show the location of the GCPs which were marked on the ground during field survey. The reconstruction of the dense point cloud (Fig. 2b) significantly increases the point density, with the number of points increasing from 5,66,935 in case of sparse point cloud to 46,31,517 in that of dense point cloud. Figure 3 shows the interpolated high-resolution DEM derived from the dense point cloud, with 10 cm cell size. The two gully heads are distinctly visible in the DEM with the lateritic outcrop jutting out between them. To reduce the computational size and processing time, the SfM-MVS model was prepared separately for three sections of the gully and later integrated to construct the DEM for the entire gully channel (Fig. 4). The elevation ranges from 35 m near the gully bed to 66 m near the gully walls adjacent to the gully head. To assess the accuracy of the DEM derived from SfM-MVS, several cross-sections were measured using the Total Station, which were then compared to those derived from the model (Fig. 5)..

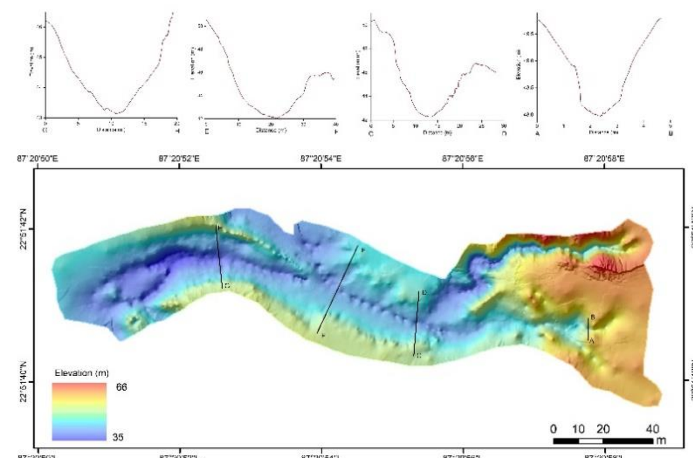

Figure 4. DEM of the total gully channel with some representative cross-sections. Lines AB, CD, EF, GH shows the location of the profiles.

For any analysis of the processes of gully erosion and gully development, it is imperative to make a comprehensive study of the morphological character of the gully. Multiple cross-sections were extracted from the DEM at regular intervals along the entire length of the gully. The morphometric parameters measured from these cross-sections are shown in Figure 6 with the help of a sample cross-section. The three primary parameters measured such as, gully top width (Wt), depth (Dmax) and cross-sectional area (S) represents the overall shape of the gully. Other parameters such as, left width (Wl), right width (Wr), depth of left side (Dl) and right side (Dr), area of left side (Sl) and right side (Sr), describes the asymmetry in the erosional process between the two gully walls. The ratio of width to depth is an important parameter which describes the relationship between lateral erosion and vertical incision along the gully. The overall shape of the gully undergoes a change from very deep V-shaped valleys near the gully head to shallow V-shaped valleys near the gully mouth. In the middle section where undercutting is predominant, collapse of the overlying sediments produces broad U-shaped valleys (Fig. 4).

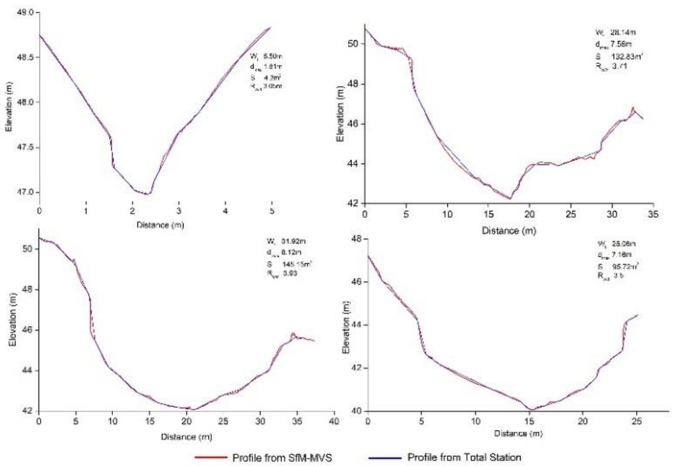

Figure 5. Cross-section comparisons between Total Station (TS) data and SFM-MVS derived DEM data for similar profiles along the gully channel.

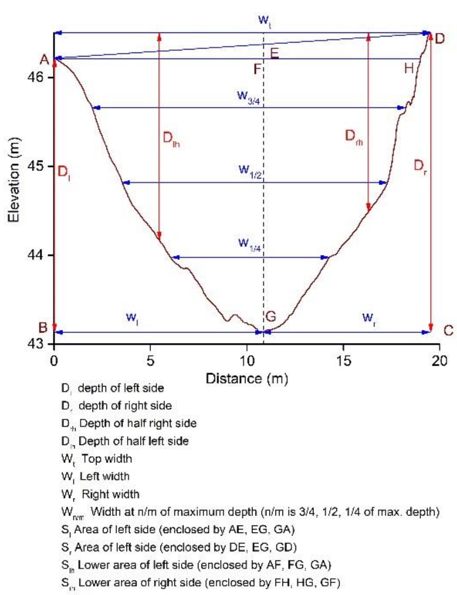

Figure 6. Morphometric parameters measured from a gully cross-section.

V. CONCLUSION

Badland topography is characterized by vertical walls and steep rugged slopes where traditional survey methods using Total station and GPS becomes arduous and challenging. Under these circumstances, close-range photogrammetric technique or SfM-MVS provides a low-cost, portable alternative to acquire a high-resolution DEM where the workflow remains identical irrespective of the temporal and spatial scales. Applying SfM-MVS over large spatial scales creates large data sets and long computational times, also the accuracy of the model depends on external factors like the texture and colour contrast of the landform and the illumination conditions raising issues of repeatability. However, for smaller areas it is very efficient in providing a very high-resolution topographic data which can be used for mapping, analysis of geological structures and as an input to numerical models to study landform development processes.

VI. ACKNOWLEDGMENTS

The authors would like to thank the Department of Geography, University of Calcutta and the Department of Geology, Jogamaya Devi College and those who have assisted in the field work.

REFERENCES

[1] Carrivick, J. L., Smith, M. W., Quincey, D. J., 2016. "Structure from Motion in the Geosciences, New Analytical Methods in Earth and Environmental Science. Wiley Blackwell, UK.

[2] Castillo, C., Pérez, R., James, M.R., Quinton, J.N., Taguas, E.V., Gómez, J.A., 2012. "Comparing the accuracy of several field methods for measuring gully erosion. Soil Sci. Soc. Am. J. 76 (4), 1319–1332. doi.org/10.2136/sssaj2011.0390.

[3] Deng, Q., Qin, F., Zhang, B., Wang, H., Luoa, L., Shu, C., Liu, H., Liu, G., 2015. "Characterizing the morphology of gully cross-sections based on PCA: A case of Yuanmou Dry-Hot Valley. Geomorphology. 228, 703–71. doi.org/10.1016/j.geomorph.2014.10.032.

[4] Fischler, M. A. and Bolles, R. C., 1987. "Random Sample Consensus: a paradigm for model fitting with applications to image analysis and automated cartography. In: Martin, A.F., Oscar, F. (Eds.), Read. Comp. Vision: Issues, Problems, Principles, and Paradigms. Morgan Kaufmann Publishers Inc., UK, 726–740.

[5] Frankl, A., Stal, C., Abraha, A., Nyssen, J., Rieke-Zapp, D, DeWulf, A., Poesen, J, 2015. "Detailed recording of gully morphology in 3D through image-based modelling. Catena, 127, 92-101. doi.org/10.1016/j.catena.2014.12.016.

[6] Furukawa, Y., Ponce, J., 2007. "Accurate, dense, and robust multi-view stereopsis. Proc. IEEE Conf. Comp. Vision and Pattern Recog. (CVPR), 1–8.

[7] Furukawa, Y., Curless, B., Seitz, M., Szeliski, R., 2010. "Clustering view for multi-view stereo. Proc. IEEE Conf. Comp. Vision and Pattern Recog. (CVPR), 1434–1441.

[8] James, M. R. and Robson, S., 2012. "Straightforward reconstruction of 3D surfaces and topography with a camera: Accuracy and geoscience

application. J. Geophys. Res. Earth Surf, 117, 1–17. doi:10.1029/2011JF002289.

[9] Kaiser, A., Neugirg, F., Rock, G., Müller, C., Haas, F., Ries, J., Schmidt, J., 2014. Small-scale surface reconstruction and volume calculation of soil erosion in complex Moroccan gully morphology using structure from motion. Remote Sens. 6, 7050–7080.

[10] Koci, J., Jarihani, B., Leon, J. X., Sidle, R. C., Wilkinson, S. N., Bartley, R., 2017. "Assessment of UAV and Ground-Based Structure from Motion with Multi-View Stereo Photogrammetry in a Gullied Savanna Catchment. ISPRS Int. J. Geo-Inf. 6, 328.

[11] Lowe, D., 2004. "Distinctive image features from scale-invariant keypoints. Int. J. Comp. Vision, 60, 91–110.

[12] Micheletti, N., Chandler, J. H., Lane, S. N., 2014. "Investigating the geomorphological potential of freely available and accessible structure-from-motion photogrammetry using a smartphone. Earth Surf. Process. Landforms, 40(4), 473-486. doi: 10.1002/esp.3648.

[13] Micheletti, N., Chandler, J. H., Lane, S. N., 2015. "Structure from Motion (SfM) Photogrammetry. Brit. Soc. Geomorphology, Geomorpho. Tech., 2(2.2).

[14] Snavely, N., Seitz, S.N., Szeliski, R., 2008. "Modelling the world from internet photo collections. Int. J. Com. Vision, 80, 189–210.

[15] Stark, M., Neugirg, F., Kaiser, A., Seta, M. D., Schmidt, J., Becht, M., Haas, F., 2020. "Calanchi badlands reconstructions and long-term change detection analysis from historical aerial and UAS image processing. J. Geomorpho. doi.10.1127/jgeomorphology/2020/0658.

[16] Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J., Reynolds, J. M., 2012. "Structure from-Motion" photogrammetry: a low-cost, effective tool for geoscience applications. Geomorphology 179, 300–314. doi.org/10.1016/j.geomorph.2012.08.021.

[17] Yang, CJ., Turowski, J.M., Hovius, N., Lin, JC., Chang, KJ., 2021. "Badland landscape response to individual geomorphic events. Nat. Commun. 12, 4631. doi.org/10.1038/s41467-021-24903-1.

[18] Yang, CJ., Yeh, LW., Cheng, YC., Jen, CH., Lin, JC., 2019. "Badland Erosion and Its Morphometric Features in the Tropical Monsoon Area. Remote Sens. 2019, 11, 3051. doi.10.3390/rs11243051.